

TRINITY COLLEGE DUBLIN
THE UNIVERSITY OF DUBLIN

DOCTORAL THESIS

**Plasmonic Waveguides for
Sub-wavelength Light Confinement**

CHUAN ZHONG

*A thesis submitted in fulfillment of the requirements
for the degree of Doctor of Philosophy*



5th July 2018

Declaration of Authorship

I declare that this thesis titled, “Plasmonic Waveguides for Sub-wavelength Light Confinement” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

Abstract

Modern electronic devices and circuits for information processing are rapidly approaching their ultimate speed and bandwidth limitations, which is an increasingly serious problem that impedes their continued use in scientific and technological applications. One promising solution is believed to be integrating electronic and photonic components on the same chip. This technology provides large bandwidth which can be used to design novel broadband electronic-photonic devices. However, a major problem with using electromagnetic waves as information carriers in optical integrated circuits is the low level of integration and miniaturization, which are not at the same scale as modern electronics. This is a consequence of the diffraction limit of light in a dielectric medium, an optical principle that sets a lower limit on how much the cross-section of light can be reduced based on the refractive index of the material, which restricts the light waves being confined to nanoscale regions much smaller than its wavelength. Therefore, other approaches of guiding light at sub-wavelength scale have to be found. One possible solution is using surface plasmon polaritons (SPP), which can achieve sub-wavelength scale light confinement and highly localized electromagnetic field intensity. The particular integrated electronic-photonic technology which motivates this work is heat-assisted magnetic recording (HAMR) technology, which has the potential to be the driving force in the next generation of magnetic storage miniaturization. This technology combines a conventional electronic device, a perpendicular magnetic recording (PMR) read/write head, with a dielectric photonic waveguide and a plasmonic focusing element. There are a number of technical issues which must be overcome in order for this technology to become commercially viable.

In this thesis, both the theoretical and the experimental work on plasmonic focusing elements for subwavelength light confinement is presented. We experimentally excite SPP through a Kretschmann-Raether configuration, and use this platform to map the dispersion of SPP in thin Ag-Au films or varying composition. The second part of this thesis deals with the design of a near-field transducer (NFT) for HAMR. This requires design and fabrication of a nanoscale tip in which a plasmonic response is generated to write bits with size below $50 \text{ nm} \times 50 \text{ nm}$. Furthermore, the incident optical energy must be guided to the plasmonic NFT using an integrated dielectric waveguide. We design an

evanescent coupling system to efficiently extract the incident light from the dielectric waveguide core to the NFT. Our design is larger scale than other proposed designs, resulting in easier fabrication, better thermal stability and better extinction of undesired optical energy continuing in the dielectric waveguide. The coupling process is optimized to maximize the electromagnetic intensity in the NFT while minimizing intensity remaining in the dielectric waveguide to avoid the miswriting of a magnetic bit in the recording medium. The final research topic includes improving the plasmonic performance of Au film. Investigations involve using an Ag-Cu-Au combined film to achieve a tunable dispersion property which can produce a superior plasmonic performance. Moreover, thin metallic layers as adhesion and capping layers will improve the excitation of the SPP mode of the NFT without degrading plasmonic performance when excited by strong optical field.

Keywords: Surface plasmon polaritons; Plasmonic waveguides; Sub-wavelength light confinement; Near-field transducer.

Acknowledgements

I would like to first express my deepest gratitude to my supervisor Prof. John F. Donegan who gave me the opportunity and the support to work in his lab during my study in Trinity College Dublin. His constructive suggestions, invaluable comments and positive attitude encouraged me moving forward with my research. I really appreciate how John took the time to visit us individually at our personal lab rooms for the weekly group meetings, which made the discussions more productive. Alongside John, I am particularly grateful to my co-supervisor Prof. David McCloskey for his skillful guidance and patient discussions on my lab work and thesis writing as well as lots of help both on my research and my life.

I would like to thank my parents for their support throughout my career. Specifically, I would like to acknowledge my father's persistence in his entire career; it is the most useful inspiration for my study even though he doesn't know too much about nanoscience. I would like to thank my mother for her kindness in always reminding me not to worry too much about the results and just take things easy each time things bugged me. Thanks to my dear brother who has been my model since we were in the same primary school. It's been great to have such an excellent brother to learn from and who always pushes you to go a step further as possible throughout your life. I would like to thank my sister-in-law for continually bothering me to do some weird translations which unfortunately doesn't make too much sense. It's been a great motivation to improve my English anyway. A warm welcome to my first nephew who is coming to say hello to the world. Hopefully, my thesis won't make him sick of physics too much in the future.

I really appreciate Dr. Kyle Ballantine's guidance on the analytical calculations in my first year. The meaningful inspiration from him helps me to handle almost all the calculation work in this thesis. I also wish to thank my co-worker Dr. Brian Jennings for the selfless help throughout my PhD. The endless conversations we've had during each lunch time with Dr. Michael Wallace let me really get to grips with Ireland's rich culture. It's been so much fun to stay with these guys both in study and in life.

I want to thank these doctors in John's group: Dr. Patrick Flanigan, Dr. Nicolás Abadia, Dr. Frank Bello, Dr. Ertugrul Karademir, Dr. Jian-Yao Zheng, Dr. Jing Jing Wang, Dr. Chris Murray and Dr. Graeme Cunningham for their help on both the numerical and the experimental work. And the PhD students: William Abbott, Stephen O'Brien, Gaurav Jain's support in the lab. Thanks to

all the PIs, postdoctors and students in Photonics group for the useful discussions in our regular group meetings. Especial thanks to Dr. James Creel for sharing the LaTeX template.

I am especially grateful to Prof. Richard Hobbs and Dr. Jing Li's guidance on the high-resolution EBL fabrication in the last year of my PhD, it really worked things out. I also need to thank Dr. Gwenael Atcheson and Dr. Jung Chang Lau for their help on the magnetron sputtering system. I want to thank Daragh Mullarkey's help on the XRR measurements and Dr. shaun mills's help on the AFM.

I'd like to thank Dermot Daly and Dr. Eoin Kieran McCarthy for all their help on the SEM, EBL and FIB. I'd like to thank all the other staff in AML for their support on the work with microscopes, especially Keith Boland for organizing the AML introduction workshop.

Thanks to all the technicians in CRANN: Neal O'Hara, Julia Kremer, Michael Finneran's support to work in the cleanroom. I'd like to thank Kenneth Concannon and Alan O'Meara for their help on the IT issues. I'd like to acknowledge Christopher Smith's comprehensive guidance on ellipsometry.

Thanks to Helen O'Halloran, Jacqueline Ballentine-Armstrong, Tracy Byrne, Amanda Murtagh, Des Keany, Michael McCarthy, Pdraic Briody and Jeanette Cummins, all these lovely staff in the administration and financial office of the School of Physics and CRANN for simplifying and taking care of all of my issues.

I'd like to thank all these members in my big Chinese community in CRANN, School of Physics and School of Chemistry for all of their support on my work in the past four years: Prof. Changyu Shen, Prof. Weichang Zhou, Prof. Xiaoping Zhou, Prof. Yangbo Zhou, Prof. Jie Sun, Prof. Jiandi Lin, Dr. Xiaopu Zhang, Dr. Hongjun Xu, Dr. Ruiyuan Tian, Dr. Xia Zhang, Dr. Gaozhong Wang, Dr. Zhengyuan Bai, Dr. Chuanfang Zhang, Dr. Yanhui Zhang, Dr. Kangpeng Wang, Dr. Zeng Lin, Dr. Saobo Xie, Dr. Xiaoyun He, Dr. Aixian Shan, Meiyin Liang, Rui Zhang and Gen Li. A big thanks as well to their families who visited, the enjoyable time we've had together during the past four year's stay on the beautiful green island was as memorable as should be.

I was very lucky to work in 4.22 CRANN and get to know the colorful crowd for people from all over the world. A bunch of people I need to thank to make my PhD life not totally boring. They are Dr. Kiril Borisov, Dr. João Coelho, Dr. Davide Betto, Stephen Porter, Jane O'Reilly, Akshara Verma, Sonia Metel, Katarzyna Siewierska, Mace Kapunkt, Robbie McGuinness and Dr. Eleanor

Holmes. All of my fantastic friends as well in TCD have made the past four years a ton of fun.

Thanks as well to all of my lovely flatmates: Alexandre, Geroge, Marcio, Alessandra, Ormando and Axel for sharing the apartment over the past four years. It's been enjoyable to live with you guys.

Another adventure begins, I again express my deepest gratitude and appreciation to everyone for the love and support. It means more than I could possibly describe over here.

Lastly, I gratefully acknowledge the fellowship support from the Science Foundation Ireland and Western Digital.

Contents

Declaration of Authorship	iii
Abstract	v
Acknowledgements	vii
1 Introduction	1
1.1 Magnetic storage and heat-assisted magnetic recording (HAMR)	2
1.2 Optical waveguides	5
1.2.1 Dielectric slab waveguides	5
1.2.2 Dielectric focusing elements	6
1.3 Plasmonic nanofocusing	9
1.3.1 What are surface plasmons?	9
1.3.2 The diffraction limit	10
1.3.3 Sub-wavelength light confinement	14
1.3.4 Review of recent nanofocusing designs	16
1.4 Scope of this thesis	18
1.4.1 Motivation	18
1.4.2 Overview of chapters	19
2 Derivation of SPP Dispersion in Multi-layer Metallic Films	21
2.1 Dispersion relation in insulator-metal-insulator (IMI) and metal-insulator-metal (MIM) structures	22
2.1.1 The symmetric mode and anti-symmetric mode	22
2.1.2 General approach to solving SPP dispersion in two interfaces	23
2.1.3 Thickness dependent of dispersion curves	26
2.1.4 Reflectivity calculation through transfer matrix method (TMM)	27
2.2 Chapter summary	28
3 Sample Fabrication and Characterization	29
3.1 Introduction	29

3.2	Facilities used in the fabrication	29
3.2.1	Ultraviolet (UV) lithography	29
3.2.2	Electron beam lithography (EBL)	30
3.2.3	Inductively Coupled Plasma (ICP) Etching	32
3.3	Film deposition facilities	35
3.3.1	Magnetron sputtering system	35
3.3.2	Temescal electron beam evaporation system	35
3.4	Samples preparation procedures	37
3.5	Facilities used in the characterization	40
3.5.1	Atomic force microscopy (AFM)	40
3.5.2	X-ray reflection (XRR)	41
3.5.3	Variable angle spectroscopic ellipsometry	42
3.5.4	Optical far-field measurements	44
3.6	Chapter summary	45
4	Surface Plasmon Polariton Modes in Thin Ag-Au Layered Composite Films	47
4.1	Introduction	47
4.1.1	X-ray reflection measurements	49
4.1.2	Angle-resolved measurements	51
4.2	Results and discussions	53
4.2.1	Measured SPP dispersion curves for individual Au and Ag films	53
4.2.2	Measured SPP dispersion curves for Ag-Au bi-metallic films	54
4.2.3	Improved propagation length	59
4.3	Biosensing application	61
4.3.1	Thickness optimization	62
4.3.2	Resolution and sensitivity improvement	64
4.3.3	Sensing performance for Ag-Au bilayer structures	67
4.4	Chapter summary	70
5	Low-loss Adiabatic Dielectric-Plasmonic Hybrid Waveguide for HAMR Applications	73
5.1	Introduction	73
5.2	Theoretical foundation	75
5.2.1	Dispersion relations of an air/ Au/SiO ₂ /Si ₃ N ₄ /SiO ₂ layer stack	75

5.2.2	Momentum matching and evanescent coupling	79
5.2.3	Analysing the symmetry of SPP modes in COMSOL	82
5.2.4	Adiabatic nanofocusing	84
5.3	COMSOL optical simulations	87
5.3.1	Evolution of the nanofocusing process	87
5.3.2	Field enhancement and coupling efficiency	91
5.4	Experimental demonstration	95
5.4.1	Measured samples	95
5.4.2	Optical far-field measurements and results	98
5.5	Chapter summary	101
6	Approaches to Improving the Plasmonic Performance of Au Thin Film	103
6.1	Introduction	104
6.2	Combined Au, Ag, Cu film	105
6.2.1	Optical reflection measurements	105
6.2.2	Field enhancement factor simulation	107
6.2.3	Dispersion relations for Au, Ag and Cu combined layers .	109
6.3	Optical performance of Au film with a varied thickness of adhe- sion layer	113
6.3.1	Optical transmission and reflection measurements	114
6.3.2	SPP reflection measurements	115
6.4	Optical performance of Au film with a varied thickness of cap- ping layer	118
6.5	Chapter summary	119
7	Outlook	121
7.1	Thermal Simulations	121
7.2	Thermal Measurements	122
7.3	Ag-Cu-Au alloy	124
A	AppendixA	127
A.1	General approach to solving SPP dispersion in multi-layer metal- lic films	127
A.1.1	Boundary between three materials	127
A.1.2	Boundary between five materials	128
B	AppendixB	133
B.1	Convergence problems in COMSOL simulations	133
B.1.1	2-D simulations	133

B.1.2	3-D simulations	133
C	List of publications and talks	137
	References	139

List of Figures

1.1	Roadmap of data storage technology. The storage density of hard disk drives has doubled every two years, the areal density will reach 10 Tb/in ² by 2025. (Figure was adapted from ASTC)	3
1.2	(a) A schematic diagram of a side view of a HAMR head. It consists of a diode laser which is used to excite the SPP modes in a nanofocusing structure. A dielectric waveguide is used to generate a hot spot $50 \times 50 \text{ nm}^2$ in size. The recording medium then is heated above the Curie temperature (650 K). A following cool down process can alter the magnetization state of the recording medium to write a magnetic bit. (b) A zoomed-in image of a side view of the nanofocusing structure in the HAMR recording head. It consists of two coupled gratings and a parabolic planar dielectric waveguide to evanescently couple the optical energy (red arrows) to the media.	4
1.3	A schematic diagram of the cross-section view of a dielectric slab waveguide. (b) Schematic configuration for an AWG demultiplexer.	6
1.4	(a) Left: Diagram of the light rays within the PSIM, The dimensions are shown corresponding to the fabricated devices. Right: Near-field measurement of light focused by a PSIM. (b) Left: SEM image of a single microdisk of diameter $8.5 \mu\text{m}$. Right: Experimental images (upper) and analytical results (lower) of $8.5 \mu\text{m}$ diameter disk. Experimental linear image (left) and $\log_{10}$ images (right) for the same microdisk. (c) Left: SEM image of the side-view of the pillar metasurface structures that modulate the phase of light passing through the lens. Right: Intensity profiles of the image plane which is $160 \mu\text{m}$ behind the micro-lens surface. The micro-lens can strongly focus light inside the wafer. The yellow-color frame depicts a $30 \mu\text{m} \times 30 \mu\text{m}$ box equivalent to the size of the micro-lens.	8

1.5	Examples of the (a) localized surface plasmon polariton (LSP). An incident electromagnetic field induces electron clouds of charges to localize at the particle poles. A dipole-like excitation is then obtained at the plasma frequency which can be considered as the LSP. (b) Long-range surface plasmon polariton (SPP) geometries. An incident field excites a surface wave that propagates along the metal and dielectric interface.	11
1.6	Example of subwavelength imaging technologies. (a) A left-handed metamaterial (LHM) sample. It consists of square copper split ring resonators and copper wire strips on fibre glass circuit board material. The rings and wires are on opposite sides of the boards, and the boards have been cut and assembled into an interlocking lattice. (b) Schematic of a superlens and numerical simulation of imaging of sub-diffraction-limited objects. The superlens is made of 16 layers of Ag/Al ₂ O ₃ . (c) SEM image of a super-oscillatory lens. A binary amplitude mask was used for direct focusing of laser light into a subwavelength spot in the post evanescent field by precisely tailoring the interference of a large number of beams diffracted from a nanostructured mask.	12
1.7	SNOM tips: Metallic tapered fibre with small aperture at the end. (a) Uncoated tip; (b) Coated tip with 50 – 100 nm aperture.	13
1.8	(a) TIR occurs in a semi-infinitely thick two layers dielectric system in which $n_1 > n_2$. (b) One dimensionally subwavelength light confinement in a metal-dielectric interface, ϵ_m is the permittivity of the metal and ϵ_d is the permittivity of the dielectric. (c) Two-dimensional light confinement in a sandwiched dielectric waveguide. (d) Two dimensional sub-wavelength light confinement in a sandwiched plasmonic waveguide (two metal claddings and a dielectric core)	15
1.9	Tapered plasmonic nanofocusing configurations. (a) A tapered metallic triangle with a dielectric core. (b) A transmission line consists of two parallel metal wires with a tapered air gap. (c) A MIM gap plasmonic waveguide with a three-dimensional linear taper. (d) A V-shaped groove. (e) A conical noble metallic tip with a grating coupler. (f) Nanofocusing in a plasmonic antenna with a taper.	17

2.1	Schematic diagram of the (a) IMI and the (b) MIM structure, in which the IMI structure consists of a metal core and two dielectric claddings, the geometry of MIM is formed inversely. The red lines in the two panels are the characteristic electric field profile in the two metal slab waveguides with a core thickness of $z = d$. The anti-symmetric mode, corresponding to the solution of L_+ ; the symmetric mode, corresponding to the solution of L_- . The wave propagates along x direction	22
2.2	Sketch of a two layer structure	24
2.3	Dispersion curves of SPP in (a) IMI and (b) MIM geometries consisting of Ag and SiO_2 for different thickness of the middle layers. The gray straight lines in both figures are the light line in air.	26
3.1	The OAI mask aligner system. It contains of a 365 nm UV radiation source; a size changeable mask holder; a vacuum system for both the substrate and the mask holder; two CCD cameras and double screen for the alignment; three-dimensional mobile platform.	31
3.2	Schematic diagram of a modern electron beam column with electromagnetic lenses adapted from SEM manual	33
3.3	Schematic of the Plasmalab system 100 with vacuum loadlock and an inductive coupled plasma source ICP180 tool.	34
3.4	Shamrock magnetron sputtering system. Top panel: a schematic drawing of the whole system (the top view). The pictures of chamber B, C and D are showing in the bottom panel from the front view. The graph was adapted from Dr. Hongjun Xu's PhD thesis.	36
3.5	Temescal FC-2000 system. It mainly consist of a deposition chamber, a pump system and a computer control system.	37
3.6	Diagram of the fabrication flow chart for the plasmonic devices.	38
3.7	SEM images of a used AFM cantilevers. (a) The scale bar is 20 μm . (b) The scale bar is 10 μm . AFM images for (c) a 188 nm thick SiO_2 film and (d) 180 nm thick Si_3N_4 film.	41
3.8	X-ray reflection for a 50 nm thick Au film. Inset: Diagram of X-ray is reflected on a film during the measurement.	42

3.9	Schematic diagram of the SOPRA GESP 5 variable angle spectroscopic ellipsometer system. It with a spectral range from 250 - 900 nm. A microspot system reduces the beam size perpendicular to the plane of incidence to less than 300 microns. The measured film thickness range from 0.1 nm to 5 μm	43
3.10	Schematic diagram of the experimental set-up for optical far-field measurements. The green line shows the path of the laser through the optical system. A diode laser with the wavelength of 850 nm is used to excite the sample; a prism pair is used to alter the elliptical beam to a circular beam. The LED white light and lens provide the bright field illumination of the sample.	44
4.1	The XRR measurements. (a) Left: a combination of the films. Right: fitting data of bi-metallic film with two distinct layers and (b) Left: a combination of the films. Right: fitting data of three layers with 4 nm Ag-Au alloy.	50
4.2	(a) Schematic of Kretschmann-Raether coupling technique with the representation of a bi-metallic layer, where the prism increases the momentum of the incident light to couple to SPP modes. (b) Example of a measurement of dispersion over angle and energy. Inset below: Typical measurement of reflection as a function of the excitation angle at a fixed wavelength. Inset right: Measurement of spectral reflectance at a fixed angle.	52
4.3	Dispersion for single Au and Ag 50 nm thin films. The film structure is given schematically in the lower right-hand corner. (a) Experimental dispersion of a 50 nm Au film, mapped as energy (eV) vs k_x (μm^{-1}). Plotted values range from low (blue) to high (red) values of the ellipsometric quantity $\tan^2 \psi$. The two blue solid lines in each figures are the air light line (left side) and SiO_2 light line in (right side) respectively. (b) Calculated values of $\tan^2 \psi$ using the TMM for single Au film. Here, eigenmode dispersions are superimposed, the scattered black points indicate the L_- modes and red scatted points indicate the L_+ modes. (c)-(d) Same analysis is repeated for a 50 nm silver film.	55

4.4	Dispersion for bi-metallic Au:Ag films with total thickness of 50 nm. The film structure is given schematically in the lower right-hand corner. (a) Experimental dispersion of bi-metallic film with 30 nm Ag capped with 20 nm Au, mapped as energy (eV) vs k_x (μm^{-1}). Plotted value range from low (blue) to high (red) values of the ellipsometric quantity $\tan^2 \psi$. The two blue solid lines in each figure are air light line (left side) and SiO_2 light line (right side) respectively. (b) Calculated values of $\tan^2 \psi$ using the TMM. Eigenmode dispersions are superimposed, the scattered black points indicate the L_- modes and red scattered points indicate the L_+ modes. (c)-(d) Same analysis is repeated for 30 nm Au capped with 20 nm Ag.	57
4.5	The longitudinal component of the electric field (E_x) is plotted for specific energies in the dispersion to allow classification of the modes as symmetric and anti-symmetric modes based on their symmetry, the corresponding energies are given in the top right-hand corner	58
4.6	Propagation length of SPP modes in thin single and bi-metallic films calculated using eigenmode method	60
4.7	The SPP reflection as a function of the thickness of Au and Ag films. The blue part indicates the low reflectivity, and inversely the red part shows the high reflectivity. The related thickness of the Au and Ag is the optimal thickness for biosensing.	63
4.8	Angle resolved SPP reflection changing as a function of the refractive index of the surrounding medium. The lower reflectivity area in all the panels indicated the SPP modes have been excited with a certain input angle. (a) and (b) show the cases for Au and Ag with the excitation wavelength of 532 nm. (c) and (d) show the same case with the excitation wavelength of 850 nm. The thickness of the Au and Ag films is 50 nm in all the panels.	65
4.9	Evolution of the sensitivity for the refractive index sensing. The SPP resonance curves shift as the refractive index of the surrounding medium is varying from 1 to 1.3. (a) and (b) show the cases for Au and Ag with the excitation wavelength of 532 nm. (c) and (d) show the same case with the excitation wavelength of 850 nm. These results are calculated through TMM by varying the refractive index of the air layer in the model.	66

4.10	Sensitivities of the Au and Ag films with the thickness of 50 nm when the excitation wavelengths are $\lambda = 532$ nm and $\lambda = 850$ nm respectively.	67
4.11	Angle resolved reflectivity changes for Ag-Au bilayers when the thickness of these two metals have different ratios. The thicknesses of Au and Ag films vary from 0 nm to 50 nm. The Au film is located on top of Ag in the modelling for improving the stability of the combined film. The excitation wavelength is 532 nm. The area of the low reflectivity part shows the width of the SPP resonance. The FWHM of the SPP resonance is varying by combining the Ag and Au film.	68
4.12	Angle resolved reflectivity changing as a function of the refractive index of the surrounding medium for Ag-Au bi-metallic layers, the thickness of Au is 20 nm and the thickness of Ag is 30 nm. (a) The cases for the bi-metallic layer with the excitation wavelength of 532 nm. It shows the Ag-Au bi-metallic structure can effectively decrease the FWHM of the SPP resonance which makes it a better candidate for biosensing applications. (b) The same case with the excitation wavelength of 850 nm.	69
4.13	Examples of the changing of the FWHM in the SPP resonance for single Au and Ag layers and Ag-Au bi-metallic layer with two distinct ratios. The wavelength of the excitation is 532 nm.	70
5.1	Schematic diagram of the proposed evanescent coupling system. It consists of a core layer of Si_3N_4 on a 2 μm thick SiO_2 on a Si substrate. A spacer layer of silicon dioxide (SiO_2) is used to match the effective refractive index of the photonic and the plasmonic modes. The NFT is formed by an isosceles triangular gold (Au) plasmonic waveguide which is situated on the SiO_2 layer. A diode laser with a wavelength of 850 nm is used to illuminate the NFT at the trench. The recording medium is formed with ferromagnetic materials.	77
5.2	(a) Real part (k'_x) and (b) imaginary part (k''_x) of the dispersion curves of the anti-symmetric mode as the thickness of the SiO_2 spacer layer (t_s) is varied. The thickness will be chosen to facilitate the evanescent coupling process and match the momenta of the modes. The dashed horizontal line corresponds to the wavelength used in the rest of the paper (850 nm, or 1.46 eV).	79

5.3	The propagation length of the coupled mode L_{spp} as a function of wavelength for the air/Au/SiO ₂ /Si ₃ N ₄ /SiO ₂ layer stack and two semi-infinite layers systems.	80
5.4	(a) Real part of the effective refractive index of the anti-symmetric plasmonic mode (with Au) and the fundamental photonic mode (without Au) as a function of the thickness of the Si ₃ N ₄ core layer without the spacer layer – the insets show the geometries of the two cases being studied. Panel (b) shows the effective refractive indices of the higher-order TM photonic modes as a function of the thickness of the Si ₃ N ₄ core layer. It is clear from the figure that none of these will couple to the higher-index plasmonic mode from panel (a). Panel (c) shows that momentum matching occurs by adding a SiO ₂ spacer layer between the Si ₃ N ₄ core layer and the Au layer. The dashed-dot lines show where the momentum match occurs: when the spacer layer is 188 nm thick. The inset figure shows the layer geometry of the case being studied. Panel (d) shows the imaginary part κ (extinction coefficient) of the anti-symmetric mode and the symmetric mode as functions of the thickness of the SiO ₂ spacer layer.	81
5.5	z -component of the electric field of (a) the anti-symmetric mode and (b) the symmetric mode in the layer stack. The symmetry of these two plasmonic modes is distinguished by the spatial distribution of the z -component of the electric field (E_z) at the two interfaces of the metal. The layer stack in the simulations is infinitely wide in the x direction and the field is not total distributed in the metal-dielectric interface because of the photonic mode is also solved. The amplitude of the electric field presents the symmetry of the hybrid photonic-plasmonic mode	83
5.6	(a) Real part and (b) imaginary part of n_{eff} as a function of the width of the NFT for the anti-symmetric and the symmetric modes. The n_{eff} for photonic mode in the core layer is also plotted to distinguish the two different type of modes. The real part of n_{eff} shows the confinement of these two modes and the imaginary part indicates the loss. (c) Examples of mode cross-section profile for the system as the width of the NFT changes. The electric field magnitude is given by the colour bar.	86

5.7	(a) Schematic diagram of the layer system that applies to all of the simulations shown in this section. The distance between the edge of the Au NFT and the edge of the simulation region is $\lambda_0/2 = 425$ nm on both sides. Optical 3-D simulations of the electric field distribution in the NFT with a tapered Au plasmonic waveguide (b)-(f) and a rectangular Au strip waveguide (g)-(k): (b), electric field at the start of the Au taper; (c), electric field at the tip of the Au taper; (d) the side view of the Au taper in the x - z plane shows mode beating; (e), top view of the Au taper shows the nanofocusing process. The same description can be applied to panels (g) – (j) which are simulated results for an Au rectangular strip acting as a reference sample, the difference being that the nanofocusing effect doesn't appear at the end of the rectangle. Light propagates in the x direction in all figures; the scale bar is $1\ \mu\text{m}$ and applies to all panels. (l) The normalized intensity distribution in the spacer layer of the tapered and rectangular waveguides along the light propagation direction (the dashed-white line in panel (a)).	89
5.8	(a) – (d) the evolution of the plasmonic mode as it propagates from the start to the tip of the NFT. It demonstrates the nanofocusing process in the NFT. The same analysis also been demonstrated for the rectangular Au strip waveguide which shown in the panel (e) – (h).	90

- 5.9 (a) The field intensity enhancement factor in the NFT at different values for the spacer layer thickness (t_s). The ratio shown is the output port of the Au layer against the input port (two blue dots in Figure 5.7(a)). The curves exhibit the expected exponential decay as well as oscillations corresponding to the coupling length (labelled L_c in (a)). (b) Ratio of electric field intensities in the core Si_3N_4 layer (intensity at the cross-section of the end against the start, dashed-black line cross the vertical direction of core layer in Figure 5.7(a)) for two different Au structures (a tapered NFT and an un-tapered rectangle). Because Si_3N_4 is modelled as a lossless material (*i.e.*, the refractive index is purely real), any change in optical intensity must be due to coupling from the starting photonic mode into the plasmonic mode, which is concentrated at the tip. The data shows that the tapered case extracts the light more efficiently. 92
- 5.10 (a) Schematic diagram of the volume integration used in the simulations. (a) The total integration volume size along x , y and z direction is $500 \times 500 \times 2100 \text{ nm}^3$ which covers all the simulation domain at the output port of the NFT. In particular, the integration volume for calculating the intensity at the tip of the NFT is $500 \times 500 \times 90 \text{ nm}^3$ in size which can be seen in the panel (a1), it is 20 nm above and below the upper (air/Au) and the lower (SiO_2/Au) interface of the NFT (thickness of Au is 50 nm) in the z direction which determines the intensity of the SPP modes in the lower and the upper interface of the NFT. The actual width of the tip is 50 nm, however the far-field measurement collects the scattered light which has an area larger than $50 \times 50 \text{ nm}^2$, the $500 \times 500 \times 2100 \text{ nm}^3$ integration size in the x and y directions allows the scattered light from the lateral side of the NFT to be taken into account. The highlighted blue cubes in panel (a2) and (a3) are the actual integration volumes for the spacer layer and core layer respectively. (b) Top view of the integration volume. It is a $500 \times 500 \text{ nm}^2$ in size in the x - y direction. 96
- 5.11 (a) SEM images of the tapered Au sample and the rectangular Au sample (the structures fabricated for characterization are much farther apart than what is shown here). (b) Image showing the tip of the tapered NFT, which is 50 nm wide in all structures. . . . 97

5.12	Experimental results and SEM images for (a) a $6\ \mu\text{m}$ long rectangular reference and (b) a tapered structure with the same length. The scale bar is $2\ \mu\text{m}$ and applies to both panels. The exposure time was the same in both measurements. Bright spots appear at the start (left) and end (right) of these structures. The colour bar, which is normalized to the maximum in both images (the centres of the dots in (b)), indicates the strength of the scattered light from the structure. This figure shows that the strength of the intensity in the tip of the taper is at least of 2 times higher than that in the rectangle, and that there is a nanofocusing effect occurring in the tapered NFT.	98
5.13	Left side of panel: SEM images; right side of panel: corresponding far-field CCD measurements. (a) Measured results of the $L = 6\ \mu\text{m}$ sample with a variable spacer layer thickness ($t_s = 0\ \text{nm}$, $100\ \text{nm}$, and $188\ \text{nm}$ from top to bottom). (b) Measured results of the samples with an optimal spacer layer ($188\ \text{nm}$), at different lengths. The light is incident from the left side. The scale bar is $2\ \mu\text{m}$ for all four images. Note that the structures were much farther apart than this ($30\ \mu\text{m}$) on the actual sample. (c) Intensity enhancement factor for the Au layer for the tapered (Π_{NFT} , intensity at start against intensity at end) and rectangular (Π_{rect}) cases. The data is both experimental (red circles, with error bars) and simulated (black squares). Each curve was normalized against its highest value (which happened to be at $L = 6\ \mu\text{m}$ for both) to show the strong correlation between the data sets. The excellent agreement between the different methods confirms the validity of our analysis.	99
6.1	Interpolated ternary plots of experimentally obtained Drude parameters for Au, Ag and Cu combined structures. (a) Plasma frequency ω_p and (b) relaxation constant τ . Middle inset indicates the atomic ratios in the experimental measurements	106
6.2	(a) Optical reflection measurements with a normal incident angle for the individual layer and combined layers. (b) The optical reflection of the Ag-Cu-Au tri-layer before and after an annealing process ($350\ ^\circ\text{C}$ for 30 minutes). The reflection of Au film is also plotted	107

6.3	(a) Schematic diagram of the evanescent coupling system. (b) and (c) Simulated field enhancement factor of the NFTs which are formed with different materials at the excitation wavelengths of 850 nm and 532 nm, respectively.	108
6.4	Analytical dispersion curves of the individual, the bi-layer and tri-layer films obtained by solving the eigenvalue solutions of the related layer structures. Panels (a) and (b) show the symmetric mode (L_-) and the anti-symmetric mode (L_+) respectively. . . .	110
6.5	Simulated SPP reflection as a function of the excitation angles. The value of the reflection are the ratio of the R_p (reflection with a P mode excitation) and R_s (reflection with a S mode excitation) which can normalize the data. The panels are related to the 6 types of layer combinations which are (a) Au individual layer; (b) Cu-Au bi-layer; (c) Cu individual layer; (d) Ag-Au bi-layer; (e) Ag individual layer; (f) Ag-Cu-Au tri-layer films. The colour scale in all the panels indicates the strength of the reflection. . . .	111
6.6	Analytical propagation length of the individual film, the combined bi-layer and tri-layer films with is proportional to the imaginary part of the k (wavevector) value. Both the L_- mode (a) and the L_+ mode (b) are plotted.	112
6.7	Schematic diagram of the measured sample. 50 nm Au with an adhesion layer on a quartz substrate. Titanium (Ti) and tantalum (Ta) are tested and the thickness of the adhesion layer is 0.5 nm, 1 nm, 2 nm and 5 nm.	113
6.8	Optical transmission (a), (b) and reflection (c), (d) measurements for the samples with Ta and Ti adhesion layers respectively. (e) and (f) are the calculated absorption of the Ta and Ti adhesion samples. It should be mentioned that the scattering is ignored when calculating the absorption for each sample.	116
6.9	Angle resolved measurements of the films with (a) Ta and (b) Ti adhesion layers. The measurement is performed with a Kretschmann configuration and the excitation wavelength is 633 nm. The results are the ratio of the reflection under a TM mode (P wave) excitation and a TE mode (S wave) excitation. The angles are varying from 42° to 50° with a step size of 0.1°	117

6.10	SPP reflection measurements of the 50 nm Au film with 0.5 nm Ti adhesion layer and a varied thickness of Al_2O_3 capping layers. The thickness of the capping layers are 0.5 nm, 1 nm, 2 nm and 5 nm.	119
7.1	Thermal simulation of the NFT with an evanescent coupling mechanism. (a) COMSOL model of the 6 μm long tapered NFT with a recording medium. The recording is consisting of a 10 nm FePt layer, 50 nm Cu heat sink on the SiO_2 substrate. There is a 4 nm air-gap between the NFT and recording medium. (b) The cross-section of the hot spot on the recording medium. The highest temperature on the recording medium can reach 800 K with a 40 mW input power in the NFT.	122
7.2	Schematic diagram of the CCD-TR microscopy setup. It consists of a visible light CCD camera and a light emitting diode (LED) illumination source that is focused on the sample by a microscope objective. An argon-iron laser with the wavelength of 488 nm is used to excite the sample. The light reflected back to the CCD in response to modulation of the sample temperature is then analysed.	123
A.1	Sketch of a three-layer structure	127
A.2	Sketch of a five-layer structure	129
B.1	(a) Intensity curve at the start of the NFT. The resonance of the back curve comes from the Fabry-Perot (F-P) cavity which is formed by the start of the NFT and the input boundary of the simulation domain. The red smooth line is the average intensity which is used to normalize the data to improve the accuracy of the calculated intensity enhancement (Π_{NFT}) in the NFT. (b) Shows the field intensity enhancement factor in the NFT at different values for the spacer layer thickness (t_s) which is normalized with data in the black curve of Figure B.1(a). (c) Shows the same results but normalized with the average value (red curve in Figure B.1(a)), the sharp peaks result from the F-P resonance between the input port boundary and the start of the NFT are now much weaker. . .	134
B.2	(a) Mesh test for the 3-D simulations. (b) Results of the simulated coupling efficiency of a tapered NFT with a fine mesh size and a coarse mesh size.	135

List of Tables

5.1	Intensity enhancement in the NFT (Π_{NFT}) and percentage of the intensity distribution in different simulation domains for a 6 μm long NFT when the thickness of the spacer layer is varied. In each case, the excess intensity is in the air or substrate layer. . . .	95
6.1	List of samples. The data consists of Au, Ag and Cu individual, bi-layer and tri-layer combined films. The value of the thickness of the spacer layer is used for the NFT design in an evanescent coupling system.	107
6.2	FWHM of the SPP reflection of the Au film with different thickness of the adhesion layers. Both Ta and Ti adhesion layers are listed in the table. The FWHM of the SPP reflection is accounted by measuring the difference of the angles to excite the SPP to reach $1/e^2$ of the lowest reflection.	117

List of Abbreviations

AFM	Atomic force microscopy
AWG	Arrayed waveguide grating
ASTC	Advanced storage technology consortium
BPMR	Bit patterned magnetic recording
CMOS	Complementary metal-oxide semiconductor
CCD	Charged coupled device
CCD-TR	CCD-based thermoreflectance
EBL	Electron beam lithography
FIB	Focused ion beam
FePt	Iron-platinum nanoparticles
FWHM	Full width half maximum
Fe ₃ O ₄	Iron(II,III) oxide
F-P	Fabry–Pérot
HDMR	Heated-dot magnetic recording
HAMR	Heat-assisted magnetic recording
HDDs	Hard disk drives
IR	Infrared
IMI	Insulator-metal-insulator
ICP	Inductively coupled plasma
K-R	Kretschmann-Raether
KOH	Potassium hydroxide
LSP	Localized surface plasmon
MIM	Metal-insulator-metal
NA	Numerical aperture
PMR	Perpendicular magnetic recording
PIC	Photonic integrated circuits
PSIM	Planar solid immersion mirror
QED	Quantum electrodynamics
RF	Radio frequency
SEM	Scanning electron microscopy
SPR	Surface plasmon resonance

SPP	Surface plasmon polaritons
Si ₃ N ₄	Silicon nitride
SNOM	Scanning near-field optical microscopy
SSD	Solid state drive
SPM	Scanning probe microscopy
TIR	Total internal reflection
TM	Transverse magnetic
TE	Transverse electric
UV	Ultraviolet

*Dedicated to my parents and grandfather
in memory of my grandmother.*

Chapter 1

Introduction

Modern electronic devices and circuits for information processing have grown exponentially in speed and bandwidth over the past decades due to scaling. As we begin to reach fundamental limits in scaling due to quantum tunnelling and heat dissipation issues, new technologies, and paradigm shifts are necessary for continued growth [1]. One promising solution is believed to be integrated photonics in silicon-based circuits [2], this new technology provides large bandwidth which can be used to design novel hybrid electronic-photonic devices. However, a major problem with using electromagnetic waves as information carriers in optical integrated circuits is the low level of integration and miniaturization, which are far poorer than what has been achieved in modern electronics. This problem is a consequence of the diffraction limit of light in dielectric medium [3], which restricts the light waves being confined to nanoscale regions much smaller than its wavelength. Therefore, other approaches of guiding light at sub-wavelength scale have to be found. One possible solution is using plasmonic waveguides which can achieve sub-wavelength scale light confinement and highly localized electromagnetic field intensity. They provide a particularly promising approach to integrating sub-wavelength electronic and photonic devices. Many modern devices utilizing plasmonic elements have been proposed and demonstrated including modulators [4], nanofocusers [5] and hot carrier devices [6]. A key new technology depending on plasmonics, which motivates this study, is heat-assisted magnetic recording (HAMR) [7]. This technology is under development for the next generation of magnetic storage.

1.1 Magnetic storage and heat-assisted magnetic recording (HAMR)

Historically, the volume of data generated worldwide has been increasing by more than 40% annually [8] which is faster than Moore's Law [9] for transistors on computing chips. Although solid state drive (SSD) technology has been increasing penetration into personal computing and high-performance applications, hard disk drives (HDDs) are still the dominant form of storage devices for large-scale storage in server farms [10]. The storage density of hard disk drives is expected to double every two years owing to several major advances in data storage technology, including the perpendicular magnetic recording (PMR, *i.e.* the magnetization of each data bit is aligned vertically to the spinning disk) [11], HAMR, bit patterned magnetic recording (BPMR, *i.e.* the magnetic bit is stored by a well-ordered array of lithographically patterned isolated magnetic islands) [12], heated-dot magnetic recording (HD MR, *i.e.* utilizes a laser to heat a bit-patterned medium before recording data) [13]. From the roadmap Figure 1.1 which was released by the Advanced Storage Technology Consortium (ASTC), the areal density ¹ will reach ten terabits per square inch (Tb/in²) by 2025. However, the density growth rate for HDD manufactures started to stall as the industry reached the limits of PMR which as a consequence of superparamagnetic effect [14] — for sufficiently small magnetic nanoparticles, magnetization can randomly flip direction due to the random thermal fluctuations.

In PMR, The data recording is performed by applying a sufficiently high magnetic field via an electromagnet to alter the magnetization state of a magnetic grain on the disk media to encode digital data, which is called a magnetic bit. Typically, areal density is improved by reducing the area of the magnetic grains on the hard disk. However, smaller grain size (*i.e.*, 40 nm for Fe₃O₄ [16]) suffers from the spontaneous magnetic moment flipping due to thermal fluctuations [17]. Using a higher anisotropy recording media, such as iron-platinum (FePt) nanoparticles, will improve thermal stability compared to today's conventional media but will not totally solve the problem [18]. An important property of FePt nanoparticles that they exhibit superparamagnetic behavior below 10 nm [19], which makes them attractive candidates to be used as a high-density recording material [20]. However, scaling the FePt grains down to that order of magnitude also requires the use of a stronger writing magnetic field to demagnetize the FePt nanoparticles for writing and re-writing the bits. [7, 21]. The

¹How many bits of information can be stored on a given surface area of the magnetic disk

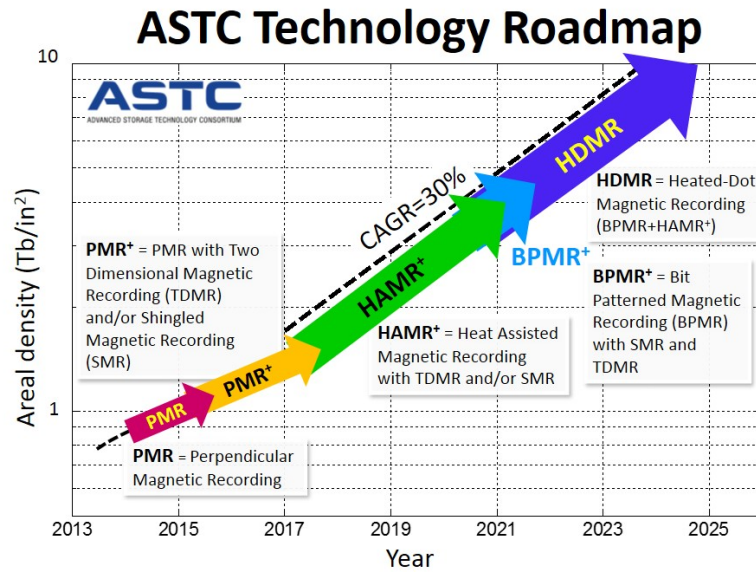


FIGURE 1.1: Roadmap of data storage technology. The storage density of hard disk drives has doubled every two years, the areal density will reach 10 Tb/in² by 2025 [15]. (Figure was adapted from ASTC)

hard disk industry invented another magnetic recording method to overcome this limitation, which is called HAMR. A nanoscale spot on the recording media is heated momentarily beyond the critical Curie temperature (650 K for FePt) during writing, which means the local coercivity² is lowered. With an elevated temperature, a magnetic bit can be written with a lower magnetic field, which is below the saturation limits of realizable electromagnets. In order to achieve a high-density magnetic recording, the heat must be applied locally to only one bit of information at a time while simultaneously applying a magnetic field. Since the rest of the material still below the Curie temperature, all the other bits will not be affected by the writing magnet. A local source to generate heat in a nanoscale region is essential for HAMR [22].

Figure 1.2 shows an example reported in 2009 by Seagate Technology of how the nanofocused light from a lollipop-shaped near-field transducer (NFT)³ can be used in a HAMR recording head [23]. Here, the incident light (input wavelength 830 nm) is coupled into a parabolic planar dielectric waveguide, which is composed of a 125 nm core of Ta₂O₅ (refractive index of 2.15), and the

²The resistance of a magnetic material to changes in magnetization, it is equivalent to the applied magnetic field needed to demagnetize the magnetized material.

³It is used to describe a plasmonic nanostructure to locally and temporally heat a nanoscale region in the recording medium

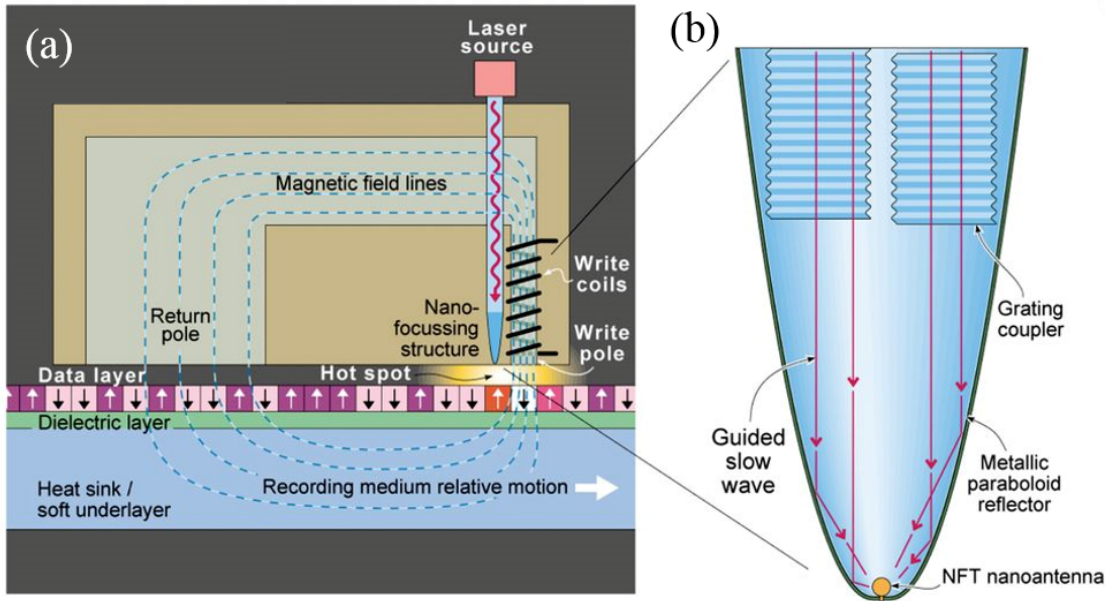


FIGURE 1.2: (a) A schematic diagram of a side view of a HAMR head. It consists of a diode laser which is used to excite the SPP modes in a nanofocusing structure. A dielectric waveguide is used to generate a hot spot $50 \times 50 \text{ nm}^2$ in size. The recording medium then is heated above the Curie temperature (650 K). A following cool down process can alter the magnetization state of the recording medium to write a magnetic bit. (b) A zoomed-in image of a side view of the nanofocusing structure in the HAMR recording head. It consists of two coupled gratings and a parabolic planar dielectric waveguide to evanescently couple the optical energy (red arrows) to the media. Figures are adapted from references [22, 23]

core is surrounded by an Al_2O_3 cladding (refractive index of 1.65). The guided light is evanescently coupled to a NFT as shown in Figure 1.2(a) to produce an intense localized hot spot with a volume of $50 \times 15 \times 10 \text{ nm}^3$. In order to achieve required local heating (650 K) to reduce the coercivity of the FePt nanoparticles in the recording medium (data layer in Figure 1.2(a)) to zero, an 80 mW laser is used to bring enough heat to a FePt ferromagnet in a nanoscale volume. The recording medium is heated up above the Curie temperature (650 K). The write pole can alter the magnetization state of the recording medium and a magnetic bit can be written after a following cool down process.

The new elements in HAMR, as compared to conventional PMR, are the integrated dielectric waveguide and the plasmonic focusing element. The dielectric waveguide is used to guide the light from an external diode laser to the plasmonic NFT. Often the dielectric waveguide is a relatively large structure such as a slab waveguide which uses an integrated dielectric focusing element to concentrate the light on the NFT [23]. A local heating source in HAMR requires a highly light confined element, and in virtually all modern applications the optical energy needs to be confined to the sub-wavelength in scale [21]. Plasmonic components can achieve the required sub-wavelength of light confinement. However, when using plasmonic waveguides instead of dielectric waveguides, a new challenge arises where the optical energy is lost to absorption and dissipation [24] — an irreversible process that has impeded many practical applications of plasmonic devices [25]. The next section will discuss the difference between dielectric and plasmonic waveguides — their compositions, underlying principles, and advantages and drawbacks.

1.2 Optical waveguides

1.2.1 Dielectric slab waveguides

Dielectric waveguides can guide light as a combination of electromagnetic modes, *i.e.* a dielectric slab waveguide as shown in Figure 1.3(a). It contains a dielectric core with the refractive index of n_1 and two dielectric claddings with the refractive index of n_2 where $n_1 > n_2$. Light is guided in the dielectric core through total internal reflection⁴. The thickness of a slab core determines the number of guided modes in the waveguide. A slab dielectric can be used in an arrayed waveguide grating (AWG) optical demultiplexer as shown in Figure 1.3(b).

⁴The reflection of light reaches an interface from a dense medium to a less dense medium when the angle of incidence is greater than the critical angle, there is no refraction in this case.

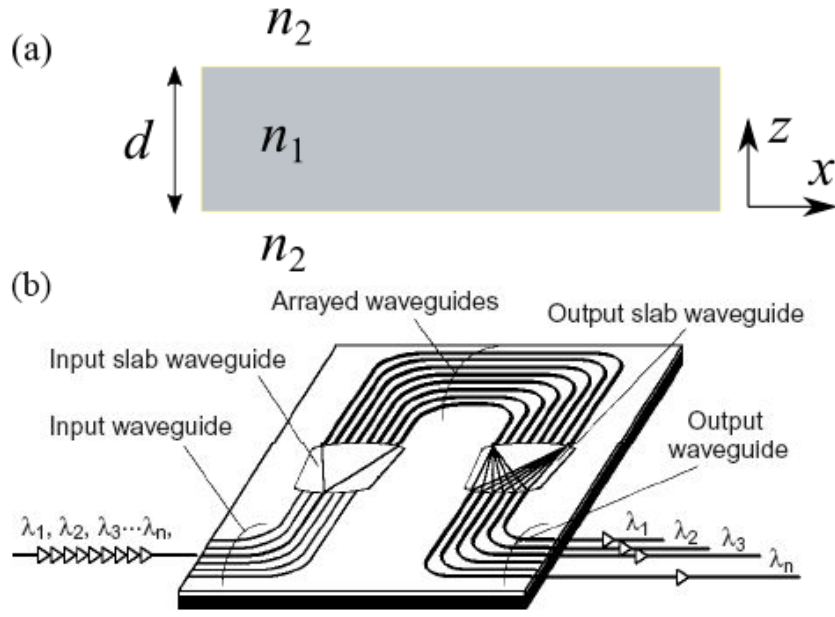


FIGURE 1.3: A schematic diagram of the cross-section view of a dielectric slab waveguide. (b) Schematic configuration for an AWG demultiplexer. Image taken from [26].

When the core thickness d of the slab decreases, the fundamental guided mode penetrates into the surrounding medium (cladding) and eventually turns to a bulk plane-wave in the medium. In the meantime, the wavelength of the guided mode monotonically increases from λ_0 (free light wavelength) to the wavelength in the surrounding medium. The mode size decreases when the thickness of the slab core d is decreased to $\sim \lambda_0$, and then increases to infinity when the thickness of the slab core d is reduced further, $d \rightarrow 0$, in which will result in high energy dissipation in the claddings. Therefore, simply decreasing the thickness of a guiding slab core close to zero cannot lead to sub-wavelength confinement of the guided mode. This feature indicates the diffraction limit of light in dielectric waveguides and constitutes the main obstacle in achieving higher degrees of miniaturization and integration of optical devices.

1.2.2 Dielectric focusing elements

It is useful to focus light to a small, intense volume which can be called a nanospot. Nanospot concentration is beneficial for various applications: biomedical imaging and sensing [27], optical microscopy with single-molecule resolution [28], data storage like HAMR, quantum electrodynamics (QEDs) studies

[29], nanolasing [30], *etc.* The ideal dielectric material for nanophotonic applications has a large refractive index at optical frequencies, which respond to both the electric and magnetic fields confinement. Artificial materials, such as metamaterials, based on metallic or polar dielectric nanostructures can achieve high confinement of light by coupling light to free electrons or phonons, respectively, but at the inevitable cost of significant energy dissipation [31, 32]. Using completely transparent and high-refractive-index dielectric materials [33] can achieve high confinement of light, making them less lossy. This superior property of all dielectric waveguides shows the exciting prospect of integrated photonic devices to achieve low-loss and sub-wavelength light confinement [24, 34]. A few simple examples for dielectric focusing elements are discussed in this subsection. They include planar solid immersion mirror (PSIM), microdisk, and a metamaterial layer which is created by fine patterning an array of dielectric nano-pillars (see Figure 1.4). There are many more examples that has been discussed in detail elsewhere, such as high-refractive-index nanoresonators [35], metasurfaces [36], zero-index metamaterials [37] and anisotropic metamaterials [38].

A PSIM with high optical throughput has been demonstrated as a focusing element [39]. A truncated parabola that is $100\ \mu\text{m}$ long, $50\ \mu\text{m}$ wide at its top opening, and $6\ \mu\text{m}$ wide at the bottom surface is shown in Figure 1.4(a). Light enters this PSIM from the top parallel to its optical axis. Due to the truncation, a portion of the central part of the beam does not strike the parabolic edge of the PSIM and does not get focused but exits the bottom of the structure without changing direction. Light rays which are a little farther from the central axis reflect off the edge of the PSIM near the bottom corner and then incident onto the focal point at high angles. It can focus light to spot sizes of $\sim 90\ \text{nm}$ at a wavelength of $413\ \text{nm}$. One drawback of this type of focusing element is its size — $\sim 50\ \mu\text{m} \times 100\ \mu\text{m}$, which is not useful for miniature integration applications. An Si_3N_4 ($n = 2.1$) microdisk on a SiO_2 ($n = 1.45$) substrate has been proposed as a compact focusing element. The microdisk focuses light through a combination of refraction and diffraction. Experimental images of a Si_3N_4 microdisk with a diameter of $8\ \mu\text{m}$ and a thickness of $400\ \text{nm}$ are shown in Figure 1.4(b). In free space, light is focused inside the disk, and a sub-wavelength spot is observed. In the case where the disk is surrounded by water, a perpendicular illumination with a focused Gaussian beam can produce a photonic nanojet which with an extremely low beam divergence, the divergence angle over ten times smaller than possible with a focused Gaussian beam in free space [40].

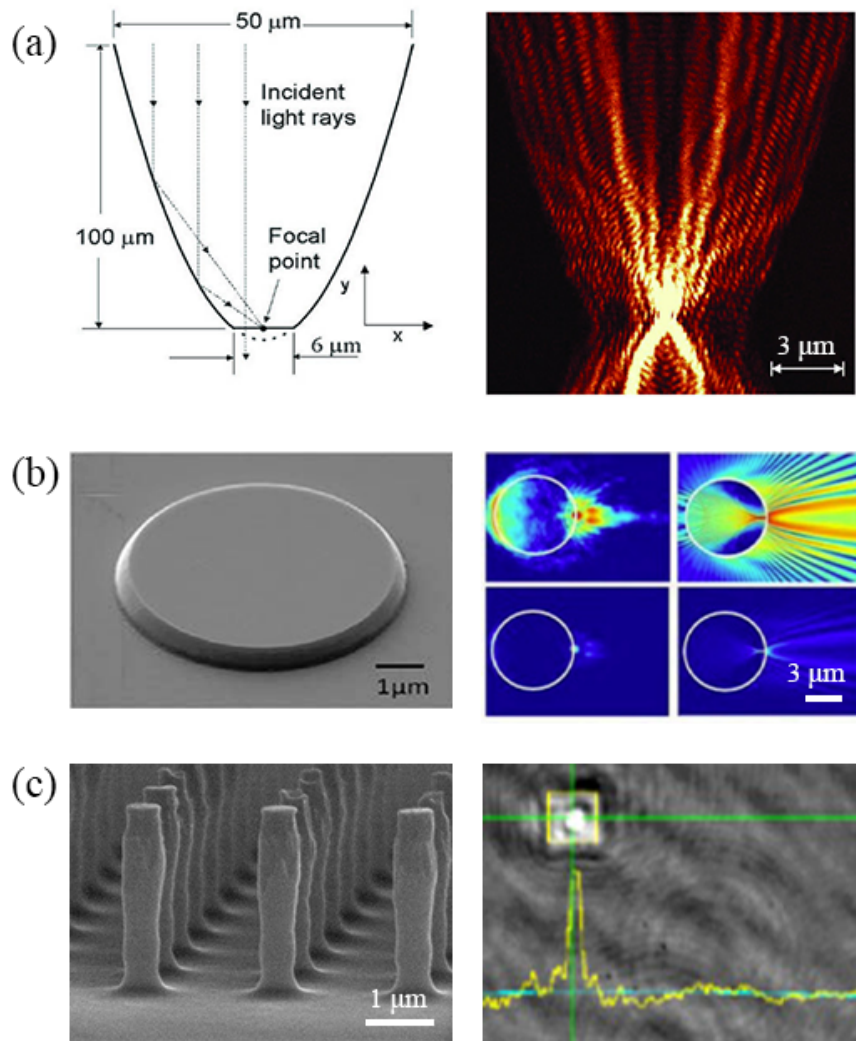


FIGURE 1.4: (a) Left: Diagram of the light rays within the PSIM, The dimensions are shown corresponding to the fabricated devices. Right: Near-field measurement of light focused by a PSIM. (b) Left: SEM image of a single microdisk of diameter $8.5\ \mu\text{m}$. Right: Experimental images (upper) and analytical results (lower) of $8.5\ \mu\text{m}$ diameter disk. Experimental linear image (left) and $\log_{10}$ images (right) for the same microdisk. (c) Left: SEM image of the side-view of the pillar metasurface structures that modulate the phase of light passing through the lens. Right: Intensity profiles of the image plane which is $160\ \mu\text{m}$ behind the micro-lens surface. The micro-lens can strongly focus light inside the wafer. The yellow-color frame depicts a $30\ \mu\text{m} \times 30\ \mu\text{m}$ box equivalent to the size of the micro-lens. Figures are adapted from [39–41].

A low loss dielectric micro-lens for infrared (IR) radiation focusing based on a dielectric metamaterial layer has also been proposed [41]. This metamaterial layer was created by fine patterning an array of dielectric nano-pillars with variable diameters as shown in Figure 1.4(c). The objective was to create a sub-wavelength, fine-patterned meta-surface as a phase mask with a smooth radial dependence of phase increment on transmission, avoiding 2π phase steps. The mask covers just one single central Fresnel zone of the transmitted beam, rather than multiple Fresnel zone rings with 2π phase steps. The mask of this type can be sufficient to reduce a laser spot diameter by a factor of about three.

Recently, the principles of relaxed total internal reflection [25] and evanescent wave skin-depth engineering [42] were introduced to significantly decrease the decay length of evanescent waves outside the core of a conventional dielectric waveguide, which is very promising for information processing at the nanoscale. However, this requires the cladding of the waveguide to have a unique metasurface that allows light to be completely reflected and simultaneously decrease the skin depth of the generated evanescent waves. This approach increases the complexity of the devices. Plasmonic waveguides are promising candidates for sub-wavelength light confinement.

1.3 Plasmonic nanofocusing

1.3.1 What are surface plasmons?

In 1957, Ritchie predicted the existence of self-sustained collective excitations at metal surfaces in his treatment of characteristic energy loss of fast electrons passing through the metal films [43]. In 1952, Marton [44] measured the energy loss spectrum of 30 keV electrons passing through thin films of metals and insulators and experimentally proved that the interaction between valence electrons in metals yields collective plasma oscillations which have been proposed by Pines and Bohm [45]. Powell and Swan [46] demonstrated the origin of these collective oscillations by measuring the electron loss spectrum of aluminum. Following Powell and Swan, the anomalous characteristic energy loss of energy lower than the plasmon energy, exhibited by some metals, are attributed to quantized surface waves of the degenerate electron gas, the quanta of which Stern and Ferrell called the surface plasmon [47]. The charge motion of a surface plasmon always creates electromagnetic fields on the surface the

metal. The total excitation, including both the charge motion and associated electromagnetic field, is called a surface plasmon polaritons (SPP).

In general, SPP are hybrid electron-photon oscillations that occur at the interface between a metal and a dielectric [31]. As longitudinal electron density oscillations, SPP behave like light waves however they are confined in the interface of the metal and the dielectric. SPP are non-radiative in nature, implying that they cannot directly couple to photons. Instead, a prism, a grating, or scattering surface must be used to resolve the momentum-mismatch between plasmons and photons for optical excitation of SPP, electrical excitation of SPP has also been demonstrated [48]. There are two types of SPP, the localized surface plasmon (LSP) and the long-range surface plasmon polaritons (we call them SPP in the entire thesis) as shown in Figure 1.5. The former is based on particle plasmons resemble dipoles, with electron clouds of charge which are localized at the poles of the particles, which can be seen in Figure 1.5(a). At their resonant frequencies, the LSP excited from these particles have a large scattering coefficient and a large extinction cross-section which results in a high electromagnetic field at the poles of the particles. Such properties of LSP have been exploited in the applications ranging from optical nano-antennae [49], surface-enhanced Raman spectroscopy [50–52] to single molecule probing [53–55]. In contrast, SPP geometries are characterized by propagating waves which are confined to the metal-dielectric interface. Depending on the excitation wavelength and the specific materials used, the skin depth (the distance that the field penetrates into the metal side) can be sub-wavelength in scale. Additionally, propagation length in SPP geometries can approach centimetre scales, which is quite significant when the waveguide themselves are on the scale of microns [56]. Figure 1.5(b) indicates the SPP in a metal-dielectric interface. It shows the SPP are propagating in the metal-dielectric interface and decay quickly in the metal layer. The red arrows illustrate the motion of the electrons when they are excited by photons.

1.3.2 The diffraction limit

In 1873, the German physicist Ernst Abbe [58] discovered that the resolution of optical imaging systems, such as telescopes and microscopes, is fundamentally limited by the diffraction of light. The ability of an imaging system to resolve detail is ultimately limited by diffraction. When an object is imaged by an optical system, the illuminating light with a wavelength λ and traveling in

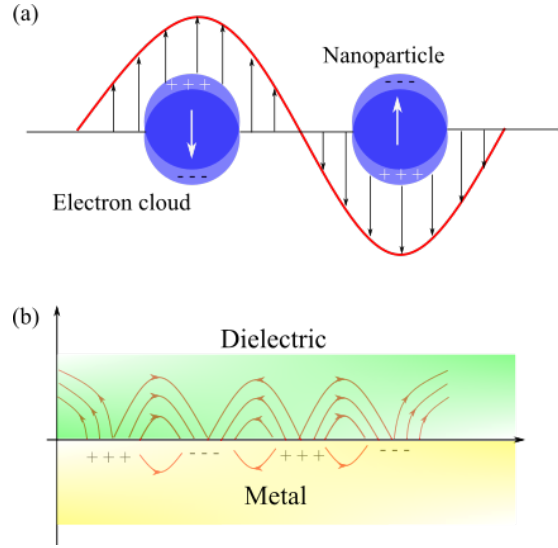


FIGURE 1.5: Examples of the (a) localized surface plasmon polariton (LSP). An incident electromagnetic field induces electron clouds of charges to localize at the particle poles. A dipole-like excitation is then obtained at the plasma frequency which can be considered as the LSP. (b) Long-range surface plasmon polariton (SPP) geometries. An incident field excites a surface wave that propagates along the metal and dielectric interface. Figures are adapted from [57].

a medium with the refractive index of n . The light is not focused to a point but forms an Airy disk having a central spot in the focal plane with radius of

$$r = \frac{\lambda}{2n \sin \theta} = \frac{\lambda}{2NA} \quad (1.1)$$

The denominator $n \sin \theta$ is called the numerical aperture (NA) which is a measure of how much light can be collected by an optical system. Two point sources will each produce an Airy pattern. As the point sources move closer together, the patterns will start to overlap, and ultimately they will merge to form a single pattern, in which case the two point sources cannot be resolved in the image. The Rayleigh criterion specifies that two point sources can be considered to be resolvable if the separation of the two images is at least the radius of the Airy disk [59, 60]. The resolution of an imaging system is constrained by the wavelength of light to be used and the aperture size of its optical components. For example, a microscope cannot resolve two objects separated by less than about half a wavelength of the input light. This phenomenon is called Abbe diffraction limit [61], and was considered as a fundamental, unbreakable

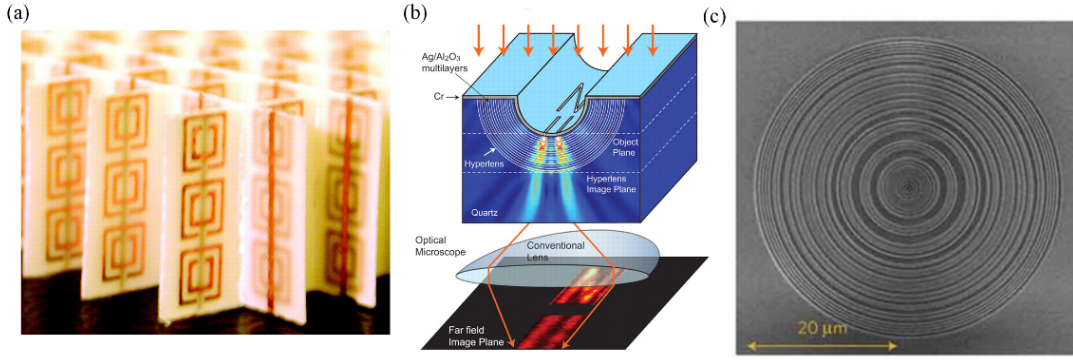


FIGURE 1.6: Example of subwavelength imaging technologies. (a) A left-handed metamaterial (LHM) sample. It consists of square copper split ring resonators and copper wire strips on fibre glass circuit board material. The rings and wires are on opposite sides of the boards, and the boards have been cut and assembled into an interlocking lattice. (b) Schematic of a superlens and numerical simulation of imaging of sub-diffraction-limited objects. The superlens is made of 16 layers of $\text{Ag}/\text{Al}_2\text{O}_3$. (c) SEM image of a super-oscillatory lens. A binary amplitude mask was used for direct focusing of laser light into a subwavelength spot in the post evanescent field by precisely tailoring the interference of a large number of beams diffracted from a nanostructured mask.

rule for over a century. However, in a series of papers in 1928, the Irishman Edward Hutchinson Synge in correspondence with Albert Einstein, showed how this was not an unbreakable rule [62]. He suggested the implementation of a miniature aperture, whose diameter is approximately 1×10^{-6} cm, illuminated from below, and placed immediately beneath the imaged sample so the transmitted light is then detected by a photoelectric cell and registered by a telephotographic apparatus which is synchronized with the motion of the aperture. He described the method "which makes the attainment of a resolution of $0.01\mu\text{m}$ and even beyond" possible. Unbeknownst to him, this was the first proposal of a combined dielectric-plasmonic focusing element.

As the emerging of nanotechnology [63], several approaches are capable for subwavelength imaging to beat the classical diffraction limit of optical microscope, such as using hypothetical material with a negative index of refraction [64, 65], a super-oscillatory lens [66], or artificially engineered metamaterials which are called superlens [67, 68]. They can have a negative dielectric permittivity ϵ and a negative magnetic permeability μ value which are not known to exist in naturally occurring. Figure 1.6 shows the schematics of a few examples of the subwavelength imaging technologies.

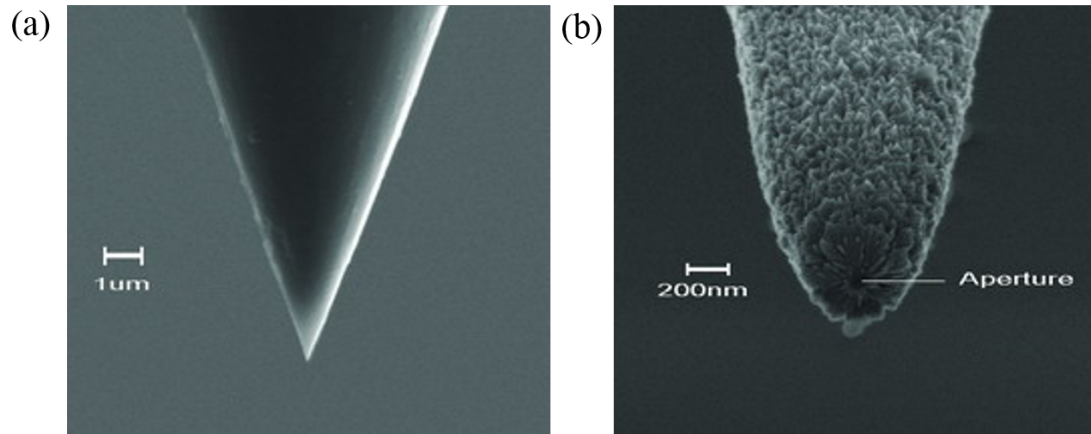


FIGURE 1.7: SNOM tips: Metallic tapered fibre with small aperture at the end. (a) Uncoated tip; (b) Coated tip with 50 – 100 nm aperture. Images from NT-MDT.

In the domain of optical instruments, a key step was the invention in 1984 of the scanning near-field optical microscopy (SNOM) by Pohl Dieter [69] and co-workers, allowing sub-wavelength near-field optical resolution for the first time. Here, an image of a structure is created by scanning a physical probe with a sub-wavelength aperture in close proximity to the illuminated specimen. The mechanism of this microscope is based on the excitation of LSP at the metallic tip, which generates a nanoscale light spot at the apex of the tiny tip. By using this tiny light spot as the light source of an optical microscope, an extremely high spatial resolution image can be obtained. Figure 1.7 shows the SEM images of the SNOM tips with and without a metallic coating. A design similar to this was already proposed by Edward Hutchinson Synge in 1928.

The use of materials with negative dielectric permittivity is one of the most feasible ways of circumventing the diffraction limit and achieving localization of electromagnetic energy (at optical frequencies) into nanoscale regions. Noble metals (copper, silver, and gold) are available materials for this purpose below the plasma frequency. The excitation electromagnetic waves on the metal surface can couple to the electron plasma in the metal [31], which the basis of SPP formation and sub-wavelength light confinement in order to break the Abbe diffraction limit.

1.3.3 Sub-wavelength light confinement

Modern computation and communication systems rely on the ability to route and transfer information using electronic and electromagnetic signals. Massive efforts over the last decade have been driven by miniaturization and integration of electronics and photonics on the same platform [70]. However, the diffraction limit of light is a fundamental barrier to interfacing micrometer-scale waveguides to nanoscale electronic circuits. Furthermore, dense photonic integration is hampered because cross-talk between waveguides increases as the separation between the integration waveguides is reduced.

The rapid development of plasmonic waveguides with highly confined SPP modes has shown their potential for achieving sub-wavelength of light confinement over traditional dielectric waveguides [71, 72]. This remarkable capability is promising for the design of densely integrated photonic devices with nanoscale resolution. Basically, the sub-wavelength confinement of light in the plasmonic waveguide is associated with engineering the evanescent fields outside the core of the waveguide [73]. When an optical ray traverses a flat interface between two different dielectrics, (to simplify, we consider a two-layer system with semi-infinitely thick which can be seen in Figure 1.8(a)) light is partially reflected back to the core medium and is partly refracted in the cladding medium. Snell's law governs the angle of reflection and refraction. If $n_1 > n_2$ (n_1 and n_2 are the refractive index of the two dielectrics) and the incident angle is greater than the critical angle θ_c , as shown in equation 1.2, light is totally reflected back to the core medium and evanescently decays in the cladding medium, this process is known as total internal reflection (TIR).

$$\theta_c = \arcsin\left(\frac{n_2}{n_1}\right) \quad (1.2)$$

However, if the cladding medium is metal (like Au or Ag), the SPP can be excited when the certain phase matching conditions are met, energy can be transferred from the excitation light wave to the free electron to form propagating SPP at the metal-dielectric surface. The SPP have a shorter wavelength than free excited light. Moreover, an extremely small skin-depth is achievable as the energy decays fast in the metal which can be seen in Figure 1.8(b). In a more complicated sandwich structure, the dielectric waveguide (Figure 1.8(c)) could not achieve sub-wavelength of light confinement because of the long evanescent tails in the claddings, moreover, as the thickness of the core layer becomes too thin, the guiding modes will be cut-off hindering its ability to guide light in

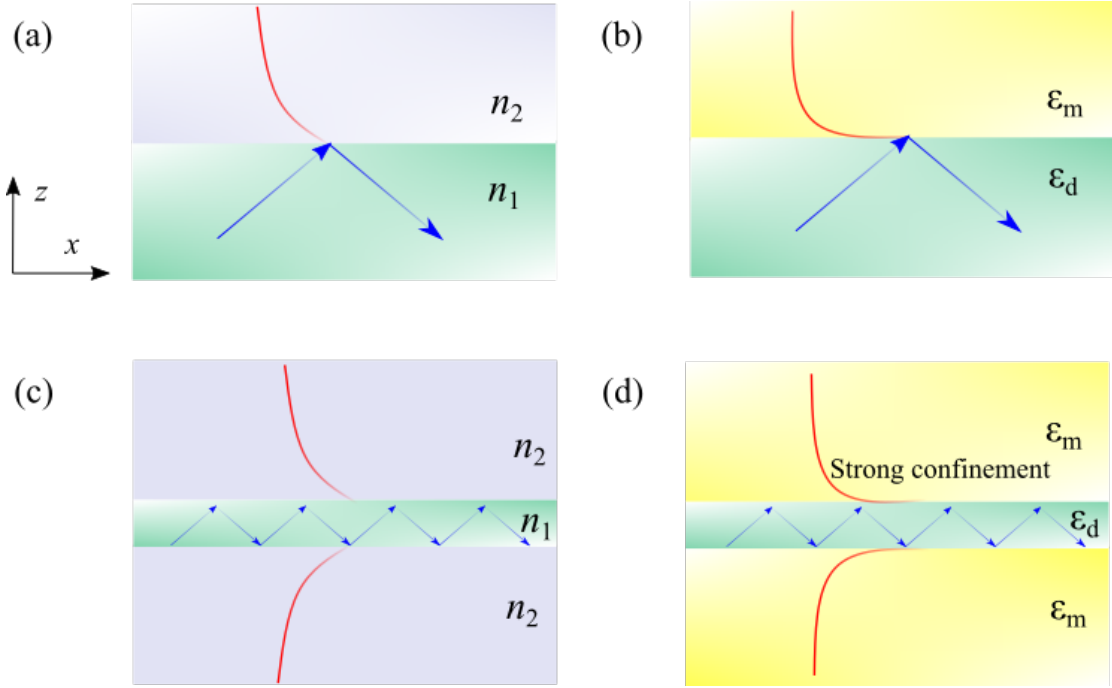


FIGURE 1.8: (a) TIR happens in a semi-infinitely thick two dielectric layers system in which $n_1 > n_2$. (b) One dimensional sub-wavelength light confinement in a metal-dielectric interface, ϵ_m is the permittivity of the metal and ϵ_d is the permittivity of the dielectric. (c) Two-dimensional light confinement in a sandwiched dielectric waveguide. (d) Two dimensional sub-wavelength light confinement in a sandwiched plasmonic waveguide (two metal claddings and a dielectric core) Figures are adapted from [25]

nanoscale. For the plasmonic waveguide as shown in Figure 1.8(d), which can be described as a metal-insulator-metal (MIM) structure. In this type of structure, it is possible to control the resonance wavelength, the thickness of the core layer and the skin depth of the evanescent waves in the cladding medium to achieve sub-wavelength light confinement in the waveguide core.

The remarkable properties of SPP show that it is possible to squeeze visible light into SPP modes which have sub-wavelength light confinement. Owing to this attribution, SPP have found applications in fields such as nanoscale on-chip amplifiers and lasers [74], nanoscale integrated photonic devices, circuits and systems [75], optical sensing of molecules, atoms and nanoparticles [76], optical imaging and spectroscopy systems with sub-wavelength resolution [77], nanoscale optical trapping systems [78], and nano-focusing for high density data storage [23]. Plasmonic waveguides however have significantly higher losses than dielectric waveguides, limiting their propagation lengths from 10-100 μm [79]. Therefore plasmonic and dielectric elements must be integrated in

order to achieve the required performance.

1.3.4 Review of recent nanofocusing designs

Efficiently concentrating optical energy to nanoscale dimensions has been demonstrated in academia and industry over the past few decades [80]. This concept has been widely investigated in the design of photonic integrated circuits (PIC). Compared to the integrated electronic devices, integrated photonic devices have a larger bandwidth, higher immunity to electromagnetic interference and feasible compatibility with current complementary metal-oxide-semiconductor (CMOS) fabrication technologies [81] are being developed. The possibility of achieving nanoscale photonic integration has been largely due to the utilization of SPP described in the previous section, and mechanisms taking advantage of them have been proposed for overcoming the diffraction limit of conventional focusing devices [79]. The concentration of optical energy into the nanoscale can be achieved using a range of nano-focusing elements, such as nano-optical antennae, high refractive index dielectric antennae, tapered SPP devices, or nanohole arrays. Nano-optical antennae use the geometry of the element to concentrate and enhance light confinement. Since there are no propagating modes, momentum matching is not required. The resonance frequency can be tuned either by geometry or surrounding materials.

Alternatively propagating SPP modes can be used to concentrate light. SPP intrinsically confine light to the metal-dielectric interface. If the metal layer is then structured in the x - y direction, the light can be further confined in three dimensions. Mark I. Stockman [82] predicted theoretically that SPP propagating toward the tip of a tapered plasmonic waveguide are slowed down and asymptotically stopped when they are approaching the tip, never actually reaching it. This corresponds to the accumulation of energy at the tip, as well as a reduction of the optical cross-section (*i.e.*, nanofocusing). The SPP nanofocusing is typically achieved by using tapered metallic plasmonic nanostructures. Examples include a tapered metallic triangle [83], a tapered gap between two metallic media or air-slot structure [84, 85], a three dimensional taper [86], a V-shaped groove plasmonic waveguide [87–89], a conical noble metallic tip [90, 91], and a plasmonic antenna with a nano-taper [92]. Nanofocusing is typically associated with a significant reduction of both phase and group velocities of the SPP modes by varying the geometry of the waveguides. The local field enhancement is the main characteristic of all the nanofocusing nanostructures.

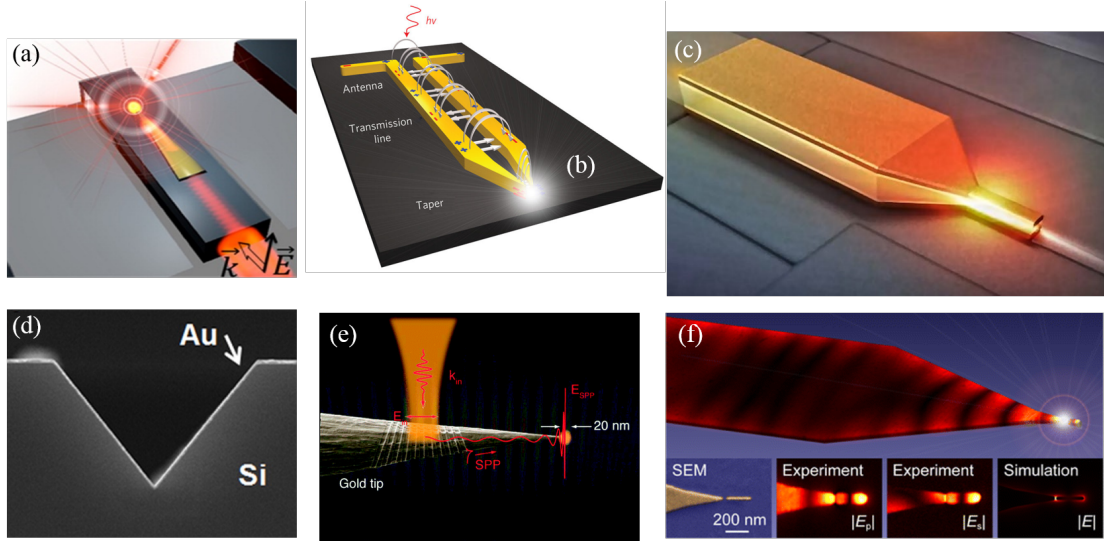


FIGURE 1.9: Tapered plasmonic nanofocusing configurations. (a) A tapered metallic triangle with a dielectric core [83]. (b) A transmission line consists of two parallel metal wires with a tapered air gap [84]. (c) A MIM gap plasmonic waveguide with a three-dimensional linear taper [86]. (d) A V-shaped groove [89]. (e) A conical noble metallic tip with a grating coupler [93]. (f) Nanofocusing in a plasmonic antenna with a taper [92].

Figure 1.9 shows six typical examples of nanofocusing structures. Figure 1.9(a) shows an Au nanotaper (an Au isosceles triangle of 300 nm base width and 750 nm in length) placed on a Si core waveguide with a 20 nm thick SiO_2 buffer layer. The propagating guided mode in the Si core is coupled to a plasmonic mode in the Au nanotaper through an evanescent coupling mechanism. A field enhancement factor of ~ 4.9 is achieved at the apex of the nanotaper. Figure 1.9(b) shows a nanofocusing structure with a tapered transmission line. The SPP in a mid-infrared wavelength range propagates along an 8 μm long transmission line and the energy is compressed into a spot with a diameter of 60 nm at the taper apex. Figure 1.9(c) is an Au- SiO_2 -Au gap plasmonic waveguide using a three-dimensional linear taper. The 3-D linearly tapered SiO_2 core in the MIM gap waveguide can reduce the excess losses that occur during the nanofocusing process occur. The simulation suggests that this structure can confine the energy of light with a wavelength of 830 nm from a $200 \times 500 \text{ nm}^2$ into a $2 \times 5 \text{ nm}^2$ area with an intensity enhancement factor of 3×10^4 , which currently the highest value from the reported literature. Figure 1.9(d) illustrates a gold V-shaped groove waveguides in the length of 1.6 μm . This V-shaped groove supports a SPP mode with a coupling efficiency of over 50%. A sharp

groove angle is fabricated by UV-lithography together with a subsequent crystallographic etch in a potassium hydroxide (KOH) bath or thermal oxidation of the silicon substrate which can ensure a well-confined SPP mode in the V-shaped groove. Figure 1.9(e) is a new nanofocusing concept based on a conical noble metallic tip. An electrochemically etched Au taper with a plasmonic grating achieves an efficient transformation of light from microscale to nanoscale. An enhancement factor of 2 is achieved and the spatial confinement at the apex of the tip is 20 nm. The low enhancement factor mainly because of the high loss during grating coupling and propagation. Figure 1.9(f) shows an on-chip structure followed by the impedance matched antenna excitation through the end-fire coupling at 1550 nm [92]. The efficient excitation of dipole and dark antenna modes contributes to a field enhancement factor of ~ 12000 over a gap volume of $30 \times 30 \times 10 \text{ nm}^3$.

1.4 Scope of this thesis

1.4.1 Motivation

In this thesis, both the theoretical and the experimental studies of plasmonic waveguides for subwavelength of light confinement applications are described. We experimentally demonstrate the excitation of SPP through a Kretschmann-Raether configuration with the aim to understand the dependence of SPP on the metallic composition and alloying. The major part of this thesis is the design of a NFT for HAMR application. We design an evanescent coupling system to couple light efficiently from a Si_3N_4 core to an Au NFT to heat up the recording medium. We study the possibility to boost the field enhancement factor of NFT by using low loss plasmonic materials and a multilayer design for the NFT. An evanescently coupled taper design is proposed and experimentally demonstrated. This design is longer than typical tapers, allowing more efficient transfer of energy from the dielectric waveguide mode to the plasmonic mode. This is particularly important in HAMR designs to avoid overwriting bits with stray light remaining in the waveguide. The solutions to increase the thermo-mechanically stability of the Au by using a thin adhesion and a capping layer is discussed in this thesis.

1.4.2 Overview of chapters

In Chapter 2, the fundamental theory needed to understand the mechanism of SPP are presented. Starting with Maxwell's equations, the characteristic equations are derived. Next, a theoretical analysis is given to show the dispersion properties of SPP propagating along an interface between a metal and a dielectric. We theoretically show the dispersion curve of two standard types of film geometries for plasmonic applications, an insulator-metal-insulator (IMI) and a metal-insulator-metal (MIM). Our discussions show how the thickness of each layer can influence the dispersion properties. A general approach to solve the SPP dispersion in multi-layer structures is discussed, it is applied by solving the transcendental equation determined by the wave function and the boundary condition between each adjacent layers.

In Chapter 3, the facilities which are used for the sample fabrication and characterization are introduced. They include electron beam lithography (EBL), UV lithography, inductively coupled plasma (ICP) etching and film deposition. Two different films deposition techniques are used: electron beam evaporation and magnetron sputtering deposition. Characterization techniques include: scanning electron microscopy (SEM), atomic force microscopy (AFM), X-ray reflection (XRR), profilometry, ellipsometry and charged coupled device (CCD) imaging.

In Chapter 4, the dispersion property of Au-Ag composited bi-metallic films are explored. We experimentally map the full dispersion range available in the Kretschmann-Raether setup to understand the mechanism of the SPP excitation and propagation in these films. The dispersion is compared to the analytical dispersion relations for bound IMI modes and a full transfer matrix model. The potential of a bi-metallic film can improve the biochemical sensing performance is also discussed in this chapter.

In Chapter 5, the experimental, simulation, and theoretical techniques to characterize a particular NFT composed of an evanescently coupled plasmonic taper are discussed. The design can efficiently extract the incident light from the waveguide core to the NFT while overcoming the ohmic losses incurred by increasing the optical path length. The coupling process is optimised to maximize the electromagnetic intensity in the NFT while minimising the intensity remaining in the dielectric waveguide to avoid the miswriting of bits in a HAMR structure.

Chapter 6 is devoted to the development of the thermo-mechanically stability of the Au film for the NFT design in HAMR. Three approaches are investigated: an Ag-Cu-Au combined film can achieve tunable dispersion properties for superior plasmonic performance. The effort to make an Ag-Cu-Au alloy film is discussed which can improve the robustness of the combined film; a thinner adhesion layer can improve the plasmonic performance owing to the lower absorption and less diffusion of a thin adhesion layer; a thin oxidized Al_2O_3 is used as the capping layer to further improve the plasmonic performance of the metallic film is also discussed.

Chapter 7 provides an outlook for the future work on plasmonic waveguide design. They include thermal simulations, measurements, and NFT design by using Ag-Cu-Au alloy.

Chapter 2

Derivation of SPP Dispersion in Multi-layer Metallic Films

This chapter deals with the fundamental theory needed to understand the mechanism of SPP. The metal is described by the experimental data determined by Johnson and Christy [94] rather than a damped free electron gas or Drude-Lorentz model [95]. The dispersion of SPP wave in a metallic slab embedded in a symmetric dielectric or an anti-symmetric environment shows a wavelength-dependent behavior. The analytic dispersion calculations indicate a splitting of the SPP modes, they are corresponding to a symmetric and an anti-symmetric electromagnetic distribution. The formation of these two distinct modes resulted from the coupling of the SPP modes to the upper and the lower interfaces of the metallic slab. This coupling is usually evident when the thickness of the metallic slab is below 50 nm [96]. A simple theoretical analysis shows the dispersion properties of SPP propagating along an interface between a metal and a dielectric when both media are considered as semi-infinitely thick. Finally, we expand the derivation to a more general model by solving the transcendental equation determined by the wave function and the boundary condition between each adjacent layers. The method can be applied to solve the SPP dispersion in multi-layer structures, two examples of multi-layer structure are discussed in detail at the end of this chapter — an insulator-metal-insulator (IMI) and a metal-insulator-metal (MIM) structures.

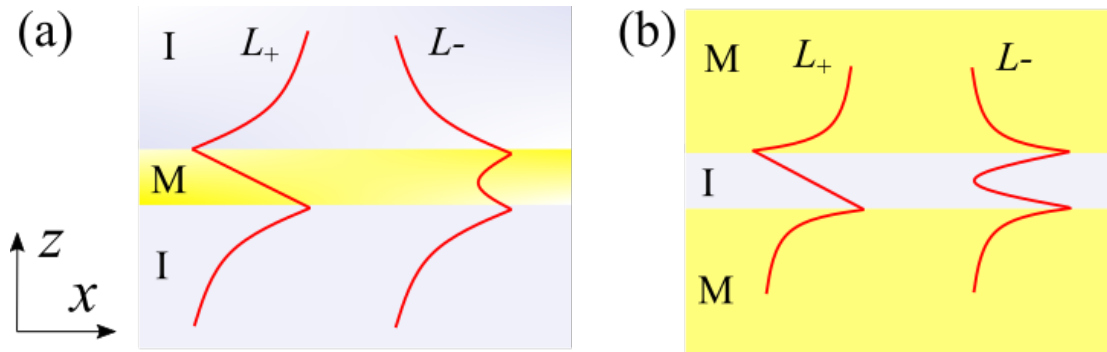


FIGURE 2.1: Schematic diagram of the (a) IMI and the (b) MIM structure, in which the IMI structure consists of a metal core and two dielectric claddings, the geometry of MIM is formed inversely. The red lines in the two panels are the characteristic electric field profile in the two metal slab waveguides with a core thickness of $z = d$. The anti-symmetric mode, corresponding to the solution of L_+ ; the symmetric mode, corresponding to the solution of L_- . The wave propagates along x direction

2.1 Dispersion relation in insulator-metal-insulator (IMI) and metal-insulator-metal (MIM) structures

2.1.1 The symmetric mode and anti-symmetric mode

For a thin film, plasmons at the metal-air and metal-dielectric interfaces can couple to form composite symmetric and anti-symmetric modes, as shown in the Figure 2.1. These configurations, known as IMI and MIM structure, can produce either anti-symmetric mode or symmetric mode [96]. The IMI is a configuration which with a metal core covered by two dielectric claddings, SPP can be excited on the two dielectric-metal interfaces, the SPP have long propagation length and poor confinement in this structure. Inversely, the MIM structure has two metal claddings and a dielectric core which can achieve highly light confinement but the loss is high in this structure. The SPP mode in the MIM structure can be tightly confined in the dielectric core which has a lower propagation length than the SPP mode in an IMI structure. In this thesis, we write the symmetric mode (low momentum SPP mode) as L_- modes and the anti-symmetric mode as L_+ mode for simplicity. The derivation of these modes was described in detail by E. N. Economou, *et. al.* [97] and can be written analytically for a single metal thin film by considering the boundary conditions at the interface as [98]

$$\begin{aligned}
L_+ : \epsilon_m k_a^z + \epsilon_d k_m^z \tanh\left(\frac{-ik_m^z d}{2}\right) &= 0 \\
L_- : \epsilon_m k_a^z + \epsilon_d k_m^z \coth\left(\frac{-ik_m^z d}{2}\right) &= 0
\end{aligned} \tag{2.1}$$

with

$$(k_m^z)^2 = \epsilon_{m,a} \frac{\omega^2}{c^2} - k_x^2, k_x = \frac{\omega}{c} \sqrt{\frac{\epsilon_m \epsilon_a}{\epsilon_m + \epsilon_a}} \tag{2.2}$$

k_m^z and k_a^z are defined as the z component of the wavevector in the metal and dielectric respectively. The analysis assumes a three-layer symmetric structure with core thickness of d and the core (cladding) is composed of material with dielectric constant ϵ_m (ϵ_a), centred at $z = 0$. The dispersion relations given in equation (2.1) are transcendental equations in complex space which must be solved numerically. The solution can be either even or odd modes, these supermodes are denoted herein as symmetric bound and anti-symmetric bound modes, respectively, since their main transverse electric field component E_z varies either asymmetrically or symmetrically across the structure (along the x axis), as sketched in Figure 2.1. The charge density in the metal linked to the L_- mode has a symmetric distribution over d , as indicated by the red curves in Figure 2.1, whereas the charge density associated with the L_+ mode is anti-symmetric over d [99].

2.1.2 General approach to solving SPP dispersion in two interfaces

Since the transcendental equations (2.1) needs to be solved numerically, we consider a simple metal-dielectric case to analytically solve the propagating solutions confined to the boundary along plane of z , propagating in the x direction which can be seen in Figure 2.1. From Economou [97] we know that we seek solutions to the following, which is equivalent to Maxwell's equations under the assumptions that the solutions are TM waves proportional to $e^{i(\omega t - kx)}$:

$$\frac{\partial^2}{\partial z^2} E_z - K_j^2 E_z = 0 \tag{2.3}$$



FIGURE 2.2: Sketch of a two layer structure.

where

$$K_j = \sqrt{k^2 - \omega^2 \epsilon_j / c^2} \quad (2.4)$$

and ϵ_j is the dielectric constant of the region labelled by j . Solutions to equation 2.3 are of the form

$$\alpha e^{K_j z} + \beta e^{-K_j z} \quad (2.5)$$

We can also find E_x by differentiation

$$E_x = -(i/k) \frac{\partial E_j}{\partial z} \quad (2.6)$$

The strategy in the following will be to use equation (2.5) in each region, taking note of requirement that the field $E_z \rightarrow 0$ as $z \rightarrow \pm\infty$. We then ensure the boundary conditions at each interface. These conditions tell us that the parallel component of the electric field E is constant and the perpendicular component of the magnetic field H , $H = \epsilon E$, is constant.

$$\begin{aligned} \epsilon_1 E_{1z} &= \epsilon_2 E_{2z} \\ E_{1x} &= E_{2x} \end{aligned} \quad (2.7)$$

These conditions give us $2b$ equations where b is the number of boundaries. We have $2b$ coefficients of the fields. (2 for each of the $b + 1$ materials, minus the 2 which must be zero so that the fields decay as $z \rightarrow \pm\infty$). We can thus eliminate these coefficients leaving an equation in terms of the ϵ_j , boundary positions, *etc.* which are known, and the K_j which are not. This equation is of the form of $f(K_1(k, \omega) \cdots, K_j(k, \omega) \cdots)$, which gives a transcendental equation for $\omega(k)$.

Consider the simplest geometry, which contains material 1 for $z > 0$ and material 2 for $z < 0$. From equation 2.5 the field is

$$E_z = \begin{cases} A_1 e^{-K_1 z} & z > 0 \\ A_2 e^{K_2 z} & z < 0 \end{cases} \quad (2.8)$$

since these are the exponentials which decay at $\pm\infty$. From equation (2.6) we find the x - component is

$$E_x = \begin{cases} (iK_1 A_1 / k) e^{-K_1 z} & z > 0 \\ -(iK_2 A_2 / k) e^{K_2 z} & z < 0 \end{cases} \quad (2.9)$$

inserting these in equation 2.7 at $z = 0$ gives two equations:

$$\begin{aligned} \epsilon_1 A_1 &= \epsilon_2 A_2 \\ A_1 K_1 &= -A_2 K_2 \end{aligned} \quad (2.10)$$

eliminating the coefficients gives

$$\epsilon_2 K_1 = -\epsilon_2 K_2 \quad (2.11)$$

Although equation (2.10) is simple to solve, it is worth rewriting as a matrix equation as an example for more complicated situations which we be discussed further. This gives

$$\begin{bmatrix} \epsilon_1 & -\epsilon_2 \\ K_1 & K_2 \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = 0 \quad (2.12)$$

which is only possible if

$$\Delta \begin{bmatrix} \epsilon_1 & -\epsilon_2 \\ K_1 & K_2 \end{bmatrix} = \epsilon_1 K_2 + \epsilon_2 K_1 = 0 \quad (2.13)$$

This eigenvalue of this matrix can be simply solved by the roots finder function in Wolfram Mathematica. It returns the solutions of k for different ω are related to the dispersion curves of the SPP in a metal-dielectric interface. This general approach can be applied to multi-layer structures with the arbitrary

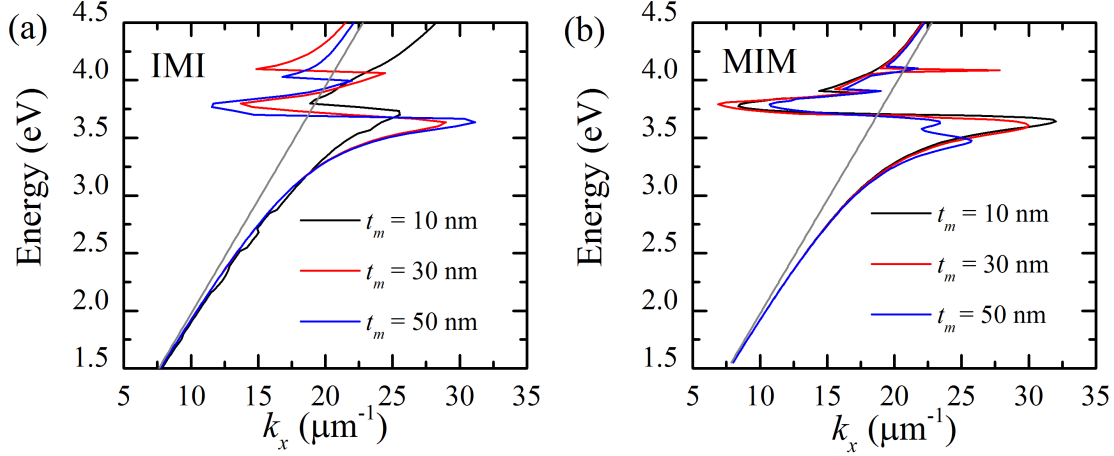


FIGURE 2.3: Dispersion curves of SPP in (a) IMI and (b) MIM geometries consisting of Ag and SiO₂ for different thickness of the middle layers. The gray straight lines in both figures are the light line in air.

material. The detailed derivation of three-layered and five-layered structures are described in Appendix A.

2.1.3 Thickness dependent of dispersion curves

The eigenmodes for IMI and MIM structures arise from evanescent coupling between the SPP supported by the individual metal-dielectric surfaces. Figure 2.3 plotted the dispersion curves of the IMI and MIM structures in which the dispersion relations are solved through general approach described in the previous section. To simplicity, only the dispersion curves of the anti-symmetric mode are plotted for both cases. The dispersion curves are shifting as the thickness of the core layer is varying which shows the thickness dependent of the dispersion curves.

In an IMI geometry, the dispersion of an air/Ag/air geometry is plotted in Figure 2.3(a) for core thickness of 10, 30 and 50 nm respectively. The maximum wavevector of the SPP modes is varying with the different thickness of the middle layer. A k_x value of $25 \mu\text{m}^{-1}$ is obtained as the thickness of the middle layer is 10 nm, by increasing the thickness of the metal core layer, the k_x value is increasing. A k_x value of $32.5 \mu\text{m}^{-1}$ is achieved when the core thickness goes to 50 nm which shows an IMI couldn't have a highly confine the light when the core layer goes to thin, the SPP mode is only confined at the two metal-dielectric interfaces. The situation is different in MIM geometry. The dispersion in an

Ag/air/Ag geometry is plotted in Figure 2.3(b) for core thicknesses of 10, 30 and 50 nm. As can be seen, the maximum wavevector of the SPP modes is increasing when the thickness of the core layer is decreasing. It shows that a MIM structure can confine the SPP mode in the insulator layer without the cut-off thickness [100].

2.1.4 Reflectivity calculation through transfer matrix method (TMM)

The eigenvalue solutions give the frequency and propagation length of the SPP. In our experiments, we measure the light reflected from our samples as a function of the excitation angle and wavelength to reveal the dispersion curve. For a given wavelength, the momentum matching between the photonic mode and plasmonic mode will be satisfied with a certain input angle, the light coupled into SPP will not be reflected, thus the lower intensity (close to zero) region in the reflection spectrum contains the information of the plasmonic mode that can be excited. To model the experimental data we use the transfer matrix method (TMM) [101]. The relationship of the tangential components of the electric field $\mathbf{E}$ vector on opposite sides of a film is found to be linear. Thus, TMM can be applied to describe the electromagnetic waves propagating through a stack of layers at normal incidence or at a certain angle. For a system with n layers, each layer j has a transfer matrix $\mathbf{M}_j$. The system transfer matrix is

$$\mathbf{M}_j = \begin{bmatrix} \cos k_j d & \frac{-i\epsilon_j}{k_j} \sin k_j d \\ \frac{-ik_j}{\epsilon_j} \sin k_j d & \cos k_j d \end{bmatrix} \quad (2.14)$$

in a system of n layers, the total transfer matrix of the system is found by matrix multiplication of the transfer matrix of each layer, which is give by

$$\mathbf{M} = \mathbf{M}_n \cdots \mathbf{M}_2 \cdot \mathbf{M}_1 \quad (2.15)$$

The reflectance of the light propagation through a n layer can be described as

$$R = \frac{(\mathbf{M}_{11} + \mathbf{M}_{12} \cdot \frac{k_n}{\epsilon_n}) \cdot \frac{k_1}{\epsilon_1} - (\mathbf{M}_{21} + \mathbf{M}_{22} \cdot \frac{k_n}{\epsilon_n})}{(\mathbf{M}_{11} + \mathbf{M}_{12} \cdot \frac{k_n}{\epsilon_n}) \cdot \frac{k_1}{\epsilon_1} + (\mathbf{M}_{21} + \mathbf{M}_{22} \cdot \frac{k_n}{\epsilon_n})} \quad (2.16)$$

2.2 Chapter summary

In this chapter, we start with Maxwell's equations to solve the characteristic equations of the dispersion for a single interface between a metal and a dielectric layer. Then the transfer matrix method is used for a general approach to solving SPP dispersion in multi-layer metallic films. The eigenvalue solutions for two, three and five layers with different permittivity of each layer are numerically solved. The dispersion curves which are related to the transcendental equation for $\omega(k)$ can be plotted. The odd and even solutions of the equation $\omega(k)$ are corresponding to the anti-symmetric and symmetric plasmonic modes in these layer structures. The dispersion curves for two particular plasmonic structures (IMI and MIM) are discussed in the end of this chapter. The feature of the dispersion curves of these structures is highly dependent on the thickness of the composite layers. It gives information on how to engineer the thickness of each layer to control the energy loss and plasmon intensity distribution in the IMI and MIM layer structures. The theory in this chapter can be applied to calculate the dispersion curves for bi-metallic layers in Chapter 4, and the plasmonic waveguide designs in Chapter 5 and Chapter 6.

Chapter 3

Sample Fabrication and Characterization

3.1 Introduction

Fabrication of good samples is perhaps the most important step for experimental work. The purpose of this chapter is to describe in detail the various facilities used in sample preparation and characterization throughout the thesis. It can be used as a reference throughout the rest of the thesis. The detailed facilities used for fabrication in this thesis mainly include electron beam lithography (EBL), UV lithography, inductively coupled plasma (ICP) etching and film deposition. Two different films deposition techniques are used: electron beam evaporation and magnetron sputtering deposition. Characterization techniques include: scanning electron microscopy (SEM), atomic force microscopy (AFM), X-ray reflection (XRR), profilometry, ellipsometry and charged coupled device (CCD) imaging. A brief introduction of these techniques is provided.

3.2 Facilities used in the fabrication

3.2.1 Ultraviolet (UV) lithography

In UV lithography process, a photosensitive polymer known as a photoresist is spin coated onto the substrate. The thickness of this resist layer is determined by the speed of the spin coater, and then can be accurately controlled from hundreds of nanometers to tens of microns if the viscosity of the resist is known. The film thickness is proportional to the spin speed [102]. Maximum coating uniformity is typically attained between the spin speeds of 3500 rpm and 5500 rpm. The MICROPOSIT S1800 series photoresist is used in this thesis. The

photoresist spins for 45 s at a speed of 5000 rpm/s and results in a film thickness of 1.2 μm . The first form of UV lithography was known as a contact lithography and was used to produce integrated circuits (ICs) in the early 1960s [103]. In this system, a glass plate mask coated with copper was placed on the surface of the substrate. A pattern defined in the mask allowed light pass through in certain areas. The mask was exposed using a homogeneous intensity of UV radiation which can induce a chemical change in the areas of the polymer which have been exposed to UV radiation. Figure 3.1 shows the OAI mask aligner system which is located in the Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN) in Trinity College Dublin. There are two common categories of resist known as positive and negative tone resists. For the positive tone resist, the areas which are exposed will be washed away in a development process, whereas, for a negative tone resist the exposed areas remain on the substrate.

The patterns are obtained after the development process, MF 319 developer is used in the development process of this thesis. The exposed resist is “developed” by immersion in a solvent which will dissolve only the exposed (unexposed) areas for positive tone (negative tone). After development, the remaining resist can be used as a mask for the etching process to transfer the patterns to the substrate. If the resist is not robust enough for the etching process a metal deposition step may be needed to be followed by a “lift-off” step. Etching refers to the removal of the actual material of the substrate. The resist could be removed with chemical solvent (*i.e.* acetone) without any modification to the original substrate. Etching transfers the pattern of the resist into the underlying material. It can be done chemically using acids (wet etching) or physically using accelerated ions (dry etching), or using a combination of the two. Wet etching can produce anisotropic etch or etch along one particular crystallographic direction. Dry etching allows more control over the etching process and can produce highly anisotropic etches. Energetic ions are accelerated towards the substrate and depending on the gas composition and ion velocities both physical and chemical etching can be achieved.

3.2.2 Electron beam lithography (EBL)

For electron beam lithography (EBL), the substrate is coated with a polymer which is sensitive to electrons [104]. Similarly to UV lithography, this can be a positive or a negative tone (we are using PMMA A3 positive tone electron resist). The sample is then raster-scanned with the focused electron beam, the

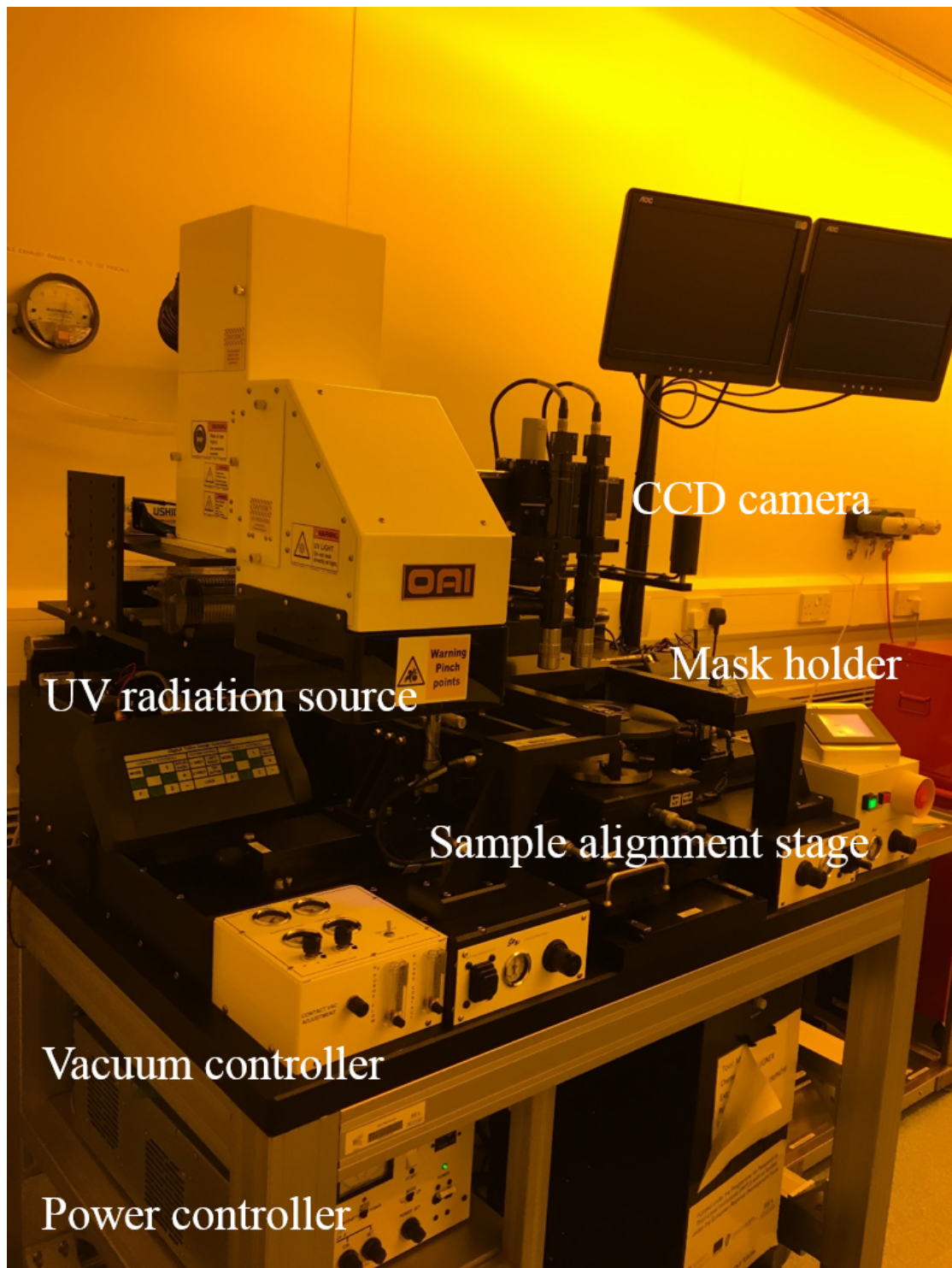


FIGURE 3.1: The OAI mask aligner system. It contains of a 365 nm UV radiation source; a size changeable mask holder; a vacuum system for both the substrate and the mask holder; two CCD cameras and double screen for the alignment; three-dimensional mobile platform.

electron beam changes the solubility of the resist. A beam blanker controls which areas are exposed and which are not. A development process is followed enabling selective removal of either the exposed or non-exposed regions of the resist. IPA: MIBK with a concentration ratio of 1:3 is used for the development process of the thesis. The same ICP etch process like the UV lithography will be used to transfer the patterns to the substrate. The effective wavelength of the beam of electrons is much smaller than that of UV radiation meaning that a much higher resolution can be obtained. EBL has the advantage of nanofabrication for making nanostructures over a commercial facility that use UV lithography. Even though the ASML manufactures extreme ultraviolet lithography (EUV) machines that can produce 22 nm structure [105], the machines are very costly for research usage.

It is very common to convert a scanning electron Microscopy (SEM) into an EBL system for research applications [104]. SEM uses an electron beam to image samples with a resolution down to the nanometer scale. The electrons are emitted from a heated tungsten filament and accelerated with a high voltage (5-100 keV). The electron beam is then focused on the sample surface by a set of lenses in the electron column [107]. Standard electron beam column is depicted in Figure 3.2. Ultrahigh vacuum is required to avoid scattering of electrons in the column ($< 9 \times 10^{-9}$ mbar), whereas high vacuum (10^{-6} - 10^{-7}) is sufficient for practical applications [108, 109]. We were using a Carl Zeiss Electron Beam Lithography SEM – Supra 40 system to do the fabrication in this thesis. The electron beam is passed through a physical aperture of fixed size (10 - 30 μm). By controlling the current in the beam, the beam is focused to a diffraction limited spot (~ 8 nm) using the magnetic and electrostatic lenses. Fine tuning of the electromagnetic lenses can change the focal position and adjust for astigmatism to give the best results.

3.2.3 Inductively Coupled Plasma (ICP) Etching

An inductively coupled plasma (ICP) is a type of plasma source in which the energy is supplied by electric currents which are produced by electromagnetic induction. ICP reactive ion etching is a particular form of plasma etching, which allows independent control over the density and energy of ions in the plasma. It allows the use of both physical and chemical etching to create highly anisotropic etches which are essential for photonic applications [108, 110]. A Oxford Instruments Plasmalab 100 Inductively Coupled Plasma etch system is shown in Figure 3.3 which has been used for the etch process in this thesis.

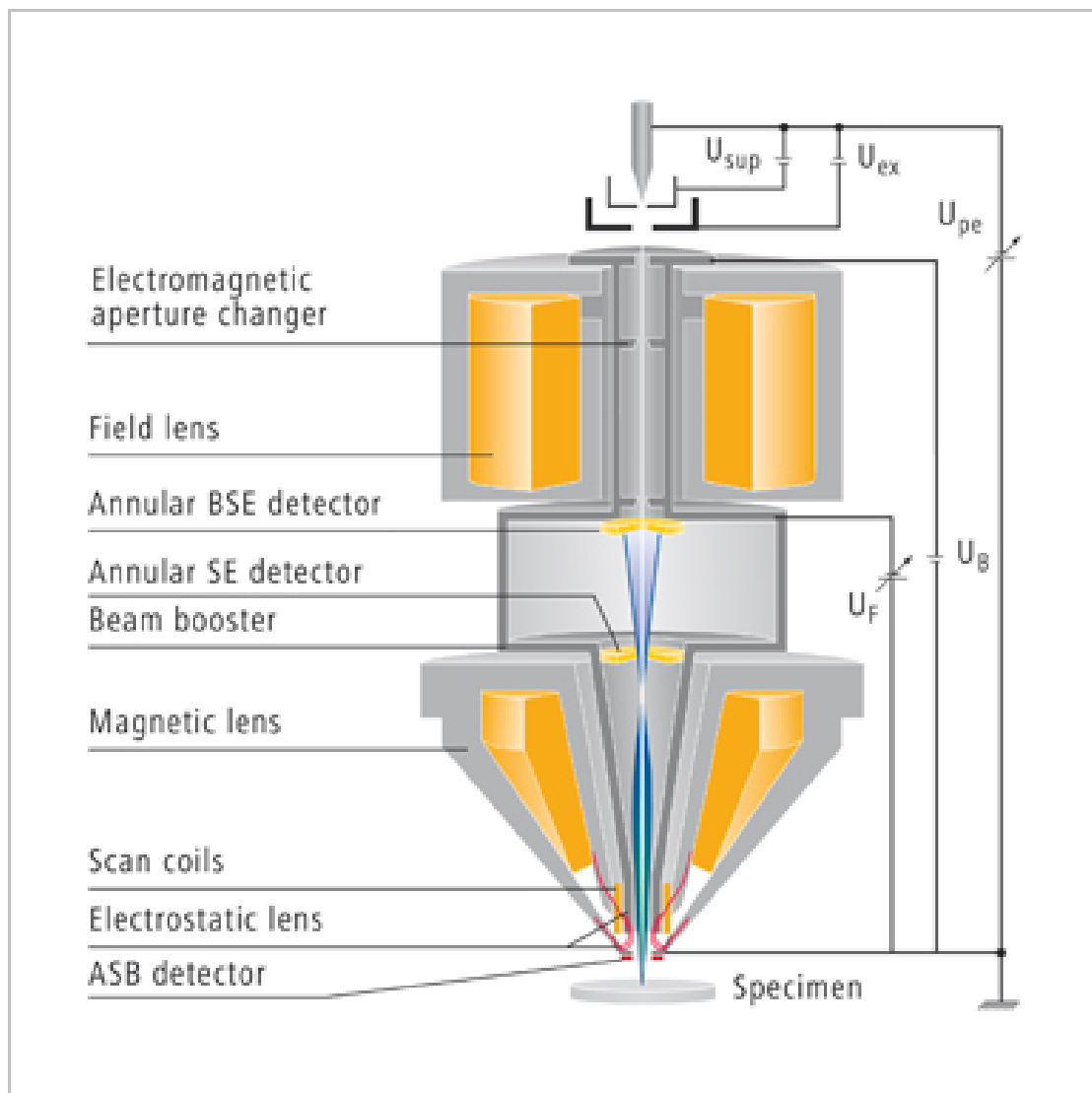


FIGURE 3.2: Schematic diagram of a modern electron beam column with electromagnetic lenses. Figure was adapted from the SEM manual [106]

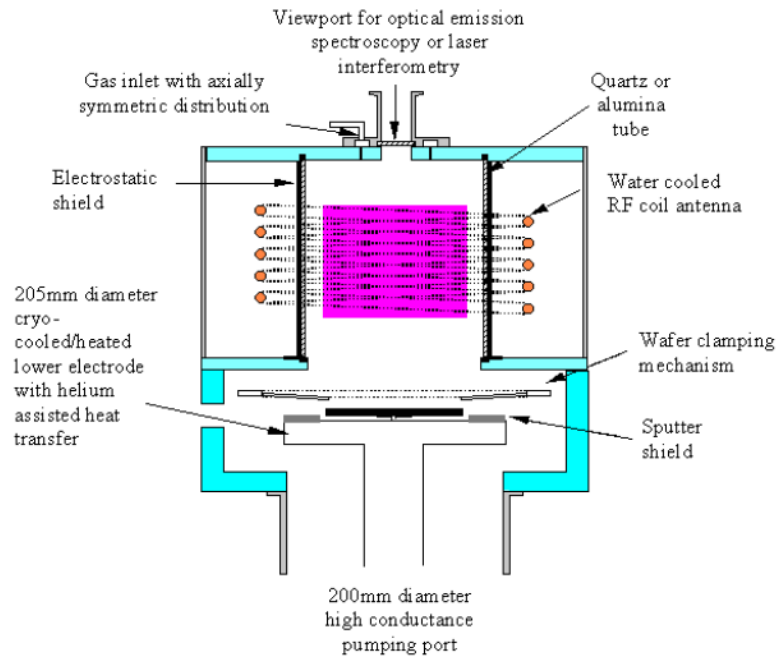


FIGURE 3.3: Schematic of the Plasmalab system 100 with vacuum loadlock and an inductive coupled plasma source ICP180 tool. [111].

In an ICP etching process, the plasma is generated inductively using a water-cooled radio frequency (RF) coil antenna source around a vacuum chamber. Gases are injected into the chamber, and the magnetic field generated circulates electrons around the coil causing collisions and ionizing of the injected gases. The RF frequency allows for efficient ionization of the gases due to the mismatch in mass between the electrons and the ions. The massive ions cannot track the change in electric field. Thus the electrons have multiple passes to ionize the gas [112]. Electrons are absorbed by the anode and build up a negative charge on a capacitor placed between the anode and the RF source. This creates a bias (V_b) between the neutral plasma and the negatively charged plate which accelerates the ions towards the substrate. Thus the density of the plasma can be controlled via the ICP power and the momentum of the ions can be controlled via the capacitively coupled plasmas (CCP) power. High bias results in ions with large momentum and increases the physical aspect of the etch process, decreasing selectivity, whereas low bias results in a more chemical etch process [113]. In this thesis, SF_6/CH_3 with a varied gas flow ratio has been used to etch the Si_3N_4 wafer.

3.3 Film deposition facilities

3.3.1 Magnetron sputtering system

The Shamrock magnetron sputtering system mainly consists of three interconnected chambers, A, B and D. The original part of the tool is chamber A, a process module (PM), which contains 6 DC magnetron sputtering guns for metal deposition. Chambers B and D are custom-designed chambers for the deposition of insulators, as well as metals under ultra-high vacuum (UHV) conditions. Chamber B includes 6 DC guns for metal deposition and 2 RF guns for the deposition of insulators such as MgO, AlO_x and SiO₂. A heating capability up to 700 °C is available in this chamber. Chamber D includes a low pressure AJA (AJA INTERNATIONAL, INC) magnetron sputtering gun which is mainly used for CoFeB deposition and four e-beam evaporation pockets which are applicable for MgO, Fe, Au and Cr deposition [115–117]. Figure 3.4 shows the schematic layout of the whole sputtering system. The base pressures of chambers A, B and D are around 1×10^{-7} , 3×10^{-8} and 1×10^{-9} Torr respectively and they are separated from the transfer module (TM) by a slot valve. Each transfer module includes a computer-controlled robot to pick up the wafers from the load lock cassette module (CM) and transfer them to one of the deposition chambers. The thin film growth process in these chambers is computer controlled. The system is located in the class 10000 clean room at CRANN building, this tool is currently used for depositing ultra-thin and uniform metal and insulator stacks. In our work, this magnetron sputtering system is used to deposit the SiO₂ spacer layer.

3.3.2 Temescal electron beam evaporation system

In the electron beam evaporation system, the electrons are emitted from a heated tungsten source and are accelerated across 10 kV [118]. The electrons are directed towards a crucible containing the desired metal for deposition. The beam of electrons is swept across the crucible using the magnetic field to achieve uniform heating until evaporation. The material then disperses into the vacuum and coats all the surfaces evenly with the material. The deposition rate is monitored by observing the change in frequency of a quartz resonator in the chamber. This process results in a very homogeneous coating of material that can be controlled to the angstrom level. Figure 3.5 shows the Temescal FC-2000 system which is used for all the metal deposition in this thesis.

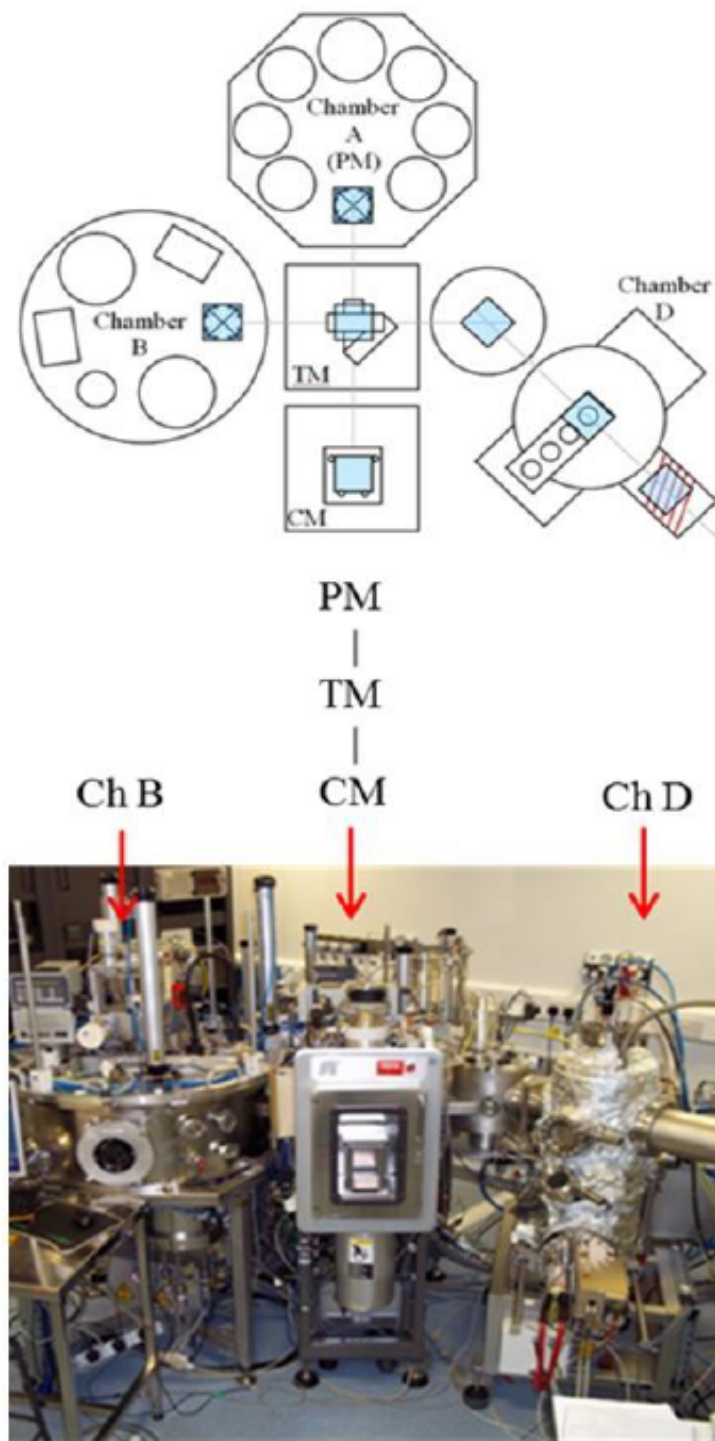


FIGURE 3.4: Shamrock magnetron sputtering system. Top panel: a schematic drawing of the whole system (the top view). The pictures of chamber B, C and D are showing in the bottom panel from the front view. The graph was adapted from Dr. Hongjun Xu's PhD thesis [114].

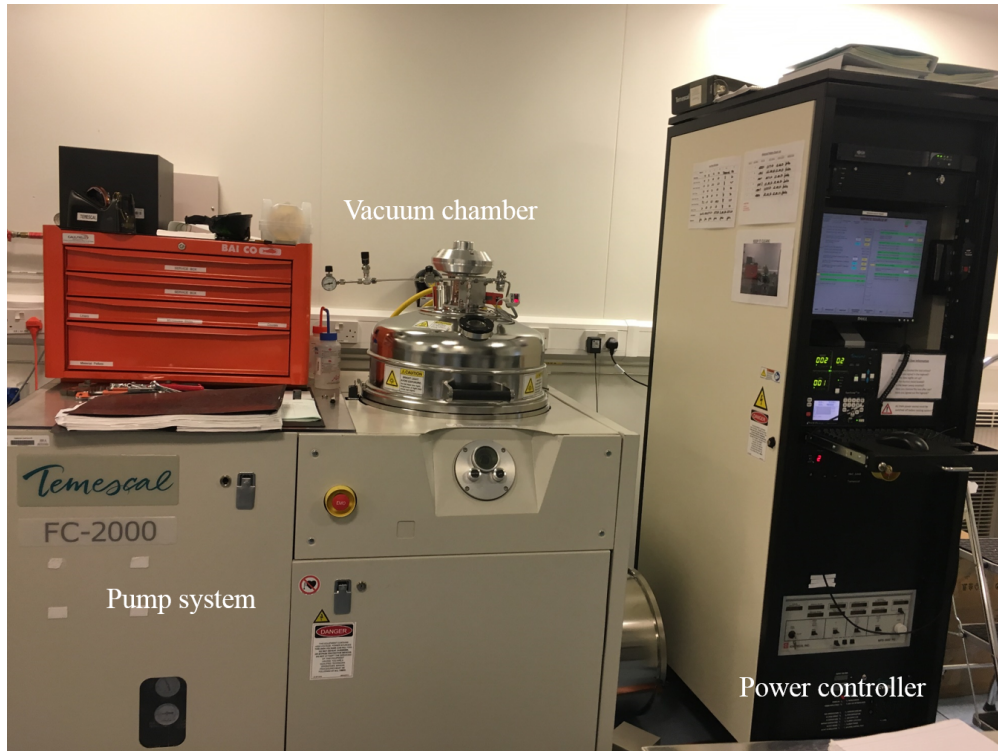


FIGURE 3.5: Temescal FC-2000 system. It mainly consist of a deposition chamber, a pump system and a computer control system.

3.4 Samples preparation procedures

UV lithography, EBL and metal deposition are used frequently in the samples preparation of this thesis. Figure 3.6 shows the fabrication flow chart for plasmonic devices in this thesis. It consists of a UV lithography and an ICP etch processes to make an opening in the edge of the substrate for the end-fire coupling. A standard EBL process is used to pattern the Au plasmonic structures which will be discussed in Chapter 5. The detailed processes are described as follow,

(a) A Si_3N_4 wafer with the thickness of 180 nm for processing. The substrate consists of a $2\ \mu\text{m}$ SiO_2 buffer layer on a Si base;

(b) Magnetron sputtering: a SiO_2 spacer layer was sputtered from a target-facing-target magnetron setup using stoichiometric targets in a magnetron sputtering tool, at 100 W RF power and 20 sccm of Ar, at a deposition rate of $0.200\ \text{\AA}/\text{s}$. Prior to deposition, the chamber was at a base pressure of 2.5×10^{-8} torr;

(c) UV lithography: a S1813 positive-tone photoresist was spin coated at a spin speed of 5000 rpm for 45 s. The resulting film thickness was $\sim 1.2\ \mu\text{m}$. The samples were then baked on a hot plate at $130\ ^\circ\text{C}$ for 75 s. The UV lithography

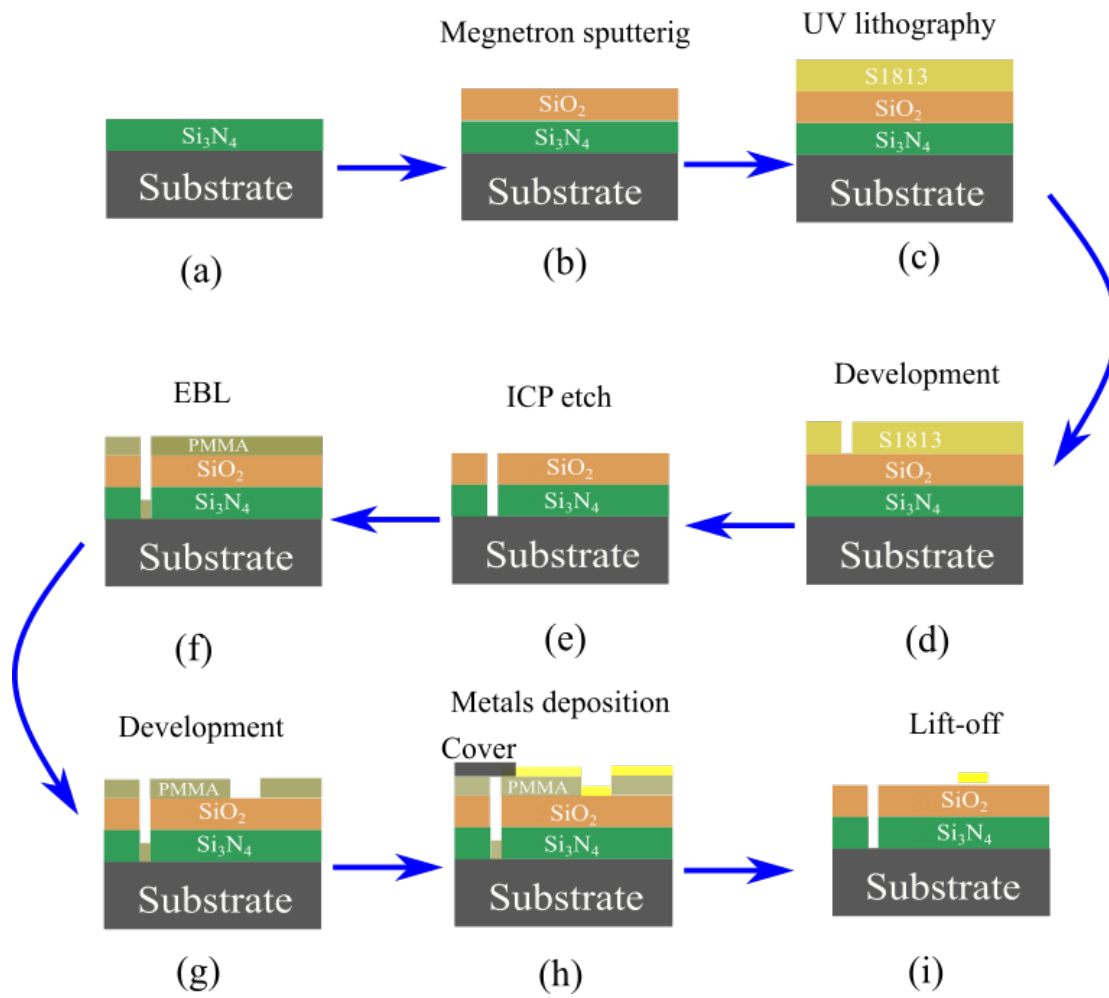


FIGURE 3.6: Diagram of the fabrication flow chart for the plasmonic devices.

was performed by exposing the samples at a 365 nm UV laser with an exposure dose of $\sim 14 \text{ mW/cm}^2$ for 6 s;

(d) Development: the sample was immersed in MF319 (Microposit MF319 developer, MicroChem Corp.) for 45 s and rinsed in DI water immediately for 15 s. The pattern of a flat edge opening (the rectangular trench) was made for end-fire coupling;

(e) ICP etch: the pattern of the flat edge was transferred to the Si_3N_4 core by using SF_6/CHF_3 (gas flow ratio 40 sccm : 10 sccm) in an ICP plasma etch tool (ICP forward power 1500 W) for 40 s, a rectangular trench with a depth of $\sim 400 \text{ nm}$ was made (calibrated by a Dektak profilometer); this was a sufficient depth to ensure the entire SiO_2 spacer layer and Si_3N_4 core layer were etched through. The residual photoresist was removed by a pure O_2 plasma clean;

(f) EBL process: a PMMA (polymethyl methacrylate A3, 950K MicroChem Corp.) positive-tone electron beam resist was spin coated on the sample at a speed of 3000 rpm for 45 s; the thickness of the PMMA layer is 150 nm which was calibrated by an ellipsometer (SOPRA GESP 5 Variable Angle Spectroscopic Ellipsometer), then baked on a hot plate at 180°C for 3 min. The plasmonic structure was patterned by EBL in a Carl Zeiss Supra system. The acceleration voltage was 20 kV and the area dose was $200 \mu\text{C/cm}^2$. A small beam aperture of $10 \mu\text{m}$ and low beam current mode were used to get a beam current of 28.9 pA and a beam speed of 3.595 mm/s for the exposure, which are lower than normal to optimize the EBL process and fabricate fine structures;

(g) Development: the development was performed by immersing the samples in 3:1 IPA:MIBK (3:1 isopropyl alcohol:methyl isobutyl ketone) for 45 s and rinsing in IPA for 15 s;

(h) Metals deposition: a 2 nm Ti adhesion layer and 50 nm Au layer were deposited sequentially on the wafer using an electron beam evaporation (Temescal FC-2000) system with a deposition rate of $1 \text{ \AA/s}$. The rectangular trench was covered by a heat resistant tape during the metals deposition;

(i) Lift-off: The PMMA lift-off was done in NMP (N-methyl-2-pyrrolidone) at 65°C for 15-30 minutes [119]. Acetone and IPA were used to remove the NMP.

3.5 Facilities used in the characterization

3.5.1 Atomic force microscopy (AFM)

The AFM was invented by IBM scientists Gerd Binnig in 1985 [120]. The scanning tunneling microscope (STM) which is the precursor to the AFM, was developed by Gerd Binnig and Heinrich Rohrer in the early 1980s at IBM Research - Zurich, they shared half of the 1986 Nobel Prize for Physics for the development of STM. The first experimental implementation of AFM was made by Binnig, Quate and Gerber in 1986 [121]. The first commercially available AFM was introduced in 1989 by Park Scientific Instruments [122]. The AFM is one of the foremost tools for imaging, measuring, and manipulating matter at the nanoscale. AFM is a type of scanning probe microscopy (SPM) with a very high resolution, the demonstrated resolution of AFM is on the order of a nanometer, more than 1000 times better than the optical instruments which are constrained by the optical diffraction limit [121]. The AFM consists of a cantilever (as shown in Figure 3.7) with a sharp tip (probe) at its end that is used to scan the specimen surface. The cantilever is typically silicon or silicon nitride with a tip radius of curvature on the order of nanometers. When the tip is brought into proximity of a sample surface, forces between the tip and the sample lead to a deflection of the cantilever according to Hooke's law. The AFM has three major abilities: force measurement, topographical imaging, and manipulation. In force measurement, AFMs can be used to measure the forces between the probe and the sample as a function of their mutual separation [123]. For topographical imaging, the reaction of the probe to the forces that the sample imposes on it can be used to form an image of the three-dimensional shape (topography) of a sample surface at a high resolution. The surface topography is commonly displayed as a pseudocolor plot [124]. Simultaneous with the acquisition of topographical images, other properties of the sample can be measured locally and displayed as an image, often with similarly high resolution. Examples of such properties are mechanical properties like binding forces intrinsic to adhesion molecules [125] and electrical properties such as conductivity or surface potential [126]. In manipulation [127], the forces between tip and sample can also be used to change the properties of the sample in a controlled way. It is typically performed in an ultra-high vacuum. Examples of this include atomic manipulation, scanning probe lithography and local oxidation [128]. Additional quantities may simultaneously be measured through the using of specialized types of probes, such as scanning thermal microscopy [129], scanning joule expansion

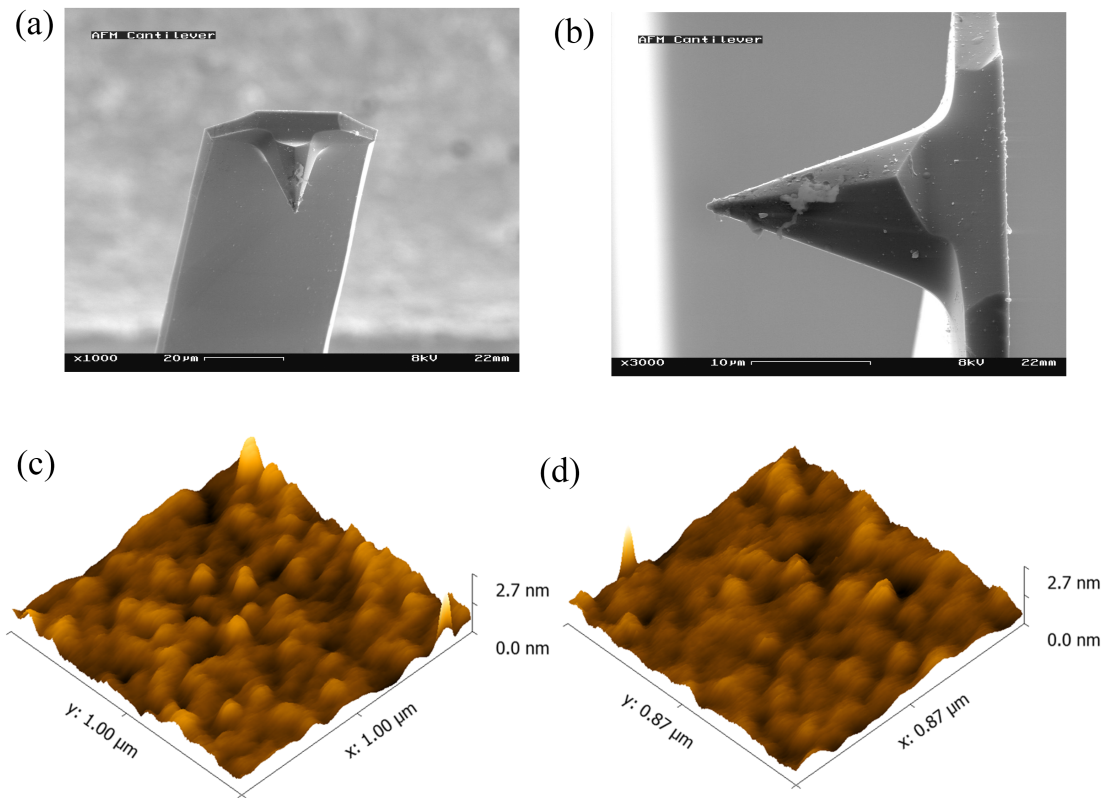


FIGURE 3.7: SEM images of a used AFM cantilevers. Figures were adapted from [132]. (a) The scale bar is 20 μm . (b) The scale bar is 10 μm . AFM images for (c) a 188 nm thick SiO_2 film and (d) 180 nm thick Si_3N_4 film.

microscopy [130], magnetic force microscopy probes [131]. The AC-air in the standard topography mode of an Asylum AFM has been used to characterize the roughness of the thin films in this thesis.

3.5.2 X-ray reflection (XRR)

X-ray reflection (XRR) is a surface-sensitive analytical technique used in chemistry, physics, and materials science to characterize surfaces, thin films and multilayers. It is related to the complementary techniques of neutron reflectometry and ellipsometry [133]. The Bruker D8 Discovery X-Ray Diffractometer has been used to characterize the thickness of the Au, Ag individual and Au-Ag bilayer films.

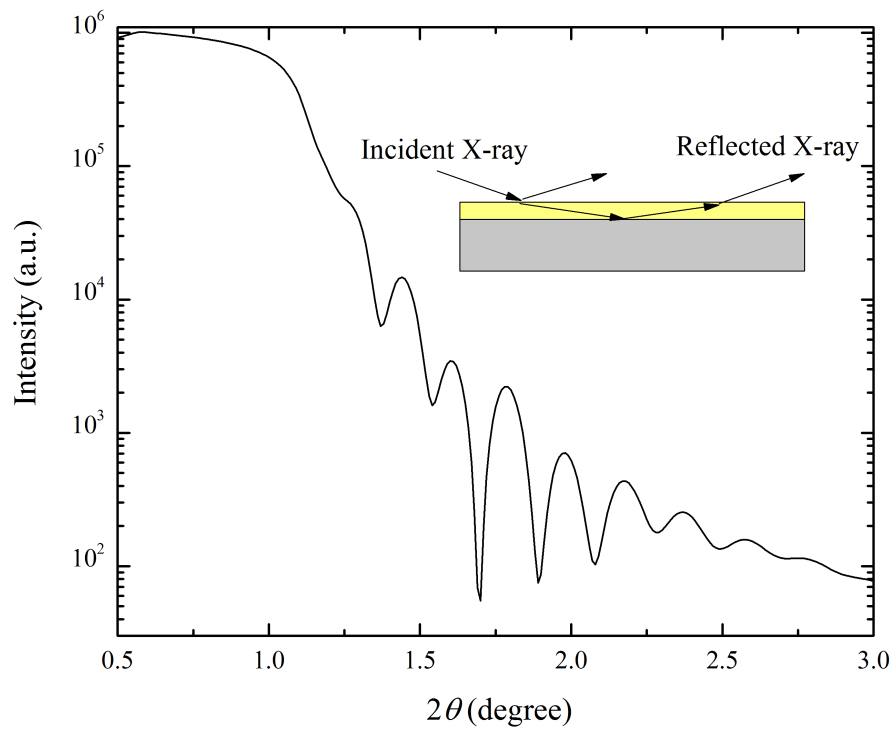


FIGURE 3.8: X-ray reflection for a 50 nm thick Au film. Inset: Diagram of X-ray is reflected on a film during the measurement.

The basic idea behind the technique is to reflect a beam of X-rays from a flat surface and to measure the intensity of X-rays reflected in the specular direction. If the interface is not perfectly sharp and smooth, then the reflected intensity will deviate from that predicted by the law of Fresnel reflection [134]. The deviations can then be analyzed to obtain the density profile of the interface normal to the surface. When X-rays enter the surface of with multiple layers at a glazing angle, the X-rays cause a total reflection. By measuring the total reflectivity as a function of the incident angle with respect to the thin film surface, a profile such as the one shown in Figure 3.8 can be obtained, it shows oscillations analogous to the Fabry-Pérot effect and structural parameters such as density, thickness, and roughness of each layer of the thin film can be evaluated non-destructively [135].

3.5.3 Variable angle spectroscopic ellipsometry

Ellipsometry uses the principle that plane polarized light can become elliptically polarized when reflected from or transmitted through a material's surface [136]. The polarization change is quantified by the amplitude ratio and the phase difference of the light. By measuring the changing of the polarization we

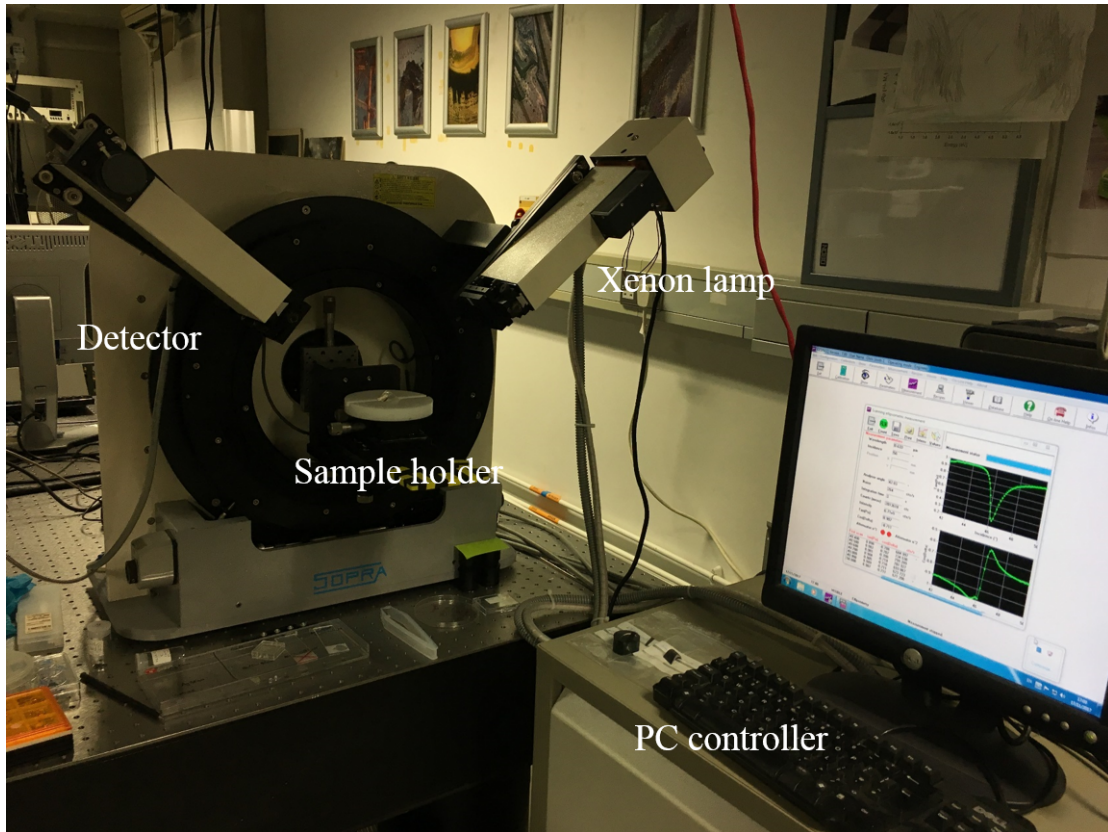


FIGURE 3.9: Schematic diagram of the SOPRA GESP 5 variable angle spectroscopic ellipsometer system. It with a spectral range from 250 - 900 nm. A microspot system reduces the beam size perpendicular to the plane of incidence to less than 300 microns. The measured film thickness range from 0.1 nm to 5 μm .

can investigate the properties of thin films. It can be used to characterize the composition, roughness, thickness, crystalline nature, doping concentration, and electrical conductivity of the materials [136]. It is a well-established non-destructive technique for the optical investigation of materials and especially it a useful technique for thin film metrology characterization. The ellipsometry is commonly used to characterize film thickness for single layers or complex multilayer stacks ranging from a few angstroms or tenths of a nanometer to several micrometers with excellent accuracy. Figure 3.9 shows the SOPRA GESP 5 variable angle spectroscopic ellipsometer system in the Optical Analysis Lab of School of Physics in Trinity College Dublin. In this thesis, we used ellipsometry to verify the thickness and refractive indices of a $\text{Si}_3\text{N}_4/\text{SiO}_2/\text{Si}$ layer substrate.

In addition to measuring the optical constant and thickness of Si_3N_4 wafer been used, we also applied the ellipsometer to from a Kretschmann configuration to study the SPP dispersion relations of Au and Ag films in this thesis.

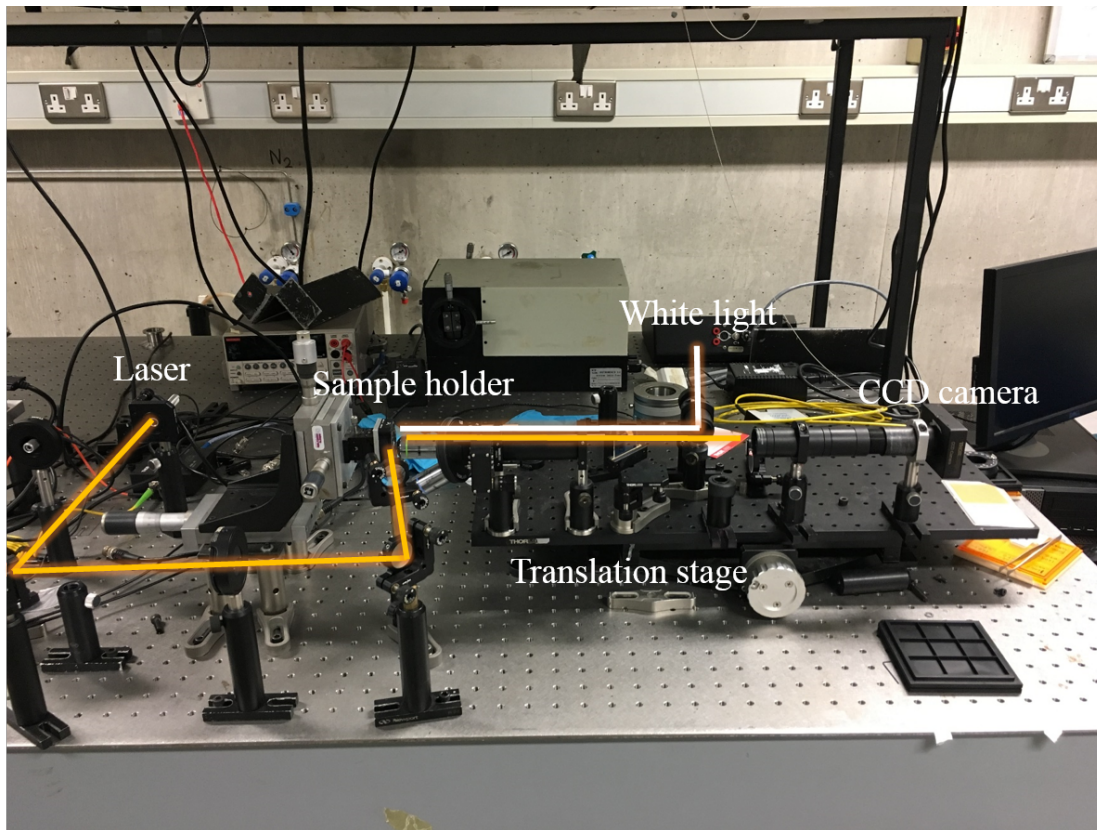


FIGURE 3.10: Schematic diagram of the experimental set-up for optical far-field measurements. The green line shows the path of the laser through the optical system. A diode laser with the wavelength of 850 nm is used to excite the sample; a prism pair is used to alter the elliptical beam to a circular beam. The LED white light and lens provide the bright field illumination of the sample.

For a photon to excite an SPP, both must have the same frequency and momentum. The photonic mode can couple to the SPP mode through a Kretschmann configuration with a certain input angle, the VASE system as mentioned above has been applied to measure the reflection of the metallic film as a function as the input angles to map the dispersion curve in a wide wavelength range (from 200 nm – 800 nm). More detail of these measurements will be discussed in the Chapter 4.

3.5.4 Optical far-field measurements

Figure 3.10 is the schematic diagram of the experimental set-up setup for the optical far-field measurements which is used in Chapter 5 to excite the SPP in

the NFT and image the occurring of the nanofocusing process. It is a home built setup for the NFT sample characterization.

The laser was end-fire coupled to the waveguides in order to excite multiple modes. The angle of incidence to the waveguide end-face was $\sim 15^\circ$. Both the microscope arm and the sample holder in the set-up are built on a separate translation stage which gives more flexibility to do the alignment.

3.6 Chapter summary

In this chapter, the facilities that have been used in this thesis are briefly introduced. They include microscale to nanoscale fabrication techniques (UV lithography and electron beam lithography); Thin metallic and insulating films deposition techniques (e-beam evaporation and magnetron sputtering deposition); Thin film characterization techniques (ellipsometry, X-ray reflection and atomic force microscopy); Angle-resolved measurements and optical far-field measurements. All the fabrications are conducted in a cleanroom and the specification is from class 100 in the lithography area to class 10000 in the deposition areas. The recipes and procedures for the fabrication of the devices will be discussed in detail in the corresponding chapters.

Chapter 4

Surface Plasmon Polariton Modes in Thin Ag-Au Layered Composite Films

Propagating surface plasmon polaritons (SPP) at metal-dielectric interface allow extremely confine of light enabling important technologies such as label-free real-time sensing, and nanoscale optical wave guiding. In this chapter, we experimentally and theoretically map the surface plasmon dispersion of thin films of sequentially deposited silver and gold based on a Kretschmann-Raether (K-R) configuration using spectroscopic ellipsometry. The results show efficient excitation of SPP modes related to the symmetric and anti-symmetric modes of an insulator-metal-insulator (IMI) waveguide. Since the symmetric modes have larger electric field inside the bi-metallic layer than the anti-symmetric modes, we show that the dispersion for both modes can be tuned independently by controlling the thickness ratio and deposition order of metals in the film. This behavior is fundamentally different than modes in a single film, or thin film alloy. Results are in agreement with the analytical eigenmode dispersion of these modes, and with a full transfer matrix model. The results provide a complete understanding of surface plasmon modes in thin bi-layer or multi-layer metallic films and their ability to influence the propagation of surface plasmon waves.

4.1 Introduction

SPP are surface waves which can be localized at the interface of a metal and a dielectric. The strongly dispersive nature of SPP can lead to modes with effective wavelengths much smaller than that of the exciting free space light. This localization results in a strong field enhancement at the interface and a sensitivity to

local refractive index changes. These properties have resulted in numerous applications including extreme light concentration [137], sub-wavelength optics [138], data storage [23], nanoscale heating [139], microscopy [140] and sensing [141]. Thin metallic-dielectric films are also under investigation for metamaterial applications [142, 143]. Loss due to inter-band absorption in the metal is an intrinsic limiting factor for both plasmonic waveguiding and sensing applications. For waveguiding, material absorption limits the propagation length, and for sensing determines the resonance width and ultimately the sensitivity of the sensor [144]. Silver (Ag) and gold (Au) are the two most commonly used metals for SPP as their surface plasmon resonance exists in the UV-Visible range (2.2 eV for Au and 3.5 eV for Ag). For sensing applications, Au is preferred due to the noble metals bio-compatibility and chemical stability. Ag has significantly lower material absorption in the visible region, however, it tarnishes in air through reaction with oxygen and sulphur, to significantly degrade the quality of the thin film and the SPP properties [145]. Timothy proposed in 1995 that an Ag-Au bi-metallic film has a narrower reflection spectrum through prism coupling which will help to improve the sensitivity for sensing application of this film [146]. Recent work has also suggested that combining Au and Ag thin films can improve the sensitivity of the SPP based sensors by taking advantage of the low material losses in Ag and the stability of Au. Xia [147] did the experiments on Ag-Au bi-metallic film based biosensors in 2011 showing that the sensitivity enhancement reaches as high as 80%. Chen [148] tried an Ag-Au bi-metallic film in a commercial surface plasmon resonance (SPR) instrument, the sensitivity of the instrument has been improved by six times compared to an Au film. The stability of a bi-metallic film system has also been improved by Yuan [149] and Wang [150]. Apart from the outstanding sensing properties of bi-metallic films, there is also discussion of the tunability of the surface plasmon resonance frequency of this simple bi-metallic geometry. The surface plasmon resonance frequency can be easily tuned by changing thickness ratio of the metals in an Ag-Au bi-metallic film [151] or alloy film [152]. However, the full dispersion of these bi-metallic films has not been reported to date. In this chapter, we explore the properties of SPP formed on the interfaces between thin bi-metallic and dielectric layers experimentally using a K-R configuration excitation. We show that the excited SPP modes in this configuration are related to the symmetric and anti-symmetric IMI modes of thin films. In bi-metallic films, the SPP on the top and bottom metal-dielectric interfaces of the thin films have significantly different dispersion and damping. The resulting coupled modes

differ significantly from those of a single metal IMI waveguide. Previous work explored the dispersion property of thin bi-metallic films of Ag and Au at a specific wavelength over a small range of angles, the sensitivity of these thin bi-metallic films for biochemical sensing has also been examined [149]. Here we experimentally map the full dispersion range available in the K-R setup to understand the mechanism of the SPP excitation and propagation in these films. The dispersion is compared to the analytical dispersion relations for bound IMI modes and a full transfer matrix model. The results and conclusions from this work are of importance for understanding the SPP modes in bi-layer or multi-layer metallic films which provide a good reference for plasmonic waveguiding applications.

4.1.1 X-ray reflection measurements

The Au and Ag films in our experiments were deposited on quartz substrates using electron beam evaporation (Temescal FC-2000) system. We prepared a group of bi-metallic samples with different thickness ratio of Au and Ag by sequential deposition. The total thickness of the bi-metallic films was fixed at 50 nm for comparison. Film thickness was confirmed independently using an ellipsometer. The detailed mechanism of these two tools is described in Chapter 3. We performed X-ray reflection (XRR) measurements to verify the thickness and surface roughness of the thin films. Figure 4.1(a) shows a representative sample which has a measured thickness of 17 nm Ag and 23 nm Au for a total thickness of 40 nm. Fitting the angle dependent X-ray reflection we can extract the film thicknesses and the surface roughness. The surface roughness of each metal layer is measured at 1.7 nm. The XRR measurements show no evidence of the formation of an alloy layer at the interface of the two metals. Also, we do not expect to form this alloy layer as the sample did not go through a heating procedure after the deposition [153]. The simulation with two distinct layers fits the measured data quite well as shown on the right-hand side of Figure 4.1(a). For completeness, we simulate the case where a thin 4 nm interface alloy is formed as shown in Figure 4.1(b). The quality of the fit is poor compared to the case of no interface alloy which indicates the absence of the alloy in the bilayer samples.

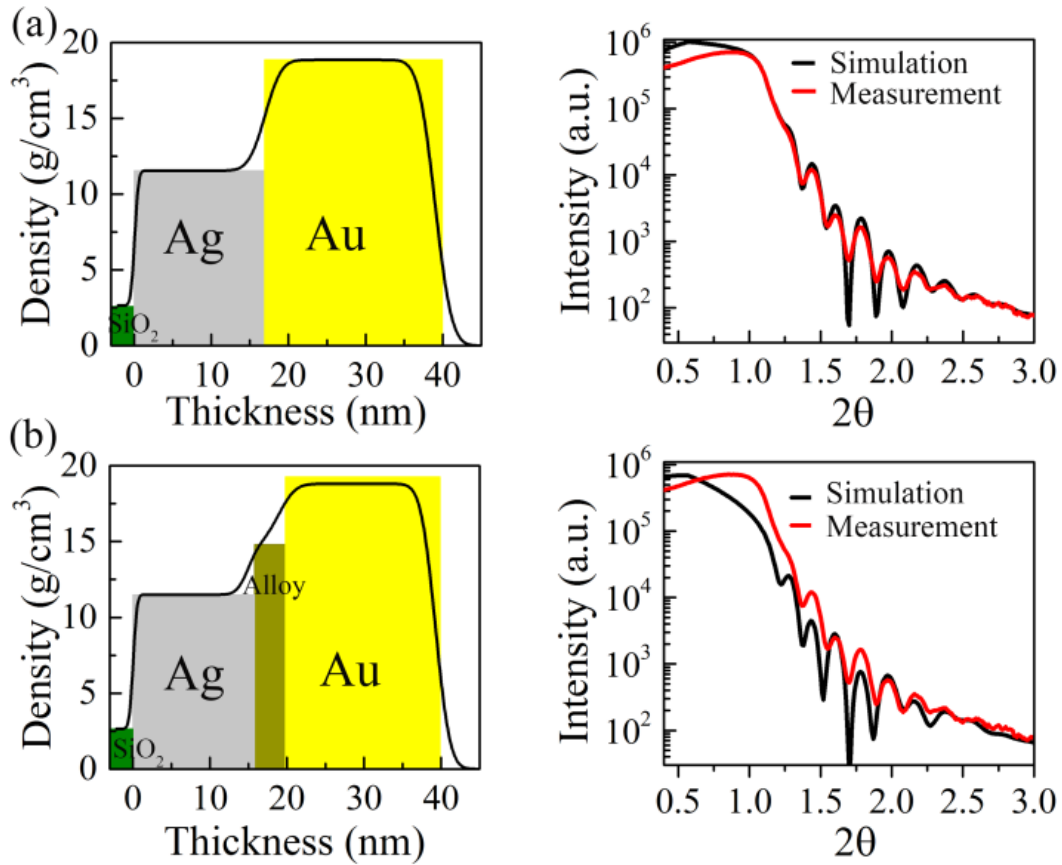


FIGURE 4.1: The XRR measurements. (a) Left: a combination of the films. Right: fitting data of bi-metallic film with two distinct layers and (b) Left: a combination of the films. Right: fitting data of three layers with 4 nm Ag-Au alloy.

4.1.2 Angle-resolved measurements

As mentioned earlier, we employ the common K-R prism coupling configuration to experimentally excite the SPP modes as depicted in Figure 4.2(a). A quartz rectangular prism (N-BK7, refractive index = 1.451) [154] is used to provide the additional optical momentum required to match the SPP modes and immersion oil is introduced to match the refractive indexes of prism and samples. A typical reflectivity measurement is taken over a range of angles and energies for a single Ag film is shown as a 2-D surface map in Figure 4.2(b). The blue areas represent low reflection due to coupling to SPP modes, while the red areas are high reflection. Both the symmetric and anti-symmetric modes are visible as dips in the reflectivity. The K-R configuration is commonly used for SPR sensing by scanning through a range of angles at a fixed wavelength, and monitoring the position of the minimum reflectivity, which depends on the refractive index variation of the upper dielectric. The inset under the surface map of Figure 4.2(b) shows the reflectivity as a function of angle for the Ag film taken at 2.5 eV. Scatter points are experimentally measured values, with a solid line from the TMM fit. Alternatively, a wavelength scan at a fixed angle can be used. The inset at the right side of Figure 4.2(b) shows the reflectivity as a function of wavelength at a fixed angle of 55.60° .

It is important to note that the K-R attenuated total reflectance (ATR) technique in this configuration does not excite the purely bound plasmonic modes (the modes to the right of the SiO_2 light line). Prism coupling allows momentum matching and efficient coupling into the SPP modes, but simultaneously allows coupling back out. This adds an additional radiative damping term to the modes, shifting and broadening the resonance. The minimum in reflectivity observed experimentally is caused by coupling to leaky modes and can be interpreted as the destructive interference of the reflected and leaked radiation as originally described by Raether [31]. Tuning the thickness of the layer allows tuning of the coupling efficiency, and critical coupling can be achieved for certain thicknesses. The shift in resonance position is not large, however, allowing the use of this technique to map the otherwise leaky modes available in the system. In this work, a SOPRA GESPP5 ellipsometer was used to measure the ellipsometric quantities by amplitude ratio ψ and phase difference Δ as a function of incident angle from 40° to 65° in the energy range of 1.4 eV to 4.5 eV. Due to the relatively high absorption coefficient and thickness of both the Au and Ag layers, the influence of the interface on the spectral range of interest is minimal. The value of $\tan \psi$ is related to the Fresnel reflection coefficients

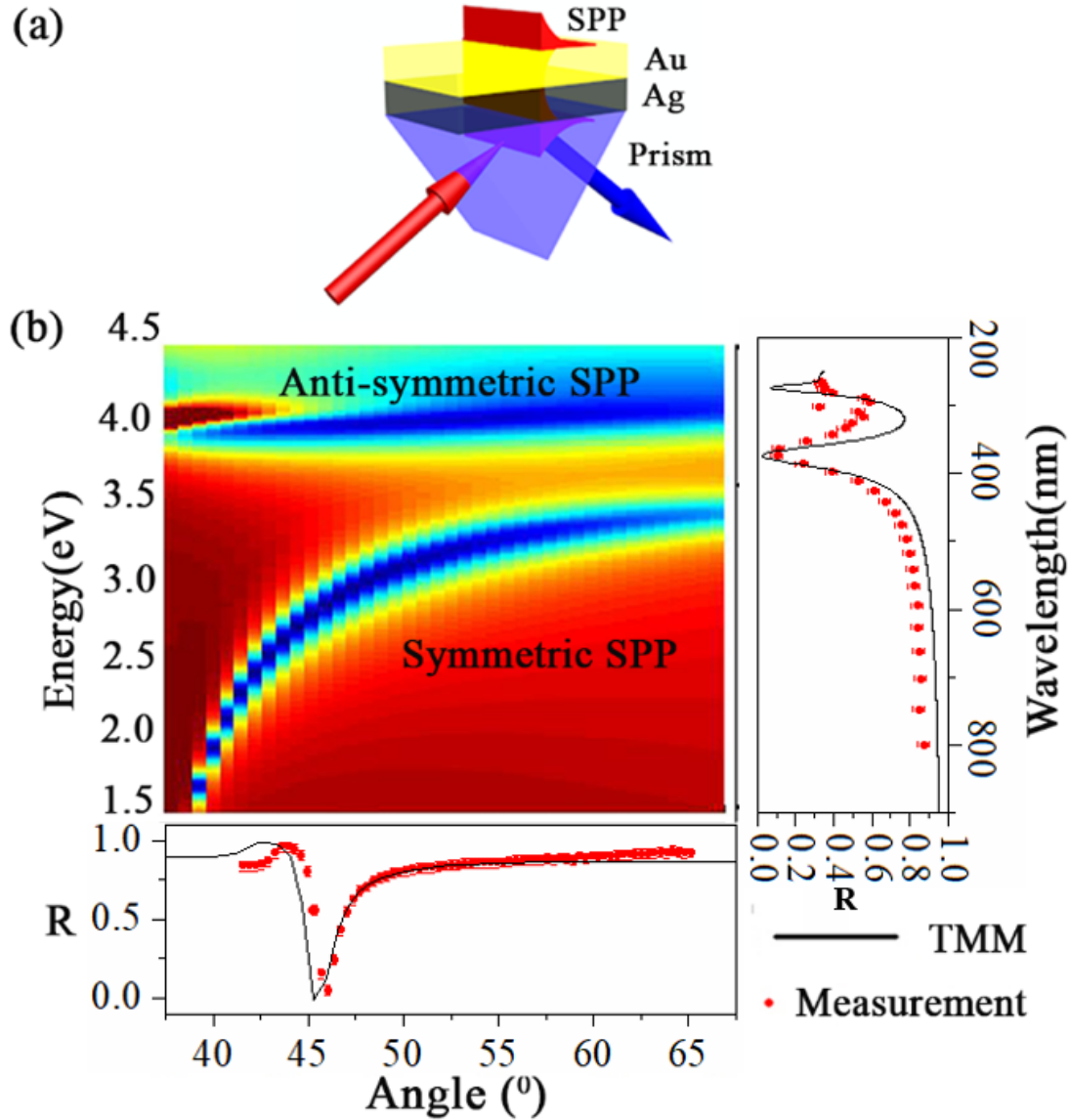


FIGURE 4.2: (a) Schematic of Kretschmann-Raether coupling technique with the representation of a bi-metallic layer, where the prism increases the momentum of the incident light to couple to SPP modes. (b) Example of a measurement of dispersion over angle and energy. Inset below: Typical measurement of reflection as a function of the excitation angle at a fixed wavelength. Inset right: Measurement of spectral reflectance at a fixed angle.

for the amplitudes of the s and p polarized components (r_s and r_p), which is defined by

$$\tan \psi e^{i\Delta} = \frac{r_p}{r_s} \quad (4.1)$$

Taking the modulus of this equation we can find a relation to the polarized reflectance,

$$\tan^2 \psi = \frac{R_p}{R_s} \quad (4.2)$$

Where $R_p = r_p \cdot r_p^*$ and $R_s = r_s \cdot r_s^*$ are the polarized reflectivity for the p-polarized and the s-polarized waves respectively [136]. We can thus ignore the phase information and use $\tan(\psi)$ only. It is advantageous to use this technique rather than measuring the reflectivity R_p directly in photometry, as any fluctuations in the light source intensity or walk-off from the sample are removed through normalization. Also the un-polarized ambient light does not significantly influence the measurement.

4.2 Results and discussions

4.2.1 Measured SPP dispersion curves for individual Au and Ag films

We investigate single thin films composed of Au or Ag. Experimental dispersion plots in the range accessible through the K-R technique (between the air and SiO₂ light lines) are displayed for single Au and Ag films in Figure 4.3(a) and (c) respectively. The incident wavelength is converted to energy [eV], and the incident angle is plotted in terms of momentum k_x [μm^{-1}]. Both Au and Ag films were deposited to a thickness of 50 nm, close to optimal thickness for critical SPP coupling in single films. Figure 4.3(b) shows the TMM results for the reflectivity of the single Au films. The TMM results for a single 50 nm Ag film are shown in Figure 4.3(d). The permittivity of the metals in the TMM is got from the experimentally determined optical constants reported by Johnson and Christy [94]. In both the TMM results, the eigenmode solution for the L_- modes (leaky modes) and L_+ (bound modes) are superimposed as a series of scattering points. The Au film (Figure 4.3(a) and (b)) has a bound L_+ mode on the right of the SiO₂ light line which bends back to the leaky L_- modes area

at an energy of 2.4 eV and momentum of $20 \mu\text{m}^{-1}$, as shown in the dashed elliptical blue circle of Figure 4.3(b). There are not bound modes which can be excited in a single Au film in the high k (momentum is larger than $20 \mu\text{m}^{-1}$) range owing to the large damping in Au. A metal-insulator-metal (MIM) [155] geometry can permit more bound modes in the high k range. The modes observed experimentally through prism coupling are the leaky modes associated with the L_- modes which lie between the air light line and the SiO_2 light line, they are plotted in the 2-D surface map of Figure 4.3(a) and (b).

It must be noted that in the measurements, the largest valid input angle is 65° owing to the big beam offset under a large input angle of the ellipsometer. This will prevent part of the leaky modes being observed through our technique, so there is a blank area which is on the left side of the SiO_2 light line in Figure 4.3(a). While in the theory, we can set the input angle to 90° , so all the leaky modes can be observed, as shown in Figure 4.3(b). All the other measurements in this work follow this principle. The Ag thin film (Figure 4.3(c) and (d)) similarly has bound L_+ modes to the right of the SiO_2 light line. These modes bends back at a much higher energy of 3.5 eV and a momentum of $48 \mu\text{m}^{-1}$ (not shown in plot range). Both the upper (>3.8 eV) and lower (<3.6 eV) branches of the leaky L_- mode are visible between the air and SiO_2 light lines. Compared to Au, the bound modes in Ag can reach a much higher k range, as shown in Figure 4.3(d) of the L_+ branch (red scattered points lie on the right of SiO_2 light line), the maximum momentum that can be reached is $48 \mu\text{m}^{-1}$, these high k bound modes can be excited through other techniques, such as grating coupling [156]. Through the angular resolved measurement on Au and Ag films, we have fully investigated the dispersion properties of these films, the leaky modes have been observed successfully through our technique. Also the full dispersion map provides good reference to know the phase match condition in order to excite the high k bound modes. Hybrid metallic films are more flexible to tune the SPP modes properties, and they will have more unique dispersion properties.

4.2.2 Measured SPP dispersion curves for Ag-Au bi-metallic films

Next, we explore the interesting case of thin bi-metallic films. For brevity, we restricted our experimental study to bi-metallic films with a total thickness of 50 nm for comparison with the single film case. The measured dispersions of

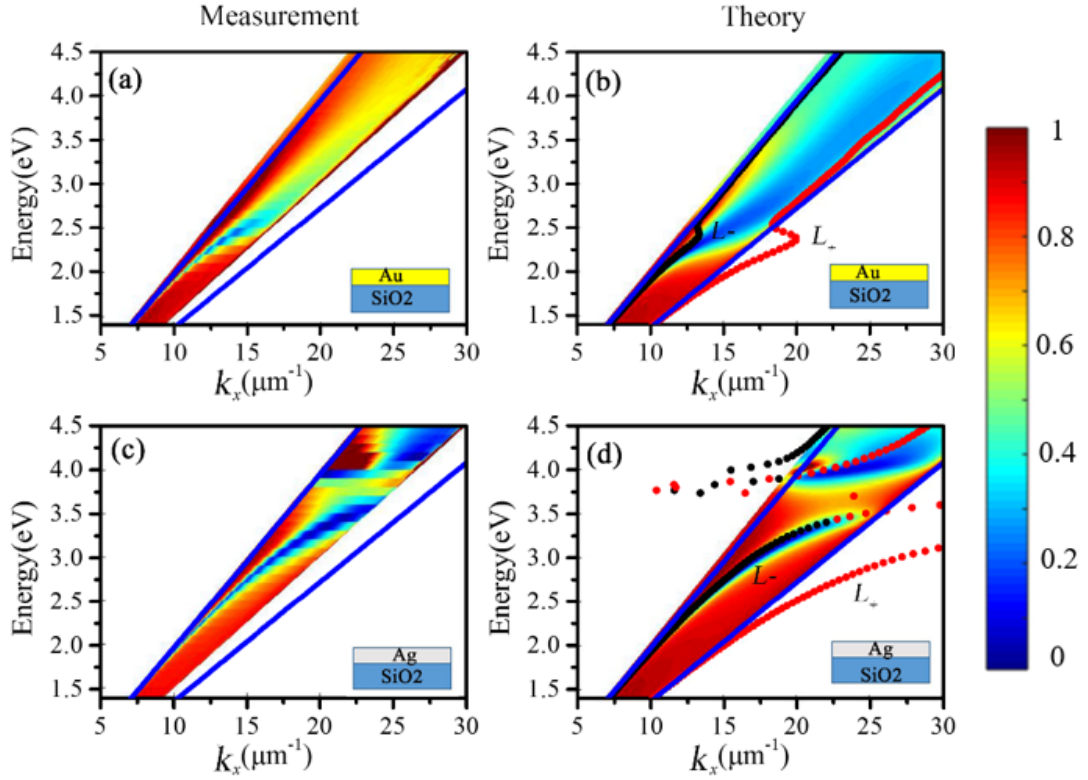


FIGURE 4.3: Dispersion for single Au and Ag 50 nm thin films. The film structure is given schematically in the lower right-hand corner. (a) Experimental dispersion of a 50 nm Au film, mapped as energy (eV) vs k_x (μm^{-1}). Plotted values range from low (blue) to high (red) values of the ellipsometric quantity $\tan^2 \psi$. The two blue solid lines in each figures are the air light line (left side) and SiO₂ light line in (right side) respectively. (b) Calculated values of $\tan^2 \psi$ using the TMM for single Au film. Here, eigenmode dispersions are superimposed, the scattered black points indicate the L_- modes and red scattered points indicate the L_+ modes. (c)-(d) Same analysis is repeated for a 50 nm silver film.

two such films are plotted in Figure 4.4, with the specific film geometries inset in the lower right-hand corner. Two cases were chosen to illustrate the effect of material deposition order on the dispersion. The first case illustrated in Figure 4.4(a) shows the measured dispersion for 30 nm film of Ag on a SiO₂ substrate capped with a 20 nm film of Au. Figure 4.4(b) shows the dispersion relation derived from TMM matrix results and eigenvalue method of the same case. The results show features similar to both the Au and Ag single films. The L_- modes don't change much with an Ag under-layer added in the bi-metallic films, as can be seen from Figure 4.3(b) and Figure 4.4(b), both follow the dispersion of L_- modes in single Au film. The L_+ modes, however, are distinctly different from the single film cases, as the curve bends back at $20 \mu\text{m}^{-1}$ for single Au (the blue elliptical circle in Figure 4.3(b)), while in the bi-metallic case for 30 nm Au capped with 20 nm Ag, the L_+ modes can reach high k bound modes range just like single Ag. This interesting phenomenon demonstrates that it is possible to use bi-metallic films to reach the high k bound modes range just by carefully designing the combined sequence of the two films. The TMM matrix results plotted in Figure 4.4(b) show good agreement with the experimentally measured dispersions. Similarly, Figure 4.4(c) shows the measured dispersion of the second case, a 30 nm thick film of Au on a SiO₂ substrate, capped with 20 nm of Ag. Figure 4.4(d) shows its dispersion relation derived from TMM matrix results and eigenvalue method. It follows the same pattern as the first case, with the L_+ modes displaying a large modification from the case of a single film, it bends back to the leaky modes area at the energy of 2.4 eV and the momentum of $20 \mu\text{m}^{-1}$ (the blue elliptical circle in Figure 4.4(d)). It is the same feature as single Au and would be of interest for further study in relation to negative refraction [157].

The L_- modes in single film and bi-metallic films don't show huge differences, as can be seen in the L_- branch of the dispersion curve in Figure 4.3(b) and 4.4(b) which are close to the air light line, this indicates that the L_- modes exist mainly on the metal-air interface for the K-R configuration. While the L_+ modes change a lot in the bi-metallic films in comparison with a single film, as is visible in the L_+ branch of the dispersion curve of Figure 4.4(b) which is close to the SiO₂ light line. The curve stretches out to show the properties of single Ag, as shown in Figure 4.4(d). Similarly, the L_+ branch of the dispersion curve of Figure 4.4(d) bends back to show the properties of single Au as shown in Figure 4.3(b). It is interesting to indicate that the L_+ modes exist mainly on the metal-SiO₂ interface for the K-R configuration. Our experimental and

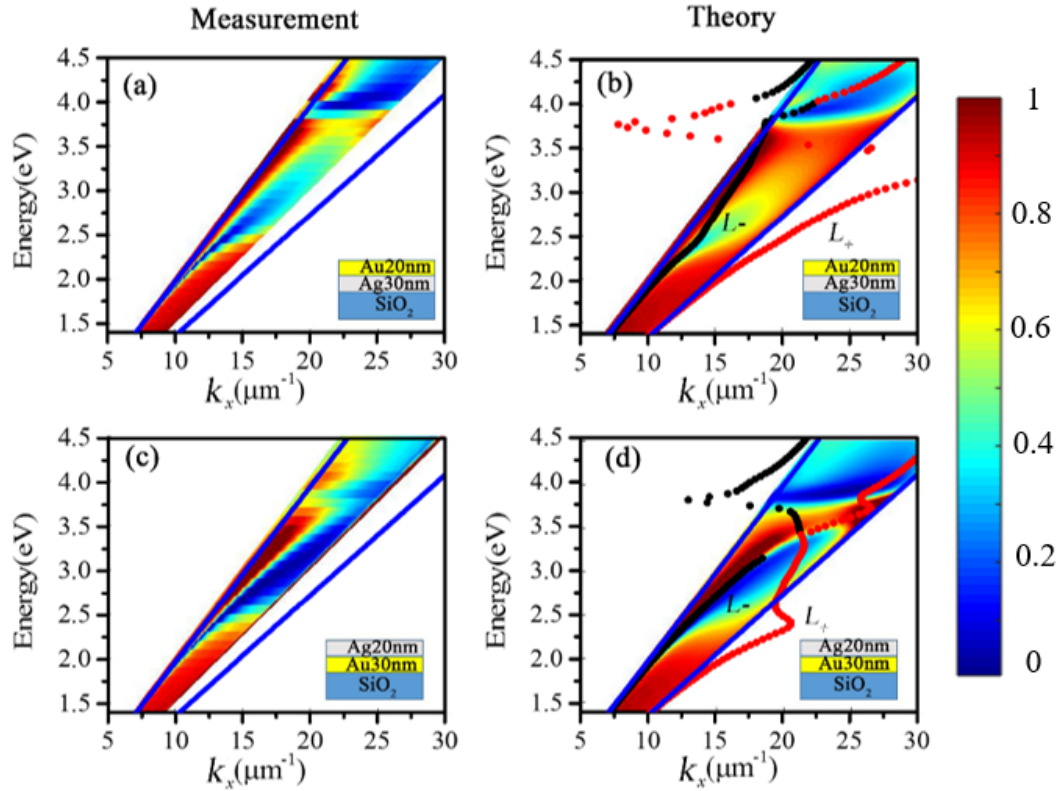


FIGURE 4.4: Dispersion for bi-metallic Au:Ag films with total thickness of 50 nm. The film structure is given schematically in the lower right-hand corner. (a) Experimental dispersion of bi-metallic film with 30 nm Ag capped with 20 nm Au, mapped as energy (eV) vs k_x (μm^{-1}). Plotted value range from low (blue) to high (red) values of the ellipsometric quantity $\tan^2 \psi$. The two blue solid lines in each figure are air light line (left side) and SiO_2 light line (right side) respectively. (b) Calculated values of $\tan^2 \psi$ using the TMM. Eigenmode dispersions are superimposed, the scattered black points indicate the L_- modes and red scattered points indicate the L_+ modes. (c)-(d) Same analysis is repeated for 30 nm Au capped with 20 nm Ag.

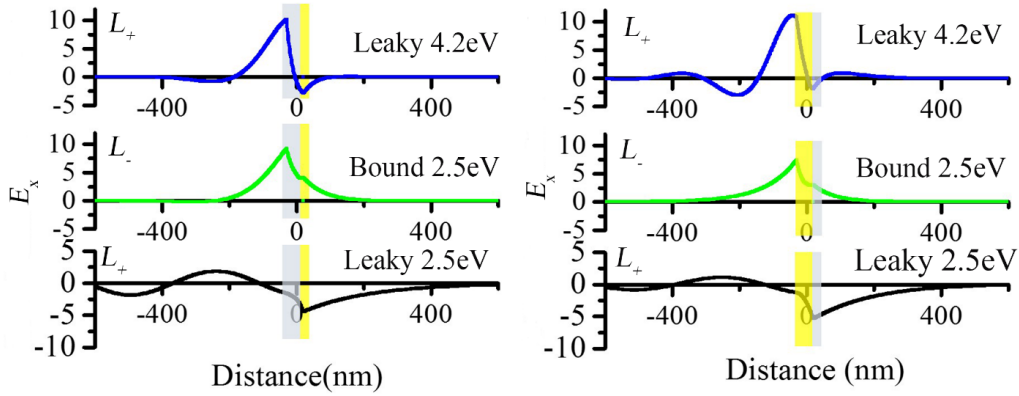


FIGURE 4.5: The longitudinal component of the electric field (E_x) is plotted for specific energies in the dispersion to allow classification of the modes as symmetric and anti-symmetric modes based on their symmetry, the corresponding energies are given in the top right-hand corner. (a) Case of 30 nm Ag film on SiO₂ with 20 nm Au capping layer. (b) Case of 30 nm Au film on SiO₂ with 20 nm Ag capping layer.

calculated results have firstly clarified the distribution of the L_+ and L_- SPP modes in bi-metallic films through prism coupling. This clarification can also be used on the single layer or multi-layers, and is a good reference for studying the modes distribution in surface plasmon circuitry [158].

The symmetry of the modes in Figure 4.5(a) and 4.5(b) can be defined by examining the longitudinal component of the electric field calculated from the eigenmode solution for each branch in the dispersion. Figure 4.5 shows examples of the E_x components of the electric field at specific energies for the bi-metallic films. Figure 4.5(a) corresponds to the 30 nm film of Ag on SiO₂ capped with 20 nm Au studied in Figure 4.4(a) and 4.4(b). At the energy of 4.2 eV and the momentum of $25 \mu\text{m}^{-1}$, the corresponding position is the black star on dispersion curve in Figure 4.4(b), the electric field is oscillating with opposed sign in the metal-dielectric interface, thus the SPP modes at 4.2 eV can be called anti-symmetric modes where distributed in the leaky modes range as can be seen in Figure 4.4(b). There are two branches in the dispersion curve at 2.5 eV, one branch with the momentum of $13 \mu\text{m}^{-1}$, the other one with the momentum of $21 \mu\text{m}^{-1}$, the corresponding position is the orange arrow and the blue sphere in Figure 4.4(b), respectively. We will find that both of their electric fields are oscillating with an identical sign in the metal-dielectric as shown in Figure 4.5(a), so they are symmetric modes. Through plotting the longitudinal component

of the electric field, it is clear that both symmetric and anti-symmetric can be excited through prism coupling. Figure 4.5(b) corresponds to the 30nm film of Au on SiO₂ capped with 20nm Ag studied in Figure 4.4(c) and 4.4(d). The same analysis on Figure 4.5(a) can be applied to this Figure 4.5(b). Our results have clarified the symmetry of SPP modes excited through prism coupling.

4.2.3 Improved propagation length

For plasmonic waveguiding applications, it is desirable to increase the propagation length L of the plasmon as much as possible and indeed to be able to control precisely the propagation length. The propagation length of a mode is inversely proportional to the imaginary component of the mode propagation constant k_{spp}'' through the equation [159]:

$$L = \frac{1}{2|k_{spp}''|} \quad (4.3)$$

The propagation lengths of SPP on single interfaces depend strongly on metal absorption and frequency of light used. The single Ag-air interface supports SPP modes with the propagation length of 60 μm @633 nm compared to ~ 10 μm @633 nm for Au interfaces. Due to the reactivity of Ag, however, Au is more commonly used in applications. Clearly, it would both be beneficial and economical to use Ag as the SPP material with a capping layer of Au for stability. Bi-metallic films have been investigated in this regard to increase propagation lengths in dielectric-loaded SPP waveguides [158]. The propagation length calculated from the eigenmode theory for the specific cases examined in this work, single 50 nm Au film, single 50 nm Ag film, bi-metallic 30 nm Ag capped with 20 nm Au, and bi-metallic 30 nm Au capped with 20 nm Ag are plotted in Figure 4.6. They are separated in L_- (Figure 4.6(a)) and L_+ (Figure 4.6(b)) modes for clarity.

From Figure 4.6 it is clear that a single Ag interface still offers the longest propagation length over most of the wavelength range, however bi-metallic films offer distinct advantages over single Au films. The L_- modes show more distinct features from the single films, as shown in Figure 4.6(a). For the bi-metallic sample with Ag on top of Au as shown in Figure 4.6(a), its propagation length is larger than 60 μm @633 nm (single Ag propagation length). Also we notice that the whole propagation length curve of this bi-metallic sample is close to single Ag (the green line and black in Figure 4.6(a)), it proves that the metal-air interface supports the L_- modes, it has a good agreement with the

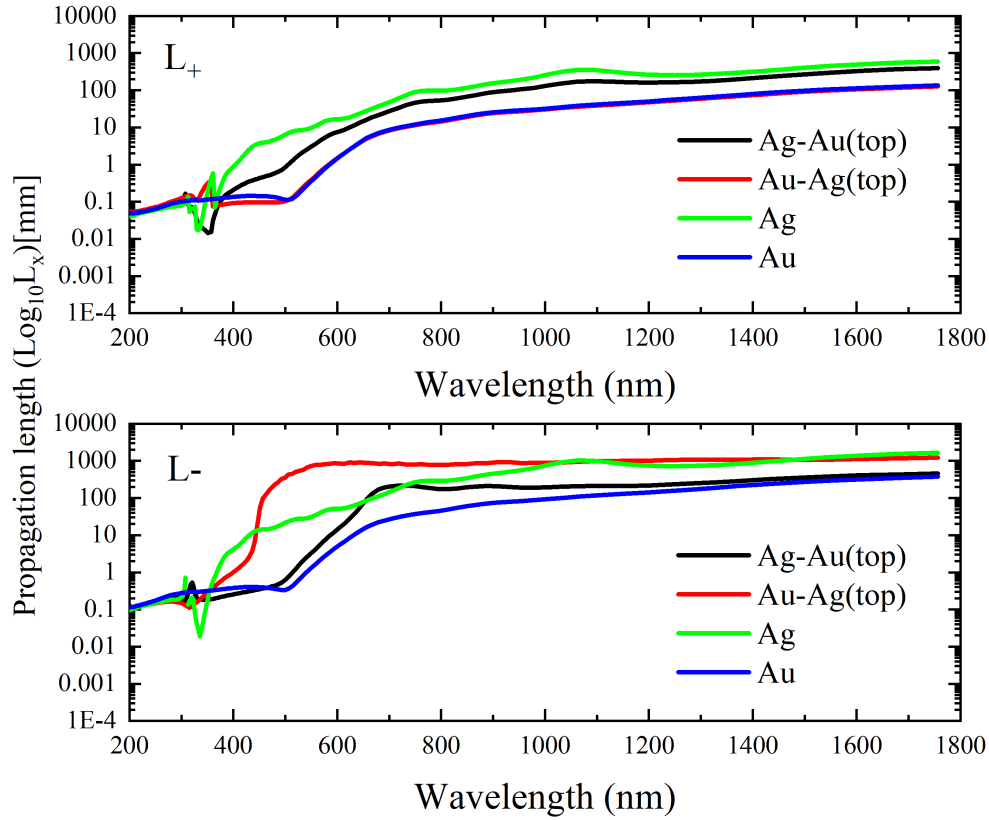


FIGURE 4.6: Propagation length of SPP modes in thin single and bi-metallic films calculated using eigenmode method. (a) The L_- modes for the specific cases of single 50 nm Au film, single 50 nm Ag film, bi-metallic 30 nm Ag topped with 20 nm Au, and bi-metallic 30 nm Au topped with 20 nm Ag. (b) The L_+ modes for the same cases. The insets show the propagation length in the range 200 nm to 600 nm.

conclusions we get from Figure 4.3 and 4.4. We should point out that we got infinite solutions between 500 nm to 1100 nm when using the “roots finder” function in our eigenmode theory, that’s why we see a discontinued line in Figure 4.6(a) [160], this might occur since the dispersion curve of L_- mode in this geometry is so close to the light line and presented a cut-off region with low energy. For the bi-metallic sample with Au on top of Ag, the propagation length is $50\ \mu\text{m}$ @633 nm, 5 times the length of a single Au film which is $\sim 10\ \mu\text{m}$. The whole propagation length curve of this bi-metallic sample is close to single Au (the blue line and red line in Figure 4.6(a)), this is further evidence that the metal-air interface supports the L_- modes. In general, the bi-metallic film can improve the propagation length of L_- modes in comparison with the single film, the ability to tune the propagation length allows optimization of the SPP mode for specific frequencies and applications. In terms of the L_+ modes which are shown in Figure 4.6(b), the bi-metallic films do not show advantages on enhancing the propagation length, but we can confirm the position of L_+ modes from the propagation length. The propagation length of bi-metallic films is close to that of the single film which is identical to the underneath layer of the bi-metallic films (the black curve close to the blue curve and the green line close to the red line in Figure 4.6(b)), this proves that the metal-SiO₂ interface supports the L_+ modes, it also has good agreement with the conclusions drawn from Figure 4.3 and 4.4.

4.3 Biosensing application

Particularly the Kretschmann geometry of attenuated total reflectance method has been found to be very suitable for biochemical sensing and has become the most widely used geometry in SPP sensors. In this configuration, the light is totally reflected at the interface between a prism coupler and a thin metal layer (the thickness of about 50 nm). The SPP waves are excited at the interface of the base of the prism and the external surface of the metal, the SPP wave evanescently tunnelling through the thin metal layer to interact with the outside medium. The condition to excite the SPP waves, is very sensitive to the variations in the optical properties of the dielectric adjacent to the metal layer as well as the external medium (transducing medium). Therefore, variations in the optical parameters of the transducing medium can be detected by monitoring the interaction between the SPP wave and the external medium [161, 162].

Multiple detection approaches have been demonstrated in the SPP prism-based sensors: measurement of the intensity of the SPP reflection near the resonance [163]; measurement of the excitation angle while the wavelength of the excitation is fixed (angular approach) [141]; measurement of the excitation wavelength while the excitation angle is fixed (wavelength approach) [164]; measurement of the polarization and phase change associated with the SPP resonance [165]. The approach based on the measurement of the SPP reflection through a prism coupling as a function of the excitation angles is discussed in this section. In this case, a minimum reflection is observed at the angular position where SPP are excited. These propagating SPP are prone to changes in the environment and as a result, the excitation angle will vary when there is any parameters changes in the biochemical solution or binding events occur at the metal surface [166].

4.3.1 Thickness optimization

Recent developments have greatly improved the sensitivity of optical sensors based on localized surface plasmon (LSP) which are generally formed by metal nanoparticle arrays and single nanoparticles [55]. The sensitivity of SPP sensors is defined as the derivative of the monitored SPP parameters (*e.g.* resonant angle or wavelength) with respect to the parameter to be measured (*e.g.* refractive index, thickness of a thin layer, concentration of the liquid, molecule bounding time, *etc.*). The sensitivity of SPP angular or wavelength resolved sensors to changes in the refractive index has been found to be associated with the decreasing or increasing of the operation wavelength [164]. In general, the sensitivity of the biosensors are related to the feature of the plasmonic resonance [147], such as the reflectivity and full-width at half-maximum (FWHM) of the resonance signal. The first item determines the strength of the SPP excitation which can also be described as an evanescent wave interacts with the surrounding medium and the second item shows the sharpness of resonance which determines the operating range and the resolution of the sensors when detecting the small refractive index variation of the medium [167].

The SPP wave vector generated at the interface of metal and dielectric interface is associated with the thickness of the metal being used. It can be understood as the changing of the Fresnel's reflection coefficient when the thickness of the metal is varied [168]. Figure 4.7 shows the SPP reflection as a function of the thickness of Au and Ag films through a prism coupling, the low reflectivity parts (blue parts) means the strong coupling between the photonic mode

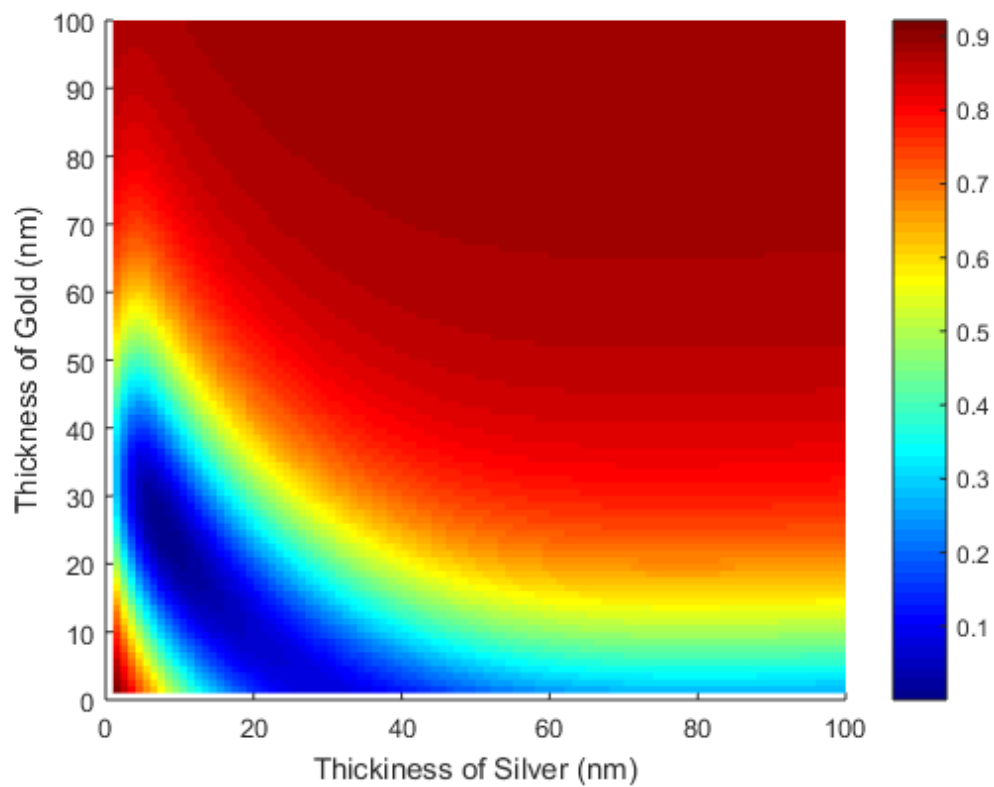


FIGURE 4.7: The SPP reflection as a function of the thickness of Au and Ag films. The blue part indicates the low reflectivity, and inversely the red part shows the high reflectivity. The related thickness of the Au and Ag is the optimal thickness for biosensing.

and the plasmonic mode. The Au film is the external layer which is located on top of the Ag film in the modelling, the wavelength of the input light is 532 nm and the corresponding excitation angle of the SPP mode for the Au film is 50° . It tells the optimal thickness for both Au and Ag to yield the low reflectivity in which the coupling of the SPP mode is strongest at that thickness. Since the light will be completely transmitted in a very thin layer of Au or Ag (~ 5 nm) [169]. Furthermore, the SPP waves couldn't strongly bound to the metal-dielectric interface when the metal layer is thick (not comparable to the skin depth) [170]. The thickness of the metal needs to be optimized for efficiently exciting and propagating the SPP mode. There is a low reflectivity area when the thickness of the Au and Ag is between 40 nm to 60 nm which indicates a well SPP excitation [168]. We fix the thickness of the Au and Ag single film as 50 nm and the total thickness of the Ag-Au combined film the same thickness to get an efficient plasmonic mode coupling [171].

4.3.2 Resolution and sensitivity improvement

The sensitivity of SPP angular resolved sensors to changes in the refractive index has been found to increase with decreasing operation wavelength [172]. Sensor resolution is the minimum change in the parameter to be determined which can be resolved by a sensing device [144]. An optimal thickness of the metal can improve the excitation efficiency of the plasmonic mode, and the feature of the plasmonic resonance determines how sensitive of them to the fluctuation of the surrounding medium. For biosensing, the biological signals are detected by measuring the changing of the refractive index of the surrounding medium of the sensors. SPP sensors based on wavelength and intensity measurement may benefit from using Ag as an SPP active metal instead of Au because of a narrow SPP resonance [173]. In general, a narrower FWHM of the plasmonic resonance is more sensitive to the changing of the refractive index. Both the wavelength and the plasmonic materials (Au and Ag are discussed in this thesis) can influence the FWHM of the plasmonic resonance. Two wavelengths of 532 nm and 850 nm are chosen to show the related sensitivity. Au has a wide FWHM in the plasmonic resonance at the excitation wavelength of 532 nm which can be seen in Figure 4.8(a), it shows the reflectivity of the Au as a function of the input angles, the area of the low reflectivity region (blue part) indicates the width of the plasmonic resonance. Ag has a smaller FWHM at 532 nm as shown in Figure 4.8(b) which has a better performance for biosensing than Au. However, the sensing performance of Au and Ag at near-infrared

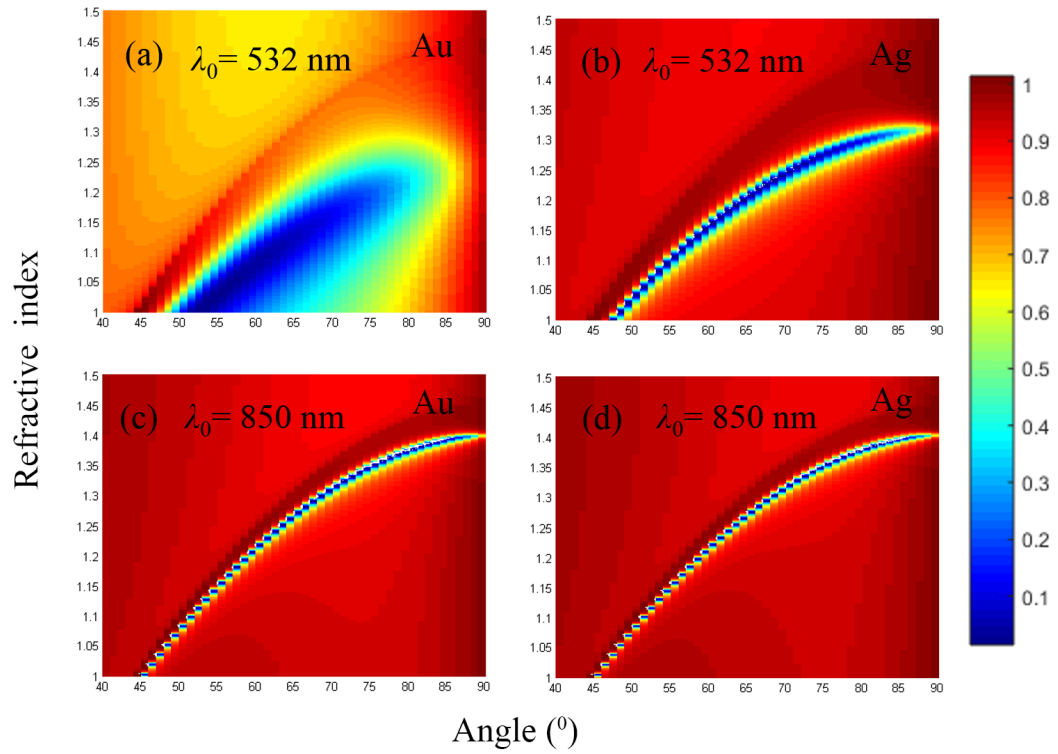


FIGURE 4.8: Angle resolved SPP reflection changing as a function of the refractive index of the surrounding medium. The lower reflectivity area in all the panels indicates the SPP modes have been excited with a certain input angle. (a) and (b) show the cases for Au and Ag with the excitation wavelength of 532 nm. (c) and (d) show the same case with the excitation wavelength of 850 nm. The thickness of the Au and Ag films is 50 nm in all the panels.

wavelength range 850 nm is different. Figure 4.8(c) and (d) show the reflectivity of Au and Ag as a function of the exciting angles, they have similar FWHM at 850 nm because the permittivity values are close. This tells us that Au and Ag have the similar sensitivity for sensing at 850 nm, Au is more stable than Ag when takes the oxidization issue into account which indicates Au is a better candidate for biosensing applications than Ag at the excitation wavelength of 850 nm.

The panels in Figure 4.9 show one of the mechanisms of the Au and Ag metallic plasmonic structures for biosensing applications (refractive index sensing). Measurement of the excitation angle while the wavelength of the excitation is fixed (angular approach). The SPP excitation angles which shift with the

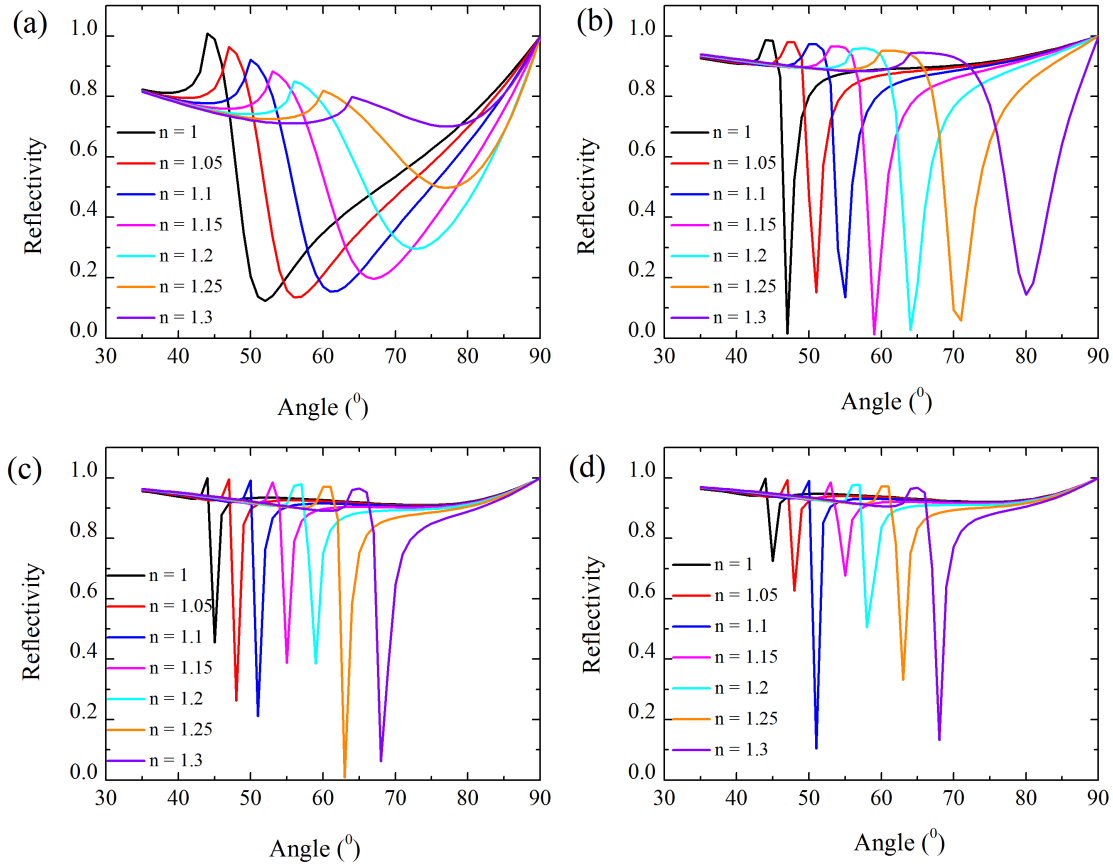


FIGURE 4.9: Evolution of the sensitivity for the refractive index sensing. The SPP resonance curves shift as the refractive index of the surrounding medium is varying from 1 to 1.3. (a) and (b) show the cases for Au and Ag with the excitation wavelength of 532 nm. (c) and (d) show the same case with the excitation wavelength of 850 nm. These results are calculated through TMM by varying the refractive index of the air layer in the model.

changing of the refractive index gives the fingerprint information of the biological signals to be detected. Figure 4.9(a) and (b) show the excitation angle shifts when the refractive index of the surrounding medium is varying for 1 to 1.3 for Au and Ag at the input wavelength of 532 nm, Au has wider SPP resonance than Ag as respected. Figure 4.9(c) and (d) show the same case when the input wavelength is 850 nm, both Au and Ag have sharp SPP resonance which shows the similar sensing performance.

Figure 4.10 shows the sensitivities of Au and Ag films with thickness of 50 nm when excitation wavelengths are $\lambda = 532$ nm and $\lambda = 850$ nm respectively. The Ag individual film has a highest sensitivity of 106.1 nm/RIU when the excitation wavelength is 532 nm. Similar sensitivities of 77.15 nm/RIU and 79.94 nm/RIU are achieved for Au and Ag films when the excitation wavelength is

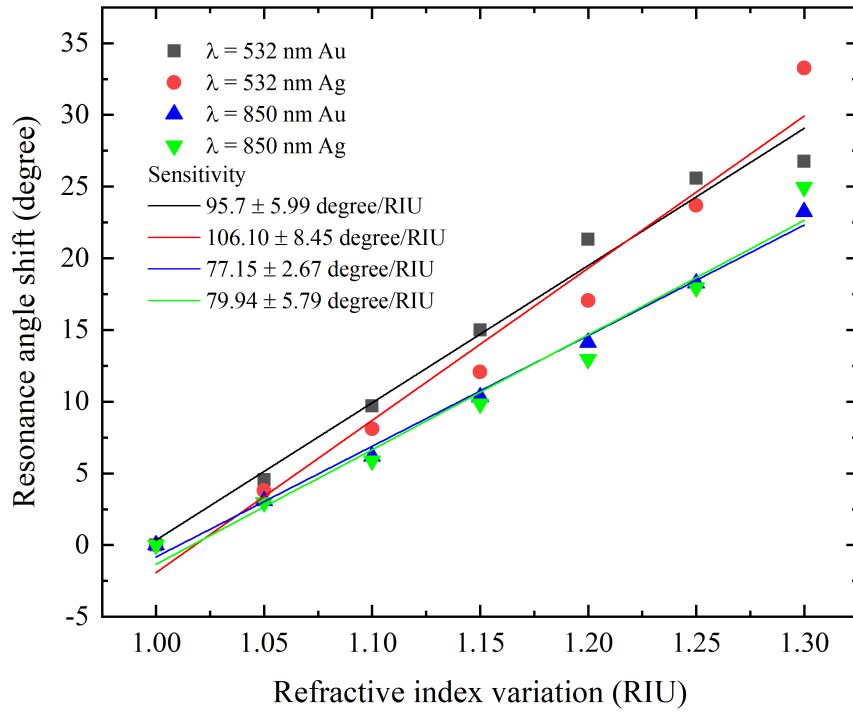


FIGURE 4.10: Sensitivities of the Au and Ag films with the thickness of 50 nm when the excitation wavelengths are $\lambda = 532$ nm and $\lambda = 850$ nm respectively.

850 nm. An excitation wavelength of 532 nm is preferred when using Au or Ag for biosensing applications in order to achieve a higher sensitivity. A sharper SPP resonance can be achieved when the excitation wavelength is 850 nm which result in a higher resolution.

4.3.3 Sensing performance for Ag-Au bilayer structures

Au and Ag have pros and cons if considering the properties of sensitivity and stability. In the previous sections of this chapter we discussed the tunable dispersion properties of the bi-metallic film, here we will discuss the optimal sensing performance by combining these two films. Au has a wider SPP resonance than Ag which will limit its sensitivity, the SPP resonance with a tunable width can be obtained by combining these two films which can be seen in Figure 4.11. The thicknesses of Au and Ag films vary from 0 nm to 50 nm. The Au film is located on top of Ag in the modelling for improving the stability of the combined

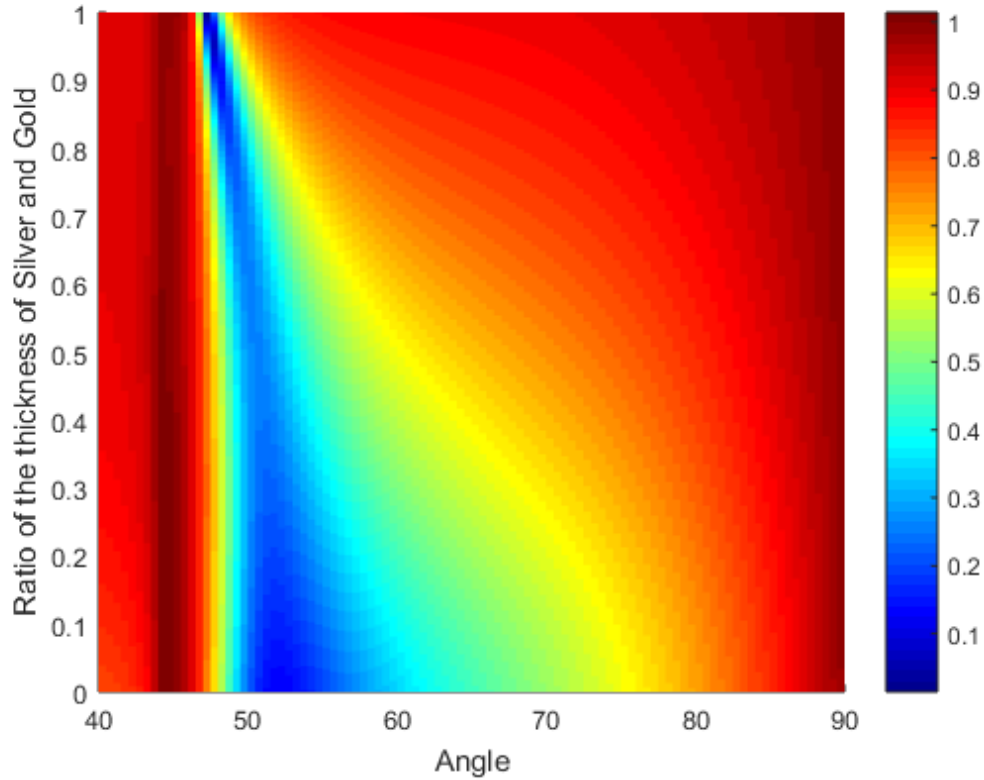


FIGURE 4.11: Angle resolved reflectivity changes for Ag-Au bilayers when the thickness of these two metals have different ratios. The thicknesses of Au and Ag films vary from 0 nm to 50 nm. The Au film is located on top of Ag in the modelling for improving the stability of the combined film. The excitation wavelength is 532 nm. The area of the low reflectivity part shows the width of the SPP resonance. The FWHM of the SPP resonance is varying by combining the Ag and Au film.

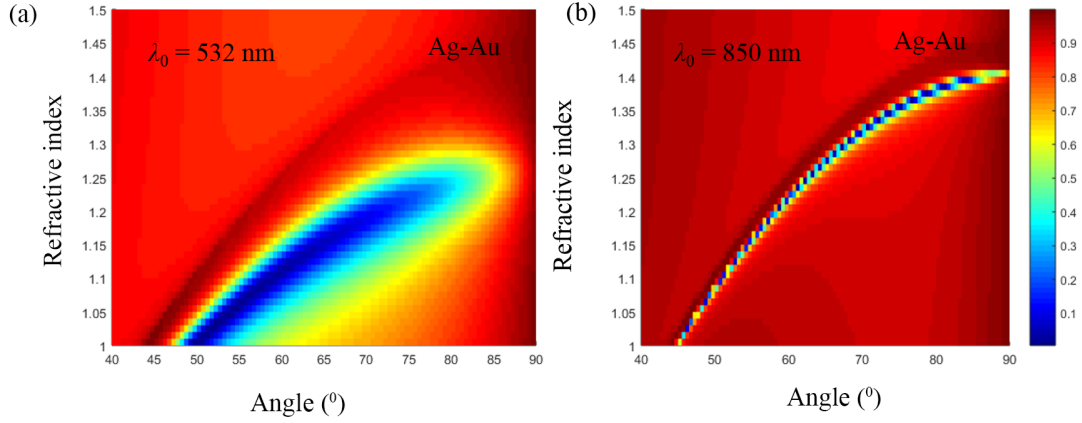


FIGURE 4.12: Angle resolved reflectivity changing as a function of the refractive index of the surrounding medium for Ag-Au bi-metallic layers, the thickness of Au is 20 nm and the thickness of Ag is 30 nm. (a) The cases for the bi-metallic layer with the excitation wavelength of 532 nm. It shows the Ag-Au bi-metallic structure can effectively decrease the FWHM of the SPP resonance which makes it a better candidate for biosensing applications. (b) The same case with the excitation wavelength of 850 nm.

film. The excitation wavelength is 532 nm. We calculate the angle-resolved reflectivity for Ag-Au bi-metallic layers when the thickness of these two metals are combined with different ratios. Figure 4.11 shows the FWHM of the SPP resonance versus the thickness ratio of Ag and Au in the bi-metallic film, pure Ag has the narrowest resonance spectra which can be seen on the top part of the low reflectivity area (blue part) of Figure 4.11. The width of the SPP resonance increases gradually with the presence of Au in the Ag-Au bi-metallic films.

Figure 4.12 show an example of the bi-metallic sample with 30 nm Ag underneath a layer of 20 nm Au. The Ag-Au bi-metallic structure has a narrow SPP resonance at the excitation wavelength of 532 nm (Figure 4.12(a)) than Au itself (Figure 4.8(a)) which indicates a better biosensing performance. The FWHM width of the SPP resonance are almost identical to Figure 4.8(c), Figure 4.8(d) and Figure 4.12(b). There is not a large difference in the FWHM of the SPP resonance of the bi-metallic structure compared with the single Ag or Au layer at 850 nm, both Au and Ag are good candidates for bio-sensing applications if only taking the sensitivity into account, it gives alternative options when choosing plasmonic materials for biosensing applications at near-infrared input wavelength range.

Figure 4.13 shows a few examples of the changing of the FWHM values in

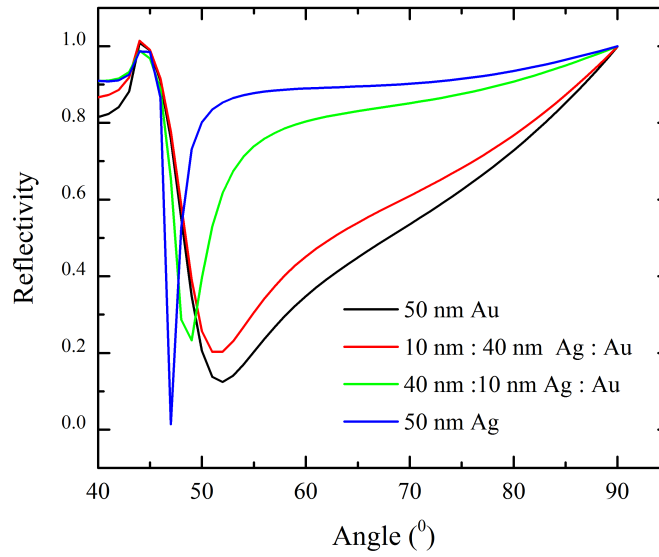


FIGURE 4.13: Examples of the changing of the FWHM in the SPP resonance for single Au and Ag layers and Ag-Au bi-metallic layer with two distinct ratios. The wavelength of the excitation is 532 nm.

Au and Ag combined films. Two cases of bi-metallic films are shown here, one with 10 nm Ag and 40 nm Au and the other one with 40 nm Ag and 10 nm Au. The features of the SPP resonance is dominated by the metal with a larger proportion. By using the Au as the cap layer and the Ag as the underneath layer of the bi-metallic structure, this combination can take advantage of the stability of Au and sharp SPP resonance of Ag. We have theoretically shown the possibility of bi-metallic plasmonic structures for designing stable and high sensitive biochemical sensors.

4.4 Chapter summary

In this chapter, we have experimentally and theoretically mapped the dispersion curves in a thin single Au or Ag metal film and bi-metallic films to study the symmetric and anti-symmetric SPP modes distribution in each layer. Both angle and energy dependent ellipsometric measurements were performed to observe the full dispersion in these structures. The transfer matrix method was used to reproduce the experimental results, and an eigenmode analysis was performed to give insight into the mode symmetry and the complex propagation constant. Varying the ratio of Ag to Au in the thin film allows continuous

tuning of the surface plasmon mode properties such as surface plasmon frequency, field enhancement, and propagation length, between that of individual Ag and Au films. We show that the mode propagation length of low energy bound SPP modes (L_-) can be significantly extended from the case of a single Au interface by the inclusion of an under-layer of Ag. For bi-metallic films with anti-symmetric metal thicknesses, the symmetric modes (L_-) follow the dispersion of the upper metal and air interface, whereas the anti-symmetric modes (L_+) depend on the lower metal prism interface only. This allows a unique ability to tune independently the dispersion of the L_+ and L_- modes in an IMI waveguide. The detailed experimental and theoretical results presented in this study clarify the tuning of the surface plasmon resonance frequency through the use of hybrid metallic layers. This can be implemented to design hybrid metal plasmonic devices with sensing performance. One of the applications of the Ag-Au hybrid metallic layered structure is biosensing. We discuss the superior sensing performance of bi-metallic structures on stability and sensitivity than single Au- and Ag-based structures. These make the Ag-Au bi-metallic structures good candidates for biosensing applications.

Chapter 5

Low-loss Adiabatic Dielectric-Plasmonic Hybrid Waveguide for HAMR Applications

Magnetic discs have attained a large capacity now reaching 1.4 Tb/in². However, future growth in capacity requires a new technology termed heat-assisted magnetic recording (HAMR). This new technology requires a laser device excites a tiny Au structure. The Au structure in turn heats the magnetic material allowing the bits to be written. This is termed HAMR and it will dominate the large data centres being built throughout the world. It turns out that the Au structure can be easily damaged by the laser, so making a high efficient structure is a key research challenge where a lower laser power would be required. Coupling light effectively into the NFT is a key challenge in the design of a HAMR system. In this chapter, we theoretically and experimentally investigate the properties of coupling between a slab Si₃N₄ waveguide and a long tapered Au plasmonic waveguide through an evanescent coupling mechanism. The most important insight is how to construct an adiabatic taper with a length on the order of 10 μm (one order of magnitude longer than typical devices) that can efficiently extract the incident light from the waveguide core to the NFT while overcoming the ohmic losses incurred by increasing the optical path length.

5.1 Introduction

Nanofocusing – the process of concentrating light to dimensions below the conventional diffraction limit – has been utilized in a wide variety of practical applications [84, 86], and is currently driving the development of a data storage process known as HAMR[7]. Studies have shown that HAMR can achieve areal memory densities as high as 1.4 Tb/in² [174], but it is still not yet ready

for full-scale commercial implementation [175]. HAMR operates by directing nanofocused light onto the surface of a ferromagnetic material to raise the local temperature, which reduces the coercivity of the material. When placed in the field of a writing magnet, the magnetization state of the illuminated area can be altered without affecting its surroundings, creating a magnetic bit. Thus, the memory density is dependent on the degree of spatial confinement in the optical nanofocusing process. Although heating the magnetic material can be done through other means, the optical method is the most common, particularly with a NIR (near infrared) diode laser coupled to a dielectric waveguide integrated with a plasmonic element known as a near-field transducer (NFT) at an air-bearing surface. When designing a nanofocusing element for commercial applications, the NFT's ability to harvest incident light while maintaining its structural integrity under strong optical intensities is of critical importance [23, 176, 177]. While there has been a significant amount of research on optimizing nanofocusing in terms of spatial confinement (for example, achieving a spot-size diameter of 60 nm in a tapered transition line [84]) and field concentration (for example, a theoretical intensity enhancement of ~ 12000 in a tapered stripe nanofocuser [92]), these papers are typically concerned neither with damage imparted to the optical structures during use, nor with the need for the nanofocusing element to efficiently absorb all the incident power. For the first concern, concentrating such a large amount of radiation in such a small space can cause the nanostructures to melt, or alter the material's thermal, optical, and electrical properties in a deleterious manner – the structural integrity of the nanofocusing element needs to be maintained for repeated use [178]. For the second concern, any uncoupled incident light can illuminate and heat the wrong part of the magnetic medium, potentially causing a bit to be lost or miswritten. In certain instances, light reflected from the end of the waveguide can destabilise the light source. This chapter will combine experimental, simulated, and theoretical techniques to characterize a particular NFT composed of an evanescently coupled plasmonic taper [176, 179–181], designed to address the issues that hinder HAMR development. In an effort to maximize the dielectric waveguide to plasmonic waveguide coupling efficiency, the length of the NFT is chosen to be one order of magnitude longer than what is typically used in similar devices [92]. The NFT – typically a noble metal like gold or silver – works by coupling the incident light to a surface plasmon polariton (SPP) mode and directing the radiation to the tip. The NFT is situated on a slab waveguide and illuminated by an external, far-field source that is coupled to a

trench 4 nm away from the NFT. A dielectric spacer layer in between the NFT and the waveguide core is used to match the momentum of the photonic and plasmonic modes in the NFT. Adjusting the spacer layer thickness alters the dispersion relation of the modes, and the spacer layer thickness at which the effective refractive index curves overlap leads to the most efficient coupling, causing the evanescent part of mode in the dielectric waveguide to couple to the metal and produce a long-range hybrid mode that will propagate to the tip of the NFT. A systematic study of the three main parameters of field intensity enhancement, mode coupling efficiency, and coupling length are described in this chapter. To be more specific, the coupling process is optimised to maximize the electromagnetic intensity in the NFT while minimising intensity remaining in the dielectric waveguide. Additionally, a long taper can simplify the fabrication and characterization process. A short (several hundred nanometres in length) taper will require the use of high-resolution electron-beam lithography, while a longer taper can employ a UV (ultraviolet) lithography process. Additionally, far-field measurements cannot resolve the bright spots at the beginning and ends of a short NFT, making it difficult to quantify the nanofocusing factor. This requires the use of a scanning near-field optical microscopy system [182], which can be very difficult and time-consuming. When the NFT is on the micrometre scale, a properly calibrated far-field measurement system can work just as well.

5.2 Theoretical foundation

5.2.1 Dispersion relations of an air/Au/SiO₂/Si₃N₄/SiO₂ layer stack

The evanescent coupling system of interest is shown in Figure 5.1. A silicon nitride (Si₃N₄) film with a thickness of $t_c = 180$ nm is used as a dielectric core layer, which can support only one transverse magnetic (TM) and one transverse electric (TE) mode at the free space wavelength of $\lambda_0 = 850$ nm [183]. A spacer layer of silicon dioxide (SiO₂) is used to match the effective refractive index of the photonic (characterized by negligible loss and is confined in the dielectric layers) and the plasmonic (characterized by the higher loss but more spatial confinement) modes. The NFT is formed by an isosceles triangular gold (Au) plasmonic waveguide (50 nm thick) which is situated on the SiO₂ layer. A diode laser with a wavelength of 850 nm is used to illuminate the NFT at the

trench (see the left side of Figure 5.1). Evanescent coupling between the core Si_3N_4 (refractive index = 2.02) waveguide and the NFT occurs in the presence of another dielectric layer with a smaller index than the core, here chosen to be SiO_2 (refractive index = 1.45). The evanescent coupling can be understood in the context of momentum conservation, as the effective indices of the photonic and plasmonic modes (corresponding to the momentum of the light) have to match for the process to occur efficiently. The coupled mode is a hybridization of the photonic mode and the plasmonic mode, which propagates towards the tip of the taper to be concentrated there. Because plasmonic modes are always excited by TM polarized wave, the light source will be TM polarized for the entire chapter. Au is one of the most commonly used materials used for NFT in HAMR applications because of its high thermal conductivity and because it does not degrade as quickly as silver. All of the NFTs in this chapter are 50 nm thick Au. The thickness of 50 nm was chosen to ensure that it was thin enough that SPP modes at the top and bottom interface of the NFT could combine to form symmetric and anti-symmetric modes (the detailed description of these two distinct modes in the layer stack can be seen in Figure 5.5); additionally, the tip of the tapered NFT is 50 nm wide, so choosing this thickness will result in a square cross-section ($50 \times 50 \text{ nm}^2$ in size) at the tip. The complex permittivity of Au used in the calculations was obtained from Palik [95].

In a semi-infinitely thick dielectric-metal system, the well-known complex wavevector for an SPP mode confined to the interface can be written as [98, 184]

$$k_x = k'_x + ik''_x = \frac{2\pi}{\lambda} \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (5.1)$$

in which k'_x and k''_x are the real part and imaginary part of the wavevector, respectively; λ is the free space wavelength, ϵ_m is the complex permittivity of the metal ($\epsilon_m(\lambda) = \epsilon'_m(\lambda) + i\epsilon''_m(\lambda)$), and ϵ_d is the permittivity of the dielectric layer. Our system (Figure 5.1) has been modelled as a five-layer stack with a semi-infinite superstrate and substrate, going from top to bottom as air/Au/ SiO_2 / Si_3N_4 / SiO_2 (the lower SiO_2 layer in the wafers used during the experiments is 2 μm thick, which is enough to treat it as semi-infinitely thick). The thickness of the middle layers will affect the dispersion relation curves; we are particularly interested in manipulating the spacer layer thickness (t_s) to optimize the evanescent coupling process. The five-layer SPP wavevector k_x is calculated by solving the eigenvalue equations [96] of the corresponding wave functions of the layer stack shown in Figure 5.1, which has been discussed in

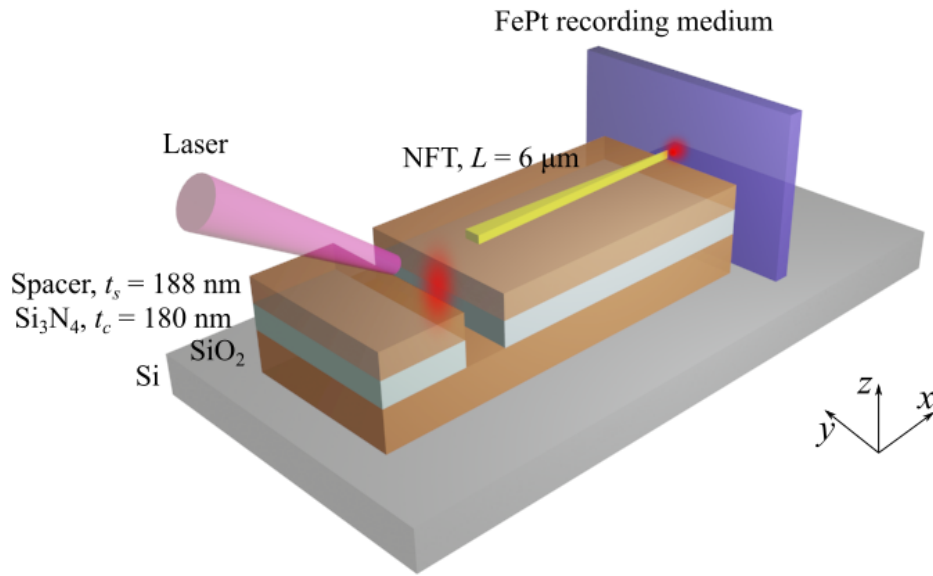


FIGURE 5.1: Schematic diagram of the proposed evanescent coupling system. It consists of a core layer of Si₃N₄ on a 2 μm thick SiO₂ on a Si substrate. A spacer layer of silicon dioxide (SiO₂) is used to match the effective refractive index of the photonic and the plasmonic modes. The NFT is formed by an isosceles triangular gold (Au) plasmonic waveguide which is situated on the SiO₂ layer. A diode laser with a wavelength of 850 nm is used to illuminate the NFT at the trench. The recording medium is formed with ferromagnetic materials.

Chapter 3. The dispersion relations can be quantified with two parameters that are related to the spacer layer, its t_s -dependent real and imaginary parts. The first is the effective wavelength of the surface plasmon polariton mode λ_{spp} , which is defined as

$$\lambda_{spp} = \frac{\lambda}{n'_{eff}} \quad (5.2)$$

where n_{eff} is the complex refractive index of the plasmonic mode; the single prime denotes the real part. The plasmonic wavelength quantifies the degree of spatial confinement – a smaller value corresponds to a more confined mode [185]. The other parameter is the SPP propagation length L_{spp} , which is defined as the length at which the intensity decays to $1/e^2$ of its original value and is given by the expression $L_{spp} = \frac{\lambda}{4\pi\kappa}$, where κ is the imaginary component of n_{eff} . Both quantities can be found in the dispersion relation, which shows the relationship between a mode's energy and its momentum. The solid black curve in Figure 5.2(a) is the dispersion curve of the higher energy anti-symmetric plasmonic mode without a spacer layer (*i.e.*, $t_s = 0$). The solid grey curve and the dashed grey curve are the light lines of air and Si_3N_4 , respectively. The other curves show the tuneable property of the dispersion relations by inserting a SiO_2 spacer layer between the Si_3N_4 and Au layers. As the thickness of spacer layer is varied from 0 nm to 250 nm in steps of 50 nm, it is seen that the value of k'_x is maximized at $\sim 16 \mu\text{m}^{-1}$, corresponding to a λ_{spp} value of $\lambda/2.55$ at $t_s = 150$ nm. This provides a value to start searching for the ideal thickness; it will be shown below that the system is optimized when $t_s = 188$ nm for a 180 nm thick Si_3N_4 core at the operating wavelength of 850 nm (corresponding to the dashed horizontal line in panels (a) and (b)).

Figure 5.2(b) shows the imaginary part of k_x which can be used to study the propagation length. The value of k''_x is maximized at $\sim 4 \mu\text{m}^{-1}$ when $t_s = 150$ nm and $\lambda = 477$ nm (the wavelength of an interband transition ¹ in Au), which corresponds to the lowest SPP propagation length of ~ 125 nm. Figure 5.3 shows the propagation length as a function of wavelength for the air/Au/ SiO_2 / Si_3N_4 / SiO_2 layer stack and two semi-infinitely thick layers systems. There is a well-established trade-off between better mode confinement (a smaller λ_{spp}) and a longer propagation length (a larger L_{spp}) [186]. Although this would indicate that the light cannot propagate very far in the Au NFT layer,

¹Noble metals, such as Au and Ag have electronic interband transitions in the visible range, specific light energy is absorbed and yield electrons to show distinct color.

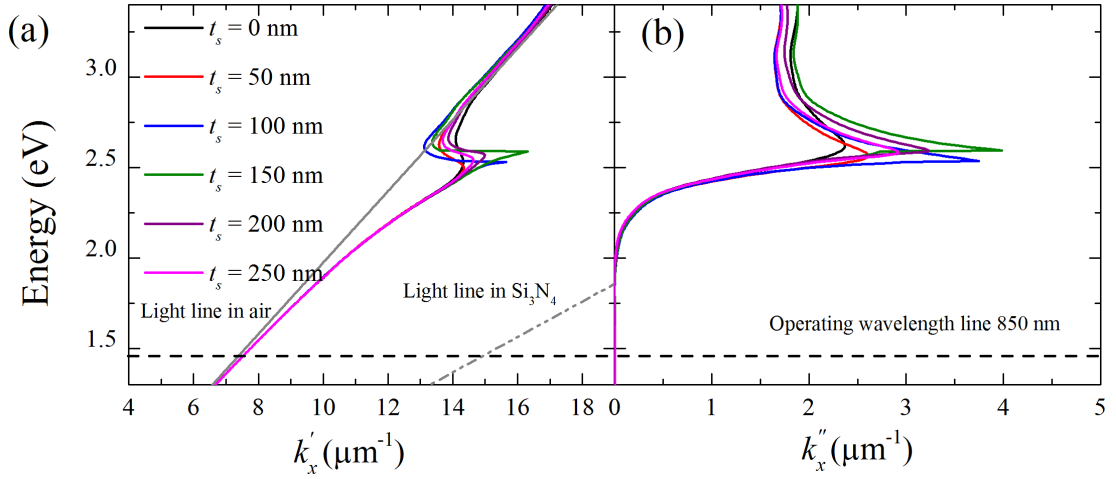


FIGURE 5.2: (a) Real part (k'_x) and (b) imaginary part (k''_x) of the dispersion curves of the anti-symmetric mode as the thickness of the SiO₂ spacer layer (t_s) is varied. The thickness will be chosen to facilitate the evanescent coupling process and match the momenta of the modes. The dashed horizontal line corresponds to the wavelength used in the rest of the paper (850 nm, or 1.46 eV).

the evanescent coupling process used in this paper reduces loss by confining the light to the dielectric layer.

The propagation length in the layer stack decreases when inserting a spacer layer. The coupled mode is a hybridization of the dielectric mode and the plasmonic mode, which is at its most lossy at the plasmonic resonance wavelength $\lambda = 477$ nm. The vertical orange dashed line indicates the propagation length at the excitation wavelength of 850 nm in this chapter for two different layer systems. For the multi-layer structures which have been used in this chapter, a longest propagation length of 200 μm is achieved when the spacer layer is absent, a 188 nm SiO₂ spacer will decrease the propagation because of the higher index than the air medium ($L_{spp} = 130$ μm at this wavelength). The two semi-infinitely thick layer systems have a lower propagation length than the multi-layers evanescent coupling system, a longest $L_{spp} = 60$ μm is achieved at the air/Au interface.

5.2.2 Momentum matching and evanescent coupling

We use the electromagnetic waves frequency domain mode analysis tool in COMSOL Multiphysics 5.2a to calculate the complex effective refractive index n_{eff} ($n_{eff} = n'_{eff} + i\kappa$), where n'_{eff} is the real part and κ is the imaginary part of the effective refractive index in our waveguide system. The complex effective

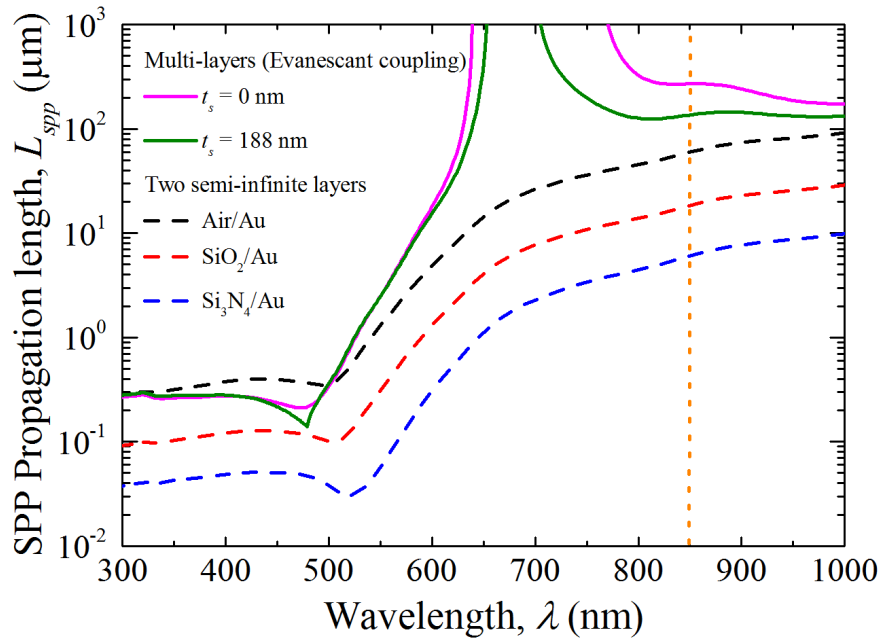


FIGURE 5.3: The propagation length of the coupled mode L_{spp} as a function of wavelength for the air/Au/SiO₂/Si₃N₄/SiO₂ layer stack and two semi-infinite layers systems.

refractive index of Au ($n_{Au} = 0.21 + 5.09i$ at 850 nm) used in the simulations is obtained from Palik [95]. Figure 5.4(a) shows the real part of n_{eff} for the fundamental photonic mode and the anti-symmetric plasmonic mode as functions of thickness of the Si₃N₄ core layer (t_c). The photonic mode is obtained when the Au layer is absent (left inset schematic). The plasmonic mode is obtained when the Au layer is present (right inset schematic). The plasmonic mode has a higher refractive index than the photonic mode for all values of t_c . The vertical dashed-black line in Figure 5.4(a) shows that the real parts of the effective refractive index of the plasmonic mode ($n'_p = 2.21$) and the photonic mode (confined to the dielectric layers, $n'_d = 1.71$) when the thickness of the Si₃N₄ core is $t_c = 180$ nm, which is the value used in the rest of the paper. The mismatch between the indices of these two modes results in poor coupling and thus more power is left in the waveguide layer that will not be nanofocused. Figure 5.4(b) shows the effective refractive indices of fundamental (TM₀) and higher order photonic modes – this is included to show that trying to couple to higher order modes (which can be done at a smaller wavelength or in a system with a thicker t_c than ours) is less efficient because their indices are even farther removed from the anti-symmetric plasmonic curve. In systems with a thicker core layer, multiple TM photonic modes will be present, and they will couple

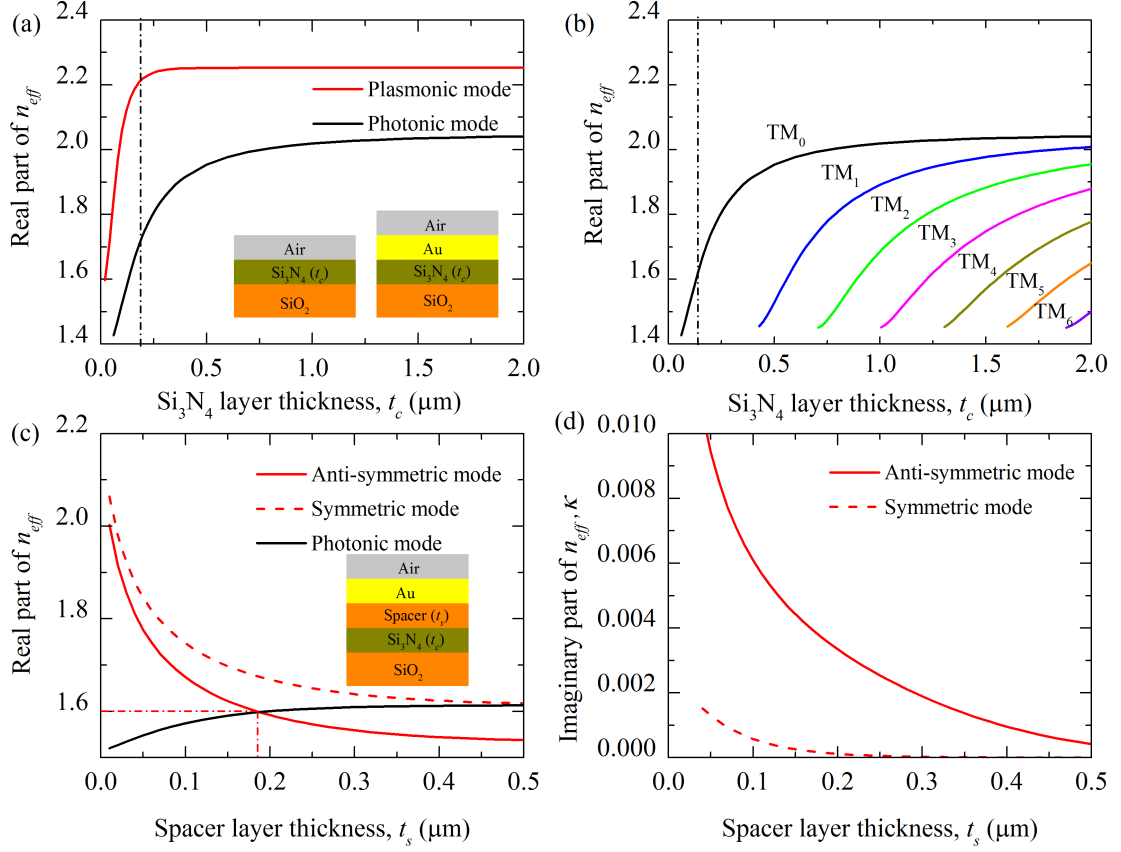


FIGURE 5.4: (a) Real part of the effective refractive index of the anti-symmetric plasmonic mode (with Au) and the fundamental photonic mode (without Au) as a function of the thickness of the Si_3N_4 core layer without the spacer layer – the insets show the geometries of the two cases being studied. Panel (b) shows the effective refractive indices of the higher-order TM photonic modes as a function of the thickness of the Si_3N_4 core layer. It is clear from the figure that none of these will couple to the higher-index plasmonic mode from panel (a). Panel (c) shows that momentum matching occurs by adding a SiO_2 spacer layer between the Si_3N_4 core layer and the Au layer. The dashed-dot lines show where the momentum match occurs: when the spacer layer is 188 nm thick. The inset figure shows the layer geometry of the case being studied. Panel (d) shows the imaginary part κ (extinction coefficient) of the anti-symmetric mode and the symmetric mode as functions of the thickness of the SiO_2 spacer layer.

to the plasmonic mode with different efficiencies. Figure 5.4(c) shows the variation of the effective refractive index of the plasmonic mode and the photonic mode after adding a SiO₂ spacer layer. The plasmonic mode includes two distinct modes: the anti-symmetric mode and the symmetric mode, which exhibit different refractive indices; the nomenclature used for identifying the symmetric and the anti-symmetric modes depends on the spatial distribution of electric field in the Au layer, see Figure 5.5 for more analysis. The anti-symmetric mode has a lower real effective refractive index than the symmetric mode for all thickness values [96]. The dashed-dot red line shows that in order to couple the TM₀ mode in the 180 nm thick Si₃N₄ core to the anti-symmetric plasmonic mode, a 188 nm SiO₂ spacer layer is needed to shift the real part of the effective refractive index of the plasmonic mode to $n'_p = 1.59$. The inset shows the geometry of the layer system with a SiO₂ spacer layer. Figure 5.4(d) shows the imaginary part κ (extinction coefficient which indicates the amount of attenuation of the electromagnetic wave propagates through the material) of the effective refractive index of the plasmonic mode when the thickness of the SiO₂ spacer layer is varied. The anti-symmetric mode has higher loss (larger κ) than the symmetric mode in infinitely wide Au films. However our further study in this chapter shows that the imaginary part curves of the anti-symmetric mode and the symmetric mode will cross over when the width of the Au structure decreases, it indicates that the anti-symmetric mode has lower loss than the symmetric mode in nanostructures which is more suitable for nanofocusing applications [187].

5.2.3 Analysing the symmetry of SPP modes in COMSOL

The electromagnetic wave (frequency domain) mode analysis study in COMSOL is used to compute the propagation constants or wave numbers as well as propagating mode shapes at inlets, outlets, and cross sections of guiding structures for a given frequency. The thickness of the dielectric core determines the number of the modes in the z direction. It is possible to use this tool to find the eigenvalue solutions of the layer stack used in this chapter, the only requirement being that of an adequate initial guess to search for the correct solutions. We are using the refractive index of the core layer ($n_{core} = 2.02$) as the starting value to search all the possible modes in the layer stack. Two models are used to study the momentum matching condition and adiabatic nanofocusing process respectively. In the case of studying the momentum matching condition, the model considers a two-dimensional cross-section of a plasmonic slab waveguide which is infinitely wide in the y direction (direction parallel to the

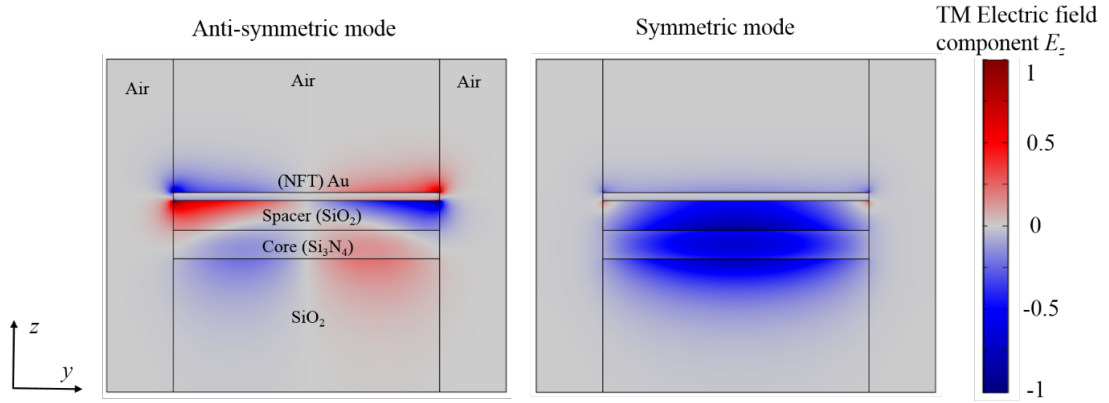


FIGURE 5.5: z -component of the electric field of (a) the anti-symmetric mode and (b) the symmetric mode in the layer stack. The symmetry of these two plasmonic modes is distinguished by the spatial distribution of the z -component of the electric field (E_z) at the two interfaces of the metal. The layer stack in the simulations is infinitely wide in the x direction and the field is not total distributed in the metal-dielectric interface because of the photonic mode is also solved. The amplitude of the electric field presents the symmetry of the hybrid photonic-plasmonic mode.

core of the slab). The light is propagating in the x direction (out of the page), so the y - z cross-section at any point along the axis of the slab waveguide will look the same. By looking at the modes that exist in an arbitrary cross-section can give the information of the modes propagate in the whole slab waveguide. When taking the shape of the NFT into account to study the nanofocusing process, the width of the NFT varies from $1\ \mu\text{m}$ to $50\ \text{nm}$ along the direction of tapering (x direction) and it cannot be considered as a simple infinitely wide system. Technically, the modes profile and effective refractive index in each y - z cross-section of the NFT (light propagate along x direction) are not identical. We perform a parametric sweep study of a number of cross-sections of the NFT with variable widths (w_t) rather than study an arbitrary cross-section. The effective refractive index and modes profile in each cross-section with variable w_t are obtained which are used to study the nanofocusing process. To differentiate between the different solutions provided by the mode analysis tool, it is first noted that the photonic mode will have a negligibly small imaginary index, while the plasmonic mode will have a non-negligible imaginary index. Between the two plasmonic modes, they are distinguished as symmetric or anti-symmetric depending on the amplitude of the z component of the electric field

(perpendicular to the interface of each layer) across the metal layer. The amplitude of the electric field is in phase across the Au film for the symmetric mode and that is out of phase for the anti-symmetric mode, see Figure 5.5.

5.2.4 Adiabatic nanofocusing

Currently, nanofocusing NFT's for HAMR are relatively short, on the order of 100 nm [180]. This is to reduce the optical path length and hence reduce the amount of energy lost as heat. However, using a short NFT means that the light is coupled less efficiently from photonic to plasmonic mode. A very long NFT could, in principle, extract all the light from the waveguide mode, but that means the lossy metal will absorb all the energy and have no nanofocusing effect. If the local conditions change slowly enough as the light propagates, it will be as if the propagating light does not scatter at the edge of the plasmonic NFT, reducing the amount of energy lost. This process, known as adiabatic nanofocusing, was developed by Stockman [82] and Gramotnev [188] and is quantified by the parameter

$$\delta = \frac{\lambda}{2\pi} \left| \frac{\partial}{\partial x} \frac{1}{n'_{eff}} \right| \quad (5.3)$$

where n'_{eff} is the real part of the effective index of the plasmonic mode to be focused, and x is the direction of light propagation. The δ is the eikonal parameter, which is also called Wentzel-Kramers Brillouin (WKB) or adiabatic parameter [188]. It indicates the grading of a waveguide when the dimension of it is changing. A small δ value produces a stopping point of the propagating wave in the nanoscale tip. For the applicability of the WKB approximation, it necessary and sufficient that $\delta \ll 1$ for the adiabatic nanofocusing condition. In a typical material (linear polarization, isotropic, and homogeneous), the only factor that will alter the wave's path is reaching the edge of the tapered material; thus, the geometry of the material is the main determinant in this system of whether or not adiabatic nanofocusing is achieved. The fact that the effective index changes as the plasmonic mode moves down the tapered NFT is what makes efficient nanofocusing possible, as will be discussed below. Figure 5.6(a) and (b) show the complex effective refractive indices of the anti-symmetric and the symmetric modes when the width of the NFT is varied to show the potential modes exist in our layer stack. To take the analysis on step further, the width of the NFT layer will be confined to emulate the tapered NFT layer at any given cross-section in the y - z plane (see Figure 5.1). Essentially, the data in Figure

5.6c shows the evolution of the modal indices and field distributions along the length of the NFT, since the width varies linearly. As before, the symmetric plasmonic, anti-symmetric plasmonic, and fundamental photonic modes will be analysed. Panels (a) shows the real part of the effective indices. For very narrow widths ($w_t < 200$ nm), the real effective index of the symmetric mode increases asymptotically, which will decrease the phase velocity ($v = c/n'_{eff}$) and group velocity ($v = c(\frac{\partial}{\partial \omega}(\omega n'_{eff}))^{-1}$) of the SPP mode. Consequently, the SPP waves are slowed down and concentrated at the tip of the NFT; this is known as the geometry-induced plasmonic nanofocusing process which is the key mechanism to achieve light concentration in our NFT [82, 83]. The effective refractive index of the photonic mode keeps almost constant when the width of the tip varies.

Figure 5.6(b) shows the imaginary part κ (attenuation coefficient) of the effective refractive index of the modes in the layer stack. Both the anti-symmetric and symmetric modes are lossy plasmonic modes (positive κ value in Figure 5.6(b)). In general, the symmetric mode is a long range plasmonic mode because of the smaller imaginary part of effective refractive index compared to the anti-symmetric mode (which is a short range plasmonic mode) [99, 189], since the propagation length L_{spp} can be described as $L_{spp} = \frac{1}{|k''_x|} = \frac{1}{|2\kappa k_0|}$. However, when the width of the NFT decreases, the symmetric mode is lossier than the anti-symmetric mode. It can be seen that the imaginary part of the effective refractive index of symmetric mode increase dramatically when $w_t < 450$ nm, which shows better nanofocusing property of the anti-symmetric mode in nanostructures. Figure 5.6(c) shows a few examples from simulations of cross-sections of the electric field for the anti-symmetric mode, the symmetric mode and the photonic mode, it is 2-D simulations of the cross-section of the NFT. The symmetry of the plasmonic mode in the NFT is identified through visual examination of the spatial distribution of the z -component of the electric field. For the anti-symmetric mode, the amplitude of electric field in the four corners of the Au layer is out of phase along z direction and is in phase for the symmetric mode. In this figure, the colour scale corresponds to the amplitude of the electric field. The figure shows that both the anti-symmetric and the symmetric modes can be confined when the width of the NFT is small, but becomes less so as the NFT widens. The photonic mode is dominated in the dielectric core layer and the spacer layer which show lossless property. For the rest of this chapter, the width of the start and the tip of the NFT are $1 \mu\text{m}$ and 50 nm, respectively; since the width varies linearly along the x -direction, the taper angle is purely a

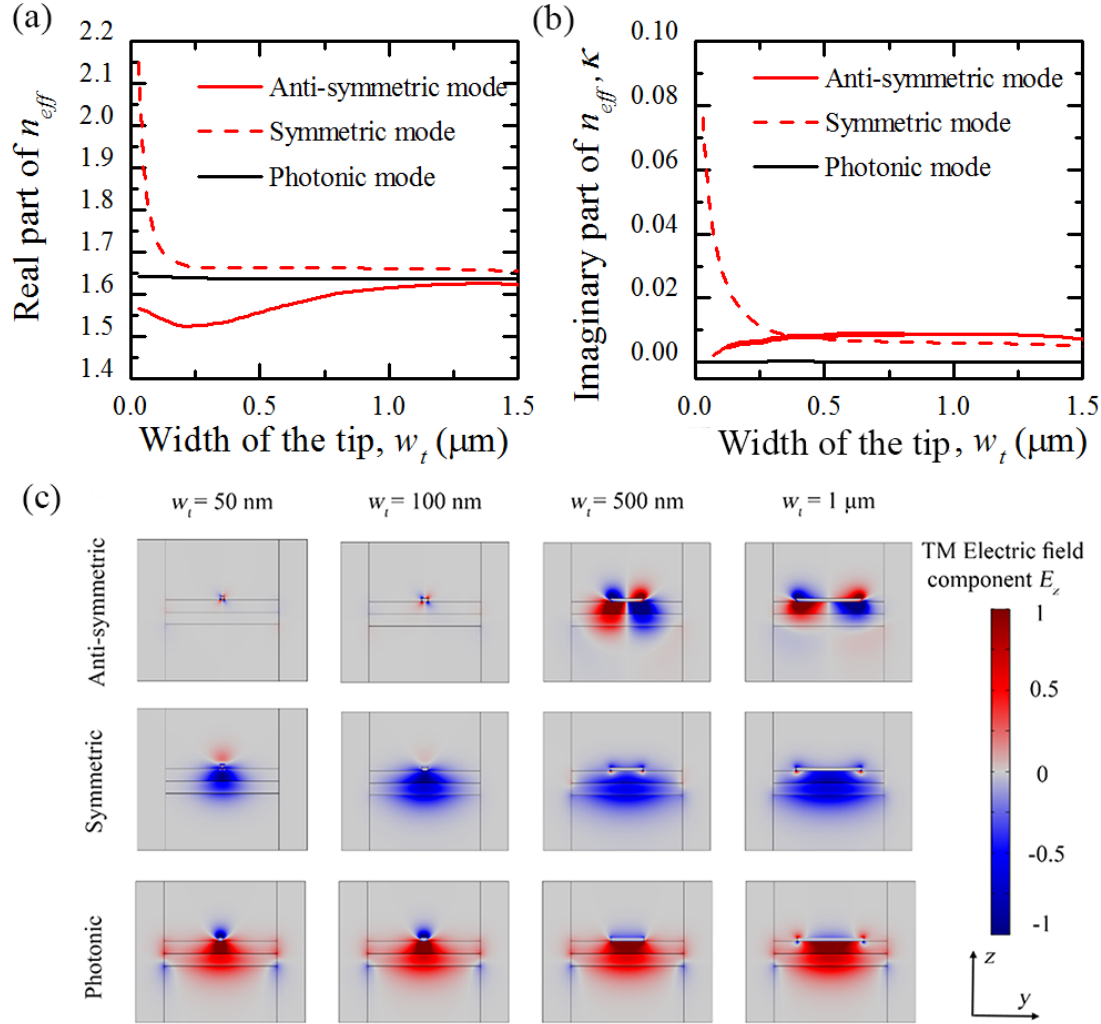


FIGURE 5.6: (a) Real part and (b) imaginary part of n_{eff} as a function of the width of the NFT for the anti-symmetric and the symmetric modes. The n_{eff} for photonic mode in the core layer is also plotted to distinguish the two different type of modes. The real part of n_{eff} shows the confinement of these two modes and the imaginary part indicates the loss. (c) Examples of mode cross-section profile for the system as the width of the NFT changes.

The electric field magnitude is given by the colour bar.

function of the total length, L . Looking at equation 5.3, the derivative of n_{eff} is supposed to be taken along the direction of propagation, but the same data can be extracted by differentiating with respect to the width of the NFT, since length and width are linearly proportional. The δ values vary from 0.0147 to 0.0012 ($\delta \ll 1$) when the lengths of the NFT vary from 2 μm to 24 μm (samples used in the experimental section), these devices can be said to be in the adiabatic regime.

5.3 COMSOL optical simulations

5.3.1 Evolution of the nanofocusing process

Figure 5.7(a) shows the schematic diagram of the cross-section of the layer system used in the monochromatic 3-D COMSOL simulations. The systems under study will be characterized by three parameters: the field intensity enhancement (*i.e.*, the degree of nanofocusing), the coupling efficiency (amount of light removed from the core layer) and the coupling length (the distance between peaks in the field oscillations below the NFT). These three things can be clearly seen in Figure 5.7(b)-(k), which are models of the electric field intensity in different planes of the system using the optimized thickness parameters. Both the tapered structure (Figure 5.7(b)-(f)) and the rectangular structure (Figure 5.7(g)-(k)) were simulated. Whenever a taper and rectangle are discussed in tandem, they will have the same length L and the width of the rectangle is the starting width of the NFT (which will always be 1 μm). We include un-tapered (rectangular) structures in our analysis to help eliminate any variability caused by changing the scale of the system (which can affect the size of the mesh in the COMSOL simulations); this is also important when analysing the experimental data because it helps account for differences in incident intensity and experimental error (discussed more below). The simulations were performed with the predefined “extremely fine” mesh setting, where the maximum mesh size is 200 nm (roughly a quarter of the input wavelength). The first three rows of the simulated results are maps of the electric field intensity at different cross-sections, Figure 5.7(b)-(e), with the light propagating in the x direction. The top row is in the y - z plane; the left panel (Figure 5.7(b)) is at the start and the right panel (Figure 5.7(c)) is at the tip of the NFT. The left panel is dominated by the photonic TM mode used to excite the system, and the right panel is dominated by the focused plasmonic mode. The side view in the x - z plane (Figure 5.7(d)) shows the mode beating in each layer and coupling efficiency (indicated

by the light removed from the core layer). The third row (x - y plane, Figure 5.7(e)) shows the nanofocusing process, with the intensity becoming very large at the tip of the NFT, but not at the end of the rectangle (Figure 5.7(j)), as expected. In both cases, mode beating is observed, with the tapered case having a shorter coupling length. Also notable is the fact that more light is concentrated in spacer layer when the structure is tapered, which indicates a better coupling efficiency. The bottom row contains SEM images that shows the corresponding fabricated NFT (Figure 5.7(f)) and rectangle (Figure 5.7(k)) samples (same dimension as in the simulations). More detailed simulated results of the electric field distribution in each layer for the tapered and the rectangular samples are shown in Figure 5.8.

In Figure 5.7(l), the intensity distribution in the spacer layer of the tapered NFT (red curve) and the rectangular waveguide (black curve) as a function of position for an Au layer that extends from $x = 1$ to $7 \mu\text{m}$ ($L = 6 \mu\text{m}$) is plotted. Each curve is normalized against its own highest value. The intensity is collected along the centre of the SiO_2 spacer layer which is indicated by the dashed white line in Figure 5.7(a). Both curves in panel (l) exhibit beat-like behaviour, there are two oscillations in Figure 5.7(l), the high frequency oscillation is due to reflection from the tip of the NFT, and the lower frequency envelope oscillation curve is due to the beating of the photonic mode and the plasmonic mode. It can be seen that the normalized intensity near the end of the taper (for $5 \mu\text{m} < x < 7 \mu\text{m}$) is higher than in the same range of the rectangle which proves that the Au NFT can extract power from the Si_3N_4 core more efficiently than the Au rectangular strip because of the strong mode beating in the tip.

Figure 5.8 shows more detailed data from Figure 5.7. This shows the cross-sections are at different locations along the x axis. The light is more confined as it moves to the tip. In the panels below (a), light is propagating to the right (along the $+x$ axis). Figure 5.8(b) shows a high intensity concentration 20 nm above the Au taper layer (in the air medium). The bright spot at the tip of the taper comes from the light concentration along the lateral side and the bottom side of the taper. The mode beating on the lateral side can be observed along the two edges of the triangle in Figure 5.8(b). Mode beating in the SiO_2 layer is shown in Figure 5.8(c) which shows the energy transfer between the dielectric Si_3N_4 core and the plasmonic Au NFT. In this form, the light is understood to be a hybrid photonic-plasmonic mode, as the light oscillates between the waveguide core and the NFT. Figure 5.8(d) shows the light remaining in the Si_3N_4 core layer after the evanescent coupling. By properly designing the length of

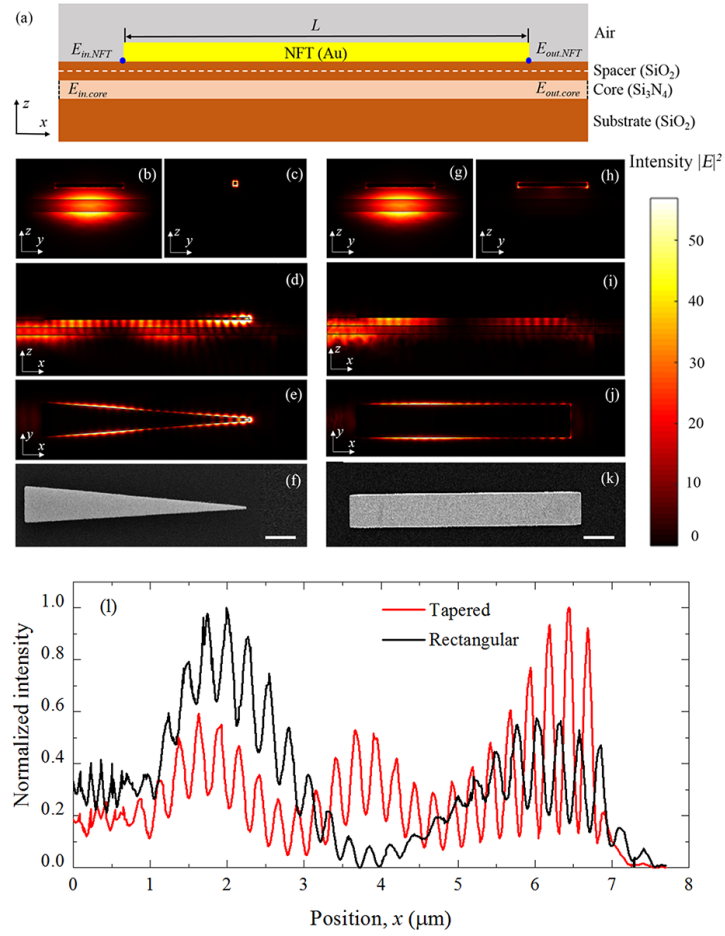


FIGURE 5.7: (a) Schematic diagram of the layer system that applies to all of the simulations shown in this section. The distance between the edge of the Au NFT and the edge of the simulation region is $\lambda_0/2 = 425$ nm on both sides. Optical 3-D simulations of the electric field distribution in the NFT with a tapered Au plasmonic waveguide (b)-(f) and a rectangular Au strip waveguide (g)-(k): (b), electric field at the start of the Au taper; (c), electric field at the tip of the Au taper; (d) the side view of the Au taper in the xz plane shows mode beating; (e), top view of the Au taper shows the nanofocusing process. The same description can be applied to panels (g) – (j) which are simulated results for an Au rectangular strip acting as a reference sample, the difference being that the nanofocusing effect doesn't appear at the end of the rectangle. Light propagates in the x direction in all figures; the scale bar is $1 \mu\text{m}$ and applies to all panels. (l) The normalized intensity distribution in the spacer layer of the tapered and rectangular waveguides along the light propagation direction (the dashed-white line in panel (a)).

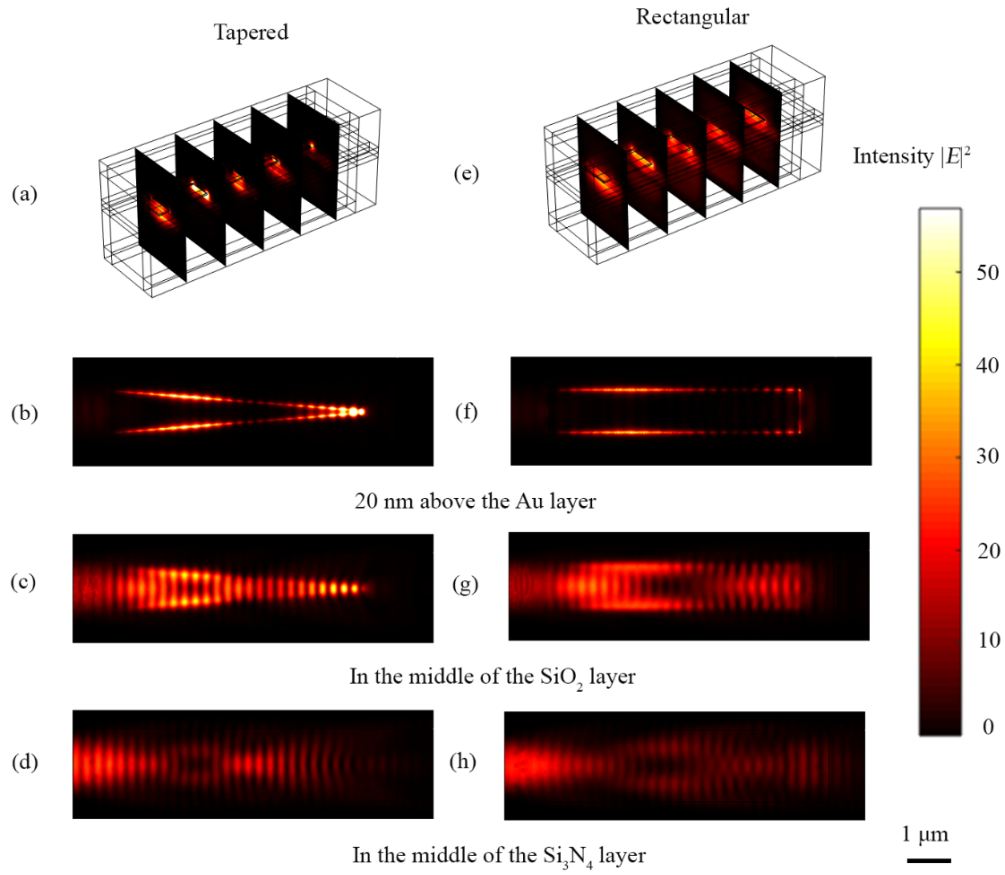


FIGURE 5.8: (a) – (d) the evolution of the plasmonic mode as it propagates from the start to the tip of the NFT. It demonstrates the nano-focusing process in the NFT. The same analysis also been demonstrated for the rectangular Au strip waveguide which shown in the panel (e) – (h).

the NFT, the power remaining in the dielectric core can be minimized (for example, a 6 μm long taper can extract 90.8% of light from the dielectric core to the Au NFT). Figures 5.8(e), (f), (g), and (h) are the same analysis for the rectangular strip, which is used as a calibration reference. Mode beating is also observed in the spacer layer and the lateral side of the rectangular Au strip. The intensity of the evanescent wave decays along the rectangular Au strip because of the ohmic loss. The rectangular shape of the Au strip keeps the effective refractive index of the plasmonic mode constant, meaning nanofocusing cannot occur in this structure.

5.3.2 Field enhancement and coupling efficiency

We theoretically analyse the field enhancement factor of the NFT as shown in Figure 5.9(a). The mode beating-induced field intensity enhancement factor Π_{NFT} ($0 < \Pi_{\text{NFT}} < \infty$) in the NFT is calculated by using the absolute square of the electric field in the output port ($E_{\text{out.NFT}}$) divided by the input port ($E_{\text{in.NFT}}$) of the NFT (the location used to account for the input port and output port of the NFT in the calculation is marked as the blue dots in the right-hand side and left-hand side of Figure 5.7(a), respectively, which are between the NFT and the spacer layer interface), and is given by the formula

$$\Pi_{\text{NFT}} = \frac{|E_{\text{out.NFT}}|^2}{|E_{\text{in.NFT}}|^2} \quad (5.4)$$

Since the mode beating dominates in the z direction of Figure 5.7(a) due to the discontinuity of the effective index between different layers, we only calculated the point intensity in a 2-D cross-section along the x direction instead of doing surface integration in the y - z plane (intensity in the entire boundary). This can avoid the scattering from the simulation boundary which is parallel to the plane where mode beating occurs. Thus, the intensity of the output and input of the NFT is the intensity at a point in the interface of the NFT and the spacer layer (plasmonic mode is confined in the Au and spacer layer interface), respectively. Figure 5.9(a) shows the field intensity enhancement factor in the Au NFT as the length L varies from 100 nm to 25 μm in steps of 100 nm. The curves exhibit exponential decay as the length increases (due to ohmic losses in the metal), as well as oscillations induced by mode beating between the photonic and plasmonic modes.

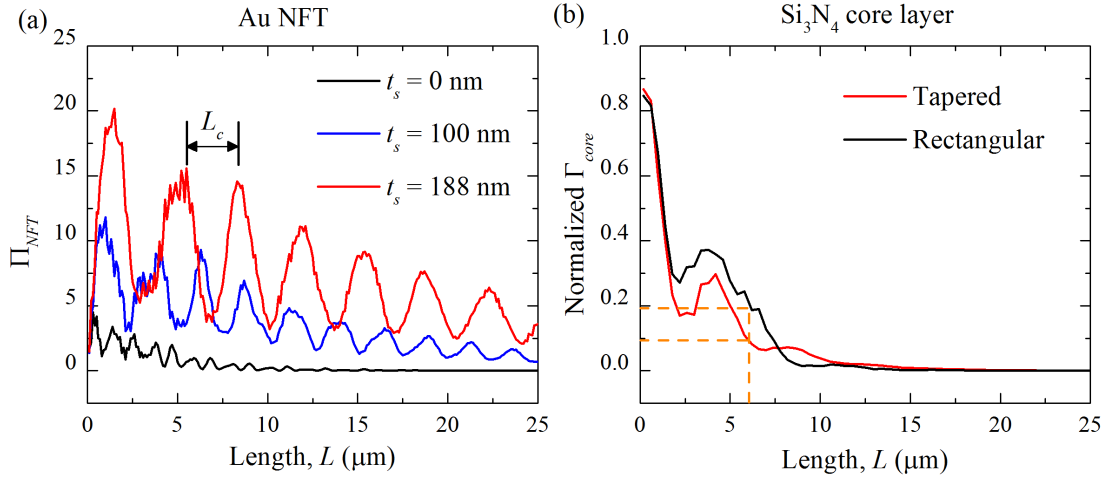


FIGURE 5.9: (a) The field intensity enhancement factor in the NFT at different values for the spacer layer thickness (t_s). The ratio shown is the output port of the Au layer against the input port (two blue dots in Figure 5.7(a)). The curves exhibit the expected exponential decay as well as oscillations corresponding to the coupling length (labelled L_c in (a)). (b) Ratio of electric field intensities in the core Si₃N₄ layer (intensity at the cross-section of the end against the start, dashed-black line cross the vertical direction of core layer in Figure 5.7(a)) for two different Au structures (a tapered NFT and an un-tapered rectangle). Because Si₃N₄ is modelled as a lossless material (*i.e.*, the refractive index is purely real), any change in optical intensity must be due to coupling from the starting photonic mode into the plasmonic mode, which is concentrated at the tip. The data shows that the tapered case extracts the light more efficiently.

The distance between the peaks of the oscillations curves seen in Figure 5.9(a) is known as the coupling length L_c [190], which is defined as

$$L_c = \frac{\lambda_0}{2} \left| \frac{1}{n'_p - n'_d} \right| \quad (5.5)$$

where n_p and n_d are the effective indices of the particular plasmonic and photonic modes that have been coupled, respectively. In our evanescent coupling system, the coupled $n'_p = 1.71$ and $n'_d = 1.59$, corresponding to a theoretical coupling length of $L_c = 3.54 \mu\text{m}$, while the simulated coupling length (shown in Figure 5.9(a)) is $L_c = 3.63 \mu\text{m}$.

When the spacer layer is at its optimized thickness (where $t_s = 188 \text{ nm}$), the value of Π_{NFT} is highest, which is needed in the Au NFT to achieve efficient nanofocusing at the tip (should be noted is that the field distributes at the interface of the NFT and the spacer layer rather than the Au NFT layer itself). The curves at other thicknesses ($t_s = 0 \text{ nm}$ and 100 nm) demonstrate the importance of correctly designing the spacer layer in the previous steps. When the taper is short, very high enhancement factors can be achieved (Π_{NFT} is found to be ~ 40 when $L = 2 \mu\text{m}$). Selecting a length value where the curve is at a maximum allows the use a very long taper ($L > 5 \mu\text{m}$) for increased coupling efficiency while still maintaining the nanofocusing effect. For example, a field enhancement factor of 10 can still be achieved when the length of the taper is $15 \mu\text{m}$ (the propagation length of the plasmonic mode in a semi-infinite Au-SiO₂ and Au-air interface at $\lambda_0 = 850 \text{ nm}$ is $L_{spp} = 18 \mu\text{m}$ and $L_{spp} = 60 \mu\text{m}$, respectively). However, the propagation length of the hybrid photonic-plasmonic mode in the five-layer stack at the same wavelength is $130 \mu\text{m}$ (see Figure 5.3 for more of the SPP propagation length in different layer structures [191]). This shows the usefulness of the evanescent coupling method – the propagation length of the plasmonic mode is not constrained by the lossy Au itself, as the beating between photonic and plasmonic modes can effectively extend the propagation length of a purely plasmonic mode. The mode coupling efficiency (Γ_{core}) is determined by measuring how much light is taken out of the lossless dielectric layers, because it is assumed that any light lost in the core layer is being coupled to the plasmonic mode, not dissipating through absorption. The coupling efficiency between the photonic mode to the plasmonic mode Γ_{core} ($0 < \Gamma_{core} < 1$) is calculated by using the integrated absolute square of the electric field in the cross-section of the input port (Figure 5.7(b)) divide the output port (Figure

5.7(c)) of the entire core layer, it is using the formula

$$\Gamma_{core} = \frac{\int |E_{out.core}|^2 \partial y \partial z}{\int |E_{in.core}|^2 \partial y \partial z} \quad (5.6)$$

$E_{out.core}$ and $E_{in.core}$ are the fields at the output port and the input port of the Si_3N_4 core, respectively. All the power in the core layer needs to be calculated to qualify the coupling efficiency between the photonic mode and the plasmonic mode. The intensity in the output and the input of the core layer is a surface integration intensity in the y - z plane. The oscillation of curves in Figure 5.9(b) shows mode coupling between the photonic mode and the plasmonic mode. In the simulation, light is incident from the entire height of the left-hand side (*i.e.*, all layers are illuminated together). Figure 5.9(b) shows the results of a parametric sweep of the length of the tapered NFT and the rectangular (un-tapered) layer. Each point in Figure 5.9(b) indicates the length of the sample studied rather than the physical distance along the waveguide. The coupling efficiency in Figure 5.9(b) can be described as shown in equation 5.6. It can be observed that the power decays exponentially in the Si_3N_4 core layer of the waveguide with both structures; when $L = 6 \mu\text{m}$, the horizontal dashed lines show that 80.6% of the intensity is absorbed for the Au rectangular strip and 90.8% for the Au NFT, meaning that a significant amount of the original light can be removed from the waveguide even for a relatively moderate NFT length. Noting that we want to maximize this value (which corresponds to bringing light into the NFT layer and removing light from the end of the waveguide), it is clear that the tapered structure performs better at moderate lengths, which is somewhat unexpected because the rectangular structure might have a better coupling efficiency due to its lateral surface having twice the area. This can be understood in the context of mode beating: n_{eff} changes along the length of the taper (which can be seen in Figure 5.6(a)), but does not change in the rectangular case. In the limit of a very long taper, both curves trend towards 0. The intensity needs to be minimized at the ends of the lower dielectric layers (SiO_2 and Si_3N_4) when used in a HAMR system to prevent interference with the magnetic medium or the light source. As before, optimizing the spacer layer thickness gives higher intensity enhancement in the NFT, but the goal is to reduce the intensity in the core layer to a minimum. Table 1 lists the intensity enhancement factor in the NFT and percentage of the intensity distribution in three different simulation domains as the thickness of the spacer layer is varied (the light distribution is calculated in 3-D simulations which can cover the light in the whole simulation domains): the intensity in the NFT tip is calculated by

TABLE 5.1: Intensity enhancement in the NFT (Π_{NFT}) and percentage of the intensity distribution in different simulation domains for a 6 μm long NFT when the thickness of the spacer layer is varied. In each case, the excess intensity is in the air or substrate layer.

$t_s(\text{nm})$	Π_{NFT}	NFT	Spacer layer	Core layer
0	0.8	1.04%	0%	12.70%
100	7	17.80%	10.60%	19.20%
188	16	57.80%	23.70%	2.90%

integrating the intensity in a $500 \times 500 \times 90 \text{ nm}^3$ cube that is 20 nm above and below the upper (air/Au) and the lower (SiO_2/Au) interface of the NFT in the z direction and it determines the intensity of the SPP modes in the lower and the upper interface of the NFT (details concerning the volume integration in the 3-D simulations can be seen in Figure 5.10).

At the optimal thickness of the spacer layer ($t_s = 188 \text{ nm}$), 57.8% of the light distributes in the upper and the lower interface of the tip of the NFT and the corresponding $\Pi_{NFT} = 16$ which is the highest value, a lower value of 17.8% is achieved when $t_s = 100 \text{ nm}$, which results in a lower $\Pi_{NFT} = 7$. The percentage of intensity in the spacer layer counts the strength of light been transferred from the core layer to the NFT, 23.7% and 10.6% are obtained when $t_s = 188 \text{ nm}$ and $t_s = 100 \text{ nm}$, respectively; It shows that the spacer layer with an optimal thickness can effectively increase the coupling efficiency between the plasmonic mode and the photonic mode. Any light in the core layer will cause potential miswriting on the recording media, it needs to be minimized (only 2.90% remaining in the core layer when $t_s = 188 \text{ nm}$). By properly designing the length of the NFT, a local minimum intensity in the dielectric layer (spacer layer and core layer) and a maximum in the NFT tip can be achieved.

5.4 Experimental demonstration

5.4.1 Measured samples

Figure 5.11(a) shows SEM images of one of the taper (above) rectangle (below) pairs that were fabricated. The width of a single NFT tapers linearly inward with respect to the position along the centre x axis, starting at $w_s = 1 \mu\text{m}$ and going to $w_t = 50 \text{ nm}$ at the tip. The structures were identified by their length

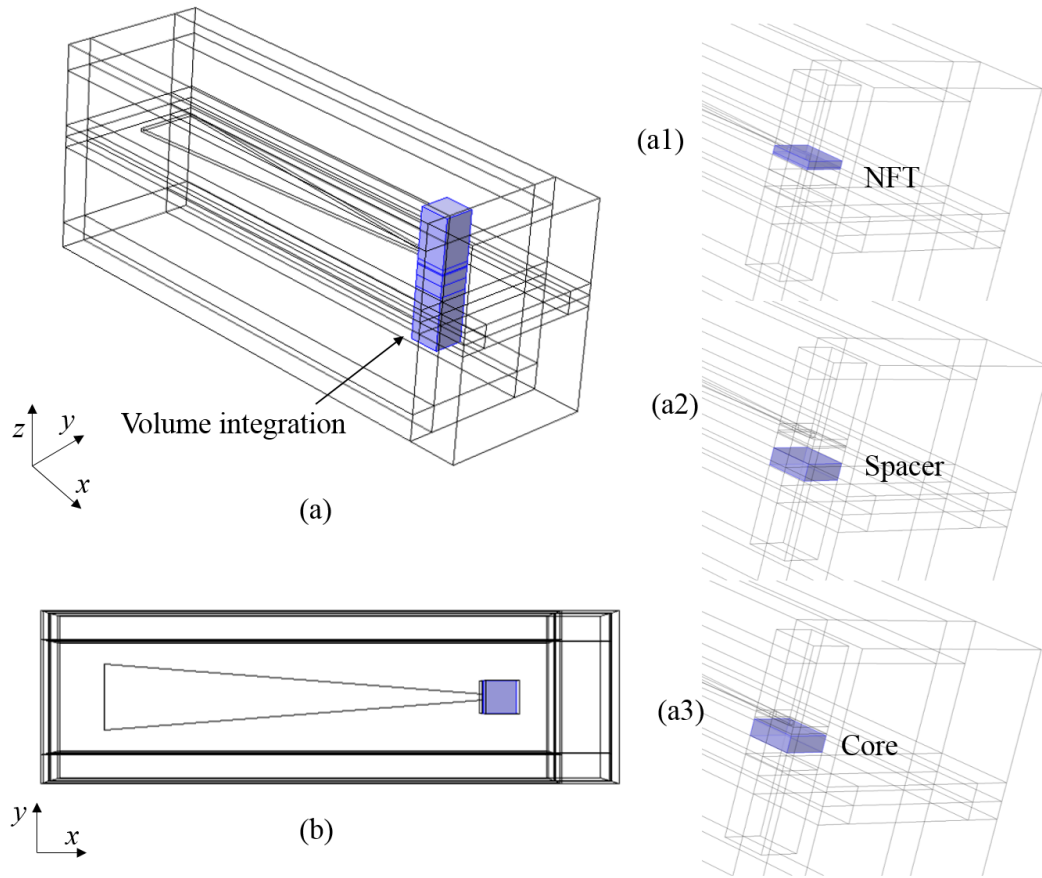


FIGURE 5.10: (a) Schematic diagram of the volume integration used in the simulations. (a) The total integration volume size along x , y and z direction is $500 \times 500 \times 2100 \text{ nm}^3$ which covers all the simulation domain at the output port of the NFT. In particular, the integration volume for calculating the intensity at the tip of the NFT is $500 \times 500 \times 90 \text{ nm}^3$ in size which can be seen in the panel (a1), it is 20 nm above and below the upper (air/ Au) and the lower (SiO_2/Au) interface of the NFT (thickness of Au is 50 nm) in the z direction which determines the intensity of the SPP modes in the lower and the upper interface of the NFT. The actual width of the tip is 50 nm, however the far-field measurement collects the scattered light which has an area larger than $50 \times 50 \text{ nm}^2$, the $500 \times 500 \times 2100 \text{ nm}^3$ integration size in the x and y directions allows the scattered light from the lateral side of the NFT to be taken into account. The highlighted blue cubes in panel (a2) and (a3) are the actual integration volumes for the spacer layer and core layer respectively. (b) Top view of the integration volume. It is a $500 \times 500 \text{ nm}^2$ in size in the x - y direction.

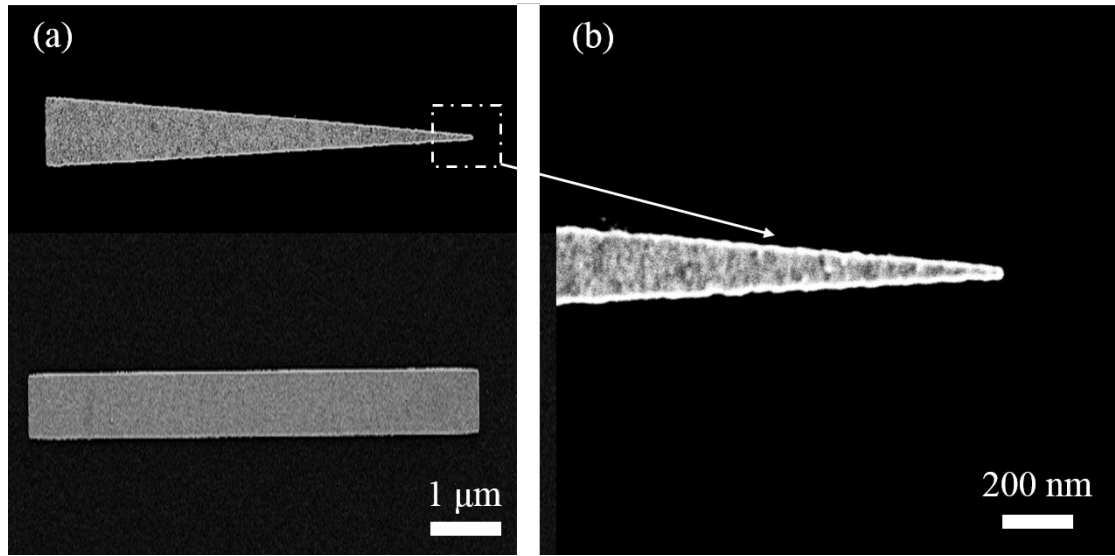


FIGURE 5.11: (a) SEM images of the tapered Au sample and the rectangular Au sample (the structures fabricated for characterization are much farther apart than what is shown here). (b) Image showing the tip of the tapered NFT, which is 50 nm wide in all structures.

(L), which went from 2 μm to 24 μm in steps of 2 μm . Six groups of structures, with 12 tapers and their corresponding rectangular strips in each, were prepared to repeat the measurements. Figure 5.11(b) is a zoomed-in image of the region marked by the white box in Figure 5.11(a) to show that ~ 50 nm tips were fabricated.

The wafer layer structure used in this work is shown in Figure 5.1. The core is a layer of Si_3N_4 on a 2 μm thick SiO_2 layer on a silicon substrate. The thickness of the Si_3N_4 is 180 nm which only supports the fundamental TM and TE modes at the input light wavelength of $\lambda_0 = 850$ nm. A 188 nm thick SiO_2 spacer layer was deposited directly on the Si_3N_4 layer through a magnetron sputtering system. The flat edge opening for coupling of the incident light was fabricated by patterning a rectangular trench through a UV lithography system. The Au taper was patterned by electron beam lithography (EBL). Since the dimensions of the NFT varied from 24 μm (the largest L value) to 50 nm (the nominal width of the tip and the layer thickness) the EBL process had to be carefully optimized [192]. The detailed fabrication procedures were provided in Chapter 3.

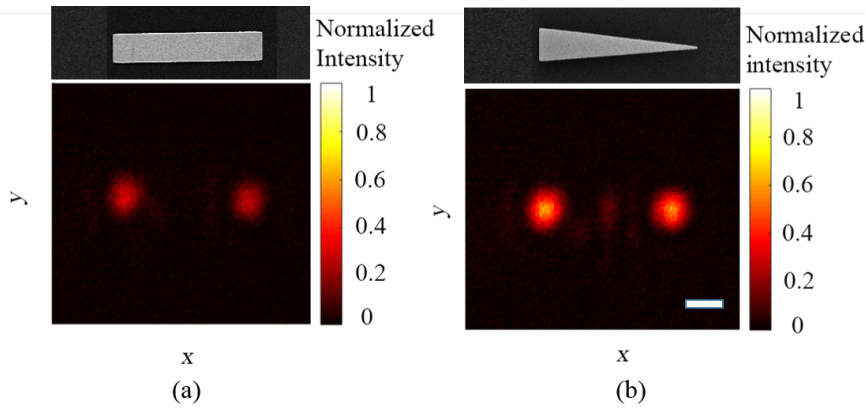


FIGURE 5.12: Experimental results and SEM images for (a) a $6\ \mu\text{m}$ long rectangular reference and (b) a tapered structure with the same length. The scale bar is $2\ \mu\text{m}$ and applies to both panels. The exposure time was the same in both measurements. Bright spots appear at the start (left) and end (right) of these structures. The colour bar, which is normalized to the maximum in both images (the centres of the dots in (b)), indicates the strength of the scattered light from the structure. This figure shows that the strength of the intensity in the tip of the taper is at least of 2 times higher than that in the rectangle, and that there is a nanofocusing effect occurring in the tapered NFT.

5.4.2 Optical far-field measurements and results

Each taper is characterized in a single CCD image and the exposure time is adjusted manually for each image to avoid over-exposure. The CCD images were captured with a $40\times$ objective lens ($\text{NA} = 0.6$) with a long working distance. The power in the start and tip of the taper are obtained by integrating the intensity in a 30×30 pixel square in the CCD images, which is shown in the dashed-white square in Figure 5.13(a). The input and output power of the structures are obtained by integrating the scattered intensity of the CCD images. Because changing the exposure time from sample to sample introduces a new variable, this will be factored out by using the same integration time for each taper-rectangle pair and normalizing the data against the rectangular case. The samples were characterized by coupling the TM-like wave to the NFT from the opening trench. An example of one group of taper and rectangular samples is shown in Figure 5.12. It shows that the strength of the intensity in the tip of the taper is at least of 2 times higher than that in the rectangle, and that there is a nanofocusing effect occurring in the tapered NFT.

Figure 5.13(a) shows the measured results of 3 tapers with the length of 6

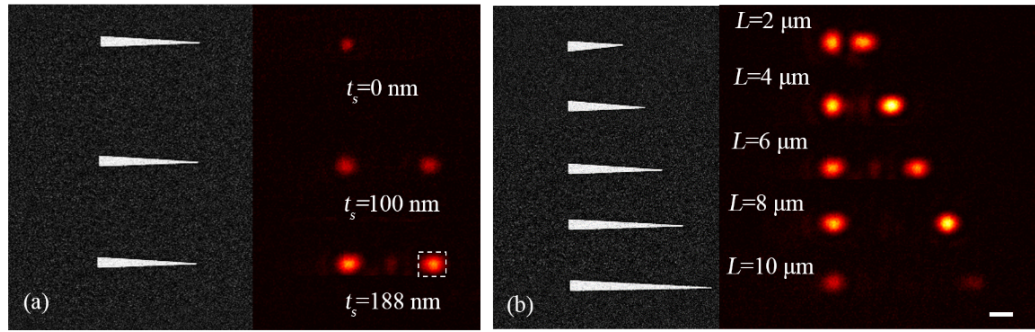


FIGURE 5.13: Left side of panel: SEM images; right side of panel: corresponding far-field CCD measurements. (a) Measured results of the $L = 6 \mu\text{m}$ sample with a variable spacer layer thickness ($t_s = 0 \text{ nm}$, 100 nm , and 188 nm from top to bottom). (b) Measured results of the samples with an optimal spacer layer (188 nm), at different lengths. The light is incident from the left side. The scale bar is $2 \mu\text{m}$ for all four images. Note that the structures were much farther apart than this ($30 \mu\text{m}$) on the actual sample. (c) Intensity enhancement factor for the Au layer for the tapered (Π_{NFT} , intensity at start against intensity at end) and rectangular (Π_{rect}) cases. The data is both experimental (red circles, with error bars) and simulated (black squares). Each curve was normalized against its highest value (which happened to be at $L = 6 \mu\text{m}$ for both) to show the strong correlation between the data sets. The excellent agreement between the different methods confirms the validity of our analysis.

μm , the thickness of the spacer layers are $t_s = 0 \text{ nm}$, 100 nm and 188 nm , respectively. The discontinuity of the effective refractive index between the photonic core and Au NFT will result in scattering when the evanescent field couples to the Au taper and excites the plasmonic mode, which will result in bright spots at the start (left end) of the structures [185]. The light is barely able to couple into the Au taper if there is no spacer layer ($t_s = 0$) and no enhancement appears in the tip because of the loss in metal, which shows a good agreement with the discussion from Figure 5.9(a) (the NFT with 188 nm spacer layer has the highest intensity enhancement factor – the experimental data for this thickness is in Figure 5.13(b)). The intensity enhancement factor in the tip of the taper with a 188 nm spacer layer is ~ 7 times higher than with a 100 nm spacer layer.

Far-field measurements were used to characterize the field enhancement factor of the Au taper. We can visually see the mode beat behaviour from Figure 5.13(b). The intensity in the tip of the NFTs is varying with different L . Figure 5.13(c) shows the data after normalization by using the field enhancement factor in each Au taper divided by the corresponded rectangular Au strip reference sample, then normalized against the maximum value of each curve. The two sets of data are remarkably similar; both of them exhibit the highest enhancement factor when the length of the taper is $L = 6 \mu\text{m}$. However, there are two distinct bright spots when $L = 4 \mu\text{m}$ and $8 \mu\text{m}$. We show note that the optimal length after the normalization which has been taken into account the effect of the rectangular Au strip. The data after the normalization won't show the mode beating behaviour and it is only used to validate of our far-field approach. The Ti adhesion layer can cause some error (it was not included as a layer in the simulations), but the effect is generally small in structures with tens of micrometres in length [193]. Note also that the two curves are different in the sense that the experimental results can only collect light scattered at the tip over a specific solid angle, while the simulations can collect all of the scattered light.

We can visually see the mode beat behaviour from Figure 5.13(b). Apart from the 10 micron case, all the tapers show a strong enhancement and this should be compared with the modelling results in Figure 5.9(a). A taper length of 10 microns in both the modelling and the experimental results shows a small enhancement due to the mode beating effect. The experimental data after normalizing with the input of the taper is overlapped with the simulated data which can be seen in Figure 5.13(b). The optical field enhancement happens

when L is an integral multiple of the coupling length. $L = 8 \mu\text{m}$ has a higher optical field enhancement than $L = 6 \mu\text{m}$, but $L = 8 \mu\text{m}$ is not an optimal length for the thermal performance. Looking at Figure 5.9 (a), we can see that $L = 10 \mu\text{m}$ is a local minimum and in Figure 5.13(b), we see this clearly in the experimental results. The experimental data show better agreement with the theory when the tapers are long. The Ti adhesion layer can cause some error (it was not included as a layer in the simulations), but the effect is generally small in structures with tens of micrometres in length [193]. Note also that the measurement and theory are different in the sense that the experimental results can only collect light scattered at the tip over a specific solid angle, while the simulations can collect all of the scattered light. Nevertheless, the data shows reasonable agreement and validates our approach. Although the 6 micron taper does not have the largest enhancement, we have chosen this particular length for ease of measurement in the results in Figure 5.13(b) and also as a length that will effectively reduce the power remaining in the core at its end.

5.5 Chapter summary

In conclusion, we theoretically and experimentally demonstrated a NFT which can achieve nanofocusing of light. An optimal thickness of 188 nm SiO_2 spacer layer can effectively transfer over 90.8% of the light in a 180 nm thick Si_3N_4 core waveguide to a tapered Au NFT. An evanescent coupling system with hybrid waveguides was applied, the mode beating between the plasmonic mode and the photonic mode contributed to an enhancement factor of $16\times$ on the Au tapered NFT over $6 \mu\text{m}$ in length, which is a huge advantage over tapers that are only several hundred nanometres in length, partially due to the easier fabrication process, and better heat dissipation. The results are shown here allow a path to use a longer NFT to collect the light more efficiently while not losing too much energy to ohmic heating when the optical path length is increased, which can be helpful in the fabrication of commercial HAMR devices. The field enhancement factor found experimentally after normalization with a rectangular Au strip reference sample has a good agreement with the 3-D simulations in COMSOL which proved the validity of the far-field measurements. The systematic study of the optimal designed evanescent coupling system provides helpful insights about the operation mechanism and performances as well as the strategies for the design of an efficient NFT in a HAMR system.

Chapter 6

Approaches to Improving the Plasmonic Performance of Au Thin Film

Gold (Au) is by far the most commonly used metal for plasmonic applications, due to its chemical stability and biological compatibility. The physical properties of Au however, are far from ideal. Au is a soft metal with a tendency to diffuse and dewett at relatively low temperature, and is poorly adhered to most oxide interfaces. The thermal stability of Au currently limits its use in photonic devices that operate at elevated temperature or with high optical powers. Au has relatively high optical absorption due to interband transitions in the visible wavelength range. Ag and Cu are other commonly used plasmonic metals in the UV-visible and near-infrared (NIR) ranges respectively. Ag has lower imaginary part of the permittivity at visible wavelength range than Au which is responsible for lower SPP losses, however it suffers more from diffusion and tarnishes easily in air. Cu is a promising material for plasmonic applications in the NIR and C-Band, however it has a strong absorption in the visible wavelength range due to interband absorption. Deposition techniques on common substrates such as SiO₂ and Al₂O₃ use an adhesion layer. However, the plasmon damping is exacerbated by the ultrathin adhesion layer that uses metals such as titanium (Ti) and chromium (Cr) due to interface damping.

In HAMR, an Au NFT is designed to focus the light to a spot size smaller than the diffraction limit, and a high electromagnetic field of the focused spot will transfer to the magnetic storage medium and get absorbed, which will raise the temperature of the medium locally for data recording [194]. The NFT's temperature significantly increases as the recording process occurs. The performance of NFTs is greatly influenced by the heat and mechanical stress during HAMR operation. Au has a relatively low mechanical strength and the Au

NFTs may experience dewetting at elevated temperatures resulting in a deformation in shape of the NFT. This can impact the coupling efficiency and reduce the amount of light energy transferred to the storage medium. It has been widely acknowledged that high temperature is the root cause of the HAMR head premature failure and low-reliability [194]. It would be desirable to have a NFT device that would be more durable for repeated HAMR operations.

In this work, we investigate three techniques aimed at improving the plasmonic performance and thermal stability of thin Au plasmonic film for the design of NFTs. The first is to investigate layered thin films composed of Au, Ag and Cu. We show that this allows us to tune the optical properties of the thin film, while maintaining thermal stability. The second approach investigates the use of a thin adhesion layer, and studies their effect on the plasmonic performance. Finally, we investigate the effect of a thin capping layer of aluminum oxide on the films to further reduce surface diffusion and stabilize the Au films.

6.1 Introduction

Different classes of materials have been explored for plasmonic and metamaterial applications, including noble metals [195], aluminium [196], silicon carbide [197], doped semiconductors [198], and 2D materials such as graphene [199–201]. If there is an option to arbitrarily modulate the dielectric function of metallic structures, this would enable unprecedented control of the behavior of SPP in plasmonic structures. This, in turn, would allow for the development of a new class of metallic materials with a tunable optical response for the optoelectronic devices with unique properties, such as a small imaginary part of the dielectric function is needed for designing [198] low-loss plasmonic devices. Conversely, in the design of photovoltaic cell or hot carriers, metal with a high light absorbing efficiency is required [202]. The SPP properties of noble metals Ag and Au have been extensively explored throughout the visible and near-infrared wavelength range. There are still considerable limitations for the design of plasmonic waveguides by using noble metals which is related to their fixed optical constants. Moreover in real-world practical applications of plasmonic devices require them to be compatible with industry standard fabrication processes, such as the complementary metal-oxide-semiconductor (CMOS) technology, which allows low-cost fabrication process of high yield plasmonic structures. Moreover, their integration with electronic logic and on-chip photonics devices are essential to meet real-life applications. Aluminum(Al) is

CMOS compatible and is widely used in microelectronics [196]. It was believed to be too lossy for practical applications for decades, however it was recently demonstrated that, unlike Ag and Au, aluminum has material properties that enable strong plasmon resonances in the ultraviolet wavelength range and consequently has a very high plasma frequency, it is superior to noble metals in the ultraviolet [203] and most importantly, it is a third most abundant element in Earth's crust, more than Au and Ag [204]. These properties make Al a highly promising material for commercial applications. It also shows reasonable SPP propagation lengths in Si-based plasmonic waveguides platform [205]. However, in the infrared wavelength range, Al cannot provide the same level of SPP mode confinement as Au and Ag [206]. Copper (Cu) which is known to have a plasma frequency very similar to that of gold ($\sim 1.33 \times 10^{16} \text{ s}^{-1}$). However, the implementation of Cu in plasmonic circuits was seriously restrained by the high ohmic losses, resulting in very short SPP propagation lengths in the waveguides [205]. In order to develop a plasmonic waveguide which could meet a variety of applications, it is worth taking advantage of the merit of each available plasmonic metal. One aim of this chapter is to investigate the possibility of obtaining a combined Au, Ag and Cu metallic film with tunable SPP performance.

6.2 Combined Au, Ag, Cu film

6.2.1 Optical reflection measurements

The previous study in Chapter 4 shows that the Ag and Au bi-layer structure with a varied proportion for each metal have tunable dispersion property. The bi-layer film has a longer propagation length and sharper SPP resonance than the individual Au film which provides a good opportunity for bi-layer structure in the application of plasmonic waveguiding or bio-sensing. Recently, the development of an alloy for plasmonics from a binary mix Au-Ag [207] and Au-Cu and Au-Pd [208] alloying composition also show improved optical performances. Alloying of different materials is an important tool that can enrich the use of metals, it is a very promising and important for engineering of the required optical response.

Figure 6.1 shows a colour map of experimentally obtained Drude parameters [210]. ω_p is related to the density of free electrons. It corresponds to the plasmonic resonance wavelength. Larger plasmon frequencies (corresponding

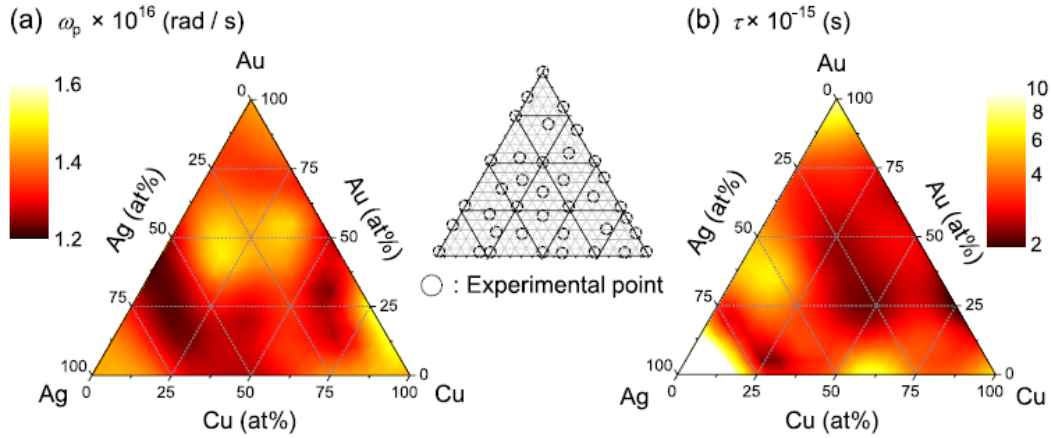


FIGURE 6.1: Interpolated ternary plots of experimentally obtained Drude parameters for Au, Ag and Cu combined structures. (a) Plasma frequency ω_p and (b) relaxation constant τ . Middle inset indicates the atomic ratios in the experimental measurements. Figures are adapted from [209].

to higher electron densities) can be obtained at the middle point of Au, Ag and Cu alloy (Figure 6.1(a)). On the other hand, τ represents the relaxation time of free electron oscillation. This parameter correlated with the quality factor of a plasmonic resonance which is related to the electromagnetic field enhancement. Table 6.1 lists the samples for investigation, they include Au, Ag and Cu individual film, binary mixed bi-layer film and tri-layer combined films. It should be emphasized that the total thickness of the film is 50 nm and the outside layer is Au for all the samples due to its chemical stolidity. Owing to that 50 nm is an optimal thickness of the film for plasmonic structures. The outside Au layer is working as a capping layer to avoid the oxidization of the Ag and Cu layers which has been discussed in Chapter 4 [191]. The thickness of the spacer layer in Table 6.1 is for the NFT design which will be used in an evanescent coupling system. A detailed mechanism of the evanescent coupling process has been discussed in Chapter 5. Two different wavelengths of the incident light are discussed (850 nm and 532 nm), and it can be seen that the combined films show tunable properties of the field enhancement factor at 532 nm.

Figure 6.2(a) shows the reflection of Au, Ag and Cu bi-layer and tri-layer films with a normal incident angle. The reflection for the individual Au and Ag film is also plotted. Ag has a high reflection in the wavelength range from 400 nm to 500 nm which shows a low loss of the plasmonic modes. The Ag-Cu-Au tri-layer film has a higher reflectivity than the Au individual layer and Au-Ag bi-layer which indicates a lower SPP loss. Thermal annealing was performed

TABLE 6.1: List of samples. The data consists of Au, Ag and Cu individual, bi-layer and tri-layer combined films. The value of the thickness of the spacer layer is used for the NFT design in an evanescent coupling system.

Layer structure	Thickness	$\lambda_{Excitation} = 850 \text{ nm}$	$\lambda_{Excitation} = 532 \text{ nm}$
Au	50 nm	188 nm	100 nm
Ag	50 nm	170 nm	105 nm
Cu	50 nm	185 nm	84 nm
Ag-Au	25 nm - 25 nm	182 nm	110 nm
Cu-Au	25 nm - 25 nm	195 nm	67 nm
Cu-Ag-Au	20 nm - 20 nm - 20 nm	187 nm	100 nm

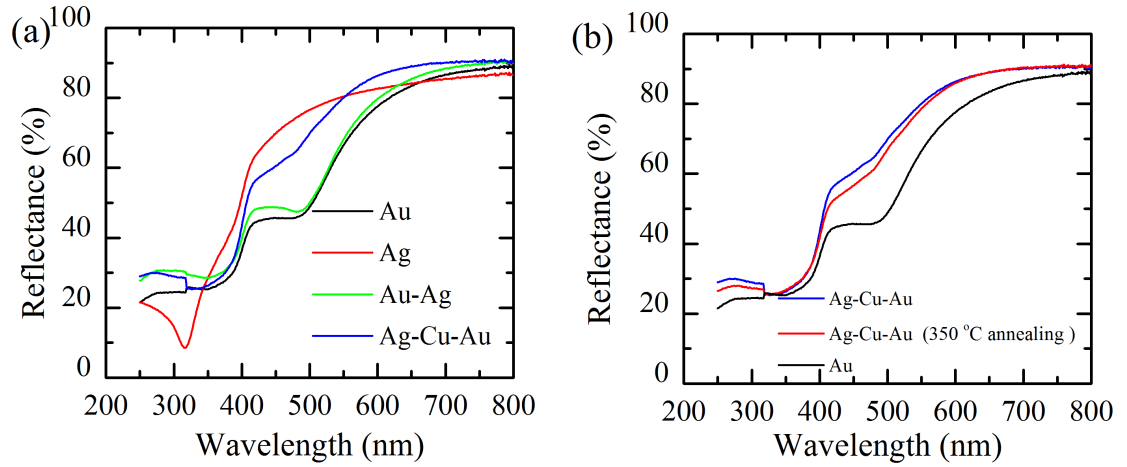


FIGURE 6.2: (a) Optical reflection measurements with a normal incident angle for the individual layer and combined layers. (b) The optical reflection of the Ag-Cu-Au tri-layer before and after an annealing process (350 °C for 30 minutes). The reflection of individual Au film is also plotted

with a nitrogen environment at 350 °C for 30 minutes on the Ag-Cu-Au tri-layer sample, Figure 6.2 (b) shows the reflection of the tri-layer sample before and after the annealing process. It shows after the annealing process the reflection in the wavelength from 400 nm to 500 nm decreases slightly, with the value of $\sim 20\%$. Future work related to annealing allows making Ag-Cu-Au alloy which is determined to improve the robustness of the film.

6.2.2 Field enhancement factor simulation

The mechanism of the NFT design has been discussed in detail in the previous chapter, here, we are aiming at investigating the possibility of using the

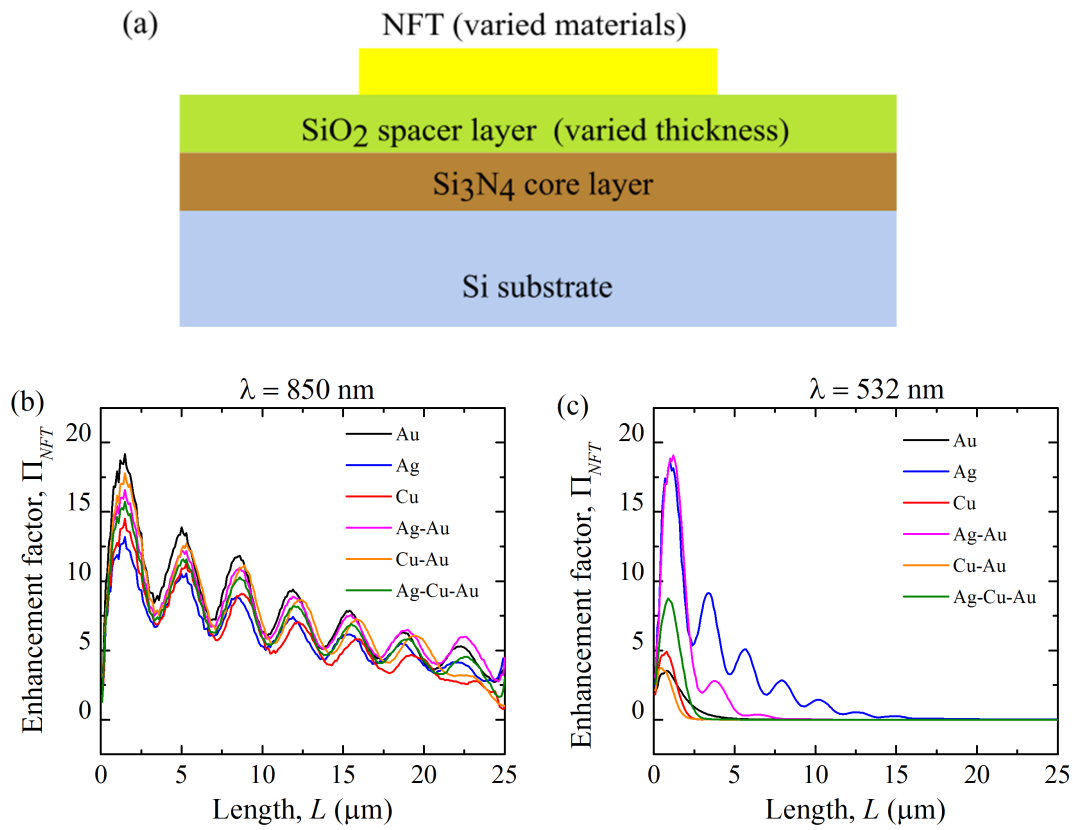


FIGURE 6.3: (a) Schematic diagram of the evanescent coupling system. (b) and (c) Simulated field enhancement factor of the NFTs which are formed with different materials at the excitation wavelengths of 850 nm and 532 nm, respectively.

multilayer structures as an alternative plasmonic material for the NFT design with improved stability. The field enhancement factor of the NFT with a variable combination of the metal are discussed. Figure 6.3(a) shows the evanescent coupling system which is used in the COMSOL model to simulate the nano-focusing process in the NFTs. All the samples listed in Table 6.1 are tested, and the thickness of the spacer layers are varied with different materials and the excitation wavelength. The thickness of the Si_3N_4 core layer is fixed at 180 nm. Two different wavelengths are used for the excitation (850 nm and 532 nm), which provide two examples of the SPP to be excited in the near-infrared and visible wavelength ranges.

Figure 6.3(b) shows the enhancement factor of the NFTs which are formed by six different metallic films at an excitation wavelength of 850 nm. The individual Au film has the highest value of the field enhancement factor, Ag has the lowest value and the Cu has the field enhancement factor value between Au and Ag individual films. For the composite films, both bi-layer and tri-layer, any film with a proportion of Au has a higher field enhancement than the individual Ag or Cu film. The combination of Cu and Au has the similar field enhancement as individual Au film owing to the closed permittivity of Au ($\epsilon = -28.269 + 1.746i$) and Cu ($\epsilon = -29.297 + 2.995i$) [94] at the wavelength of 850 nm (the permittivity of Ag at this wavelength is $\epsilon = -35.585 + 0.4772i$). Interesting results are found at the excitation wavelength of 532 nm which can be seen in Figure 6.3 (b). In contrast to 850 nm, Ag has the highest enhancement factor among the three different metals (Au, Ag and Cu) while Au is the lowest, partly because 532 nm is close to the interband transition wavelength of Au which is at 470 nm [211]. The Ag-Au bi-layer has nearly the same magnitude of the field enhancement (~ 20) as the individual Ag film which shows it is a good combination for the NFT design at the excitation wavelength of 532 nm. The results in Figure 6.3 provides valuable information for the design of the NFT by using combined metallic films.

6.2.3 Dispersion relations for Au, Ag and Cu combined layers

The varied field enhancement factor of the NFTs with Au, Ag and Cu combined films can be considered to result from the tunable dispersion properties of these films. Figure 6.4 shows the dispersion curves of the six different films by solving the eigenvalue solutions of the related layer systems, the detailed theoretical foundation was described in Chapter 2. Both the symmetric mode L_- (Figure 6.4(a)) and the anti-symmetric mode L_+ (Figure 6.4(b)) are plotted.

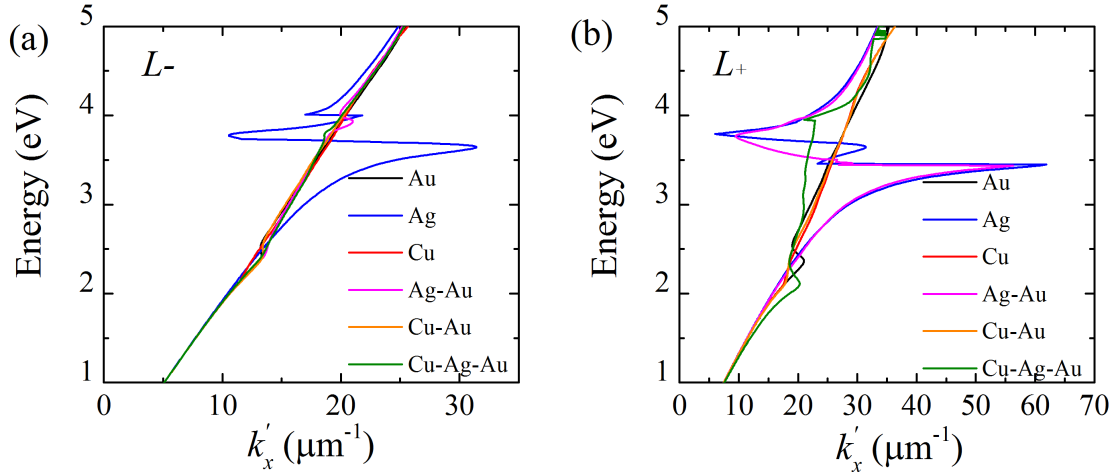


FIGURE 6.4: Analytical dispersion curves of the individual, the bi-layer and tri-layer films obtained by solving the eigenvalue solutions of the related layer structures. Panels (a) and (b) show the symmetric mode (L_-) and the anti-symmetric mode (L_+) respectively.

Ag has a high k (optical momentum) value for in both the L_- and L_+ modes which shows a high degree of modal confinement. The closeness of the Au and Cu permittivity values contribute to the nearly identical dispersion curves for the L_- mode which can be seen in Figure 6.4(a). The individual film and combined films show more distinct dispersion properties of the L_+ mode which can be seen in Figure 6.4(b). The Ag-Au bi-layer has the similar dispersion curve as the individual Ag film. The interesting property of the Ag-Cu-Au combined tri-layer can shift the plasmonic resonance wavelength, which is a useful parameter for the design of the plasmonic waveguide, since the size of the plasmonic waveguide is related to the input excitation wavelength and the plasmonic resonance wavelength of the metal been used [158].

The SPP can be excited through a prism coupling mechanism, this process can be simply simulated through the transfer matrix method. Figure 6.5 show the SPP reflection of the six types of samples as a function of the excitation angles which is calculated through the transfer matrix method. The colour scale indicates the strength of the SPP reflection. The blue and the red areas indicate a low reflection and a high reflection respectively in all panels of Figure 6.5, respectively. Figures 6.5 (a) – (f) are related to the Au individual layer, Cu-Au bi-layer, Cu individual layer, Ag-Au bi-layer, Ag individual layer and Ag-Cu-Au tri-layer films respectively. Au and Cu have wide SPP resonance and large damping especially in the wavelength range from 495 nm to 275 nm (2.5 eV to

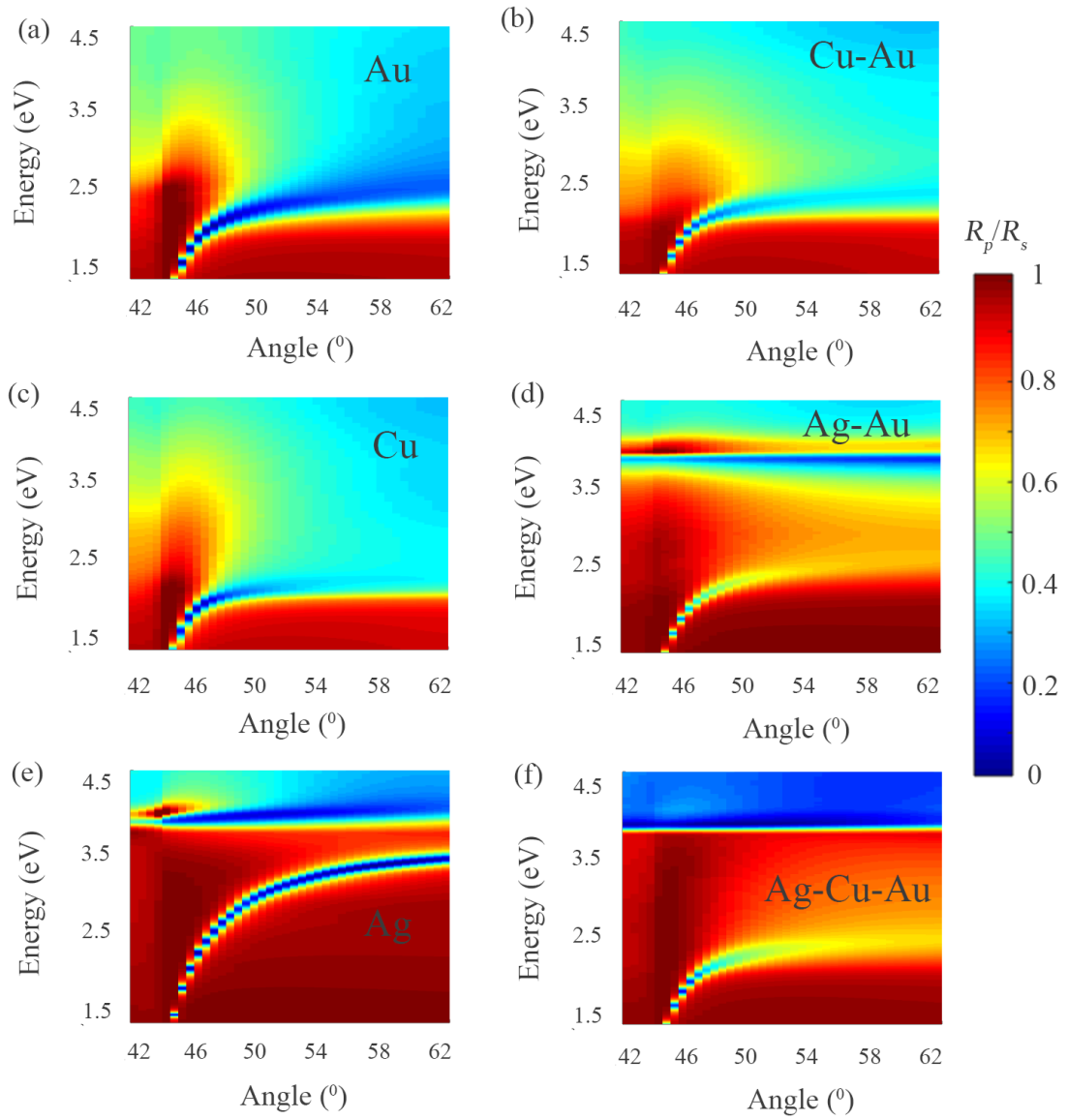


FIGURE 6.5: Simulated SPP reflection as a function of the excitation angles. The value of the reflection are the ratio of the R_p (reflection with a P mode excitation) and R_s (reflection with a S mode excitation) which can normalize the data. The panels are related to the 6 types of layer combinations which are (a) Au individual layer; (b) Cu-Au bi-layer; (c) Cu individual layer; (d) Ag-Au bi-layer; (e) Ag individual layer; (f) Ag-Cu-Au tri-layer films. The colour scale in all the panels indicates the strength of the reflection.

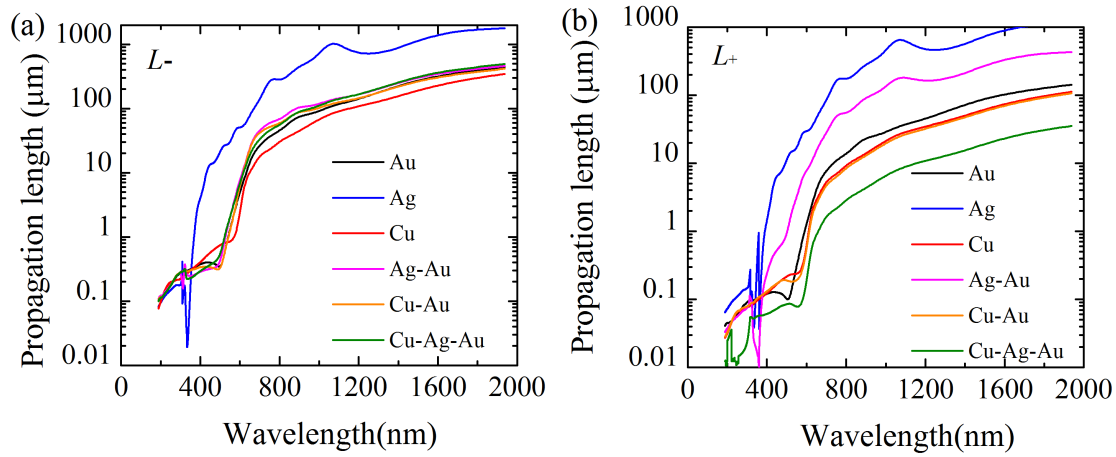


FIGURE 6.6: Analytical propagation length of the individual film, the combined bi-layer and tri-layer films with is proportional to the imaginary part of the k (wavevector) value. Both the L_- mode (a) and the L_+ mode (b) are plotted.

4.5 eV) which can be seen in Figures 6.5(a) and (c). Ag has a narrow and sharp SPP resonance and low damping well below 3.5 eV and the plasmonic bandgap also can be seen clearly in Figure 6.5(e). Regarding the combined films, they are sharing the properties of each individual layers. All the combined films have a narrow SPP resonance owing to the presence of the Ag, this noticeable feature indicates the combined films have more controllable SPP properties than the individual films.

In addition to a narrow SPP resonance, another interesting feather of the SPP reflection for the Ag-Cu-Au tri-layer is the strong coupling (low reflection) as the excitation wavelength is above 3.6 eV. It can be seen in Figure 6.5 that there is a large low reflection area when the excitation wavelength is above 3.6 eV which can be explained as the large refractive index of the metal in that wavelength range. The refractive index of prism is 1.45, and the refractive index of Au, Ag and Cu is above 1.5 when the wavelength is smaller than 344 nm (3.6 eV) and which in turn most of the light will transmit through the metal films [212].

The analytical propagation length of the SPP modes is proportional to the imaginary part of the k value, and the curves related to the L_- and L_+ modes are plotted in Figures 6.6(a) and (b) respectively. Ag has the longest propagation length either for the L_- mode or the L_+ mode among the three materials. The combined film has a superior propagation length than the individual films for the L_- mode which can be seen in Figure 6.6(a). While the combined films

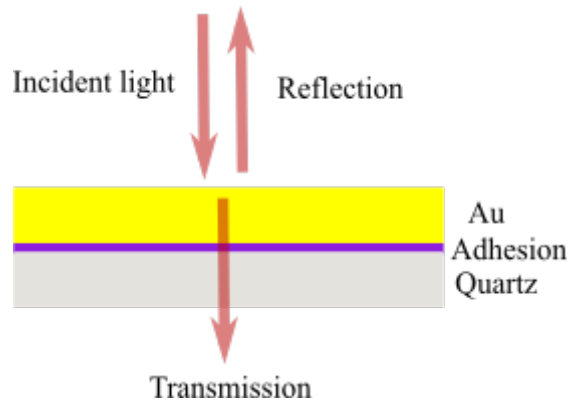


FIGURE 6.7: Schematic diagram of the measured sample. 50 nm Au with an adhesion layer on a quartz substrate. Titanium (Ti) and tantalum (Ta) are tested and the thickness of the adhesion layer is 0.5 nm, 1 nm, 2 nm and 5 nm.

show a shorter propagation length for the L_+ mode which can be seen in Figure 6.6(b), one possibility is the increased damping which comes from decreasing the thickness of the films.

6.3 Optical performance of Au film with a varied thickness of adhesion layer

Under intense optical excitation which as occurs in HAMR operation, the plasmonic element deform, then greatly degrading its performance. In addition to improving the plasmonic performance of the metallic film itself, the influence of the adhesion layers also needs to be taken into account in order to improve the thermo-mechanical stability of the films themselves.

The deposition of metal thin-film structures on dielectric or semiconductor substrates is well-known for semiconductor device manufacturing technology [213] as well as modern plasmonics applications. Due to the low chemical reactivity and the residual stresses of the noble metal, they adhere poorly to the substrate, which leads to phenomena such as delamination, and time-dependent device performance deterioration [214]. The deposition of an appropriate adhesion layer (normally 2 nm) between the substrate and the noble metal can greatly reduce the delamination [215]. Ti and Cr are known to be more chemically reactive than noble metals and therefore increase the adhesion when they chemically bind to the substrate [119]. They are used as the adhesion layers are well-known whether in plasmonic or optoelectronic devices, but the influence

of these adhesion layers on plasmonic performance or the thermo-stability of the individual metal used in the plasmonic waveguide is poorly understood especially when the adhesion layer is very thin. The influence may depend on the chemical properties of the adhesion layer, such as high damping in the visible wavelength range. The thickness of metal has a direct impact on the electrical conductivity of the nanostructures. For instance, the electrical conductivity of polycrystalline metal thin-film is lower than the bulk values, which is mainly attributed to surface and grain boundary scattering [216]. It is unclear if the presence of an adhesion layer will have any influence on the thermal and optical properties of the Au films.

Exploring the films ability to withstand high temperature is essential for designing HAMR head. The study has shown the failure of Ti as adhesion layer at the temperature above 600 °C [217]. Moreover, the diffusion of Ti in the Au film is large, leading to the formation of titanium dioxide (TiO₂) in the Au grain boundaries which progressively reduce the adhesion [215]. Unlike Ti, tantalum (Ta) exhibits a great adhesive strength, and very low mobility through the Au film as well as ensuring a device lifetime of at least half an hour at 1000 °C [218]. Ti and Ta adhesion layers with a varied thickness are discussed to understand the damping of the plasmonic response and the thermally-induced changes in the crystallographic texture of the Au films. The important insight of this chapter is to understand the influence of the adhesion layer on the optical properties of the metallic films.

The schematic diagram of the sample with a varied thickness of adhesion layer is shown in Figure 6.7. All the metal films are deposited through a DC magnetron sputtering system which has been introduced in Chapter 3.

6.3.1 Optical transmission and reflection measurements

Optical transmission and reflection measurements are performed to test the influence of the adhesion layer with varied thickness. Both Ti and Ta are chosen as the adhesion layer in order to find a superior films combination for combined thermal and plasmonic performance. Four different thicknesses are tested out (0.5 nm, 1 nm, 2 nm and 5 nm) for both Ti and Ta and they go from very thin to very thick. The thickness of the Au film been used is fixed to 50 nm and quartz is used as the substrate.

The optical reflection and transmission measurements with a normal incidence angle are conducted using a Perkin Elmer UV-Vis Spectrophotometer.

The transmission is increasing when the thickness of the adhesion layer is decreasing which is as expected. The sample with 0.5 nm Ta adhesion layer can achieve maximum transmission of 12% at 500 nm which can be seen in Figure 6.8(a). Similar results are found of the samples with the Ti adhesion layers as shown in Figure 6.8(b). The different thickness of the Ti or the Ta adhesion layer does not have a significant influence on the reflection of the films. There is a $\sim 2\%$ difference of the reflection between a 0.5 nm and a 5 nm thick adhesion layers for both Ti and Ta which can be seen in Figure 6.8(c) and (d). The data shows that $\sim 50\%$ of the absorption can be found at the wavelength of 500 nm for the film with either Ti or Ta adhesion layers.

The optical reflection and transmission do not show a huge difference for the film with either Ti or Ta adhesion layers, which gives the information that both Ti and Ta are good candidates as the adhesion layers if we only take into account the optical performance.

6.3.2 SPP reflection measurements

The decrease in adhesion layer thickness results in an improvement in the plasmonic properties, as shown in Figure 6.9. The SPP reflection of the 50 nm Au films was measured through a Kretschmann configuration at the excitation wavelength of 633 nm for different thickness of Ta and Ti adhesion layers, and it was found that thinner layers resulted in a narrower FWHM of the SPP reflection and it indicates an improved performance for the plasmonic devices loaded on these materials.

Table 6.2 lists the FWHM of the SPP reflection of the Au film with a different thickness of the adhesion layer. Both Ta and Ti adhesion layers are listed in the table. The FWHM of the SPP reflection are accounted by measuring the difference of the angles to excite the SPP to reach $1/e^2$ of the lowest reflection. It can quantitatively show that a thinner adhesion layer will contribute to a narrow SPP resonance which is related to a superior plasmonic performance [219–221].

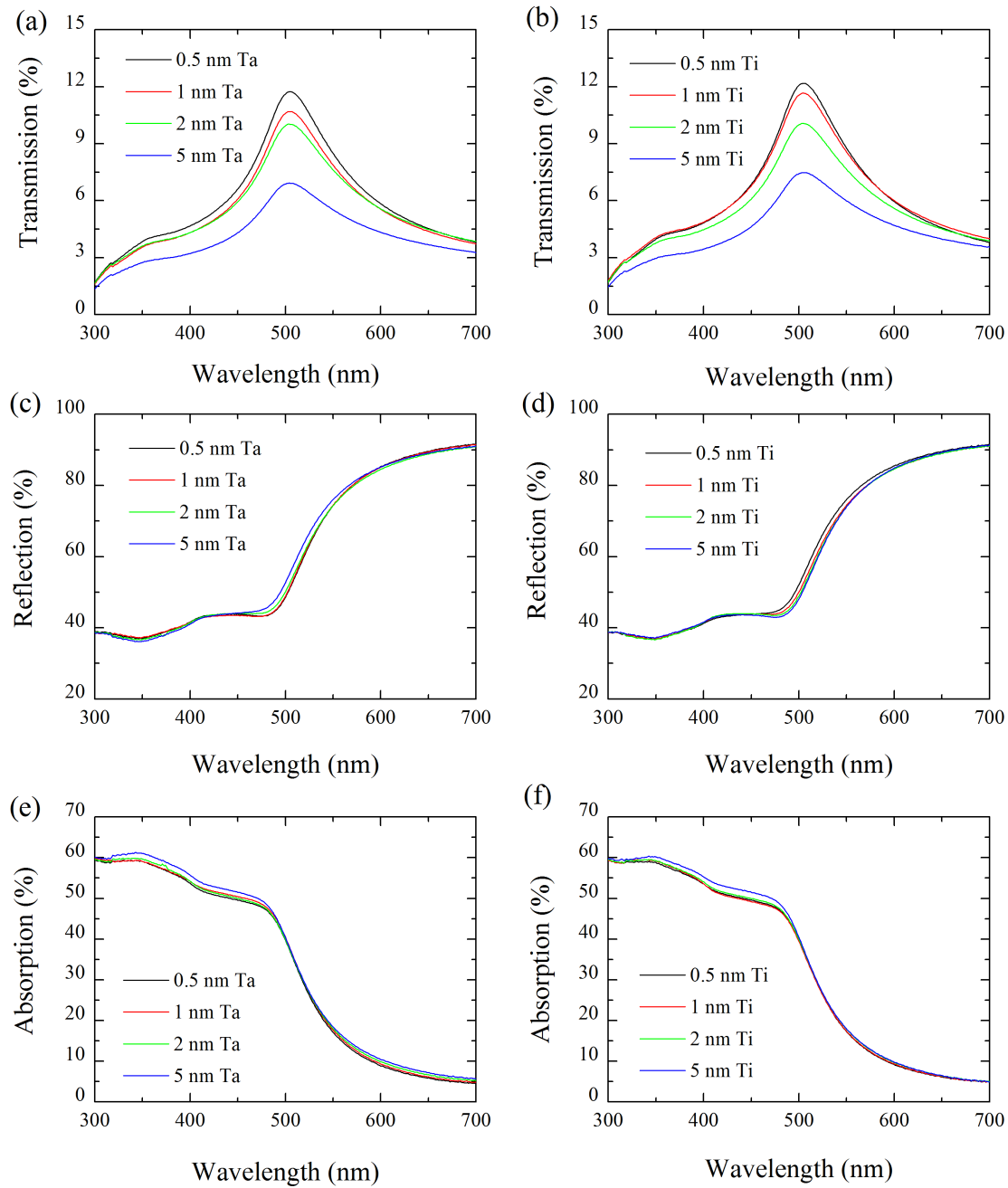


FIGURE 6.8: Optical transmission (a), (b) and reflection (c), (d) measurements for the samples with Ta and Ti adhesion layers respectively. (e) and (f) are the calculated absorption of the Ta and Ti adhesion samples. It should be mentioned that the scattering is ignored when calculating the absorption for each sample.

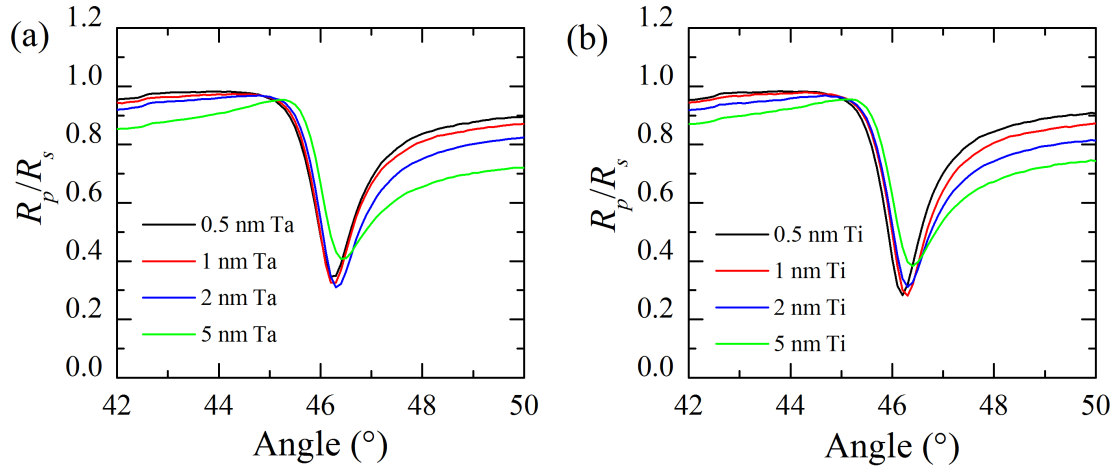


FIGURE 6.9: Angle resolved measurements of the films with (a) Ta and (b) Ti adhesion layers. The measurement is performed with a Kretschmann configuration and wavelength of the excitation wavelength is 633 nm. The results are the ratio of the reflection under a TM mode (P wave) excitation and a TE mode (S wave) excitation. The angles are varying from 42° to 50° with a step size of 0.1°.

TABLE 6.2: FWHM of the SPP reflection of the Au film with different thickness of the adhesion layers. Both Ta and Ti adhesion layers are listed in the table. The FWHM of the SPP reflection is accounted by measuring the difference of the angles to excite the SPP to reach $1/e^2$ of the lowest reflection.

Thickness (nm)	FWHM of the SPP reflection (<i>a.u.</i>)	
	Ta	Ti
0.5	0.51	0.62
1	0.54	0.66
2	0.75	0.77
5	1	1

6.4 Optical performance of Au film with a varied thickness of capping layer

It has been shown that a capping-layer can affect the morphology and plasmon excitation of Ag nanoparticles [222]. For most applications, these nanoparticles must be covered by a protective capping layer that preserves them from dramatic morphological and compositional changes. These effects have been extensively studied in the case of magnetic nanoclusters covered with metallic or oxide layers [223]. In HAMR, a capping layer with a Curie temperature lower than that of the magnetic recording layer is used [224]. The purpose of this capping layer is to provide magnetic stabilization to the lower magnetic recording layer at storage temperatures. The study shows that an aluminum oxide capping layers can strongly enhance the thermal stability of crystalline organic thin films. The thermally induced de-wetting effects at organic-inorganic interfaces can be effectively reduces owing to the interfusion at the organic-metal interface [225, 226]. Au has been a normal metal for the NFT design in HAMR, however, Au has a significant mobility at a high temperatures which has a big impact on the morphology of the Au thin films. Aluminum oxide capping layer reduces diffusion even at elevated temperature. Use a thin layer of aluminum oxide as the capping layer can presumably improve the thermal stability of the Au thin film. This section is discussing how a thin aluminum oxide can improve the plasmonic performance of the Au films as well as increase the thermo-mechanical stability of these films.

Figure 6.10(a) shows the transfer matrix method calculation of the SPP reflection of the Au film as a function of a different thickness of the capping layer. The dielectric constant for Al_2O_3 capping layer is from Querry 1985: thin film (oxidized Al mirror) [227]. The SPP in this measurement is excited by prism coupling which has been discussed in detail in chapter 4. The additional Al layer (which oxidizes to Al_2O_3 in air) capping layer has a significant influence on the SPP performance. A range of thickness for the Al_2O_3 capping layers were applied to identical samples comprised of a 0.5 nm Ti adhesion layer and a 50 nm Au layer. The measured SPP in reflection curves as a function of the excitation angles is plotted in Figure 6.10(b). The film without the capping layer is also plotted. It shows that a thicker capping adhesion will induce a wider FWHM of the SPP reflection. The film with a 0.5 nm capping has a narrower and dip SPP reflection which shows superior SPP performance. The results are very promising showing that a thinner capping layer can produce a superior

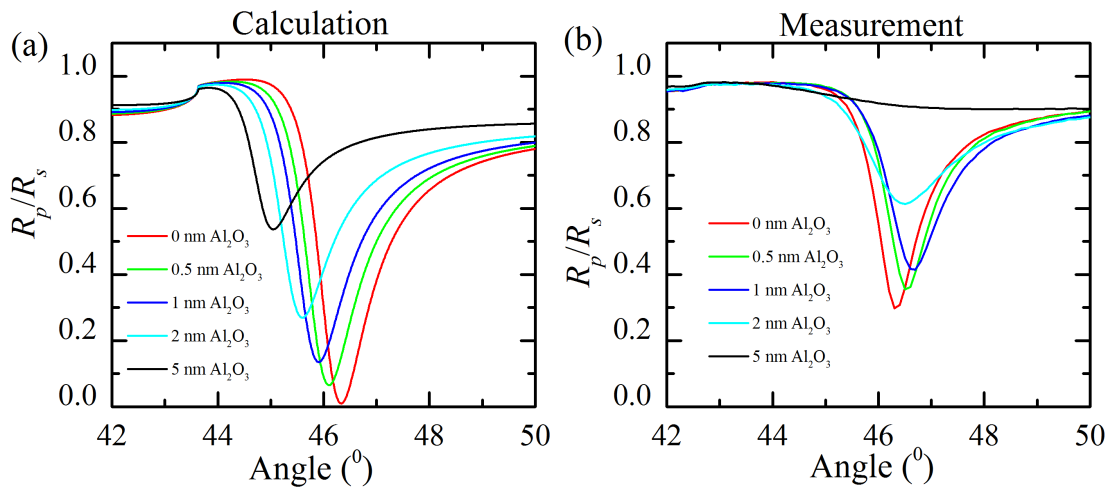


FIGURE 6.10: SPP reflection measurements of the 50 nm Au film with 0.5 nm Ti adhesion layer and a varied thickness of Al_2O_3 capping layers. The thickness of the capping layers are 0.5 nm, 1 nm, 2 nm and 5 nm.

SPP performance. The effective refractive index change as a function of the thickness of the Al_2O_3 layer will influence the coupling of SPP modes, a thicker capping layer has a larger index (1.7 for bulk Al_2O_3) which will degrade the SPP coupling because the index of the prism is 1.45. That is one evidence of the shallow dip in the SPP reflection with a thick capping layer. The calculation couldn't perfectly match the measurement somehow. The main reason behind this is that the existing n, k values from the Querry constant are not exactly the same as the measured samples, especially when the Al_2O_3 film becomes to thin. The uncertain composition of the capping layer in our structure might make the difference between the calculation and measurement.

6.5 Chapter summary

Three efforts to improve the thermo-mechanical stability of the Au film have been discussed in this chapter. The first approach is the using of an Ag-Cu-Au layered films, the high thermal conductivity of Cu can improve the thermal robustness of the film and Ag can contribute a longer propagating length of the SPP performance, moreover Au is chemically stable material which provides the layered film superior performance for both thermal and plasmonic properties than each individual film. By depositing a thinner adhesion layer results in a narrower SPP reflection which indicates a superior plasmonic performance.

A thin layer an Al_2O_3 capping layer can further improve the plasmonic performance of the Au films. Taken together it is hoped that these changes can result in a significant improvement in the thermo-mechanical stability of plasmonic structures that are to be used in HAMR devices.

Chapter 7

Outlook

In HAMR, device lifetime has reached about 100 hours. Failure occurs in the plasmonic near-field transducer during the magnetic bits writing process. In this thesis, we have worked on new materials and devices which should allow for a much improved lifetime in such devices. There are a number of studies to be completed related to this work.

7.1 Thermal Simulations

Failure of the NFT is the main difficulty holding back the introduction of HAMR. It is vital to have a good model which accurately predicts the thermal behaviour of this NFT. In addition, the thermal conductivity of the surrounding environment, is found to play a significant role in reducing the NFT temperature. We have calculated the mode distribution in the input Si_3N_4 waveguide and we use this mode propagates through the entire structure. From the optical distribution, we extracted the resistive heating losses and then we solved the steady state heat equation to calculate the temperature in all the structure. The required power to increase the temperature over 650 K with the structure of Figure 7.1 is 40 mW. With this value, the temperature in the tapered metal is around 470 K.

Figure 7.1 shows the thermal simulation of the NFT with an evanescent coupling mechanism. The COMSOL model of the 6 μm long tapered NFT with a recording medium can be seen in the Figure 7.1(a). The long NFT can couple 90.8% percent of the light from the dielectric core to the tip of the NFT which has been discussed in detail in Chapter 5. The recording medium is a consisting of 10 nm FePt layer, 50 nm Cu heat sink on a SiO_2 substrate. There is a 4 nm air-gap between the NFT and recording medium. The cross-section of the hot spot on the recording medium can be observed in Figure 7.1(b). The highest temperature on the recording medium can reach 800 K with a 40 mW input power

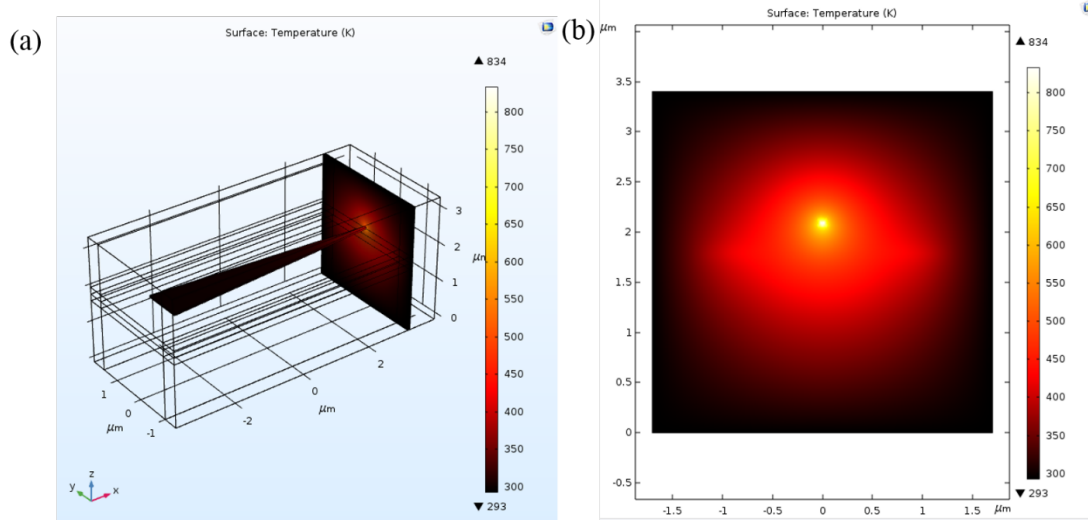


FIGURE 7.1: Thermal simulation of the NFT with an evanescent coupling mechanism. (a) COMSOL model of the $6\ \mu\text{m}$ long tapered NFT with a recording medium. The recording is consisting of a 10 nm FePt layer, 50 nm Cu heat sink on the SiO_2 substrate. There is a 4 nm air-gap between the NFT and recording medium. (b) The cross-section of the hot spot on the recording medium. The highest temperature on the recording medium can reach 800 K with a 40 mW input power in the NFT.

in the NFT. Further work needs to be done to test the thermal performance of the NFT with the optimal adhesion layer and capping layer. Ideally, we need to heat up the recording medium above 650 K and keep the temperature in the Au NFT below 450 K.

7.2 Thermal Measurements

CCD-based thermorefectance (CCD-TR) microscopy is a high resolution, non-contact imaging technique for thermal profiling and performance and reliable analysis of numerous electronic and optoelectronic devices at the micro-scale or nano-scale [228]. This thermography technique, which is based on the measurement of the relative change in the reflectivity of a sample surface as a function of the change in temperature. As the temperature of the sample changes, the refractive index of the sample is varying which results in the changing of the reflectivity. This technique provides high-resolution thermal images which are useful for detecting the 'hot spot' in the photonic devices during heating, which can be used for the failure analysis of the devices [229, 230]. The relation

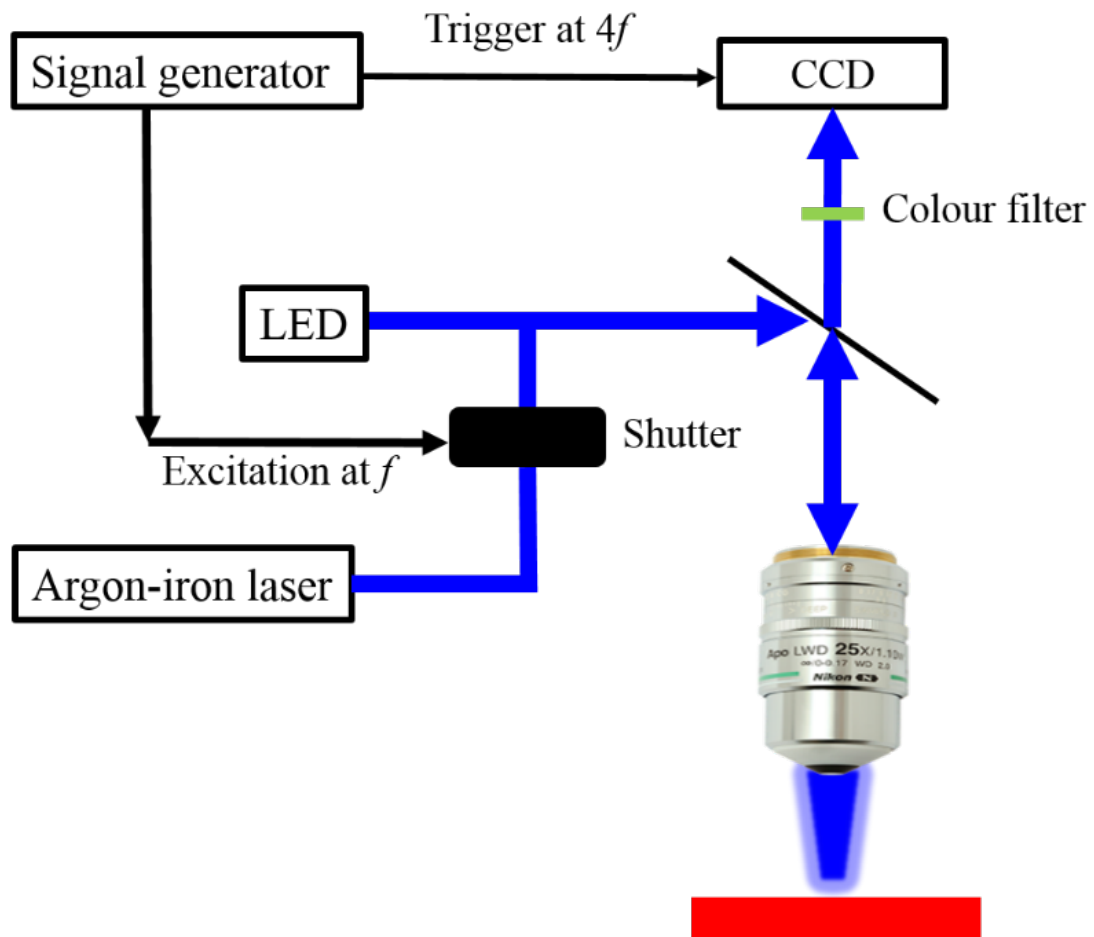


FIGURE 7.2: Schematic diagram of the CCD-TR microscopy setup [228]. It consists of a visible light CCD camera and a light emitting diode (LED) illumination source that is focused on the sample by a microscope objective. An argon-iron laser with the wavelength of 488 nm is used to excite the sample. The light reflected back to the CCD in response to modulation of the sample temperature is then analysed.

between the relative change in reflectivity and the temperature change can be approximated to first order as

$$\frac{\Delta R}{R} = \left(\frac{1}{R} \frac{\partial R}{\partial T} \right) \Delta T = \kappa \Delta T \quad (7.1)$$

where κ , which is typically very small and of the order of 10^{-6} - 10^{-4} K $^{-1}$ for metals and semiconductors [231], is the relative change in the optical reflectance per unit temperature change which is termed as the thermoreflectance calibration coefficient. The thermoreflectance coefficient varies strongly with the material and the wavelength of the illuminating light. The determination of the thermoreflectance coefficient also provides the calibration of the thermoreflectance measurements which give the information of the relative changes of reflectance with the change of temperature [232]. The basic experimental setup for a high spatial-resolution CCD-TR setup is shown in Figure 7.2. It consists of a visible light CCD camera and a light emitting diode (LED) illumination source that is focused on the sample by a microscope objective. The sample is excited by an argon-ion laser with a wavelength of 488 nm, the light reflected back to the CCD in response to modulation of the sample temperature is then analysed. The use of an incoherent light source LED instead of a focused laser beam eliminates speckle or fringe type interference patterns that may occur with coherent illumination. Various modulation schemes can be used to detect the relative change in reflectivity of the sample surface, including the homodyne method, the heterodyne method and the techniques for studying transients.

The laser beam is modulated through a shutter with a frequency of f . Using a multichannel lock-in scheme and triggering the camera at a frequency of $f_c = 4f$, the camera to take four images during each period T of the temperature modulation which is referred as the ‘four bucket’ technique [233], this technique makes best use of the CCD array’s slow readout speed by simplying accumulating four identical phased images in each bin [234]. A 2D image can be obtained that represents the modulated reflectivity $\Delta R(x, y)$, and through a calibration, the modulated temperature $\Delta T(x, y)$ [235].

7.3 Ag-Cu-Au alloy

Metal alloys enable new possibilities to tailor materials for specific optical functions. Au, Ag and Cu are prevalent in the plasmonic applications at the visible light spectrum due to their high concentration of free electrons [210]. Future

work will investigate the making of Ag-Cu-Au alloy film by annealing the sequential deposited each individual film. Samples with different thickness ratios will be alloyed. The existence of alloy will be confirmed through X-ray reflection measurements. This work is aiming at making high conductivity and chemical stability as well as a low thermal expansion alloy films. A NFT which is made of alloy film is potential to improve the robustness of the writing head in a HAMR system.

Appendix A

AppendixA

A.1 General approach to solving SPP dispersion in multi-layer metallic films

A.1.1 Boundary between three materials

We can expand the above procedure to three materials to describe an MIM, IMI *etc.* The coordinates are centered on the middle of central material so that the boundaries occur at $\pm d$ where d is the width of this region. The field is therefore given by

$$E_z = \begin{cases} A_1 e^{-K_1 z} & z > d/2 \\ A_2 e^{K_2 z} + A_2 e^{-K_2 z} & -d/2 < z < d/2 \\ A_3 e^{K_3 z} & z < -d/2 \end{cases} \quad (\text{A.1})$$

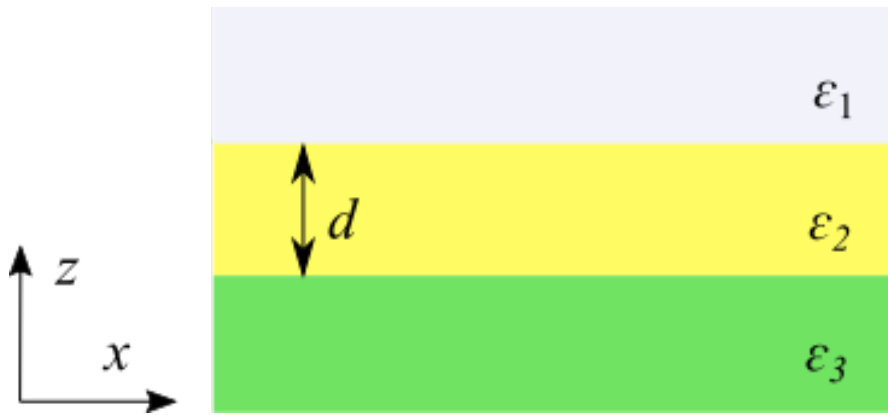


FIGURE A.1: Sketch of a three-layer structure.

and

$$E_x = \begin{cases} (iK_1 A_1 k) e^{-K_1 z} & z > d/2 \\ (iK_2 A_{2+}/k) e^{K_2 z} + (iK_2 A_{2-}/k) e^{-K_2 z} & -d/2 < z < d/2 \\ -(iK_3 A_3/k) e^{K_3 z} & z < -d/2 \end{cases} \quad (\text{A.2})$$

This gives the four boundary conditions

$$\begin{aligned} \epsilon_1 A_1 e^{-K_1 d/2} &= \epsilon_2 A_{2+} e^{K_2 d/2} + \epsilon_2 A_{2-} e^{-K_2 d/2} \\ \epsilon_3 A_3 e^{-K_3 d/2} &= \epsilon_2 A_{2+} e^{-K_2 d/2} + \epsilon_2 A_{2-} e^{K_2 d/2} \\ K_1 A_1 e^{-K_1 d/2} &= -K_2 A_{2+} e^{K_2 d/2} + K_2 A_{2-} e^{-K_2 d/2} \end{aligned} \quad (\text{A.3})$$

or in a matrix form

$$\Delta \begin{bmatrix} \epsilon_1 e^{-K_1 d/2} & -\epsilon_2 e^{K_2 d/2} & -\epsilon_2 e^{-K_2 d/2} & 0 \\ 0 & -\epsilon_2 e^{-K_2 d/2} & -\epsilon_2 e^{K_2 d/2} & -\epsilon_3 e^{-K_3 d/2} \\ K_1 e^{-K_1 d/2} & K_2 e^{K_2 d/2} & -K_2 e^{-K_2 d/2} & 0 \\ 0 & K_2 e^{-K_2 d/2} & -K_2 e^{K_2 d/2} & -K_3 e^{-K_3 d/2} \end{bmatrix} = 0 \quad (\text{A.4})$$

giving the dispersion relation

$$e^{2dK_2} = \frac{(\epsilon_2 K_1 - \epsilon_1 K_2)(\epsilon_2 K_3 - \epsilon_3 K_2)}{\epsilon_2 K_1 + \epsilon_1 K_2} (\epsilon_3 K_3 - \epsilon_3 K_2) \quad (\text{A.5})$$

A.1.2 Boundary between five materials

Skipping past the case of four different materials to concentrate on five, the same process applies with increasing complexity. We note d_2 , d_3 and d_4 as the width of the second, third and fourth layers respectively so that the boundaries

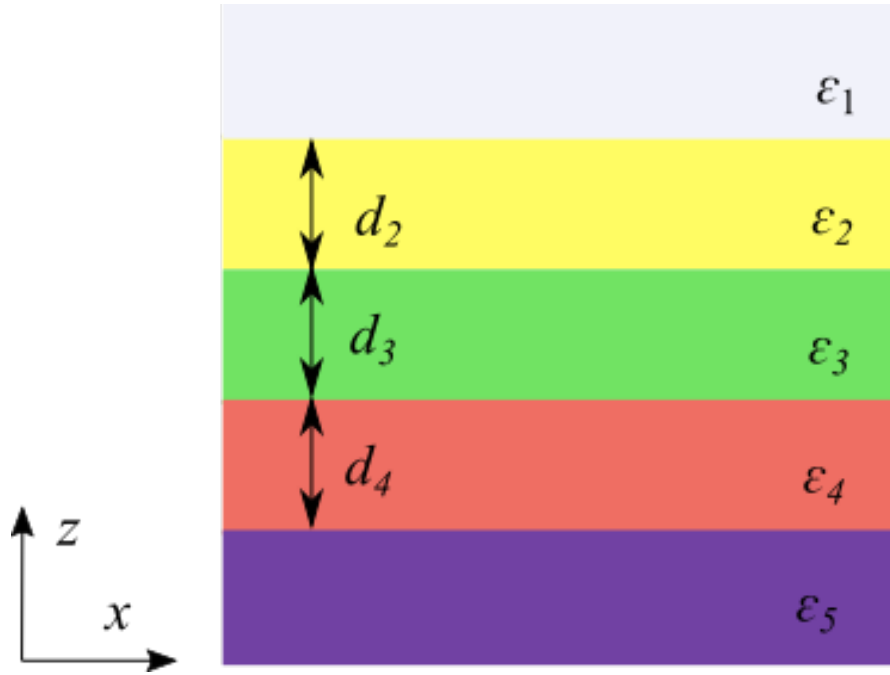


FIGURE A.2: Sketch of a five-layer structure.

occur at $d_2 + d_3/2$, $d_3/2$, $-d_3/2$ and $-d_4 - d_3/2$. The resulting field is

$$E_z = \begin{cases} A_1 e^{-K_1 z} & z > d_2 + d_3/2 \\ A_{2+} e^{K_2 z} + A_{2-} e^{-K_2 z} & d_3/2 < z < d_4 + d_3/2 \\ A_{3+} e^{K_3 z} + A_{3-} e^{-K_3 z} & -d_3/2 < z < d_3/2 \\ A_{4+} e^{K_4 z} + A_{4-} e^{-K_4 z} & -d_4 - d_3/2 < z < -d_3/2 \\ A_5 e^{K_5 z} & z < -d_4 - d_3/2 \end{cases} \quad (\text{A.6})$$

and similarly for E_x . Filling in the boundary conditions as usual gives the dispersion equation

$$\Delta = \begin{bmatrix}
\epsilon_1 e^{-K_1(d_2+d_3/2)} & -\epsilon_2 e^{K_2(d_2+d_3/2)} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \epsilon_1 e^{K_2 d_3/2} & -\epsilon_2 e^{-K_2(d_2+d_3/2)} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \epsilon_2 e^{-K_2 d_3/2} & \epsilon_3 e^{-K_3 d_3/2} & -\epsilon_4 e^{-K_4 d_3/2} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\epsilon_4 e^{-K_4(d_4+d_3/2)} & \epsilon_5 e^{-K_5(d_2+d_3/2)} & 0 & 0 \\
-K_1 e^{-K_1(d_2+d_3/2)} & -K_2 e^{K_2(d_2+d_3/2)} & K_2 e^{-K_2(d_2+d_3/2)} & 0 & 0 & 0 & 0 & 0 \\
0 & K_2 e^{K_2 d_3/2} & -K_2 e^{-K_2 d_3/2} & -K_3 e^{K_3 d_3/2} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & K_3 e^{-K_3 d_3/2} & -K_4 e^{-K_4 d_3/2} & -K_4 e^{K_4(d_4+d_3/2)} & 0 & 0 \\
0 & 0 & 0 & 0 & K_4 e^{-K_4(d_4+d_3/2)} & -K_5 e^{-K_5(d_4+d_3/2)} & -K_5 e^{-K_5(d_4+d_3/2)} & 0
\end{bmatrix} = 0 \quad (\text{A.7})$$

The relation can be simplified by putting some of the materials or distances equal to each other, or can be solved numerically.

Appendix B

AppendixB

B.1 Convergence problems in COMSOL simulations

B.1.1 2-D simulations

2-D simulations are performed to calculate the mode beating between the photonic and the plasmonic modes, the field enhancement factor in the NFT is also obtained in the same simulation. The mesh size for different simulation domain is a key issue in the parametric sweep study, we fix the maximum mesh size at 170 nm ($\lambda_0/5$) and minimum mesh size of 1 nm for the 240 samples (taper lengths are varying from 100 nm to 25 μm with a step of 100 nm) to make all the simulated results converge. Another issue to get a smooth curve in the parametric sweep study is the reflection from the boundary of the simulation domain, especially the input port. We are using the boundary mode analysis tool in COMSOL to perform the calculations and the perfect match layer (PML) boundary condition is used in all the boundaries of the simulation domain except the input port because the wave is excited at this port. In this case, the reflected light from the input boundary of the simulation domain and the start of the NFT will reflect back and forth to form a Fabry-Perot (F-P) cavity resonance, which will make the intensity curve at the start of the NFT an oscillating signal rather than a smooth curve as shown in Figure B.1. We are taking the average value of the integrated intensity at the start of the NFT as the input to determine the influence of the reflected light from the input boundary.

B.1.2 3-D simulations

Figure B.2(a) shows mesh test for the 3-D simulations. The results converge with > 0.6 M elements. We are using 1 million simulated elements in the simulation and the related maximum mesh size is 170 nm ($\lambda_0/5$) and the minimum mesh size is 1 nm which are the same as the 2-D simulation. (b) Results of the

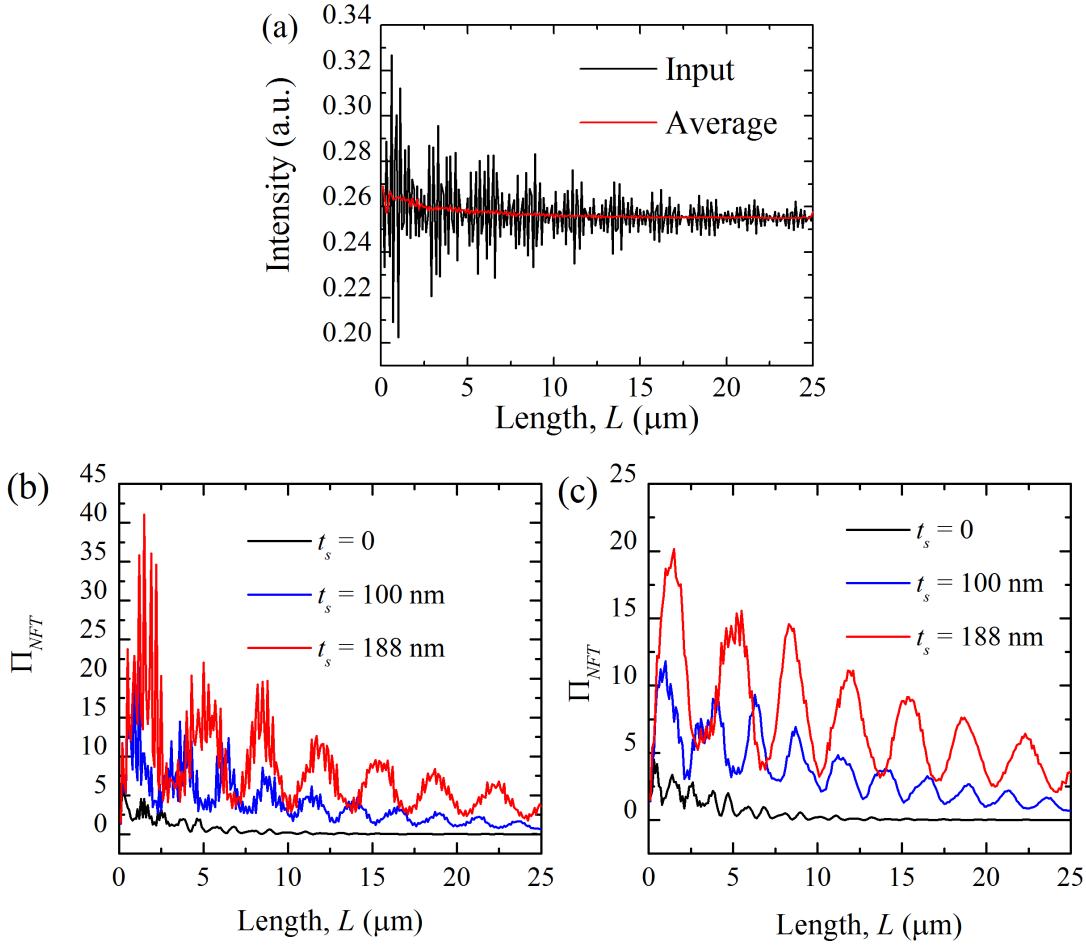


FIGURE B.1: (a) Intensity curve at the start of the NFT. The resonance of the back curve comes from the Fabry-Perot (F-P) cavity which is formed by the start of the NFT and the input boundary of the simulation domain. The red smooth line is the average intensity which is used to normalize the data to improve the accuracy of the calculated intensity enhancement (Π_{NFT}) in the NFT. (b) Shows the field intensity enhancement factor in the NFT at different values for the spacer layer thickness (t_s) which is normalized with data in the black curve of Figure B.1(a). (c) Shows the same results but normalized with the average value (red curve in Figure B.1(a)), the sharp peaks result from the F-P resonance between the input port boundary and the start of the NFT are now much weaker.

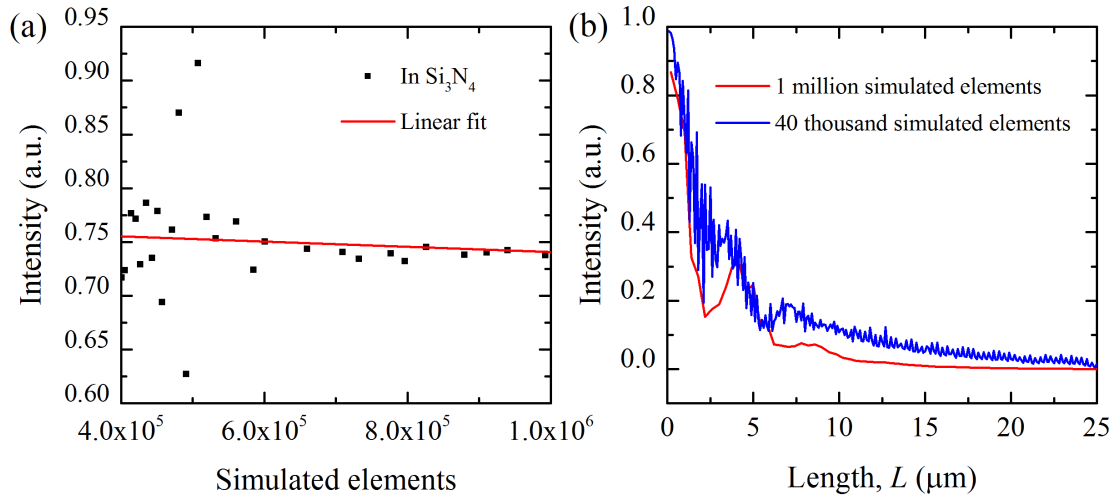


FIGURE B.2: (a) Mesh test for the 3-D simulations. (b) Results of the simulated coupling efficiency of a tapered NFT with a fine mesh size and a coarse mesh size.

simulated coupling efficiency of a tapered NFT with a fine mesh (1 million simulated elements) and a coarse mesh (40 thousand simulated elements), it can be clearly seen that a dense mesh can produce more accurate results but with a sacrifice of the simulation time and disk memory, 16 nodes are needed (24 RAM per node) to run the simulation and the simulation time is 17 hours.

Appendix C

List of publications and talks

Journal Papers

1. **Chuan Zhong**, Patrick Flanigan, Nicolás Abadía, Brian Jennings, Frank Bello, Gwenael Atcheson, Jing Li, Jian-Yao Zheng, Jing Jing Wang, Richard Hobbs, David McCloskey, and John F. Donegan, Effective heat dissipation in an adiabatic near-field transducer for HAMR. Accepted by Opt. Express (2018).
2. Nicolás Abadía, Frank Bello, **Chuan Zhong**, Patrick Flanigan, David McCloskey, Christopher Wolf, Alexander Krichevsky, Daniel Wolf, Fenghua Zong, David V. Plant and John F. Donegan. “Optical and Thermal Analysis of the Light-Heat Conversion Process in an Antenna-Based Hybrid Plasmonic Waveguide for HAMR” Opt. Express 26, 1752-1765 (2018)
3. **Chuan Zhong**, Kyle E. Ballantine, Christopher Kervick, Christopher M. Smith, Daragh Mullarkey, Igor Shvets, John F. Donegan, David McCloskey, “Mapping of surface plasmon dispersion in thin Ag-Au layered composite films”. Journal of Optical Society of America B, 566-573, (2016)
4. Brian Jennings, David McCloskey, John Gough, Thomas Hoang, Nicolás Abadía, **Chuan Zhong**, Ertugul Karademir, Louis Bradley, and John F. Donegan. “Characterisation of multi-mode propagation in silicon nitride slab waveguides” Journal of Optics 19 (1), 015604 (2016).

Conference papers

1. Patrick W. Flanigan, **Chuan Zhong**, Brian Jennings, Gwenael Atcheson, Frank Bello, David McCloskey, John Donegan. “Efficient Waveguide-to-Plasmon Coupling and Adiabatic Nanofocusing for HAMR Applications”. CLEO: QELS: Fundamental Science (2017) San Jose, California United States (2017).
2. Jian-Yao Zheng, Jing Jing Wang, Hugh Manning, **Chuan Zhong**, Finn Purcell-Milton, Rudi O'Reilly Meehan, Graeme Cunningham, Ryan Enright,

Yurii K Gun'ko, John Boland, John Donegan. "Synthesis of Millimeter-Size Freestanding Perovskite Nanofilms from Single-Crystal Lead Bromide for Optoelectronic Devices". CLEO: Applications and Technology 2017 San Jose, California United States (2017).

3. **Chuan Zhong**, David McCloskey, Jing Jing Wang, Brian D. Jennings, Nicolas Abadia, Ertugrul Karademir, Jian-Yao Zheng, and John F. Donegan. "Nano-focusing in an Air-slot Plasmonic Waveguide With a Tapered Grating Coupler". CLEO: Science and Innovations 2016 San Jose, California United States (2016).

4. Brian D Jennings, Nicolás Abadía, **Chuan Zhong**, Ertugrul Karademir, David McCloskey, John F Donegan. "Fluorescence imaging of waveguide mode beating and propagation in tapered and bend regions". CLEO: Science and Innovations 2016 San Jose, California United States (2016).

5. Jian-Yao Zheng, Jing Jing Wang, Hongjun Xu, Finn Purcell-Milton, **Chuan Zhong**, Yurii K Gun'ko, John F Donegan. "Fast and scalable synthesis of lead halide perovskite nanowires for tunable room-temperature nanolasers". CLEO: Science and Innovations 2016 San Jose, California United States (2016).

Conference talks

1. Conference on Lasers and Electro-Optics 2016 (CLEO 2016), San Jose, United States. (Oral)

2. Nanophotonics and Micro/Nano Optics International Conference 2017 (NANOP 2017), Barcelona, Spain. (Oral)

3. Advanced Laser Technology 2016 (ALT 2016), Galway, Ireland. (Oral)

4. Conference on Lasers and Electro-Optics 2016 (CLEO 2016), San Jose, United States. (Poster)

5. Photonics Ireland 2015, Cork, Ireland. (Poster)

References

- [1] S. E. Thompson and S. Parthasarathy. “Moore’s law: the future of Si microelectronics”. In: *Materials today* 9.6 (2006), pp. 20–25.
- [2] R. Soref. “The past, present, and future of silicon photonics”. In: *IEEE Journal of selected topics in quantum electronics* 12.6 (2006), pp. 1678–1687.
- [3] D. K. Gramotnev and S. I. Bozhevolnyi. “Plasmonics beyond the diffraction limit”. In: *Nature photonics* 4.2 (2010), pp. 83–91.
- [4] M. Ayata et al. “High-speed plasmonic modulator in a single metal layer”. In: *Science* 358.6363 (2017), pp. 630–632.
- [5] N. C. Lindquist et al. “Three-dimensional plasmonic nanofocusing”. In: *Nano letters* 10.4 (2010), pp. 1369–1373.
- [6] S. Cushing. “Plasmonic hot carriers skip out in femtoseconds”. In: *Nature Photonics* 11.12 (2017), p. 748.
- [7] M. H. Kryder et al. “Heat assisted magnetic recording”. In: *Proceedings of the IEEE* 96.11 (2008), pp. 1810–1835.
- [8] H. Masakatsu, S. Hiroshi, and S. Seiichi. “Trends in Technologies for HDDs, ODDs, and SSDs, and Toshiba’s Approach”. In: *TOSHIBA Review* 66.8 (2011).
- [9] R. R. Schaller. “Moore’s law: past, present and future”. In: *IEEE spectrum* 34.6 (1997), pp. 52–59.
- [10] H. Jo et al. “SSD-HDD-Hybrid Virtual Disk in Consolidated Environments.” In: *Euro-Par Workshops*. Springer. 2009, pp. 375–384.
- [11] M. Sharrock and D. Stubbs. “Perpendicular Magnetic Recording Technology”. In: *SMPTE Journal* 93.1A (1984), pp. 137–151.
- [12] T. R. Albrecht et al. “Bit-patterned magnetic recording: Theory, media fabrication, and recording performance”. In: *IEEE Transactions on Magnetics* 51.5 (2015), pp. 1–42.
- [13] W. Tipcharoen et al. “Investigation of writing error in staggered heated-dot magnetic recording systems”. In: *AIP Advances* 7.5 (2017), p. 056511.

- [14] C. Bean and u. D. Livingston. "Superparamagnetism". In: *Journal of Applied Physics* 30.4 (1959), S120–S129.
- [15] B. Marchon et al. "The head-disk interface roadmap to an areal density of Tb/in²". In: *Advances in Tribology* 2013 (2013).
- [16] A. Elster and J. Burdette. "Questions and answers in MRI". In: *London: Mosby* (2001).
- [17] M. Akhter et al. "Thickness and grain-size dependence of the coercivity in permalloy thin films". In: *Journal of applied physics* 81.8 (1997), pp. 4122–4124.
- [18] C. Luo, S. Liou, and D. J. Sellmyer. "FePt: SiO₂ granular thin film for high density magnetic recording". In: *Journal of Applied Physics* 87.9 (2000), pp. 6941–6943.
- [19] S. Sun et al. "Controlled synthesis and assembly of FePt nanoparticles". In: *The Journal of Physical Chemistry B* 107.23 (2003), pp. 5419–5425.
- [20] J. Christodoulides et al. "CoPt and FePt thin films for high density recording media". In: *Journal of Applied Physics* 87.9 (2000), pp. 6938–6940.
- [21] S. Bhargava. *Heat-assisted magnetic recording: Fundamental limits to inverse electromagnetic design*. University of California, Berkeley, 2015.
- [22] K. L. Tsakmakidis et al. "Ultraslow waves on the nanoscale". In: *Science* 358.6361 (2017), ean5196.
- [23] W. Challener et al. "Heat-assisted magnetic recording by a near-field transducer with efficient optical energy transfer". In: *Nature photonics* 3.4 (2009), pp. 220–224.
- [24] S. Jahani and Z. Jacob. "All-dielectric metamaterials". In: *Nature nanotechnology* 11.1 (2016), pp. 23–36.
- [25] S. Jahani and Z. Jacob. "Transparent subdiffraction optics: nanoscale light confinement without metal". In: *Optica* 1.2 (2014), pp. 96–100.
- [26] J. Song and J. Ding. "Silicon Nanowire Waveguides and Their Applications in Planar Wavelength Division Multiplexers/Demultiplexers". In: *Nanowires-Fundamental Research*. InTech, 2011.
- [27] J. L. West and N. J. Halas. "Engineered nanomaterials for biophotonics applications: improving sensing, imaging, and therapeutics". In: *Annual Review of Biomedical Engineering* 5.1 (2003), pp. 285–292.

- [28] E. Betzig and R. J. Chichester. "Single molecules observed by near-field scanning optical microscopy". In: *Science New York Then Washington* 262 (1993), pp. 1422–1422.
- [29] T. Hümmer et al. "Weak and strong coupling regimes in plasmonic QED". In: *Physical Review B* 87.11 (2013), p. 115419.
- [30] J. Liu et al. "Random nanolasing in the Anderson localized regime". In: *Nature Nanotechnology* 9.4 (2014), pp. 285–289.
- [31] H. Raether. "Surface plasmons on smooth surfaces". In: *Surface plasmons on smooth and rough surfaces and on gratings*. Springer, 1988, pp. 4–39.
- [32] R. Hillenbrand, T. Taubner, and F. Keilmann. "Phonon-enhanced light-matter interaction at the nanometre scale". In: *Nature* 418.6894 (2002), pp. 159–162.
- [33] Y. Yang et al. "Dielectric metasurface analogue of electromagnetically induced transparency". In: *CLEO: QELS_Fundamental Science*. Optical Society of America. 2015, FW4C–7.
- [34] T. J. Cui, D. R. Smith, and R. Liu. *Metamaterials*. Springer, 2010.
- [35] A. I. Kuznetsov et al. "Magnetic light". In: *Scientific reports* 2 (2012), srep00492.
- [36] A. V. Kildishev, A. Boltasseva, and V. M. Shalaev. "Planar photonics with metasurfaces". In: *Science* 339.6125 (2013), p. 1232009.
- [37] P. Moitra et al. "Realization of an all-dielectric zero-index optical metamaterial". In: *Nature Photonics* 7.10 (2013), pp. 791–795.
- [38] I. I. Smolyaninov et al. "Anisotropic metamaterials emulated by tapered waveguides: application to optical cloaking". In: *Physical review letters* 102.21 (2009), p. 213901.
- [39] W. A. Challener et al. "Miniature planar solid immersion mirror with focused spot less than a quarter wavelength". In: *Optics Express* 13.18 (2005), pp. 7189–7197.
- [40] D. McCloskey, J. J. Wang, and J. Donegan. "Low divergence photonic nanojets from Si_3N_4 microdisks". In: *Optics Express* 20.1 (2012), pp. 128–140.
- [41] P. R. West et al. "All-dielectric subwavelength metasurface focusing lens". In: *Optics express* 22.21 (2014), pp. 26212–26221.

- [42] S. Jahani and Z. Jacob. "Photonic skin-depth engineering". In: *JOSA B* 32.7 (2015), pp. 1346–1353.
- [43] R. Ritchie. "Plasma losses by fast electrons in thin films". In: *Physical Review* 106.5 (1957), p. 874.
- [44] L. Marton and L. B. Leder. "Energy loss of electrons in passage through thin films". In: *Physical Review* 94.1 (1954), p. 203.
- [45] D. Pines and D. Bohm. "A collective description of electron interactions: II. Collective vs individual particle aspects of the interactions". In: *Physical Review* 85.2 (1952), p. 338.
- [46] C. Powell and J. Swan. "Origin of the characteristic electron energy losses in aluminum". In: *Physical Review* 115.4 (1959), p. 869.
- [47] E. Stern and R. Ferrell. "Surface plasma oscillations of a degenerate electron gas". In: *Physical Review* 120.1 (1960), p. 130.
- [48] P. Bharadwaj, A. Bouhelier, and L. Novotny. "Electrical excitation of surface plasmons". In: *Physical review letters* 106.22 (2011), p. 226802.
- [49] N. Liu et al. "Nanoantenna-enhanced gas sensing in a single tailored nanofocus". In: *CLEO: Science and Innovations*. Optical Society of America. 2011, PDPC11.
- [50] E. Le Ru and P. Etchegoin. *Principles of Surface-Enhanced Raman Spectroscopy: and related plasmonic effects*. Elsevier, 2008.
- [51] M. Moskovits. "Surface-enhanced Raman spectroscopy: a brief retrospective". In: *Journal of Raman Spectroscopy* 36.6-7 (2005), pp. 485–496.
- [52] A. Tao et al. "Langmuir-Blodgett silver nanowire monolayers for molecular sensing using surface-enhanced Raman spectroscopy". In: *Nano letters* 3.9 (2003), pp. 1229–1233.
- [53] D.-K. Lim et al. "Nanogap-engineerable Raman-active nanodumbbells for single-molecule detection". In: *Nature materials* 9.1 (2010), pp. 60–67.
- [54] S. Nie and S. R. Emory. "Probing single molecules and single nanoparticles by surface-enhanced Raman scattering". In: *science* 275.5303 (1997), pp. 1102–1106.
- [55] J. N. Anker et al. "Biosensing with plasmonic nanosensors". In: *Nature materials* 7.6 (2008), pp. 442–453.
- [56] K. M. McPeak et al. "Plasmonic films can easily be better: rules and recipes". In: *ACS photonics* 2.3 (2015), pp. 326–333.

- [57] G. Das et al. "Plasmonic nanostructures for the ultrasensitive detection of biomolecules". In: *Rivista Del Nuovo Cimento* 39.11 (2016), pp. 547–586.
- [58] E. Abbe. "A contribution to the theory of the microscope and the nature of microscopic vision". In: *Proc. Bristol Nat. Soc* 1 (1874), pp. 200–261.
- [59] A. Lipson, S. G. Lipson, and H. Lipson. *Optical physics*. Cambridge University Press, 2010.
- [60] X. Michalet and S. Weiss. "Using photon statistics to boost microscopy resolution". In: *Proceedings of the National Academy of Sciences* 103.13 (2006), pp. 4797–4798.
- [61] M. Born and E. Wolf. "Principles of Optics, Cambridge University Press". In: *New York* (1999), p. 704.
- [62] D. Weaire, J. F. Donegan, and P. S. Florides. "Unknown genius". In: *Physics World* 25.12 (2012), p. 26.
- [63] M. T. Hill. "Nanophotonics: Lasers go beyond diffraction limit". In: *Nature nanotechnology* 4.11 (2009), pp. 706–707.
- [64] V. G. Veselago. "The electrodynamics of substances with simultaneously negative values of ϵ and μ ". In: *Soviet physics uspekhi* 10.4 (1968), p. 509.
- [65] R. A. Shelby, D. R. Smith, and S. Schultz. "Experimental verification of a negative index of refraction". In: *science* 292.5514 (2001), pp. 77–79.
- [66] E. T. Rogers et al. "A super-oscillatory lens optical microscope for sub-wavelength imaging". In: *Nature materials* 11.5 (2012), p. 432.
- [67] J. B. Pendry et al. "Extremely low frequency plasmons in metallic mesostructures". In: *Physical review letters* 76.25 (1996), p. 4773.
- [68] X. Zhang and Z. Liu. "Superlenses to overcome the diffraction limit". In: *Nature materials* 7.6 (2008), pp. 435–441.
- [69] W. D. Pohl. *Optical near-field scanning microscope*. US Patent 4,604,520. 1986.
- [70] S. Zamek. *Miniaturization of chip-scale photonic circuits*. University of California, San Diego, 2011.
- [71] S. Ramo, J. R. Whinnery, and T. Van Duzer. *Fields and waves in communication electronics*. John Wiley & Sons, 2008.
- [72] Z. Han and S. I. Bozhevolnyi. "Radiation guiding with surface plasmon polaritons". In: *Reports on Progress in Physics* 76.1 (2012), p. 016402.

- [73] E. Verhagen. "Subwavelength light confinement with surface plasmon polaritons". PhD thesis. Utrecht University, 2009.
- [74] P. Berini and I. De Leon. "Surface plasmon-polariton amplifiers and lasers". In: *Nature Photonics* 6.1 (2012), pp. 16–24.
- [75] P. Yupapin. *Nanophotonics: Devices, Circuits, and Systems*. CRC Press, 2013.
- [76] I. Ament et al. "Single unlabeled protein detection on individual plasmonic nanoparticles". In: *Nano letters* 12.2 (2012), pp. 1092–1095.
- [77] N. Fang et al. "Sub-diffraction-limited optical imaging with a silver superlens". In: *Science* 308.5721 (2005), pp. 534–537.
- [78] J. D. Thompson et al. "Coupling a single trapped atom to a nanoscale optical cavity". In: *Science* 340.6137 (2013), pp. 1202–1205.
- [79] R. Zia et al. "Plasmonics: the next chip-scale technology". In: *Materials today* 9.7 (2006), pp. 20–27.
- [80] S. Hayashi and T. Okamoto. "Plasmonics: visit the past to know the future". In: *Journal of Physics D: Applied Physics* 45.43 (2012), p. 433001.
- [81] T. L. Koch and U. Koren. "Photonic integrated circuits". In: *Bell Labs Technical Journal* 71.1 (1992), pp. 63–74.
- [82] M. I. Stockman. "Nanofocusing of optical energy in tapered plasmonic waveguides". In: *Physical review letters* 93.13 (2004), p. 137404.
- [83] Y. Luo et al. "On-chip hybrid photonic-plasmonic light concentrator for nanofocusing in an integrated silicon photonics platform". In: *Nano letters* 15.2 (2015), pp. 849–856.
- [84] M. Schnell et al. "Nanofocusing of mid-infrared energy with tapered transmission lines". In: *Nature photonics* 5.5 (2011), pp. 283–287.
- [85] D. Pile and D. K. Gramotnev. "Adiabatic and nonadiabatic nanofocusing of plasmons by tapered gap plasmon waveguides". In: *Applied Physics Letters* 89.4 (2006), p. 041111.
- [86] H. Choo et al. "Nanofocusing in a metal-insulator-metal gap plasmon waveguide with a three-dimensional linear taper". In: *Nature Photonics* 6.12 (2012), pp. 838–844.
- [87] A. R. Davoyan et al. "Nonlinear nanofocusing in tapered plasmonic waveguides". In: *Physical review letters* 105.11 (2010), p. 116804.
- [88] J. Mao and S. Blair. "Nanofocusing of UV light in aluminum V-grooves". In: *Journal of Physics D: Applied Physics* 48.18 (2015), p. 184008.

- [89] C. L. Smith et al. "Efficient excitation of channel plasmons in tailored, UV-lithography-defined V-grooves". In: *Nano letters* 14.3 (2014), pp. 1659–1664.
- [90] D. K. Gramotnev, M. W. Vogel, and M. I. Stockman. "Optimized nonadiabatic nanofocusing of plasmons by tapered metal rods". In: *Journal of Applied Physics* 104.3 (2008), p. 034311.
- [91] T. J. Antosiewicz, P. Wróbel, and T. Szoplik. "Nanofocusing of radially polarized light with dielectric-metal-dielectric probe". In: *Optics Express* 17.11 (2009), pp. 9191–9196.
- [92] V. A. Zenin et al. "Boosting local field enhancement by on-chip nanofocusing and impedance-matched plasmonic antennas". In: *Nano letters* 15.12 (2015), pp. 8148–8154.
- [93] S. Berweger et al. "Light on the Tip of a Needle: Plasmonic Nanofocusing for Spectroscopy on the Nanoscale". In: *The Journal of Physical Chemistry Letters* 3.7 (2012), pp. 945–952.
- [94] P. B. Johnson and R.-W. Christy. "Optical constants of the noble metals". In: *Physical review B* 6.12 (1972), p. 4370.
- [95] E. D. Palik. *Handbook of optical constants of solids*. Vol. 3. Academic press, 1998.
- [96] J. Dionne et al. "Plasmon slot waveguides: Towards chip-scale propagation with subwavelength-scale localization". In: *Physical Review B* 73.3 (2006), p. 035407.
- [97] E. Economou. "Surface plasmons in thin films". In: *Physical review* 182.2 (1969), p. 539.
- [98] J. A. Dionne et al. "Planar metal plasmon waveguides: frequency-dependent dispersion, propagation, localization, and loss beyond the free electron model". In: *Physical Review B* 72.7 (2005), p. 075405.
- [99] P. Berini. "Long-range surface plasmon polaritons". In: *Advances in optics and photonics* 1.3 (2009), pp. 484–588.
- [100] J. A. Dionne. *Flatland photonics: circumventing diffraction with planar plasmonic architectures*. California Institute of Technology, 2009.
- [101] C. C. Katsidis and D. I. Siapkas. "General transfer-matrix method for optical multilayer systems with coherent, partially coherent, and incoherent interference". In: *Applied optics* 41.19 (2002), pp. 3978–3987.

- [102] D. Sheet. "Microposit S1800 series photoresists". In: *Shipley Company, Marlborough, MA* (1993).
- [103] R. F. Pease and S. Y. Chou. "Lithography and other patterning techniques for future electronics". In: *Proceedings of the IEEE* 96.2 (2008), pp. 248–270.
- [104] M. McCord and M. Rooks. "SPIE Handbook of Microlithography". In: *Micromachining and Microfabrication* (2000).
- [105] O. Wood et al. "EUV lithography at the 22nm technology node". In: *Extreme Ultraviolet (EUV) Lithography*. Vol. 7636. International Society for Optics and Photonics. 2010, p. 76361M.
- [106] J. Ackermann. "Manual for the SUPRA (VP) and ULTRA Scanning Electron Microscopes". In: *Carl Zeiss SMT Ltd* (2005), p. 15.
- [107] L. Reimer. *Scanning electron microscopy: physics of image formation and microanalysis*. 2000.
- [108] D. McCloskey. "Visible Light Scattering from Micron Scale Silicon Nitride Structures". PhD thesis. Trinity College Dublin, 2012.
- [109] A. Khursheed. *Scanning electron microscope*. US Patent 7,294,834. 2007.
- [110] T. Standaert et al. "High density fluorocarbon etching of silicon in an inductively coupled plasma: mechanism of etching through a thick steady state fluorocarbon layer". In: *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films* 16.1 (1998), pp. 239–249.
- [111] L. Deng and A. Goodyear. "Etching of III-V materials using inductively coupled plasma (ICP) systems". In: *Plasma Technology Process Newsletter* 2 (2004).
- [112] F. Khan and I Adesida. "High rate etching of SiC using inductively coupled plasma reactive ion etching in SF₆-based gas mixtures". In: *Applied physics letters* 75.15 (1999), pp. 2268–2270.
- [113] R. Shul et al. "Inductively coupled plasma etching of GaN". In: *Applied Physics Letters* 69.8 (1996), pp. 1119–1121.
- [114] H. Xu. "Spin Injection, Detection and Magnetoresistive Effects in Organic Systems". PhD thesis. Trinity College Dublin, 2015.
- [115] J. F. Landsbergen and J. Visser. *Magnetron sputtering system*. US Patent 5,868,914. 1999.

- [116] P. Kelly and R. Arnell. "Magnetron sputtering: a review of recent developments and applications". In: *Vacuum* 56.3 (2000), pp. 159–172.
- [117] D. Wang et al. "70% TMR at room temperature for SDT sandwich junctions with CoFeB as free and reference layers". In: *IEEE Transactions on Magnetics* 40.4 (2004), pp. 2269–2271.
- [118] K. S. Harsha. *Principles of vapor deposition of thin films*. Elsevier, 2005.
- [119] M. Todeschini et al. "Influence of Ti and Cr Adhesion Layers on Ultra-thin Au Films". In: *ACS applied materials & interfaces* 9.42 (2017), pp. 37374–37385.
- [120] G. K. Binnig. *Atomic force microscope and method for imaging surfaces with atomic resolution*. US Patent 4,724,318. 1988.
- [121] G. Binnig, C. F. Quate, and C. Gerber. "Atomic force microscope". In: *Physical review letters* 56.9 (1986), p. 930.
- [122] R. Howland, L. Benatar, and P. S. Instruments. *A practical guide to scanning probe microscopy*. Park scientific instruments, 1996.
- [123] P. G. Hartley et al. "Surface forces and deformation at the oil- water interface probed using afm force measurement". In: *Langmuir* 15.21 (1999), pp. 7282–7289.
- [124] A. Lugstein et al. "Fabrication of a ring nanoelectrode in an AFM tip: novel approach towards simultaneous electrochemical and topographical imaging". In: *Surface and interface analysis* 33.2 (2002), pp. 146–150.
- [125] U. Dammer et al. "Binding strength between cell adhesion proteoglycans measured by atomic force microscopy". In: *Science* 267.5201 (1995).
- [126] D. Xu et al. "Electrical conductivity of ferritin proteins by conductive AFM". In: *Nano letters* 5.4 (2005), pp. 571–577.
- [127] T. Junno et al. "Controlled manipulation of nanoparticles with an atomic force microscope". In: *Applied Physics Letters* 66.26 (1995), pp. 3627–3629.
- [128] A. Requicha. "Nanomanipulation with the atomic force microscope". In: *Nanotechnology* (2008).
- [129] A. Majumdar. "Scanning thermal microscopy". In: *Annual review of materials science* 29.1 (1999), pp. 505–585.
- [130] J. Varesi and A. Majumdar. "Scanning Joule expansion microscopy at nanometer scales". In: *Applied Physics Letters* 72.1 (1998), pp. 37–39.

- [131] K. Babcock et al. "Field-dependence of microscopic probes in magnetic force microscopy". In: *Applied physics letters* 69.5 (1996), pp. 705–707.
- [132] L. Burgens. *The Atomic Force Microscopic (AFM) Characterization of Nanomaterials*. Tech. rep. PRAIRIE VIEW A and M UNIV TX COLL OF ENGINEERING, 2009.
- [133] L. G. Parratt. "Surface studies of solids by total reflection of X-rays". In: *Physical review* 95.2 (1954), p. 359.
- [134] W. Bartels, J. Hornstra, and D. Lobeek. "X-ray diffraction of multilayers and superlattices". In: *Acta Crystallographica Section A: Foundations of Crystallography* 42.6 (1986), pp. 539–545.
- [135] J. Daillant and A. Gibaud. *X-ray and neutron reflectivity: principles and applications*. Vol. 770. Springer, 2008.
- [136] R. M. Azzam and N. M. Bashara. *Ellipsometry and polarized light*. North-Holland. sole distributors for the USA and Canada, Elsevier Science Publishing Co., Inc., 1987.
- [137] J. A. Schuller et al. "Plasmonics for extreme light concentration and manipulation". In: *Nature materials* 9.3 (2010), pp. 193–204.
- [138] W. L. Barnes, A. Dereux, and T. W. Ebbesen. "Surface plasmon subwavelength optics". In: *Nature* 424.6950 (2003), pp. 824–830.
- [139] G. Baffou and R. Quidant. "Thermo-plasmonics: using metallic nanostructures as nano-sources of heat". In: *Laser & Photonics Reviews* 7.2 (2013), pp. 171–187.
- [140] A. Hohenau et al. "Surface plasmon leakage radiation microscopy at the diffraction limit". In: *Optics express* 19.25 (2011), pp. 25749–25762.
- [141] J. Homola. "Surface plasmon resonance sensors for detection of chemical and biological species". In: *Chemical reviews* 108.2 (2008), pp. 462–493.
- [142] S. V. Zhukovsky et al. "Photonic-band-gap engineering for volume plasmon polaritons in multiscale multilayer hyperbolic metamaterials". In: *Physical Review A* 90.1 (2014), p. 013801.
- [143] V. E. Babicheva et al. "Finite-width plasmonic waveguides with hyperbolic multilayer cladding". In: *Optics express* 23.8 (2015), pp. 9681–9689.
- [144] E. M. Yeatman. "Resolution and sensitivity in surface plasmon microscopy and sensing". In: *Biosensors and Bioelectronics* 11.6-7 (1996), pp. 635–649.

- [145] M. McMahon et al. "Rapid tarnishing of silver nanoparticles in ambient laboratory air". In: *Applied Physics B: Lasers and Optics* 80.7 (2005), pp. 915–921.
- [146] T. T. Ehler and L. J. Noe. "Surface plasmon studies of thin silver/gold bimetallic films". In: *Langmuir* 11.10 (1995), pp. 4177–4179.
- [147] L. Xia et al. "Sensitivity enhancement for surface plasmon resonance imaging biosensor by utilizing gold–silver bimetallic film configuration". In: *Plasmonics* 6.2 (2011), pp. 245–250.
- [148] Y. Chen et al. "Bimetallic chips for a surface plasmon resonance instrument". In: *Applied optics* 50.3 (2011), pp. 387–391.
- [149] X. Yuan et al. "Sensitivity–stability-optimized surface plasmon resonance sensing with double metal layers". In: *Journal of Optics A: Pure and Applied Optics* 8.11 (2006), p. 959.
- [150] Z. Wang et al. "Stable and sensitive silver surface plasmon resonance imaging sensor using trilayered metallic structures". In: *Analytical chemistry* 86.3 (2014), pp. 1430–1436.
- [151] C. Liu et al. "Bimetallic structure fabricated by laser interference lithography for tuning surface plasmon resonance". In: *Optics express* 16.14 (2008), pp. 10701–10709.
- [152] O. Peña-Rodríguez et al. "Optical properties of Au-Ag alloys: An ellipsometric study". In: *Optical Materials Express* 4.2 (2014), pp. 403–410.
- [153] L. E. Murr et al. "Fabrication of metal and alloy components by additive manufacturing: examples of 3D materials science". In: *Journal of Materials Research and technology* 1.1 (2012), pp. 42–54.
- [154] A. D. Rakić et al. "Optical properties of metallic films for vertical-cavity optoelectronic devices". In: *Applied optics* 37.22 (1998), pp. 5271–5283.
- [155] H. Aouani et al. "Crucial role of the adhesion layer on the plasmonic fluorescence enhancement". In: *ACS nano* 3.7 (2009), pp. 2043–2048.
- [156] D. Woolf, M. Loncar, and F. Capasso. "The forces from coupled surface plasmon polaritons in planar waveguides". In: *Optics express* 17.22 (2009), pp. 19996–20011.
- [157] Z. Chen, I. R. Hooper, and J. R. Sambles. "Grating-coupled surface plasmon polaritons and waveguide modes in a silver-dielectric-silver structure". In: *JOSA A* 24.11 (2007), pp. 3547–3553.

- [158] Y. Fang and M. Sun. "Nanoplasmonic waveguides: towards applications in integrated nanophotonic circuits". In: *Light: Science & Applications* 4.6 (2015), e294.
- [159] L. Novotny and B. Hecht. *Principles of nano-optics*. Cambridge university press, 2012.
- [160] H. Zhao, Y. Li, and G. Zhang. "Study on the performance of bimetallic layer dielectric-loaded surface plasmon polariton waveguides". In: *Journal of Optics* 13.11 (2011), p. 115501.
- [161] S. Lal, S. Link, and N. J. Halas. "Nano-optics from sensing to waveguiding". In: *Nature photonics* 1.11 (2007), pp. 641–648.
- [162] M. Piliarik, H. Vaisocherová, and J. Homola. "Surface plasmon resonance biosensing". In: *Biosensors and Biodetection* (2009), pp. 65–88.
- [163] K. Matsubara, S. Kawata, and S. Minami. "Optical chemical sensor based on surface plasmon measurement". In: *Applied Optics* 27.6 (1988), pp. 1160–1163.
- [164] J. Homola, S. S. Yee, and G. Gauglitz. "Surface plasmon resonance sensors". In: *Sensors and Actuators B: Chemical* 54.1 (1999), pp. 3–15.
- [165] K. Lodewijks et al. "Boosting the figure-of-merit of LSPR-based refractive index sensing by phase-sensitive measurements". In: *Nano letters* 12.3 (2012), pp. 1655–1659.
- [166] E.-M. Erb et al. "Characterization of the surfaces generated by liposome binding to the modified dextran matrix of a surface plasmon resonance sensor chip". In: *Analytical biochemistry* 280.1 (2000), pp. 29–35.
- [167] G. Nenninger et al. "Long-range surface plasmons for high-resolution surface plasmon resonance sensors". In: *Sensors and Actuators B: Chemical* 74.1 (2001), pp. 145–151.
- [168] A. Alparslan and M. Aksun. "Thickness dependent behavior of surface plasmon polaritons in layered media". In: *PhotonicsGlobal@ Singapore, 2008. IPGC 2008. IEEE*. IEEE. 2008, pp. 1–4.
- [169] H. A. Macleod. *Thin-film optical filters*. CRC press, 2017.
- [170] F. Chiadini et al. "Composite surface-plasmon-polariton waves guided by a thin metal layer sandwiched between a homogeneous isotropic dielectric material and a periodically multilayered isotropic dielectric material". In: *Journal of Nanophotonics* 9.1 (2015), pp. 093060–093060.

- [171] K. Kurihara and K. Suzuki. "Theoretical understanding of an absorption-based surface plasmon resonance sensor based on Kretschmann's theory". In: *Analytical chemistry* 74.3 (2002), pp. 696–701.
- [172] J. Homola, I. Koudela, and S. S. Yee. "Surface plasmon resonance sensors based on diffraction gratings and prism couplers: sensitivity comparison". In: *Sensors and Actuators B: Chemical* 54.1 (1999), pp. 16–24.
- [173] K.-S. Lee and M. A. El-Sayed. "Gold and silver nanoparticles in sensing and imaging: sensitivity of plasmon response to size, shape, and metal composition". In: *The Journal of Physical Chemistry B* 110.39 (2006), pp. 19220–19225.
- [174] G. Ju et al. "High density heat-assisted magnetic recording media and advanced characterization—Progress and challenges". In: *IEEE Transactions on Magnetics* 51.11 (2015), pp. 1–9.
- [175] C. Rea et al. "High track pitch capability for HAMR recording". In: *IEEE Transactions on Magnetics* 53.2 (2017), pp. 1–7.
- [176] N. Zhou et al. "Plasmonic near-field transducer for heat-assisted magnetic recording". In: *Nanophotonics* 3.3 (2014), pp. 141–155.
- [177] V. Krishnamurthy et al. "Maximizing the plasmonic near-field transducer efficiency to its limit for HAMR". In: *Journal of Lightwave Technology* 34.4 (2016), pp. 1184–1190.
- [178] B. V. Budaev and D. B. Bogy. "On the lifetime of plasmonic transducers in heat assisted magnetic recording". In: *Journal of Applied Physics* 112.3 (2012), p. 034512.
- [179] S. P. Powell et al. "The influence of media optical properties on the efficiency of optical power delivery for heat assisted magnetic recording". In: *Journal of Applied Physics* 109.7 (2011), 07B775.
- [180] G. Singh et al. "Efficient plasmonic transducer for nanoscale optical energy transfer in heat-assisted magnetic recording". In: *Journal of Lightwave Technology* 32.17 (2014), pp. 3074–3080.
- [181] V. Krishnamurthy et al. "Efficient integrated light-delivery system design for HAMR: Maximal optical coupling for transducer and nanowaveguide". In: *IEEE Transactions on Magnetics* 52.2 (2016), pp. 1–7.
- [182] A. Andryieuski et al. "Direct characterization of plasmonic slot waveguides and nanocouplers". In: *Nano letters* 14.7 (2014), pp. 3925–3929.

- [183] B. Jennings et al. "Characterisation of multi-mode propagation in silicon nitride slab waveguides". In: *Journal of Optics* 19.1 (2016), p. 015604.
- [184] E. Arakawa et al. "Effect of damping on surface plasmon dispersion". In: *Physical Review Letters* 31.18 (1973), p. 1127.
- [185] X. Fan, W. Zheng, and D. J. Singh. "Light scattering and surface plasmons on small spherical particles". In: *Light: Science & Applications* 3.6 (2014), e179.
- [186] R. G. Hobbs et al. "High-yield, ultrafast, surface plasmon-enhanced, Au nanorod optical field electron emitter arrays". In: *ACS nano* 8.11 (2014), pp. 11474–11482.
- [187] D. K. Gramotnev and S. I. Bozhevolnyi. "Nanofocusing of electromagnetic radiation". In: *Nature Photonics* 8.1 (2014), pp. 13–22.
- [188] D. K. Gramotnev. "Adiabatic nanofocusing of plasmons by sharp metallic grooves: Geometrical optics approach". In: *Journal of applied physics* 98.10 (2005), p. 104302.
- [189] P. Berini. "Plasmon-polariton waves guided by thin lossy metal films of finite width: Bound modes of symmetric structures". In: *Physical Review B* 61.15 (2000), p. 10484.
- [190] H. Ditlbacher et al. "Coupling dielectric waveguide modes to surface plasmon polaritons". In: *Optics express* 16.14 (2008), pp. 10455–10464.
- [191] C. Zhong et al. "Mapping of surface plasmon dispersion in thin Ag–Au layered composite films". In: *JOSA B* 33.4 (2016), pp. 566–573.
- [192] R. G. Hobbs et al. "High-energy surface and volume plasmons in nanopatterned sub-10 nm aluminum nanostructures". In: *Nano letters* 16.7 (2016), pp. 4149–4157.
- [193] R. Hobbs et al. "Ultrafast, surface plasmon-enhanced, au nanorod optical field electron emitter arrays". In: *Vacuum Nanoelectronics Conference (IVNC), 2014 27th International*. IEEE. 2014, pp. 16–17.
- [194] T. Zhao et al. *HAMR NFT materials with improved thermal stability*. US Patent 8,427,925. 2013.
- [195] P. K. Jain and M. A. El-Sayed. "Plasmonic coupling in noble metal nanostructures". In: *Chemical Physics Letters* 487.4 (2010), pp. 153–164.
- [196] D. Gérard and S. K. Gray. "Aluminium plasmonics". In: *Journal of Physics D: Applied Physics* 48.18 (2014), p. 184001.

- [197] J. D. Caldwell et al. "Low-loss, extreme subdiffraction photon confinement via silicon carbide localized surface phonon polariton resonators". In: *Nano letters* 13.8 (2013), pp. 3690–3697.
- [198] A. Boltasseva and H. A. Atwater. "Low-loss plasmonic metamaterials". In: *Science* 331.6015 (2011), pp. 290–291.
- [199] G. V. Naik, V. M. Shalaev, and A. Boltasseva. "Alternative plasmonic materials: beyond gold and silver". In: *Advanced Materials* 25.24 (2013), pp. 3264–3294.
- [200] B. Dastmalci et al. "A new perspective on materials for plasmonics". In: *arXiv preprint arXiv:1604.07389* (2016).
- [201] A. Grigorenko, M. Polini, and K. Novoselov. "Graphene plasmonics". In: *Nature photonics* 6.11 (2012), pp. 749–758.
- [202] J. Wong et al. "High Photovoltaic Quantum Efficiency in Ultrathin van der Waals Heterostructures". In: *ACS nano* (2017).
- [203] M. W. Knight et al. "Aluminum for plasmonics". In: *ACS nano* 8.1 (2013), pp. 834–840.
- [204] T. Kelly et al. *Historical statistics for mineral and material commodities in the United States*. Tech. rep. US Geological Survey, 2005.
- [205] A. V. Krasavin and A. V. Zayats. "Silicon-based plasmonic waveguides". In: *Optics express* 18.11 (2010), pp. 11791–11799.
- [206] M. W. Knight et al. "Aluminum plasmonic nanoantennas". In: *Nano letters* 12.11 (2012), pp. 6000–6004.
- [207] Y. Nishijima and S. Akiyama. "Unusual optical properties of the Au/Ag alloy at the matching mole fraction". In: *Optical Materials Express* 2.9 (2012), pp. 1226–1235.
- [208] Y. Nishijima et al. "Engineering gold alloys for plasmonics". In: *Applied Physics A* 117.2 (2014), pp. 641–645.
- [209] F. Habashi. *Alloys: preparation, properties, applications*. John Wiley & Sons, 2008.
- [210] Y. Hashimoto et al. "Au-Ag-Cu nano-alloys: tailoring of permittivity". In: *Scientific reports* 6 (2016), p. 25010.
- [211] P. G. Etchegoin, E. Le Ru, and M Meyer. "An analytic model for the optical properties of gold". In: *The Journal of chemical physics* 125.16 (2006), p. 164705.

- [212] I. A. Starkov and A. S. Starkov. "The thickness dependence of dielectric permittivity in thin films". In: *Journal of Physics: Conference Series*. Vol. 741. 1. IOP Publishing. 2016, p. 012004.
- [213] H. Kim. "Atomic layer deposition of metal and nitride thin films: Current research efforts and applications for semiconductor device processing". In: *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena* 21.6 (2003), pp. 2231–2261.
- [214] D. Marshall and A. Evans. "Measurement of adherence of residually stressed thin films by indentation. I. Mechanics of interface delamination". In: *Journal of Applied Physics* 56.10 (1984), pp. 2632–2638.
- [215] H. Deng et al. *Adhesion layer for thin film magnetic recording medium*. US Patent 7,964,297. 2011.
- [216] A. A. Talin et al. "Tunable electrical conductivity in metal-organic framework thin-film devices". In: *Science* (2013), p. 1246738.
- [217] M. N. Hamidon et al. "Fabrication of high temperature surface acoustic wave devices for sensor applications". In: *Sensors and Actuators A: Physical* 123 (2005), pp. 403–407.
- [218] T. Aubert et al. "Study of tantalum and iridium as adhesion layers for Pt/LGS high temperature SAW devices". In: *Ultrasonics Symposium (IUS), 2009 IEEE International*. IEEE. 2009, pp. 1672–1675.
- [219] A. G. Brolo. "Plasmonics for future biosensors". In: *Nature Photonics* 6.11 (2012), pp. 709–713.
- [220] C.-Y. Chen et al. "Asymmetric coupling between subradiant and super-radiant plasmonic resonances and its enhanced sensing performance". In: *Optics express* 17.17 (2009), pp. 15372–15380.
- [221] S. V. Jayanti et al. "Low-temperature enhancement of plasmonic performance in silver films". In: *Optical materials express* 5.5 (2015), pp. 1147–1155.
- [222] D. Lantiat et al. "Evidence for capping-layer effects on the morphology and plasmon excitation of Ag nanoparticles". In: *Journal of Applied Physics* 102.11 (2007), p. 113518.
- [223] M. Brands, B Leven, and G Dumpich. "Influence of thickness and cap layer on the switching behavior of single Co nanowires". In: *Journal of applied physics* 97.11 (2005), p. 114311.

- [224] G. A. Bertero et al. *Energy assisted magnetic recording medium capable of suppressing high DC readback noise*. US Patent 8,743,666. 2014.
- [225] W. Ma et al. "Thermally stable, efficient polymer solar cells with nanoscale control of the interpenetrating network morphology". In: *Advanced Functional Materials* 15.10 (2005), pp. 1617–1622.
- [226] S. Sellner et al. "Strongly enhanced thermal stability of crystalline organic thin films induced by aluminum oxide capping layers". In: *Advanced Materials* 16.19 (2004), pp. 1750–1753.
- [227] M. R. Querry. *Optical constants*. Tech. rep. MISSOURI UNIV-KANSAS CITY, 1985.
- [228] M. Farzaneh et al. "CCD-based thermorefectance microscopy: principles and applications". In: *Journal of Physics D: Applied Physics* 42.14 (2009), p. 143001.
- [229] C. Schmidt, F Altmann, and O Breitenstein. "Application of lock-in thermography for failure analysis in integrated circuits using quantitative phase shift analysis". In: *Materials Science and Engineering: B* 177.15 (2012), pp. 1261–1267.
- [230] K. Yazawa, D. Kendig, and A. Shakouri. "Time-resolved thermorefectance imaging for thermal testing and analysis". In: *Int. Symp. Testing and Failure Analysis*. 2013, pp. 194–202.
- [231] D. Pierścińska et al. "CCD thermorefectance spectroscopy as a tool for thermal characterization of quantum cascade lasers". In: *Semiconductor Science and Technology* 31.11 (2016), p. 115006.
- [232] D. Pierścińska, K. Pierściński, and M. Bugajski. "CCD thermorefectance for thermal characterization of optoelectronic devices". In: *Mixed Design of Integrated Circuits and Systems (MIXDES), 2011 Proceedings of the 18th International Conference*. IEEE. 2011, pp. 393–397.
- [233] P. P. M. Mayer. "High-density thermoelectric power generation and nanoscale thermal metrology". PhD thesis. Massachusetts Institute of Technology, 2007.
- [234] P. M. Mayer et al. "Theoretical and experimental investigation of the thermal resolution and dynamic range of CCD-based thermorefectance imaging". In: *JOSA A* 24.4 (2007), pp. 1156–1163.

- [235] S. Grauby et al. "High resolution photothermal imaging of high frequency phenomena using a visible charge coupled device camera associated with a multichannel lock-in scheme". In: *Review of Scientific Instruments* 70.9 (1999), pp. 3603–3608.