Structural, Optical, and Electrical Properties of Silver Gratings Prepared by Nanoimprint Lithography of Nanoparticle Ink

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Abstract

A facile method for fabrication of silver gratings using silver nanoparticle ink and nanoimprint lithography is investigated. The properties of silver nanoparticle ink grating and planar samples, with and without a PMMA layer, are compared with thermally evaporated silver on nanoimprinted PMMA. The grating pattern is successfully fabricated using nanoimprint lithography with the silver nanoparticle ink directly on a glass substrate and on a PMMA layer. We find that the use of PMMA adversely affects the structural, optical and electrical properties of the silver nanoparticle planar surfaces and gratings. Gratings nanoimprinted directly into silver nanoparticle ink on a glass substrate are found to have similar performance to gratings produced by thermal evaporation of silver on nanoimprinted PMMA and benefit from an easier fabrication process. The silver nanoparticle ink shows promise for the fabrication of patterned silver thin films and may be useful for upscaling and roll-to-roll processes.

Keywords: nanoimprint lithography, gratings, nanoparticle, silver, ink
<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Description</th>
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<tr>
<td>Ag</td>
<td>Silver</td>
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<tr>
<td>AgNPI</td>
<td>Silver Nanoparticle Ink</td>
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<tr>
<td>FIrpic</td>
<td>Bis<a href="picolinato">2-(4,6-difluorophenyl)pyridinato_C2,N</a>iridium(III)</td>
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<td>NIL</td>
<td>Nanoimprint Lithography</td>
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<td>PDMS</td>
<td>Polydimethylsiloxane</td>
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<td>PMMA</td>
<td>Poly(methylmethacrylate)</td>
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<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
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<tr>
<td>PVK</td>
<td>Poly(9-vinylcarbazole)</td>
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<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
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<td>TE</td>
<td>Thermal Evaporation</td>
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1. Introduction

Metasurfaces are novel, nanostructured, thin-film, synthetic materials that can be used to manipulate and confine electromagnetic radiation and achieve properties that are not normally achievable in nature. They are lightweight, ultracompact and ultrathin and can be incorporated into optoelectronic devices and biosensors, (e.g., novel wave-guiding structures, solar cells, miniaturised cavity resonators, electronic switches, glucose and blood oxygen level measurements) to improve their efficiency and overcome limitations of conventional optical devices [1]–[3].

Current methods of fabrication can be expensive, time consuming, energy inefficient, and require specialised equipment (i.e., vacuum chambers, clean rooms, highly trained personnel, and high precision). These methods can also cause damage to surrounding areas of the surface. Fabrication methods include direct-write (electron-beam, focused ion beam, and laser) and pattern-transfer lithography [4]–[10]. Nanoimprint lithography (NIL) was introduced by Chou et al. [11] as a low-cost, high throughput alternative to UV-lithography and other direct-write lithography processes for the fabrication of metasurfaces [12]. This conventional method of using NIL involves imprinting a mould into PMMA and coating the transferred pattern with a thermally evaporated metal. However, it is not without challenges. It can be difficult to fabricate the high-resolution mould required for the pattern transfer, and a residual imprint layer can be left behind on the nanostructures.

To overcome some of these limitations, inkjet printing was introduced [13], using metallic inks to print desired patterns. Inkjet printing, like NIL, can be considered a cheap process, and a good example of another use for nanoparticle metallic ink. However, it is also not without limitations, e.g., particles can easily agglomerate, the nozzle can get plugged with larger particles, the printed metal films can have high contact resistance and there can be poor flatness of the surface of the printed film. NIL has been used for the fabrication of nanostructures, using metallic ink. However, in the past, the silver ink has been spin coated onto the mould and imprinted onto the substrate using pressure. The sample is then demoulded and heat treated [14], [15]. Herein, we report on a solution-based process, using NIL and metallic ink for fabrication of silver gratings where the metallic ink is placed on to the substrate and heat treated before demoulding. The optical and electrical properties of silver gratings fabricated using this method are shown to favourably compare with those fabricated using the more
conventional NIL method [16]. Additionally, this approach does not require specialised equipment, is potentially more energy efficient, cheaper and less time consuming that more conventional NIL methods.

2. Materials and Methods

2.1. Materials

The composition of the silver ink with nanoparticle size < 10 nm in diameter is as follows: silver, dispersion, nanoparticle, 50 – 60 wt. % in tetradecane, spec. resistivity ~ 2.7 µΩ cm for printing on polyimide films (Sigma Aldrich, product code: 736503). Poly(methylmethacrylate) (PMMA), with a molecular weight ($M_\text{w}$) ~ 120,000 g/mol by Gel Permeation Chromatography (GPC) and methanol, HPCL grade, were also purchased from Sigma-Aldrich. Corning cover glass no. 1 thickness, 22 mm x 22 mm (Sigma-Aldrich), were cleaned by immersion in a methanol:HCl 1:1 mixture for ten minutes, then rinsed in deionised (DI) water (Sigma Aldrich), twice, before being rinsed in isopropanol (IPA) (HPLC grade, Sigma-Aldrich). Hydrochloric acid was purchased from Merck. Polydimethylsiloxane (PDMS; Sylgard®184, Sigma-Aldrich) was used in the fabrication of the mould, and the grating structure on compact discs (Verbatim CD-R, Radionics) were used as the master grating pattern from which the PDMS mould patterns were formed.

2.2. Methods

To create the grating, a blank compact disc (CD) was cleaned by removing the foil, and then submerging the CD in a methanol:HCl 10:1 mixture for ten minutes. The CD was then rinsed in DI water three times, before rinsing in IPA. To ensure all coatings were removed the CD surface was inspected using a bright-field microscope. Once cleaned, the CD was placed, grating side up, in a clean Pyrex dish. PDMS was mixed by hand constantly for ten minutes, to ensure effective cross-linking, and subsequently, the viscous PDMS was poured onto the CD. The PDMS-coated CD was then placed in an ambient condition oven at 130 °C for 30 minutes to cure the mould. The Pyrex dish was removed from the oven and allowed to cool to room temperature before a section of the PDMS was cut and carefully peeled from the CD. A planar (flat) PDMS mould was also fabricated by pouring the PDMS onto a cleaned microscope slide, which enabled the fabrication of planar Ag films from silver ink. This mould was cured under the same conditions.

A PMMA solution, with a concentration of 5 wt. % in chloroform, was spin coated onto cleaned glass cover slips using the following dynamic spin coating parameters: 6000 RPM, 60 seconds, and 40 µL of PMMA
solution. To make the PMMA solution, a small PTFE-coated stir bar was added to a small amber vial. 150 mg of PMMA powder was added to the vial, with 3 mL of chloroform. The vial was sealed with a lid and Parafilm and placed into a water bath heated to 45 °C and stirred at a rate of 1000 RPM for 20 minutes. After 20 minutes, the heat was turned off and the solution was allowed to cool to room temperature before being removed from the water bath. The solution was stored at room temperature until required [17].

Ag grating and planar surfaces were created using the following methods: (i) imprinting the AgNPI on a glass substrate by the PMDS mould (grating/planar) and subsequent thermal annealing (AgNPI); (ii) as with (i), but on a PMMA-coated glass substrate (AgNPI/PMMA); and (iii) imprinting a PMMA-coated glass substrate using the PDMS mould (grating/planar) and subsequent thermal evaporation (TE) of Ag onto the imprinted PMMA (TE Ag/PMMA). The details of each method are described in detail below.

To create samples using method (i), as shown in Figure 1, a ~ 60 µL drop of room temperature AgNPI was placed onto a cleaned glass cover slip, leading to a thickness of ~ 800 nm, measured by ellipsometry. The PDMS mould (grating/planar) was placed on top, imprint side down, and the sample was placed between two aluminium plates, each weighing 50 g. Extra weights, totalling 1.35 kg, were placed on top to facilitate mould transfer. The sample was then placed in an ambient condition oven for three hours at 180 °C to anneal the ink. These conditions were chosen after testing various temperatures and times (see Figure S1 and the related explanation in the Supporting Information). They allowed enough time for solvents to evaporate and for the ink to anneal, with minimal cracking to the metallic ink. The samples were allowed to cool to room temperature in the oven before being removed. This limited thermal shock cracking of the metallic ink. The PDMS mould was peeled off the Ag layer, revealing an Ag grating. The procedure for the AgNPI planar thin film is shown in Supporting Information Figure S4.
Figure 1: Schematic of the NIL process for fabrication of AgNPI grating using method (i). A drop of room temperature AgNPI is placed onto a cleaned glass coverslip. The PDMS mould, cut from the original large template, is placed on top of the AgNPI, imprint side down. This is placed between two Al plates, with extra weights added to ensure grating pattern transfer. It is subsequently annealed at 180 °C for three hours in an ambient condition oven. After annealing the oven is turned off and the sample is allowed to cool to room temperature before removed. The PDMS mould is then peeled off, revealing an Ag grating.

To create samples using method (ii), a 1.3 µm thick layer of PMMA was spin coated onto cleaned glass coverslips. The drop of room temperature AgNPI was placed on the PMMA-coated coverslip and the PDMS mould (grating/planar) placed on top, as shown in Supporting Information Figures S2 and S5. The rest of the procedure is identical to method (i).

To fabricate samples using method (iii), PMMA was spin coated onto clean glass coverslips. The PDMS mould (grating/planar) was placed directly onto the PMMA. The subsequent steps are the same as for method (i), except that the sample is placed in an ambient condition oven at 170 °C for two and a half hours [18]. These samples were allowed to cool to room temperature in the oven before being removed, and subsequently, the PDMS mould was peeled off the PMMA film. An ~ 100 nm thick Ag films was deposited by thermal evaporation under vacuum (3 x 10^-6 Torr), at a rate of 1 Å/s for ~ 20 minutes, as seen in Supporting Information Figures S3 and S6.

For the photoluminescence studies, PVK:Flrpic was spin coated onto all Ag surface. PVK:Flrpic was prepared using the following protocol: 0.036 g of poly(9-vinylcarbazole) (PVK) and 1 mL of chlorobenzene were added to a small amber vial. A PTFE-coated stir bar was also added to the vial. The vial was sealed with a lid and Para film and placed in a water bath heated to 40 °C and stirred at 1000 RPM for ten minutes. 0.004 g of bis[2-
(4,6-difluorophenyl)pyridinato-C^2,N](picolinato)iridium(III) (FIrpic) and 1 mL of chlorobenzene were added to a small amber vial. A PTFE-coated stir bar was also added to the vial. The vial was then sealed with a lid and Para film and placed in a water bath heated to 40 °C and stirred at 1000 RPM for ten minutes. These stock solutions were allowed to cool to room temperature in the water bath and then wrapped in aluminium foil, without removing the Para film sealing the lid, and stored at room temperature until used. To make a useable solution of PVK:FIrpic, equal amounts of the stock solutions were added to an amber vial with a PTFE-coated stir bar. The vial was sealed with a lid and Para film. It was then placed in a water bath heated to 40 °C and stirred at 1000 RPM for ten minutes. The following dynamic spin coating protocol was used: 100 µL PVK:FIrpic solution was dropped on to the substrate at 2000 RPM and spun for 25 seconds, producing a film thickness of ~ 62 ± 8.1 nm. The samples were then allowed to dry at room temperature, overnight, in the dark.

Four-point probe measurements were carried out on all samples. Ossila Sheet Resistance Measurement Software was used to calculate the conductivity of the samples. In order to convert from sheet resistance to conductivity, the software requires the dimensions of the sample, e.g., length, width, and thickness. This allows the software to use appropriate geometrical correction factors when calculating the conductivity of the sample, and to ensure accurate results are obtained.

2.3. Characterisation

Throughout the fabrication process the CD, moulds and samples were inspected using bright-field optical microscopy (Leitz Optical Microscope) to assess the surface for artefacts or damage caused during the cleaning and fabrication processes, and to ensure good quality pattern transfer. To analyse the microstructure of the grating, scanning electron microscopy (SEM) (SEM Zeiss Ultra) and atomic force microscopy (AFM) (AFM Asylum MFP-3D) were employed. To determine the depth of the grating from the AFM images, Gwyddion 2.53 image analysis software was used to plot line profiles of the gratings. It was also used to reconstruct 3D images of all surfaces, including the CD, and the PDMS mould.

UV/Visible spectroscopy (PE Lambda 650 S) was used to determine the reflectance and transmittance of the fabricated surfaces over a broad wavelength range, at normal incidence. The integrating sphere detector collects both specular and diffuse reflection (R) and diffuse transmission (T). From these spectra the absorption (A) of the samples can be calculated using:

\[ A = \frac{1 - T}{R} \]
Angle-resolved reflectance spectra were collected by a home-built setup. The angles were measured from 10° to 70° with a collimated incident light beam. The photoluminescence studies were carried out to determine if the nanoparticle ink and/or thermally evaporated Ag structures caused enhancement or quenching of a photoemissive layer. The photoluminescence mapping (Andor) was performed using an excitation wavelength of 405 nm, a 450 nm long pass filter, a 100X objective and a 0.5 second integration time. To obtain the photoluminescence spectra (Edinburgh Instruments FS5), an excitation wavelength of 365 nm, a step size of 0.5 nm and an integration time of 0.5 seconds were used. During emission scan set up, emission correction and background subtraction were selected. The resulting measurement is a true spectrum, undistorted by instrumental effects.

3. Results and Discussion

3.1. Structural Characterisation

The gratings were fabricated according to methods (i), (ii), and (iii) using a CD with a grating pattern with a nominal period of 1.6 µm, as described in Section 2.2.
Figure 2: SEM images showing: (A) AgNPI grating; (B) AgNPI/PMMA grating; (C) TE Ag/PMMA grating; (D) AgNPI planar surface; (E) AgNPI/PMMA planar surface; and (F) TE Ag/PMMA planar surface. All surfaces were fabricated on a glass substrate.

Bright-field microscopy, shown in Supporting Information Figure S7 (A-C), confirms good transfer of the grating pattern is achieved for the three fabrication methods. Supporting Information Figure S7 (D-F) shows that a planar surface is also achieved. SEM measurements seen in Figure 2A-F, and in Supporting Information Figure S8 confirm these observations.

Further inspection of both the grating and planar surfaces using SEM, as shown in Figure 2, reveals the nanoparticle ink samples have a rougher surface than those fabricated using thermal evaporation. The nanoparticles in the ink have a diameter ~ 10 nm; however, particle size analysis shows a range of nanoparticle diameters from ~11 nm to >– 200 nm. This suggests nanoparticle clustering occurs during the annealing process. This effect is even more evident for the samples prepared with a PMMA layer, as seen in Figure 2B and 2E. It is thought that during the annealing step, the PMMA and AgNPI amalgamate. In Figure S9, a cross-section of the grating samples fabricated with AgNPI shows that there is a rougher surface, more clustering and that the clustering of Ag nanoparticles penetrates further in the AgNPI/PMMA sample, leading to the possibility that the AgNPI/PMMA mixture has changed the properties of the Ag. The larger distribution of particle sizes results in a rougher surface for both the AgNPI/PMMA grating and the planar surfaces, when compared to those prepared using thermally evaporated Ag and PMMA. This is also evident in Supporting Information Figure S7.

The pitting observed in the planar surfaces in Figure 2E and 2F and Supporting Information Figure S6 may arise during the fabrication of the PDMS mould. The PDMS moulds were examined using bright-field microscopy before use, but pitting/bubbles were not seen. It may be possible to eliminate these features by using a vacuum oven when fabricating the PDMS mould, with periodic degassing to burst the bubbles [19], [20].
Figure 3: AFM 3D representation of: (A) CD; (B) PDMS mould; (C) AgNPI grating; (D) AgNPI/PMMA grating; (E) TE Ag/PMMA grating; (F) AgNPI planar surface; (G) AgNPI/PMMA planar surface; and (H) TE Ag/PMMA planar surface. All surfaces were fabricated on a glass substrate.

Topographic AFM was carried out on the CD, PDMS mould, and all fabricated samples. From these AFM images, the morphology of the samples, and the difference in the surface roughness, particularly in the planar samples, could be seen. 3D topographical representations, are shown in Figure 3, with line profiles shown in Supporting Information Figure S10. Figure 3 also shows that good transfer of the grating pattern is clearly observed. The pitting evident in the SEM images can also be seen in the AFM measurements on all the planar surfaces. From the line profiles, the period of the grating, the depth of the ridges and the space between the grating ridges can be determined and are given in Table 1. The AFM data again confirms that the surface of the AgNPI samples is rougher than those prepared with thermal evaporation of Ag.

Figure 4: Schematic of a silver grating on a glass substrate, depicting the period, ‘d’, and the space between grating ridges, ‘a’. These measurements are obtained for each grating and shown in Table 1.
Table 1: Average period (d), height, and space between grating ridges (a) measured using AFM line profiles see in Supporting Information Figure S7. To measure the space between grating ridges, the midpoint of the peak and trough was used.

Table 1 shows a comparison between the dimensions of the original grating from the CD, and the three fabricated gratings. A difference in the spaces between ridges for the PDMS mould and the CD and fabricated gratings is attributed to the fact that the PDMS mould is an inverse of the CD grating. Therefore, the space between the ridge seen in the CD, or any of the grating samples, will correspond to the thickness of the ridges in the mold.

3.2. Optical Characterisation

UV/Visible spectroscopy was carried out on all fabricated surfaces over a wavelength range from 400 nm to 800 nm using an integrating sphere detector. Reflectance and transmittance spectra were measured, and the absorbance spectra were calculated using Equation 1, and are shown in Figure 5. For comparison with the experimental spectra, the reflectance spectrum of an Ag planar surface was calculated using Equation 2 below:

\[ R = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2} \]  

(2)

where \( n \) and \( k \) are the real and imaginary (extinction coefficient) parts of the complex refractive index of silver, respectively [21]. The Ag layer is optically thick, with almost zero transmittance across the spectral range (not shown). Looking firstly at the planar samples, Figure 5C and 5D, it can be seen that the reflectance for all samples is lower than for an ideal planar Ag surface, with the reflectance of the TE Ag/PMMA sample closest to the ideal case. This sample has significantly higher reflectance than the AgNPI surfaces. While the reflectance is lower for the AgNPI sample, it has the same overall trend as a function of wavelength.
reflectance is lowest for the AgNPI/PMMA, and, in contrast with the other samples, it shows decreasing intensity at longer wavelengths. The lower measured reflectance for the planar samples may be attributed to surface roughness and the presence of the Ag nanoparticles resulting in higher absorption as seen in Figure 5B and 5D [22].

The grating samples have similar spectral dependence, Figure 5A and 5B, with highest reflectance observed for the thermally evaporated Ag sample. However, in contrast to the planar samples, there is less variation in the overall magnitude of the reflectance and absorbance between the Ag gratings prepared by the different methods. Additionally, the peaks and troughs in the spectra of the AgNPI and TE Ag/PMMA gratings occur at similar wavelengths indicating that the gratings are interacting with the incident light in a similar way. The peaks are less well-resolved for the AgNPI/PMMA grating and occur at different wavelengths compared to the other two gratings.
Figure 5: UV/Visible reflectance and absorbance spectra: (A) Reflectance for grating samples; (B) Absorbance for grating samples; (C) Experimental and theoretical reflectance for planar samples; (D) Experimental and theoretical absorbance for planar samples; AgNPI fabricated using method (i); AgNPI/PMMA fabricated using method (ii); and TE Ag/PMMA fabricated using method (iii).

The angle dependence of the reflectance spectra is shown in Figure 6. The reflectance spectra of TE Ag/PMMA grating show clear dips in intensity at larger angles and well-defined peaks that can be seen at small angles (Figure 6C). These spectral features are likely due to diffraction by the gratings that reduces specular reflection and/or coupling to propagating surface plasmon modes [23]–[25]. However, the spectra for the AgNPI grating sample show the dips in intensity to be red-shifted and weaker (Figure 6A), with little spectral structure evident in the case of the AgNPI/PMMA grating (Figure 6B). In particular, the AgNPI/PMMA planar surface shows no significant angle dependence of the reflectance spectrum. It is notably different to the other two planar samples. The shape of the spectrum of the corresponding planar AgNPI/PMMA sample is typical of localised surface plasmon resonance scattering from Ag nanoparticles. This is consistent with the large nanoparticles observed on the surface in Figure 2E. From the angle resolved data, it is apparent that TE Ag/PMMA (both planar and grating) have better optical quality (high reflectance, well-resolved grating response) than the AgNPI and AgNPI/PMMA samples; however, the reflectance of the AgNPI grating shows significantly better optical quality than the AgNPI/PMMA grating.
Figure 6: Angle resolved reflectance, where specular reflection was measured. Here, the incident angle is kept equal to the detection angle. (A) AgNPI grating; (B) AgNPI/PMMA grating; (C) TE Ag/PMMA grating; (D) AgNPI planar surface; (E) AgNPI/PMMA planar surface; and (F) TE Ag/PMMA planar surface.

It is also of interest, for light-emitting and sensing applications, to assess how the grating modifies the emission of a proximal light-emitting layer. PVK:Flrpic was spin coated onto each sample as an ~62 nm thick photo-emissive layer. Photoluminescence (PL) maps, shown in Figure 7, show non-uniform emission over the whole area for the AgNPI/PMMA and AgNPI planar samples, typical of the effect of surface roughness. More discrete regions of increased emission were observed for the TE Ag/PMMA sample, consistent with the pitting observed in the bright-field and SEM images. In the case of the grating samples, the PL intensity is lowest for the AgNPI samples, and highest for the TE Ag/PMMA grating.

To further compare the effect of the gratings on emission, PL spectra of PVK:Flrpic on the different surfaces are shown in Figure 8. A reference spectrum of the photo-emissive layer on a cleaned glass cover slip was also taken for comparison. Figure 8 shows that the emission of the photo-emissive layer is enhanced by a factor of ~1.8 on the grating TE Ag/PMMA sample and a factor of ~1.3 on the planar TE Ag/PMMA sample. However, in contrast, the emission is always partially quenched for the AgNPI samples, with the AgNPI samples
quenching more than the AgNPI/PMMA samples. In all cases, there is no significant modification of the spectral shape of the emitter. The quenching is consistent with the higher absorbance for the AgNPI samples observed in Figure 5. In particular, the AgNPI samples have ~10 nm diameter Ag nanoparticles, which absorb EM energy, but do not scatter efficiently, contributing to these samples having the highest quenching.

Figure 7: Photoluminescence maps of: (A) AgNPI grating; (B) AgNPI/PMMA grating; (C) TE Ag/PMMA grating; (D) AgNPI planar surface; (E) AgNPI/PMMA planar surface; and (F) TE Ag/PMMA planar surface.

Figure 8: Photoluminescence spectra. (A) Grating samples; (B) Planar surface samples, both with a glass cover slip coated with PVK:F1rpic as a reference. Emission correction and background subtraction do not modify the shape of the spectra.
Ag grating metasurfaces can play a dual role in optoelectronic devices, allowing for the manipulation of EM radiation as well as being an electrical contact. Known conductivity of the thermally evaporated Ag and the AgNPI were compared to those obtained from four-point probe measurements, with the data presented in Tables 2 and 3. For all methods of fabrication, the conductivity of the grating sample is similar to the planar sample, showing that the formation of the grating structure has not adversely affected the electrical properties. However, it can be noted that the conductivity for all samples using PMMA, which can act as an insulator [26], [27], is an order of magnitude lower than for the AgNPI only samples.

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<tr>
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<th>AgNPI</th>
<th>Grating AgNPI</th>
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<td>Average (S/m)</td>
<td>3.7 \times 10^7</td>
<td>1.548 \times 10^7 S/m</td>
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<td>\pm 0.008 x 10^7 S/m</td>
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*Table 2: Conductivity measurements for samples fabricated using AgNPI.*

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<th>Silver [29]</th>
<th>Grating, TE Ag/PMMA</th>
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<tr>
<td>Average (S/m)</td>
<td>6.3 x 10^7 S/m</td>
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<td>\pm 0.02 x 10^6 S/m</td>
<td>\pm 0.09 x 10^6 S/m</td>
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*Table 3: Conductivity measurements for samples fabricated using conventional method.*

4. Conclusion

A facile method for the fabrication of Ag thin film grating using silver nanoparticle ink in conjunction with nanoimprint lithography, without the need for specialised equipment, has been investigated. The structural, optical and electrical properties of the AgNPI have been compared with those fabricated using a more conventional method of NIL in PMMA followed by thermal evaporation of an Ag film. Bright-field microscopy showed good grating transfer using all methods of fabrication. However, the samples made with the AgNPI had a rougher surface, as seen in SEM and AFM 3D representations and line profiles, and those fabricated with AgNPI/PMMA showed a larger variance in nanoparticle size. Samples fabricated using AgNPI...
showed lower reflectance and higher absorption, in particular, for the AgNPI/PMMA sample. The presence of the Ag nanoparticles also resulted in PL quenching of a proximal emitting layer. Grating AgNPI samples showed an increased conductivity compared with ideal planar Ag but the use of PMMA resulted in an order of magnitude decrease in the conductivity for both AgNPI/PMMA and TE Ag/PMMA samples. The fabrication of the grating structures did not adversely affect the conductivity compared with a planar sample for any of the fabrication methods investigated. It can be concluded that using AgNPI shows promise for the fabrication of Ag structured thin films and may be useful for upscaling and roll-to-roll processes. The use of PMMA could be eliminated from the fabrication method as it adds an extra step to the fabrication method and does not enhance any characteristics of the Ag grating thin films.
Declaration of Competing Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References


[29] “Silver, Ag.”