



Terms and Conditions of Use of Digitised Theses from Trinity College Library Dublin

Copyright statement

All material supplied by Trinity College Library is protected by copyright (under the Copyright and Related Rights Act, 2000 as amended) and other relevant Intellectual Property Rights. By accessing and using a Digitised Thesis from Trinity College Library you acknowledge that all Intellectual Property Rights in any Works supplied are the sole and exclusive property of the copyright and/or other IPR holder. Specific copyright holders may not be explicitly identified. Use of materials from other sources within a thesis should not be construed as a claim over them.

A non-exclusive, non-transferable licence is hereby granted to those using or reproducing, in whole or in part, the material for valid purposes, providing the copyright owners are acknowledged using the normal conventions. Where specific permission to use material is required, this is identified and such permission must be sought from the copyright holder or agency cited.

Liability statement

By using a Digitised Thesis, I accept that Trinity College Dublin bears no legal responsibility for the accuracy, legality or comprehensiveness of materials contained within the thesis, and that Trinity College Dublin accepts no liability for indirect, consequential, or incidental, damages or losses arising from use of the thesis for whatever reason. Information located in a thesis may be subject to specific use constraints, details of which may not be explicitly described. It is the responsibility of potential and actual users to be aware of such constraints and to abide by them. By making use of material from a digitised thesis, you accept these copyright and disclaimer provisions. Where it is brought to the attention of Trinity College Library that there may be a breach of copyright or other restraint, it is the policy to withdraw or take down access to a thesis while the issue is being resolved.

Access Agreement

By using a Digitised Thesis from Trinity College Library you are bound by the following Terms & Conditions. Please read them carefully.

I have read and I understand the following statement: All material supplied via a Digitised Thesis from Trinity College Library is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of a thesis is not permitted, except that material may be duplicated by you for your research use or for educational purposes in electronic or print form providing the copyright owners are acknowledged using the normal conventions. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone. This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

The Development of a Surface Acoustic Wave Strain Sensor



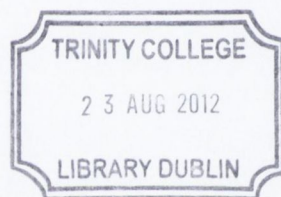
Brian Donohoe

Department of Mechanical and Manufacturing Engineering

University of Dublin

A thesis submitted to the University of Dublin in partial fulfilment of
the requirements for the degree of Doctor of Philosophy

2011



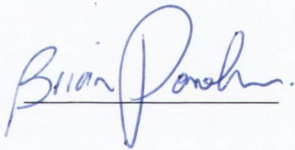
Thesis 9540

Declaration

I declare that the work in this thesis is, unless otherwise stated, entirely my own work and has not been submitted as an exercise for a degree at this or any other University. I agree that Trinity College Library may lend or copy this thesis upon request.

Brian Donohoe

March 2011

A handwritten signature in blue ink, reading "Brian Donohoe", written over a horizontal line.

Abstract

Multi sensors networks are becoming increasingly prevalent in modern engineering applications. In multi sensor networks, wireless sensors are preferred over traditional wired methods. Sensors based upon the surface acoustic wave resonators (SAWR) are often identified as a potential candidate to act as wireless and passive strain sensors. This thesis details the design, fabrication, modelling, calibration and packaging of SAW strain sensors as a general purpose modular strain sensor. The motivation of this work is to develop an understanding of the practical implementation of SAWR strain sensors for real world applications. Through collaboration with an industrial organisation a SAWR strain sensor suitable for wireless sensing was integrated into a commercial wireless SAWR temperature interrogation platform. The sensors were then calibrated through a modified version of the American standard test methods for performance characteristics of bonded resistance strain gages, for a range of temperatures and loading conditions. Experimental results were correlated against existing modelling techniques using a novel method for the validation of SAWR strain sensors. Over the course of the work a range of adhesive were tested to provide a rigorous assessment of SAWR as strain sensors. The prototype bare die sensors were then packaged to form a modular SAWR strain sensor. This thesis provides an in-depth discussion on the development of SAWR as strain sensors, it is hoped that the approach taken within will aid future work in the development of a SAWR strain sensor.

Publications

- B. Donohoe, B. McCormack, D. Geraghty and G.E O'Donnell, "An investigation into the development of Surface Acoustic Wave (SAW) Devices as strain sensors", 24th International Manufacturing Conference, DIT, September 2008
- B. Donohoe, D. Geraghty and G.E O'Donnell, "The Development of a standardised testing and calibration procedure for surface acoustic wave resonators (SAWR) strain sensors", 25th International Manufacturing Conference, TCD, September 2009
- B. Donohoe, G.E O'Donnell and D. Geraghty, "Surface acoustic wave (SAW) sensors, the development of a versatile sensor", 4M/ICOMM 2009 Conference, Forschungszentrum Karlsruhe, September 2009
- B. Donohoe, D. Geraghty and G.E O'Donnell, "Surface Acoustic Wave (SAW) Sensors: Passive Wireless Sensing", WISEN 1 Day research colloquium, Dublin, April 2010
- B. Donohoe, D. Geraghty and G.E O'Donnell, "Wireless Calibration of a Surface Acoustic Wave Resonator as a Strain Sensor", IEEE Sensors Journal, pages 1026-1032, Volume 11, Number 4, 2011

Papers accepted for publication

- B. Donohoe, B. McCormack, D. Geraghty and G.E O'Donnell, "The modelling of the alignment sensitivity of a SAWR strain sensor to applied strain", IEEE Sensor conference, Limerick, 2011
- B. Donohoe, D. Geraghty and G.E O'Donnell, "Packaging considerations for a SAWR strain sensors" IEEE Sensors Journal, ACCEPTED 2011

Funding Support

This work was jointly funded by Enterprise Ireland and the Programme for Research in Third-Level Institutions. Additional support was provided through the National Access Program (NAP 277).

Acknowledgements

It is with great pleasure that I would like to thank some of the people whose support made this work possible. I am greatly indebted to my supervisors Mr. Dermot Geraghty and Dr. Garret O'Donnell for their support and encouragement over the last few years. Their clarity, patience and guidance is greatly appreciated. A special thanks is extended to Dr. Brian McCormack without whom I would probably never have been introduced to surface acoustic waves.

A special thanks to the staff of the Department in particular Mr. Mick Reilly, Mr. Paul Normoyle and Mr. Ivor Humphreys for their help and advice during this work. To all the postgraduate students, a special thanks and best of luck in the future. A special mention to Mr. Rory Stoney for his helpfulness during the final few months of this project, I hope you find your future research as stimulating and rewarding as I have found mine. Over the course of the work several individuals and organisations have provided extremely valuable advice and help,

- Dr. Serguei Kondratiev, a special thanks for the advice and support in the design and fabrication of the SAWR strain sensors.
- Mr. Shravan Jumaní of SenGenuity Plc, for his advice and support in integrating the SAWR strain sensor into the TempTrackr interrogation platform.
- The UCD microwave lab, especially Prof. Tom Brasil, Dr. Ronan Brady and Mr. Justin King for kind use of the facilities.
- Mr. Paul Roseingrave, Mr. Ken Rogers of the Tyndall National Institute for help and support during packaging of the sensors. The access granted through funding from the National Access Program is gratefully acknowledged

- To the number of acoustic wave sensor researchers who shared their time and advice. A sincere thanks to Dr. Sylvain Ballandras, Dr. Ji Wang and Dr. Serguei Zhgoon.

My friends, who provided some much needed and appreciated bar stool wisdom, you have all have been a tremendous source of reality. To my sister, Róisín and my aunt Margaret, thank you both for all your support. To Louise, a special thanks for all your help throughout this work. Finally, to my parents, a sincere thank you for all the support and help that has brought me to this point. This thesis is dedicated to you.

Brian Donohoe August 2011

Nomenclature

Symbol	Definition	Units
Ω	SAW decay into substrate	-
α	SAW Eigenvector	-
β	SAW wave number	m^{-1}
δ_{ij}	Kronecker Delta	-
ε	Applied Strain	-
η	Electrode metallisation ratio	-
λ	SAW wavelength	m
φ	Surface Electrical Potential	V
ω	Angular Frequency	rad/s
ϵ	Dielectric Constant	F/m
ρ	Material Density	kg/m^3
a	Electrode width	m
c_{ijkl}	Elastic Stiffness constant (2 nd Order)	Pa
c_{ijklmn}	Elastic Stiffness constant (3 nd Order)	Pa
D_i	Electrical Displacement component	C/m^2
d_{kij}	Piezoelectric material property	C/N
e_{kij}	Piezoelectric material property	C/m^2
E	Applied Electric Field	V
f_r	Resonant frequency of SAWR	Hz
h	Electrode height	m
K^2	Electromechanical coupling Coefficient	-
M	Number of Electrode Pairs	-
N_t	Number of Electrodes in IDT	-
N_g	Number of Electrodes in RG	-
p	Electrode pitch	m
p_t	IDT reflector pitch	m
p_g	IDT Grating pitch	m
Q	Q factor	-
s	Grating separation	m
S_{ij}	Strain	-
S_{ij}	S-parameter	-
S_{sen}	SAW strain sensitivity	$Hz/\mu\epsilon$

Symbol	Definition	Units
T_g	Glass transition temperature	$^{\circ}\text{C}$
T_{ij}	Applied Stress Tensor	Pa
T	Temperature	$^{\circ}\text{C}$
T_{sen}	Temperature Sensitivity	$\text{Hz}/^{\circ}\text{C}$
u_i	Particle Displacement component	m
v_s	Free surface SAW velocity	m/s
v_m	Metallised SAW velocity	m/s
w_i	Static Displacement Coefficient	—
W	Electrode Aperture	m
W_o	Effective Electrode Aperture	m
Z	Impedance	Ω

Contents

Contents	ix
1 Introduction	1
1.1 Motivation	1
1.2 Project objectives	2
1.3 Contribution of thesis	3
1.4 Layout of thesis	4
2 General theory of SAW strain sensors	5
2.1 The theory of elasticity	7
2.1.1 The elasticity of piezoelectric materials	7
2.1.2 Piezoelectric materials	10
2.2 Rayleigh wave velocity calculation in AT-Quartz	11
2.2.1 Calculation of SAW velocity	11
2.2.2 Boundary conditions	14
2.2.2.1 Free surface boundary conditions	14
2.2.2.2 Metallised surface	15
2.2.3 Displacement and velocity profiles	15
2.3 SAW devices and components	20
2.3.1 The interdigital transducer	20
2.3.2 Reflective gratings	23
2.3.3 SAW delay line	25
2.3.4 One port SAW resonator	26
2.3.4.1 Unwanted wave modes	27
2.4 Strain sensing mechanism in SAWR	28
2.4.1 Geometric effects	28
2.4.2 Effects of Stress on SAW velocity	28

CONTENTS

2.5	Theoretical Strain Sensitivity of AT-X SAWR strain sensors	30
2.5.1	Strain sensitivity calculation as function of alignment	33
2.5.2	Discussion on Modelling of AT-X SAWR Strain sensors	34
2.5.3	Conclusion	36
3	Surface acoustic wave sensors	39
3.1	History of physical SAW sensors	39
3.2	Specification of project sensors	41
3.2.1	SAWR sensor type	42
3.2.2	Sources of SAWR sensors	44
3.3	SAWR Sensor Design	47
3.3.1	Non Apodized 433.42MHz	47
3.3.2	Apodized 434.42 MHz	49
3.4	Discussion on SAWR Design	51
3.5	Wireless Sensing	53
3.6	Conclusion	56
4	Bare die characterisation	59
4.1	Microwave Testing Techniques	59
4.2	Testing Equipment and Set-up	62
4.3	Bare Die Testing	65
4.3.1	Resonant Response of Dies	68
4.3.2	Magnitude Response of the dies	73
4.3.3	Device Impedance and Quality Factor	75
4.4	Analysis of Finished Devices	76
4.4.1	Conclusion	77
5	Testing apparatus and protocol	79
5.1	Design of Testing Apparatus	80
5.1.1	FEA Design of Calibration Beam	81
5.2	Automation of test procedure	83
5.3	Reference Sensor selection and bonding	85
5.3.1	Verification of test beam	88
5.4	Test Protocol	89
5.4.1	Elevated Temperature Testing	90
5.4.2	Treatment of Experimental Data	91

5.4.3	Evaluation of Testing Apparatus and Methodology	93
5.4.4	Conclusion	94
6	Bare die experimental testing	97
6.1	Attachment of bare die SAWR sensors	98
6.2	Temperature sensitivities	101
6.3	Actuator loading profile	103
6.4	Calibration results	106
6.5	Calibration results with M-Bond 200	107
6.5.1	Ambient M-Bond200	107
6.5.2	Elevated Temperature Testing with M-Bond 200	109
6.6	Calibration results with M-Bond 600	111
6.6.1	Elevated Temperature Testing with M-Bond 600	113
6.6.2	Transverse Strains	115
6.7	Calibration results with M-Bond 610	116
6.7.1	Elevated Temperature Testing with M-Bond 610	119
6.8	Orientation sensitivity of SAWR strain sensors	121
6.9	Discussion on Experimental Testing	122
6.10	Conclusions	126
7	Packaging and calibration of SAWR strain sensors	129
7.1	Commercial filter packaging technology	129
7.2	Commercial SAW sensor Packaging	131
7.3	Packaging of SAWR strain sensor	135
7.3.1	Selection of Packaging for the SAWR	136
7.3.2	Adhesives	137
7.3.3	Selection of adhesives	139
7.3.3.1	Cyanoacrylate	139
7.3.3.2	Epoxy resin adhesives	139
7.3.3.3	Addition of fillers to epoxy resin adhesives	140
7.3.3.4	Adhesive used for this project	140
7.3.4	Completed packaged SAWR strain sensors	141
7.4	Calibration of packaged sensors	144
7.4.1	Calibration results for 5L7C-1S ceramic base SAWR strain sensor	146

CONTENTS

7.4.1.1	Elevated temperature calibration results for 5L7C-1S SAWR strain sensor	147
7.4.2	Calibration results for 5L7M-1S kovar base SAWR strain sensor	148
7.4.2.1	Elevated temperature calibration results for 5L7M-1S SAWR strain sensor	149
7.4.3	Calibration results for 5L14M SAWR strain sensor	150
7.4.3.1	Elevated temperature calibration results for 5L14M SAWR strain sensor	151
7.4.3.2	Long term sensitivity stability of 5L14M SAWR strain sensor	153
7.4.4	Differential SAWR strain sensor	153
7.5	Evaluation of the packaged SAWR sensor	156
7.6	Dynamic performance of the system	158
7.6.1	SAWR sensor system dynamic performance	159
7.7	Application of SAWR strain sensor	161
7.7.1	Experimental measurement of load cell	164
7.8	Conclusion	164
8	Conclusion and future work	167
8.1	Contribution of the thesis	167
8.1.1	Specification and design of a SAWR strain sensor	168
8.1.2	Correlation between SAWR strain sensor theoretical and experimental performance through a novel testing method	169
8.1.3	Calibration and testing methodology for SAWR strain sensors	169
8.1.4	Evaluation of packaged SAWR sensors	170
8.2	Future work and final thoughts	171
	Measurement of commercial SAWR sensor	173
	SAWR load cell	175
	Euler rotations	177
	References	179

Chapter 1

Introduction

This chapter provides the project background and motivation for the research. The contribution of the thesis is discussed. The project goals are outlined along with a guideline to the thesis.

1.1 Motivation

A sensor can be described as a device which measures a physical quantity and converts it into a signal that can be read by an observer. With such a description a sensor is a broad term encompassing a wide variety of devices and measurand. Strain is one measurand which is commonly measured. In the traditional engineering definition, strain is the elongation of a body relative to unit length [1]. Strain, therefore is an analysis of how bodies deform due to an applied external load. Strain is one of the core concepts in engineering and is inherent in the measurement of other related measurand, considered principal amongst these can be pressure, force and torque.

The preferred sensor for the measurement of strain is the bonded foil resistive strain gauge. This sensor type consists of a thin metal structure formed on a foil polymer backing, which is bonded to the surface at the point of measurement. Through the piezoresistive effect, an applied strain changes the nominal resistance of the foil gauge [2]. The foil gauge usually forms part of a wheatstone bridge. As applied strain will cause a change in the resistance of the foil gauge the bridge will become unbalanced and a strain can be inferred from the resulting bridge voltage.

The integration of sensors into processes and applications has led to what is commonly described as sensor rich environments becoming increasingly widespread [3].

1.INTRODUCTION

Sensors can provide real time information in many applications thus enhancing many engineering processes and systems. In a sensor rich environment wireless methods of sensing tend to be preferable over traditional wired methods. The foil resistive strain gauge requires wiring to instrumentation which limits its usability. A sensor type which is an ideal candidate for wireless sensing are sensors based upon the surface acoustic wave (SAW) effect. SAW sensors are highly attractive for wireless sensing as they can operate both wirelessly and passively, drawing all the energy required for measurement and response through a series of RF pulses. While the ability of SAW sensors to operate wirelessly should create flexible modular sensors, currently all physical SAW sensors are highly application specific, and are mainly focused on the measurement of torque or pressure for automotive applications. Typically this is achieved with a sensor design and packaging tailored for the particular target application. Even though commercial applications have been identified. The finer details on the performance of SAW sensors is held as propriety information. // A key motivation for this work is to develop a SAW strain sensor to a level comparable to that of the foil resistive strain gauge, such that the SAW sensor can be integrated into applications with the same flexibility shown by foil resistive strain gauges. The overall goal of the project therefore is the development of a general purpose SAW strain sensor.

1.2 Project objectives

The motivation of this project is to investigate and develop SAW strain sensors and demonstrate SAW strain sensors as a modular sensing component with greater flexibility than currently available SAW sensors. This requires addressing practical considerations for the implementation of SAW strain sensors. The key aims of the research undertaken by the author in this project are:

Design and development of wireless SAW sensor measurement platform: A SAW measurement platform will require a sensor to be specified and designed subsequently a manufacture run will be undertaken. The prototype SAW device must then be integrated into a wireless measurement chain to form a modular sensor.

The development of calibration techniques for SAW sensors: Standardised procedures for the calibration of SAW strain sensors are unavailable. Methods of calibration are developed suitable for the characterisation of SAW sensors which

1.3. CONTRIBUTION OF THESIS

will determine sensor performance over a range of loading conditions and temperatures. This will provide a methodology for a comprehensive and detailed investigation into the characteristics of a SAW strain sensor.

Characterise the performance of SAW strain sensors: While SAW sensors have been documented as being strain and temperature sensitive, exact details on their performance remain unknown. A key part of this project is focused on the practical utilisation of SAW sensors including handling and methods of installation. This will develop a refined understanding of the utilisation of SAW sensor in physical measurement. Providing an investigation into the influence of adhesives on the performance of SAW strain sensors.

Packaging of SAW strain sensors: The SAW sensor is a fragile component, which is far too delicate to be utilised without proper packaging. As packaging is known to influence sensor performance, a core component of this thesis will be the investigation on the integration of the SAW strain sensor into a robust package.

Validation of Modelling Techniques: SAW devices are complicated structures fabricated on anisotropic materials. As a result the performance of the sensors can vary dramatically between relatively similar sensor designs. A project objective is to validate theoretical models that predict sensor behaviour with experimentally determined values. This will aid in the design of SAW strain sensors in future works.

1.3 Contribution of thesis

This thesis evaluates one-port surface acoustic wave resonators (SAWR) as strain sensors. Theoretical models will be experimentally verified through a novel method of modelling validation, that will aid future works in SAWR strain sensor design. A core component of this thesis will be the provision of the most comprehensive calibration data set describing the behaviour of SAWR strain at range of loading and temperature conditions. A key contribution of this thesis is the investigation into the practical considerations associated with SAWR strain sensors (mounting, handling and bonding techniques) which are generally omitted in the literature but remain critical in the implementation of SAWR sensors. These practical considerations are packaging and adhesive effects. To the author's knowledge the effects of adhesives and the relationship

1.INTRODUCTION

between adhesives and the SAWR strain sensor performance has not been discussed. Furthermore, packaging effects have not been discussed to any great extent in the literature. These omission in publications are most likely due to the propriety nature of SAW sensing. This thesis will expand the knowledge in the field of SAWR strain sensors by creating a novel, general purpose, modular and wireless SAW strain sensor.

1.4 Layout of thesis

The thesis is subdivided into several chapters which address the key objectives in this project. Chapter 2 provides details on the nature of surface acoustic waves, SAW device structures and implementation of the SAW sensor as strain sensors. Chapter 3 introduces the reader to SAW sensors and provides details on the project sensor and wireless interrogation methods including the wireless interrogation platform used for this project. In Chapter 4 the performance of the SAW sensor as electrical devices will be evaluated. A standardised testing method and apparatus will be described in Chapter 5. Chapter 6 will discuss the performance of the SAW device as a strain sensor for a range of conditions. An investigation in the methods and strain transfer performance of various adhesives will be discussed. Chapter 7 will describe details on sensor packaging. Finally, Chapter 8 will discuss the project as a whole and evaluate the project.

Chapter 2

General theory of SAW strain sensors

A surface acoustic wave (SAW) is a mechanical wave which propagates along the surface of a solid material [4], first documented by John William Strutt, the third Baron Rayleigh in 1885. Rayleigh discussed the existence of a wave motion where the associated particle displacements are confined to a surface region approximately one wavelength.

"It is proposed to investigate the behaviour of waves upon a plane free surface of an infinite homogeneous isotropic elastic solid, their character being such that the disturbance is confined to a superficial region, of thickness comparable with the wavelength"

Rayleigh described a straight crested wave propagating in an isotropic medium within an infinite half space as shown see Figure 2.1. The space $x_3 > 0$ is a vacuum and the medium occupies the space $x_3 < 0$. In the isotropic case, the wave propagates in the x_1 direction so all wavefronts are parallel to the x_2 axis. Thus the wave is said to propagate in the sagittal plane (x_1, x_3) and the associated particle displacements are negligible in the x_2 direction. This wave mode has become known as the Rayleigh wave, for the duration of this text and unless otherwise stated the acronym SAW will refer to the Rayleigh wave mode.

2. GENERAL THEORY OF SAW STRAIN SENSORS

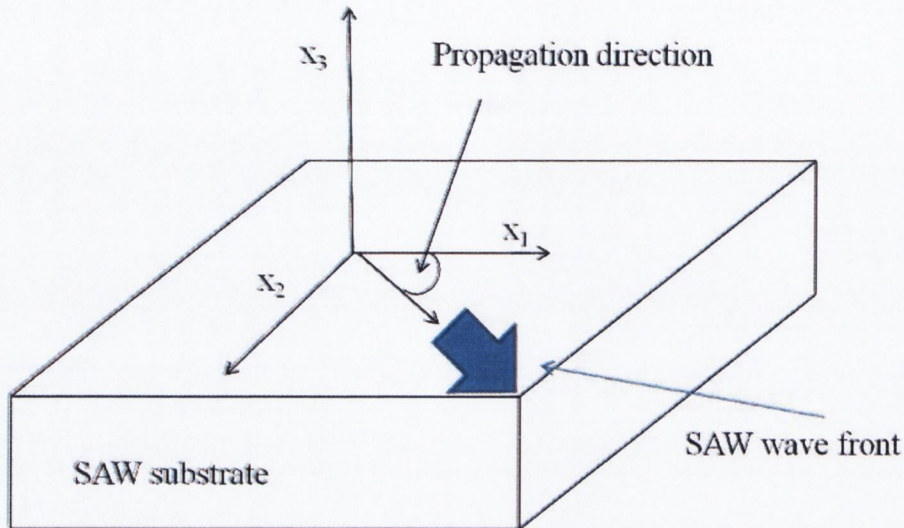


Figure 2.1: Surface Wave fronts of propagating Rayleigh SAW in an infinite half space

In his analysis Rayleigh did not address the generation of such wave modes. Rayleigh instead provided a discussion on the treatment of the isotropic case and the propagation of SAW in anisotropic materials was not dealt with. Indeed, any possible practical implementation of SAW was not considered. In Rayleigh's own words at the Presidential Address to the British Association Montreal 1884:

"The history of science teems with examples of discoveries which attracted little notice at the time, but afterwards have taken root down-wards and borne much fruit upwards"

Since Rayleigh's seminal work, several other wave modes which propagate along the surface of an infinite half space and have been discovered and can be classified as SAW. Such waves include leaky surface waves, surface transverse waves (STW), Bleustein-Gulyaev and Pseudo Surface Acoustic Waves (PSAW). The modern SAW devices can use a range of wave modes, substrates and propagation directions on the substrate depending on the proposed application of the SAW device and the preferred device characteristics. For example high frequency devices may use PSAW wave due to the higher wave velocity, while water sensors may use Love waves due to the polarised particle displacement. Details on these wave modes can be found in [5] [6] [7] [8].

2.1 The theory of elasticity

In this section the theory of elasticity is introduced. The theory of elasticity describes the deformation of solid bodies when subjected to external forces. When an external force is applied to a solid body, the body becomes deformed. Provided the applied external forces have not passed a threshold level the body may return to its original form upon removal of the applied force. This deformation is defined as an elastic deformation of the solid. If the solid body fails to return to its original form it is described as a plastic deformation. Typically materials undergo elastic deformation provided the applied forces are relatively small. The theory of elasticity is concerned with how bodies deform and the internal stresses generated within the material due to loading of the material. The theory of elasticity is designed to treat the linear and non linear response of materials to applied external forces [9].

2.1.1 The elasticity of piezoelectric materials

In this section, the description of the elastic behaviour of anisotropic piezoelectric materials will be presented. Forces will be expressed in terms of stresses T while strains will be described in terms of S (which are the standard symbol's used in surface wave texts). In most analysis of elasticity the deformation of a solid subjected to an external force is described as the displacement of a particle from its initial position $x=(x_1, x_2, x_3)$, a particle is then displaced by $u = (u_1, u_2, u_3)$, therefore the position of the displaced particle becomes $x + u$ as shown in Figure 2.2.

2. GENERAL THEORY OF SAW STRAIN SENSORS

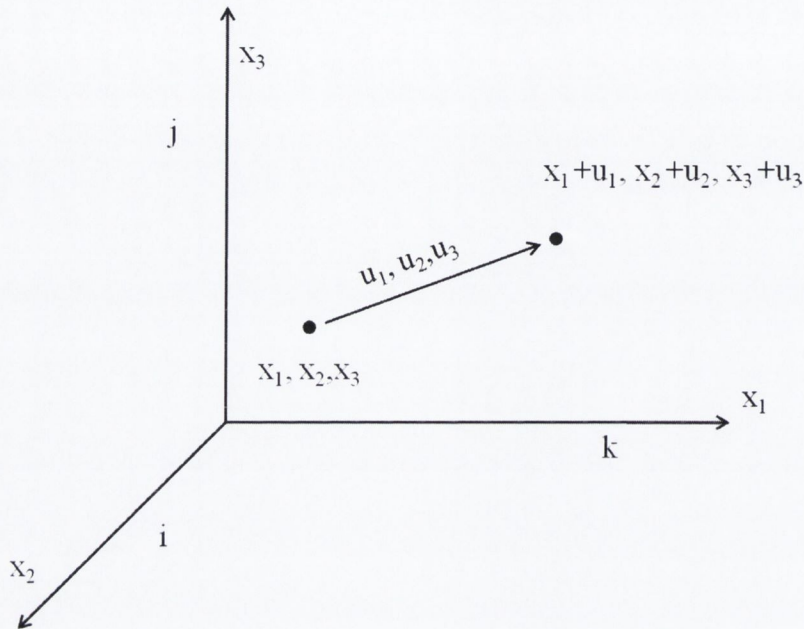


Figure 2.2: Displacement of a particle

The strain at each point is defined as a second rank strain tensor given in index notation as [10]:

$$S_{ij}(x_1, x_2, x_3) = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad i, j = 1, 2, 3 \quad (2.1.1)$$

The stress acting on the body is shown in Figure 2.3. The subscripts denote the directions of the force and the plane it is applied.

2.1. THE THEORY OF ELASTICITY

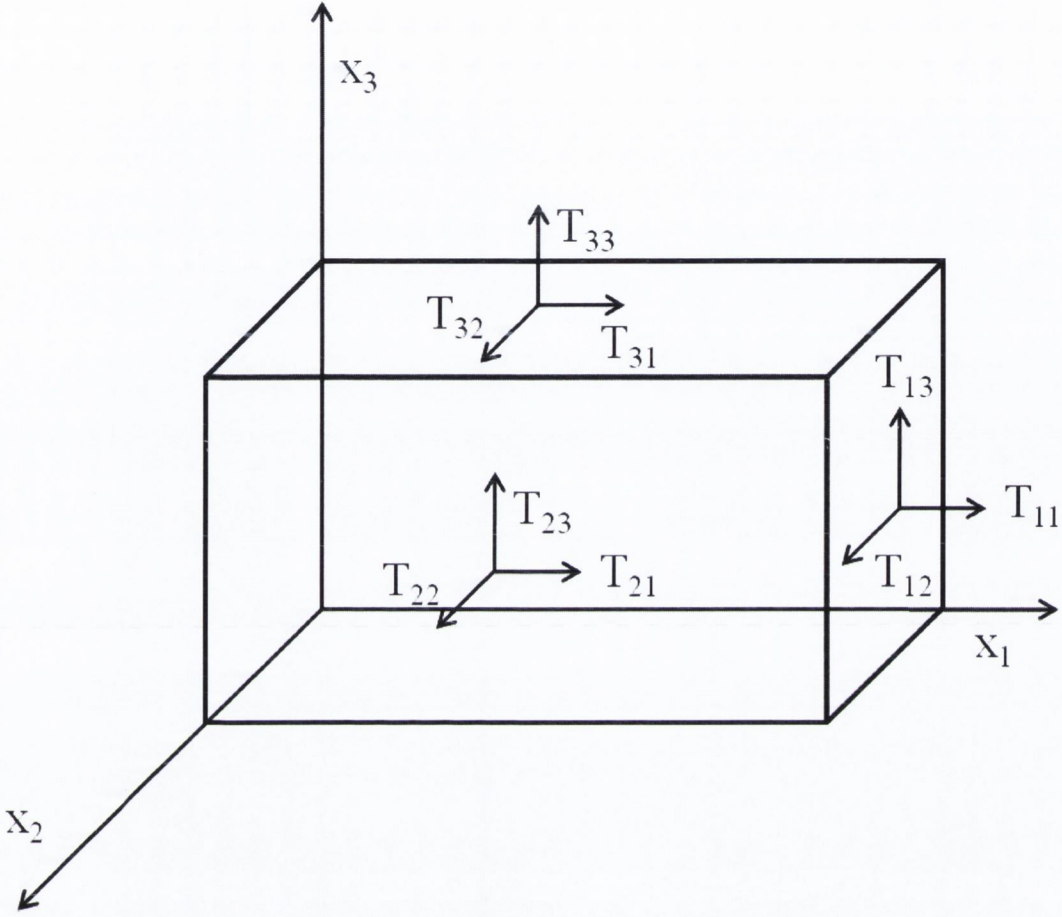


Figure 2.3: Stress forces acting on a solid element

The stress-strain relationship for linear elastic behaviour in an anisotropic material can be expressed as the general form of Hookes Law [11].

$$T_{ij} = \sum_k \sum_l c_{ijkl} S_{kl} \quad i, j, k, l = 1, 2, 3 \quad (2.1.2)$$

where c_{ijkl} is the stiffness tensor. In a piezoelectric material the stress component at each point in the material is dependent on the electric field. The mathematical description of piezoelectricity was developed by Voigt [12] and incorporates electrical characteristics of piezoelectric materials: D_i is the electrical displacement of the material, which is the charge per unit area in an insulator in an electrical field [13]. The piezoelectric properties of the material are given by e_{kij} which related to the piezoelectric constants of the material d_{kij} (i.e its inverse) and ϵ_{ij}^S is the dielectric constant. The superscript S indicates the constants were measured at a constant strain. The piezo-

2. GENERAL THEORY OF SAW STRAIN SENSORS

electric constant is described at a third rank tensor while the dielectric constant is a second rank tensor property. It can be shown that Hookes general law can be expanded to include stress generated by the applied electrical field E [14].

$$T_{ij} = \sum_k \sum_l e_{ikl} S_{kl} - \sum_k \epsilon_{ij}^S E_k, \quad i, j, k, l = 1, 2, 3 \quad (2.1.3)$$

The electrical displacement D_i , describes the charge induced per unit area in an insulator by electrical field is given by:

$$D_i = \sum_k \sum_l c_{ijkl} S_{kl} - \sum_k e_{kij} E_k, \quad i, j, k, l = 1, 2, 3 \quad (2.1.4)$$

Both equation 2.1.3 and equation 2.1.4 include components relating the mechanical and electrical nature of the piezoelectric material. Thus the updated equations relating piezoelectricity to particle displacement can be incorporated into the equations of motion for a surface wave [15], see Section 2.2.1.

2.1.2 Piezoelectric materials

It would not be possible to describe SAW devices without briefly discussing the nature of the substrate they are fabricated upon. Piezoelectric materials are fundamental for SAW devices. Piezoelectricity is the behaviour of certain materials (notably crystalline and certain ceramics) that when an external pressure is applied to the material an electrical charge accumulates. The direct piezoelectric effect was first documented by Jacques and Pierre Currie in 1885 [16]. It was discovered that an external mechanical stress applied to certain materials generates an electrical voltage. The inverse was demonstrated a short time later.

In its most general description the piezoelectric effect is caused by the displacement of the electric dipoles in a material away from their equilibrium position. When no external forces are applied a material remains in equilibrium and no polarization occurs in the materials. The application of a tensile force causes the dipoles to displace and a net polarization appears. If a compressive force is applied the displacement of the dipoles causes a polarization of opposite charge to be generated. Therefore, the polarity and magnitude of the generated voltage is a function of the applied force.

2.2 Rayleigh wave velocity calculation in AT-Quartz

In this section the velocity of a SAW propagating in AT quartz will be discussed. AT quartz is one of the first temperature stable quartz cuts introduced in the 1930's [17]. The method for the calculation of the particle displacements and SAW wave velocity will be discussed. A particle is defined as “*An elementary region smaller than a wavelength but larger than the interatomic distance*” [18]. Calculation results will be provided which detail the nature of the propagating wave as well as the sensitivity of v_s to propagation direction.

2.2.1 Calculation of SAW velocity

In this section the propagation of surface waves in anisotropic materials will be discussed. The displacement profiles and velocity curves for a Rayleigh wave propagation in AT-Quartz will be presented. A SAW propagates along the surface of a solid medium with a velocity v_s and an elliptical particle displacement which decays exponentially with penetration into the material. In an isotropic medium the wave velocity is independent of the angle of propagation within the substrate. However, SAW devices are fabricated on piezoelectric substrates which are naturally anisotropic. Therefore the characteristics of the SAW (*particle displacement, surface potential, wave velocity*) become a function of the crystal cut and the propagation orientation relative to the crystalline axis [19]. An evaluation of the characteristics of the SAW is generally achieved through a numerical determination of v_s . This section will discuss how the characteristics of the SAW are determined through numerical methods and provide results for the SAW in AT-Quartz.

The procedure for calculating v_s was developed by Campbell and Jones in 1968 based upon the superposition of partial waves [20]. An in-depth discussion is provided by Slobodnik [21]. The method involves iteratively selecting a value of v_s which satisfies the equations of motion of an acoustic wave for a given cut and propagation orientation. The material properties both mechanical and piezoelectric must be rotated using the tensor transformations. Contracted tensor notation will be given where relevant [22]. The description and notation used to describe the calculated wave velocity corresponds to the description provided in Appendix A.3 of [19]. Additional sources will be included with the relevant conversions to material properties in order to provide consistency where appropriate.

2. GENERAL THEORY OF SAW STRAIN SENSORS

Acoustic waves propagating through a solid material can be described by six linear equations. The equation of motion in piezoelectric medium as given by [21] are:

$$\sum_{j=1}^3 \frac{\partial T_{ij}}{\partial x_j} = \rho \frac{\delta^2 u_i}{\delta t^2} \quad i = 1, 2, 3 \quad (2.2.1)$$

Where ρ is the density of the material, u_i is the particle displacement, and T_{ij} is the stress tensor. A full description of SAW propagation in a piezoelectric medium would require a description which includes both mechanical and electromechanical equations of motion, however as a SAW propagates with a velocity 10^5 slower than an electromechanical wave, mechanical wave consideration can be assumed to dominate the transmission process allowing for a quasi static assumption to be applied to Maxwell's equations.

Therefore under that assumption, the electric field E_i is given by the gradient of the potential φ :

$$E_i = -\frac{\delta \varphi}{\delta x_i} \quad (2.2.2)$$

As the piezoelectric substrate is an insulator, the electrical displacement coefficient D_i is given by

$$\frac{\delta D_i}{\delta x_i} = 0 \quad (2.2.3)$$

For $x_3 > 0$ the potential radiated into free space is described by Laplace's equation

$$\nabla^2 \varphi = 0 \quad (2.2.4)$$

The above equations 2.2.1-2.2.3 can be combined with the equations governing piezoelectricity to form a description of a SAW propagating in a piezoelectric medium.

$$c_{ijkl} \frac{\delta^2 u_k}{\delta u_l \delta x_i} + e_{kij} \frac{\delta^2 \varphi}{\delta u_k \delta x_i} = \rho \frac{\delta^2 u_j}{\delta t^2} \quad (2.2.5)$$

$$e_{ikl} \frac{\delta^2 u_k}{\delta u_l \delta x_i} - \epsilon_{kij} \frac{\delta^2 \varphi}{\delta u_k \delta x_i} = 0 \quad (2.2.6)$$

The solutions of these equations 2.2.5 - 2.2.6 are assumed to be complex traveling waves. The mechanical displacements u_i and electrical potentials φ are induced by the propagating wave. This leads to a linear homogeneous system of four unknowns. A

2.2. RAYLEIGH WAVE VELOCITY CALCULATION IN AT-QUARTZ

solution can be found with the assumption the solution will have an $\exp(-j\beta x_1)$ dependence [19]. In contracted tensor notation the homogenous system of four unknowns is given by:

$$\begin{pmatrix} C_{55}\Omega^2 + 2C_{15}j\Omega & C_{45}\Omega^2 + [C_{14} + C_{56}]j\Omega & C_{35}\Omega^2 + [C_{13} + C_{45}]j\Omega & e_{33}\Omega^2 + [e_{13} + e_{35}]j\Omega \\ -C_{11} + \rho v_s^2 & -C_{16} & -C_{15} & -e_{15} \\ \hline C_{45}\Omega^2 + [2C_{14} + C_{56}]j\Omega & C_{44}\Omega^2 + 2C_{46}j\Omega & C_{34}\Omega^2 + [2C_{36} + C_{45}]j\Omega & C_{34}\Omega^2 + [e_{14} + e_{36}]j\Omega \\ -C_{16} & -C_{66}\Omega + \rho v_s^2 & -C_{56} & -e_{16} \\ \hline C_{35}\Omega^2 + [2C_{13} + C_{55}]j\Omega & C_{45}\Omega^2 + [C_{36} + C_{45}]j\Omega & C_{33}\Omega^2 + 2C_{46}j\Omega - C_{66} & e_{33}\Omega^2 + [e_{13} + e_{35}]j\Omega \\ -C_{15} & -C_{56} & +\rho v_s^2 & -e_{15} \\ \hline e_{35}\Omega^2 + [e_{15} + e_{31}]j\Omega & e_{34}\Omega^2 + [e_{14} + e_{36}]j\Omega & e_{33}\Omega^2 + [e_{13} + e_{35}]j\Omega & -\epsilon_{33}\Omega^2 \\ -e_{11} & -e_{16} & -e_{15} & \epsilon_{11} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ \varphi \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (2.2.7)$$

where $v_s = \omega/\beta$ and $\Omega = \beta^{-1}\delta/\delta x_3$. Ω describes the decay of the wave as it penetrates into the surface of the substrate. For a non trivial solution to exist the determinant of this equation must equal zero. The determinant is a polynomial generally described in terms of Ω . The general solution of equation 2.2.7 is given by:

$$u_i(x_1, x_3) = \sum_{n=1}^8 A_n \exp(\beta \Omega_n x_3 - j\beta x_1) \quad (2.2.8)$$

A_i are constants determined by the boundary conditions and may not be independent of each other. Equation 2.2.8 will provide eight values of Ω . The Rayleigh wave mode is the combination of several wave components known as partial wave vectors [20]. Each value of Ω describes a partial wave vector. While eight values for Ω can be found not all values are physically admissible for Rayleigh wave propagation. As a Rayleigh wave particle displacements decay with depth into the medium the values of Ω which satisfy this criteria must be real values. In practice these values are found to be roots of 2.2.7 which have non negative real parts, typically four values can be found that fit this requirement. Each value of Ω then has four corresponding eigenvectors; $\alpha_1, \alpha_2, \alpha_3$, and α_4 . The mechanical particle displacement and electrical field are

2. GENERAL THEORY OF SAW STRAIN SENSORS

expressed as a linear combination of the eigenvectors $\alpha_{1,2,3,4}$ at each decay constant $\Omega_{1,2,3,4}$.

2.2.2 Boundary conditions

As we are concerned with SAW propagation in piezoelectric substrates, electrical and mechanical boundary conditions must be considered in order to determine the correct v_s and displacement profile for the propagating surface acoustic wave. Two distinct boundary conditions of a surface are applied to determine the surface wave velocity.

- **Free surface boundary condition:** The space above the medium space is a vacuum and no conductors are present. In this case the free surface wave velocity v_f is determined.
- **Metallised surface boundary condition:** The surface above the material is covered by an infinitesimally thin layer of conducting metal. The role of this metal layer is to short the electric field E while not influencing the mechanical boundary conditions. For this set of boundary conditions the metallised surface wave velocity v_m is determined.

For piezoelectric materials the free surface velocity is always greater than the metallised surface. In both cases the surface is stress free. The surface is traction free and no forces are present, therefore

$$T_{3j} = c'_{3jkl}u_{k,l} + e'_{k3j}\phi_{,k} \big|_{x_3=0} = 0 \quad (2.2.9)$$

2.2.2.1 Free surface boundary conditions

In a vacuum with a permittivity ϵ_0 , only the electrostatic field exists. For the free surface case the potential in the air region $x_3 \geq 0$.

$$\phi = \alpha_4 e^{-|\frac{\omega}{v}|x_3} e^{\frac{j\omega(t-x_1)}{v}} \quad (2.2.10)$$

The piezoelectric medium can be considered an insulator for the free surface case with no free charges present on the surface the electrical displacement D_3 which is a function of free space can be written as

$$D_3 = \epsilon_0 \left| \frac{\omega}{v} \right| \phi \quad (2.2.11)$$

2.2. RAYLEIGH WAVE VELOCITY CALCULATION IN AT-QUARTZ

2.2.2.2 Metallised surface

In the last section the solutions were provided for $x_3 > 0$, for the metallised surface of thickness h . Laplace's equation must be satisfied for $-h > x_3 > 0$; If a metallised surface is present, the surface becomes shorted and the boundary condition surface potential becomes $\phi = 0$ at $x_3 = 0$.

Substitution of equations 2.2.7 and 2.2.8 into 2.2.10 results in a set of homogeneous equations for the free surface boundary condition form in A_{nn} .

$$\begin{bmatrix} f_{11} & f_{12} & f_{13} & f_{14} \\ f_{21} & f_{22} & f_{23} & f_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \\ f_{41} & f_{42} & f_{43} & f_{44} \end{bmatrix} \begin{bmatrix} A_{41} \\ A_{42} \\ A_{43} \\ A_{44} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (2.2.12)$$

where each column is given in terms of

$$\begin{bmatrix} f_{1n} \\ f_{2n} \\ f_{3n} \\ f_{4n} \end{bmatrix} = \begin{bmatrix} [jC_{15} + \Omega^l C_{66}] & [jC_{56} + \Omega^l C_{45}] & [jC_{55} + \Omega^l C_{56}] & [je_{15} + \Omega^l e_{35}] \\ [jC_{14} + \Omega^l C_{45}] & [jC_{46} + \Omega^l C_{44}] & [jC_{45} + \Omega^l C_{34}] & [je_{14} + \Omega^l e_{35}] \\ [jC_{13} + \Omega^l C_{35}] & [jC_{36} + \Omega^l C_{34}] & [jC_{35} + \Omega^l C_{33}] & [je_{13} + \Omega^l e_{33}] \\ [je_{31} + \Omega^l e_{35}] & [je_{36} + \Omega^l e_{34}] & [je_{35} + \Omega^l e_{33}] & -[j\epsilon_{13} + \Omega^l \epsilon_{33} + \epsilon_0 v] \end{bmatrix} \begin{bmatrix} \alpha_{1n} \\ \alpha_{1n} \\ \alpha_{1n} \\ \alpha_{1n} \end{bmatrix} \quad (2.2.13)$$

For the existence of SAW on the free surface case the determinant of the matrix in equation 2.2.12 must equal zero. Therefore if a value of v_s is found which minimised the determination of the matrix in equation 2.2.12 this may correspond to the velocity of the SAW on the free surface. For the metallised surface equation 2.2.12 takes the form

$$\begin{bmatrix} f_{11} & f_{12} & f_{13} & f_{14} \\ f_{21} & f_{22} & f_{23} & f_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} A_{41} \\ A_{42} \\ A_{43} \\ A_{44} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (2.2.14)$$

A similar procedure is then used to calculate the v_s of the metallised surface.

2.2.3 Displacement and velocity profiles

Numerical methods are required to calculate the wave velocity and the associated particle displacements. The displacement and velocity profiles were calculated using the

2. GENERAL THEORY OF SAW STRAIN SENSORS

methodology described and implemented in Section 2.2.1 as part of a previous project [23]. To calculate the displacement profiles of the SAW the wave profiles are often described as [15]:

$$u_i = \sum_{l=1}^4 \alpha_{(i)}^{(l)} A^{(l)} e^{\frac{-\Omega^{(l)} \omega x_3}{v}} e^{\frac{-j\omega(t-x_1)}{v}} \quad i = 1, 2, 3 \quad (2.2.15)$$

$$\varphi = \sum_{l=1}^4 \alpha_4^l A^l e^{\frac{-\Omega \omega x_3}{v}} e^{\frac{-j\omega(t-x_1)}{v}} \quad (2.2.16)$$

The $A^{(l)}$ are known as the partial field amplitudes and correspond to a weighting of the superimposed partial wave components in the final Rayleigh wave.

A value of v_s is determined for a given orientation and propagation direction. The corresponding decay constants, α vector and partial wave vectors A are calculated during the computation of v_s . The free surface wave velocity for a SAW propagating on AT-X quartz was found to be $\approx 3151\text{m/s}$

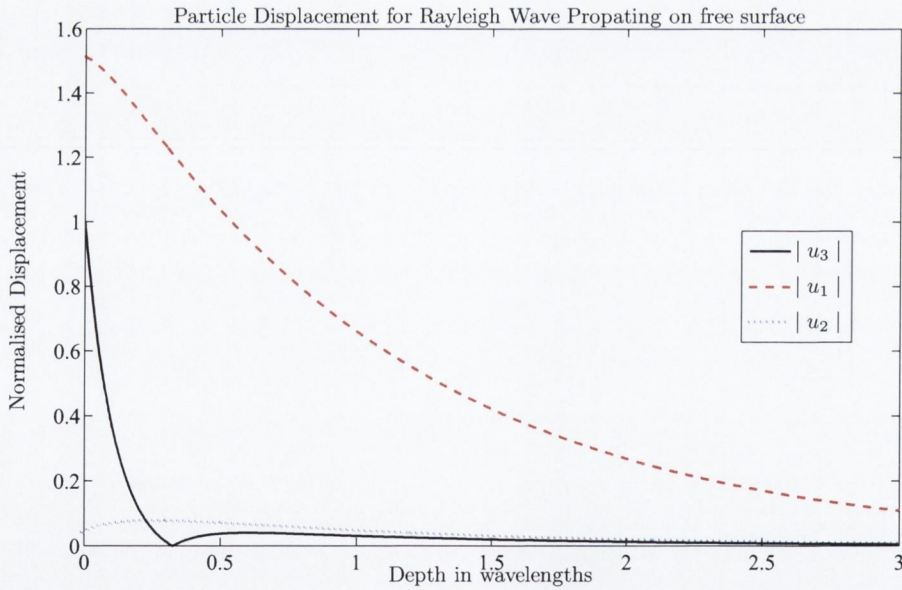


Figure 2.4: Particle displacement for a Rayleigh wave propagating on AT-X quartz

The displacement profile for a SAW propagating on AT-X quartz with free surface boundary conditions are shown in figure 2.4. The displacements were calculated for $t = x_2 = 0$. The displacements for metallised surface boundary conditions are almost

2.2. RAYLEIGH WAVE VELOCITY CALCULATION IN AT-QUARTZ

identical. The displacements are normalised by the surface displacement at $x_3 = 0$. Wave penetration into the surface is measured in SAW wavelength λ .

$$\lambda = \frac{v}{f} \quad (2.2.17)$$

Several key points can be made on the nature of the SAW propagation and particle displacement:

- The particle displacements of the Rayleigh wave decay quickly with depth. Thus the energy associated with the propagating wave remains concentrated close to the surface. This allows for ease of transduction of the wave from RF to mechanical wave and back again.
- The motion of the displacement component u_3 of the wave is in the anticlockwise direction at the surface of the material. With increasing penetration into the surface the displacement undergoes a reversal and becomes clockwise.
- Minimal particle displacements occur in the x_2 direction demonstrating the SAW is more or less confined to the sagittal plane.

The material properties of the quartz substrate are highly anisotropic. The SAW velocity will vary significantly for different propagation angles. By rotating the material properties the variation in SAW velocity can be investigated [24]. Figure 2.5 shows that substantial deviation can occur as the orientation of the propagating wave changes. The determination of SAW velocity is a key component in device design as the variation in the SAW velocity across a range of propagation angles can be severe.

2. GENERAL THEORY OF SAW STRAIN SENSORS

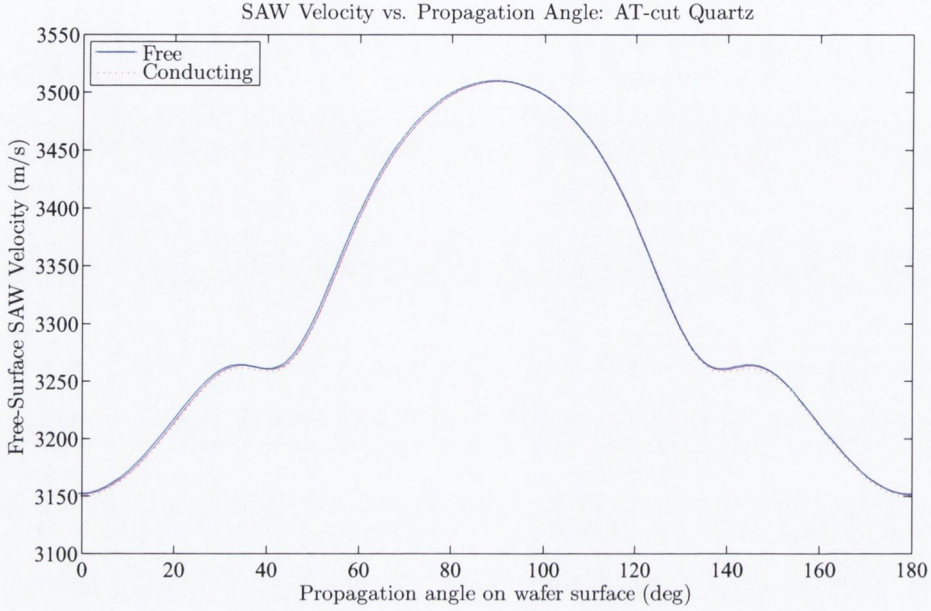


Figure 2.5: Variation in SAW velocity with rotation for AT-X Quartz

The wave velocity for a SAW propagating on a free surface and a metallised surface are shown in Figure 2.5. This difference in wave velocities is commonly used to determine the suitability of a piezoelectric material for the fabrication of SAW devices. The electromechanical coupling coefficient of the material (K^2) provides a measure of the piezoelectric coupling between the propagating SAW and the electrical perturbations on the surface of the medium is given by:

$$K^2 \approx 2 \frac{v_f - v_m}{v_f} \quad (2.2.18)$$

For weakly coupled materials such as quartz, K^2 can be as low as 0.012%. Materials such as Lithium Niobate, which are described as strongly coupled, the K^2 value can be as high as 5.4% [25]. As with wave velocities, K^2 is highly sensitive to the propagation direction of the SAW in the substrate material, as shown in Figure 2.6 .

2.2. RAYLEIGH WAVE VELOCITY CALCULATION IN AT-QUARTZ

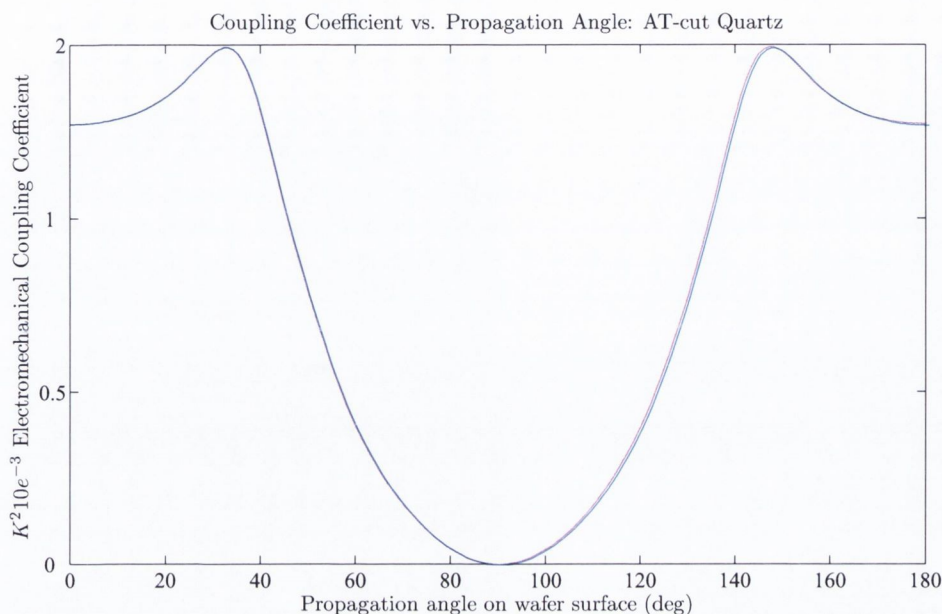


Figure 2.6: Calculated in K^2 with rotation for AT-X Quartz

It should be noted that while the maximum coupling coefficient occurs at 35° , and would indicate a highly suitable orientation for SAW devices, propagation effects have to be considered. Diffraction of a SAW wave occurs as the SAW propagates from the IDT into the far-field region (*Fraunhofer*). The wave is dispersed and is no longer concentrated into a compact wave front. In a SAWR the reflective gratings are located in the near field region (*Fresnel*) so beam diffraction is of moderate concern. Surface waves propagating in anisotropic materials are influenced by beam steering. Beam steering is an effect where the propagating wave front is steered away from the propagation direction towards a crystalline axis of the medium [24]. The beam steering angle describes the direction of the power flow of the wave and is more often called the power flow angle; it is calculated as the slope of the velocity curve. In this work the SAW propagates along the X axis of the crystal [14] where beam steering will be minimal. This pure mode propagation angle ensures the SAW propagates along the crystalline axis of the substrate. Another pure mode direction would be an orientation of 90° ; however inspection of Figure 2.6 shows that electromechanical coupling is zero along that axis therefore such an orientation is not suitable for Rayleigh wave SAW devices. In this case no piezoelectric coupling occurs, therefore a Rayleigh SAW would not be generated by an IDT. However, wave modes can exist at this orientation which have a different displacement profile than that of the Rayleigh wave. A shear

2. GENERAL THEORY OF SAW STRAIN SENSORS

horizontal SAW for example has been shown to be present at AT-90° [26]. (i.e a wave with displacements in the x_2 direction and minimal displacement in the x_3 direction).

2.3 SAW devices and components

Electronic components have taken advantage of acoustic waves for over half a century. In the 1960's the first suggestions were made that SAW might be useful for electronic applications offering enormous potential to create versatile filters and resonators. Mass production of SAW devices began in the 1970's. The success of SAW technology in electronic components is due to the robust and repeatable fabrication processes used in the manufacture. This section discusses the typical structures employed in the modern SAW device. Although many different types of SAW structures have been developed for a range of applications and to excite various wave types this section will focus on the two most important; the Interdigital Transducer (IDT) and the reflective grating (RG). These structures are fabricated on a piezoelectric wafer. Wafers are taken from the bulk crystal at various cuts. The structures are then deposited using photolithographic techniques at an orientation relative to crystalline axes [27].

2.3.1 The interdigital transducer

In 1965 Voltmer and White introduced the IDT to electrically generate surface acoustic waves in a piezoelectric material [28]. They demonstrated that interleaved metal electrodes deposited on the surface of a piezoelectric substrate could not only successfully excite surface acoustic waves but also detect a wave and reconvert it into an electrical signal. Figure 2.7 shows a single electrode non-apodized transducer. When a voltage is applied to the busbar of the IDT, a periodic electric field is generated. Due to the piezoelectric effect a contraction and expansion of the surface occurs. The resulting elastic stress is caused by the piezoelectric effect and thus surface acoustic waves are generated with a frequency strongly related to the pitch p of the transducer.

2.3. SAW DEVICES AND COMPONENTS

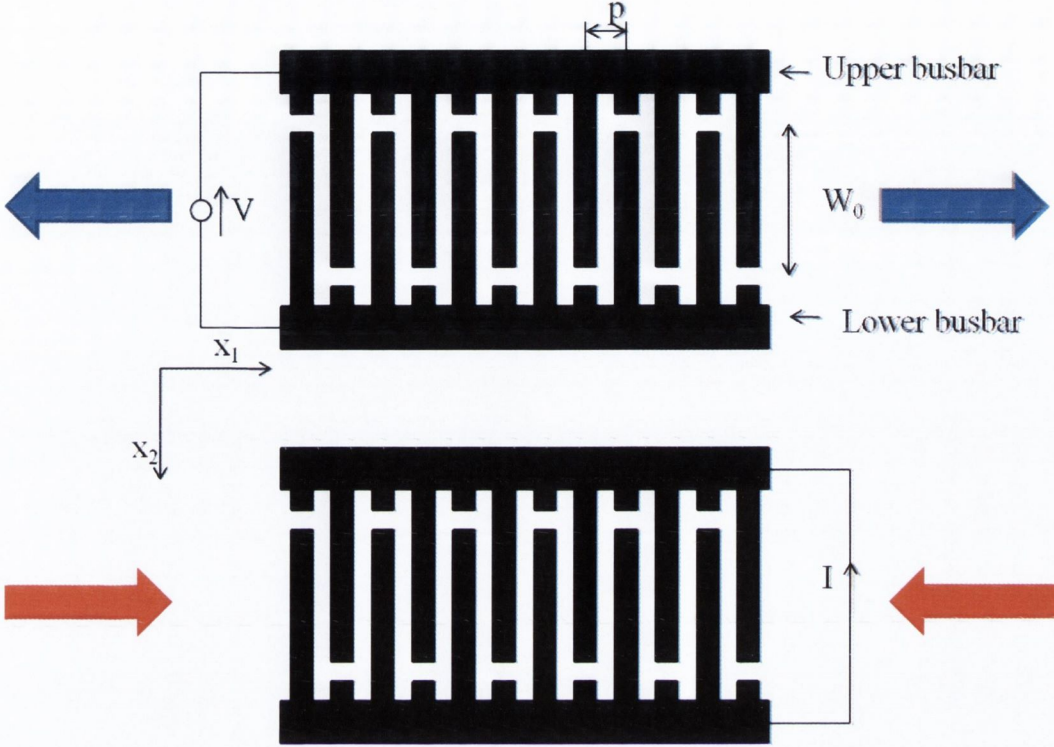


Figure 2.7: Schematic of non-apodized IDT, SAW generation top and SAW reception bottom

The IDT shown in Figure 2.7 is a bi-directional device, surface waves are launched from both ends of the IDT. The IDT consists of two separate electrode structures which are typically thin film aluminium structures fabricated by photolithographic techniques [29]. However other methods can be used to achieve the required geometric discontinuities. In general, the IDT has a periodicity p , a SAW beam width W_0 , with a ratio between p and electrode thickness known as the metallisation ratio η_0 . In a typical transducer several hundred electrodes can be present.

The response of an IDT is probably best illustrated using a basic SAW simulation tool *The Delta-function model* developed by Tancrell and Holland [30]. The delta function model is one of the earliest models for analysing SAW transducers and describing the frequency response of an IDT. The model treats each pair of electrodes in the IDT as a source of SAW. The amplitude of the generated surface wave is related to the charge density on the surface ϕ . Surface waves travel through the IDT with a velocity v_s which is independent of frequency. When an alternating voltage is applied across the busbars of the IDT, the electrical field generated across each electrode pair will cause a contraction and expansion of the piezoelectric substrate resulting in the generation

2. GENERAL THEORY OF SAW STRAIN SENSORS

of the SAW. The amplitude of the SAW will be directly related to the frequency of the input voltage applied across busbars. The total response of the IDT will then be a summation of the wave generated by each electrode pair, M . It can be shown that the approximate amplitude of the frequency of an IDT with M electrode pair is given by [18]:

$$A(\omega) = M \left| \frac{\sin(M\theta)}{(M\theta)} \right| \quad (2.3.1)$$

where

$$\theta = \pi \frac{\omega - \omega_0}{\omega_0} \quad (2.3.2)$$

ω_0 is defined as the frequency by $\lambda = 2p$ (by equation 2.2.17). Equation 2.3.1 is the approximate amplitude response of the IDT, Figure 2.8

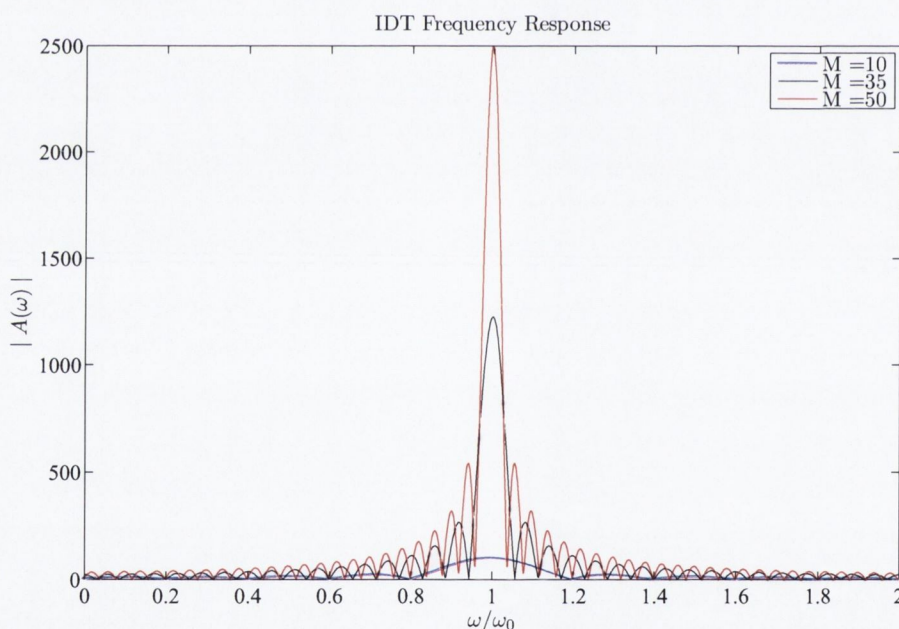


Figure 2.8: Delta Model Frequency Response of an IDT

The Delta-function model demonstrates a direct link between the periodicity of the IDT and the strength of the response. In Figure 2.8 the growth of the amplitude of the response increases at frequencies close to ω_0 . Furthermore, the amplitude of the SAW is directly related to the number of electrodes present in the IDT. This result illustrates the benefits of utilising an IDT containing numerous electrodes instead of a few high

2.3. SAW DEVICES AND COMPONENTS

powered electrodes. ω_o is known as the resonant frequency and is typically described as (f_r) . T

$$f_r = \frac{v_s}{2p} \quad (2.3.3)$$

The key result of the Delta model is that in the absence of electrode reflectivity and mass loading influences the maximum frequency response of the IDT is related to the electrode pitch and SAW wave velocity. The wavelength λ of the SAW is directly related to the pitch of the IDT.

2.3.2 Reflective gratings

The Delta-model analysis of SAW transducers assumes that the electrodes are massless and electrically non active. In reality, deposited electrodes create discontinuities both mechanical and electrical which lead to reflections of the propagating SAW. Deposited electrode structures are utilised to create reflections on the surface of a substrate for certain applications and SAW devices. The deposited electrode structures are usually deposited in large numbers to form grating structures called reflective gratings (RG). These structures can be either etched groves or deposited electrodes which are electrically open or shorted. Four distinctive types of reflection mechanisms have been outlined which contribute to how an incident SAW is reflected [31].

2. GENERAL THEORY OF SAW STRAIN SENSORS

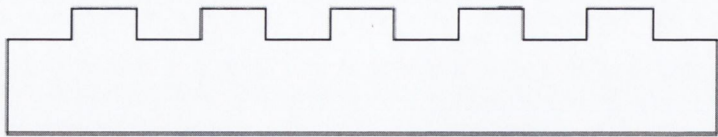


Figure 2.9: Grooved Reflective Gratings

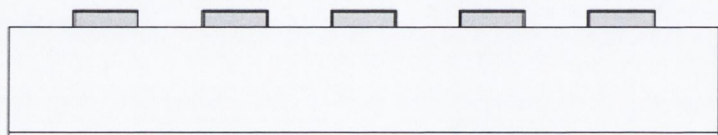


Figure 2.10: Open Reflective Gratings

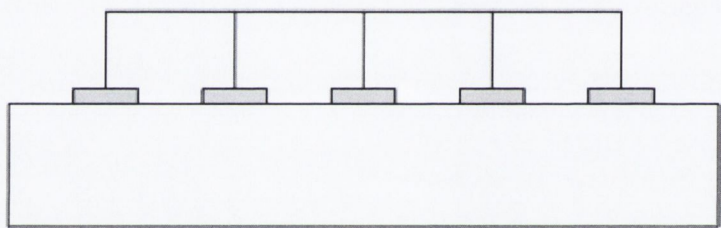


Figure 2.11: Shorted Reflective Gratings

Piezoelectric shorting: The SAW electrical field in the RG is shorted reducing the SAW velocity. Due to discontinuities in wave velocities the SAW phase is changed, this results in reflections. This tends to occur in materials where the SAW has a large electromechanical coupling coefficient K^2 see Section 2.2.3.

Electrical regeneration: The incident wave arriving at the reflective gratings produces a time varying electrical field. This electrical field causes the generation of SAWs. This regenerated component is larger than but with opposite phase to that of piezoelectric shorting.

Geometric discontinuity: The presence of grooves or deposited electrodes cause discontinuities in the surface profile in which a SAW propagates. The propagation of the SAW is then altered leading to reflections.

Mass loading: The variation in density and elasticity properties in the propagation path due to the electrodes and their presence on the substrate surface causes SAW propagation discontinuities leading to reflections.

2.3. SAW DEVICES AND COMPONENTS

The mechanisms by which a reflective grating induces reflections of the incident SAW will be dependent on the properties of the substrate. The electromechanical coupling coefficient will dictate whether piezoelectric shorting and or electrical regeneration occurs. On substrates such as AT-X quartz reflections due to geometric discontinuities will be the primary mechanism for reflections. Piezoelectric shorting and electrical regeneration may even result in decreases in reflection strengths. The effects of a reflective grating can therefore be difficult to predict theoretically and SAW device manufacturers tends to base RG design on experimental and manufacturing experience.

2.3.3 SAW delay line

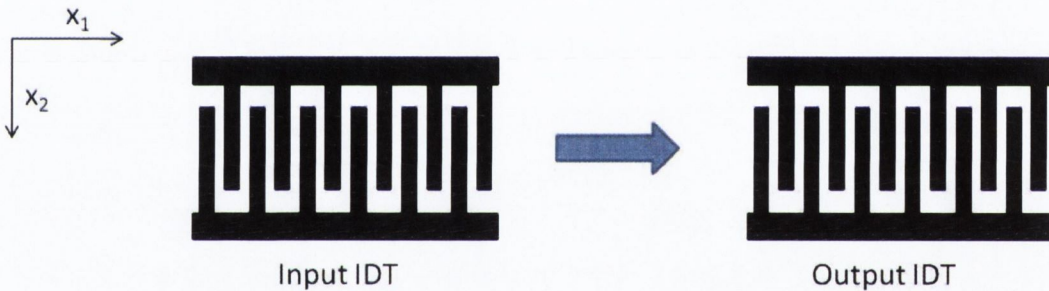


Figure 2.12: Schematic of a SAW Delay line with a SAW launched from the input IDT and propagating towards the output IDT

A second type which is commonly used incorporates an IDT with reflective electrodes placed at a distance from the IDT. As electrodes reflect an incident SAW back towards the IDT, several electrodes deposited at various positions from the IDT will result in a pulse train with a time delay between the SAW reflected by each electrode arriving back at the IDT. The time delay corresponds to the electrode separation from the IDT. Such arrangements are commonly used in RFID tags.

2. GENERAL THEORY OF SAW STRAIN SENSORS

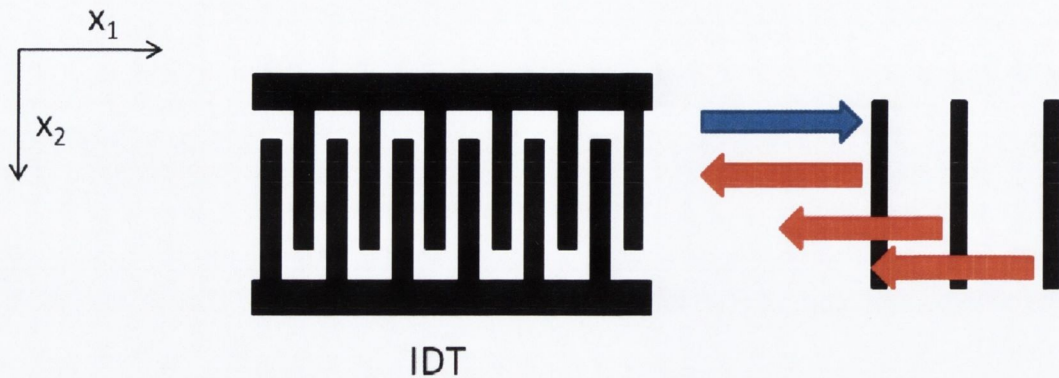


Figure 2.13: Schematic of a SAW reflective delay line with an incident SAW launched from the input IDT reflected by the reflective gratings

2.3.4 One port SAW resonator

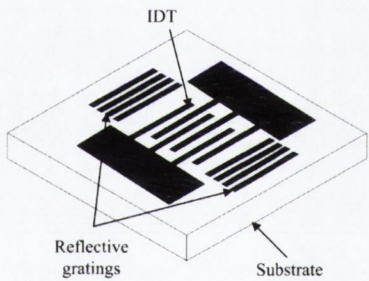


Figure 2.14: Schematic of a SAWR

The SAW resonator (SAWR) proposed by Ash [32] exploits RG to reflect a propagating SAW back towards the IDT to form a resonant structure. Figure 2.14 shows a one-port SAWR. An IDT is located between two RG, a SAW is launched from both ends of the IDT and is reflected by the RG, this produces a standing wave in the resonant cavity. The pitches of the reflective grating and IDT are usually equal. A single electrode reflects a SAW weakly, however the combined effect of several hundred electrodes allows for reflectivity's of up to 95% efficiency to be achieved. The use of long gratings limits the surface to bulk wave coupling. The RG is located within the Fresnel region of the propagating wave, which limits beam steering effects. Overall the SAWR is a highly efficient device with high Q-factors achievable. The frequency of an applied voltage which causes the SAWR to resonate is called the f_r and is the same frequency which generates the strongest response in the IDT (see equation 2.3.3).

2.3. SAW DEVICES AND COMPONENTS

2.3.4.1 Unwanted wave modes

A common source of degradation in the response of a one port SAWR occurs due to the generation of unwanted wave modes which degrade the overall response of the resonator. These spurious responses are due to the generation of unwanted transverse wave modes that occur within the reflective grating. These unwanted wave modes appear as higher order responses and are due to diffraction and beam steering within the reflective grating. Higher order responses are of particular concern as they effect the response of the resonator lowering the Q-Factor. In wireless sensing these unwanted modes can be extremely disruptive as such modes may be misinterpreted as the SAWR resonance response.

In SAW devices, responses due to acoustic waves other than SAW are spurious bulk waves [19]. Bulk waves will also be excited by an IDT. Bulk waves propagate through the bulk of a substrate material and reflect at the edges of substrates. Surface treatments such as sand blasting and lapping on the base of a resonator can suppress these bulk wave modes [33]. A separate bulk wave mode known as a surface skimming bulk wave (SSBW) cannot be suppressed by sand blasting as the wave front penetrates into the substrate slowly. A similar wave mode called the surface transverse wave (STW) mode is commonly used as the wave mode in filters due to the higher wave velocity compared to SAW [34].

2. GENERAL THEORY OF SAW STRAIN SENSORS

2.4 Strain sensing mechanism in SAWR

A strain sensor should demonstrate a measurable linear response to applied strain. The resonant frequency of a SAWR strain sensor is a distinct feature of the device and undergoes a quantifiable and measurable shift from the nominal value as strain is applied. Equation 2.3.3 described f_r as a function of two properties the electrode pitch and SAW velocity. For the SAWR to operate successfully as a strain sensor either or both of these variables must display a sensitivity to strain, the combination of which causes a repeatable linear change in the resonant frequency of the SAWR. The effects of strain on a SAWR resonant frequency are separated into two components;

- External strain biases changing the geometry of the electrode structures (IDT and reflective gratings).
- External strain biases resulting in stresses developing in the substrate altering v_s .

2.4.1 Geometric effects

Quartz provides a rigid substrate for SAWR, capable of surviving loading up to $2000\mu\epsilon$ beyond which a brittle failure of the quartz occurs. A strain applied to the SAWR causes an elastic deformation of both the substrate and aluminium electrodes. The critical dimensions of the electrodes, width a , height h and pitch p , are all deformed by the applied strain. The deformation of the IDT and reflective grating electrodes due to applied strain alters the wavelength of the resonant SAW, therefore providing a dependency between strain and resonant frequency. Reducing the pitch of the electrodes causes an increase in the f_r , conversely increasing the pitch causes a decrease in f_r .

2.4.2 Effects of Stress on SAW velocity

The velocity of an acoustic wave propagating in an elastic medium can display a stress dependence. This phenomenon termed acoustoelasticity by Hughes and Kelly in 1953 [35] was first referenced to SAW devices in 1975 when Cullen and Reeder measured the changes in the delay time of a SAW delay line device as strain fields were applied [36]. Further investigations show that the stress dependency of the SAW velocity varies significantly with substrate orientation [37]. Nalamwar and Epstein suggested that velocity-stress dependency was caused by changes in the elastic constants of the material, density and equations of motion [38]. The overall change of SAW velocity

2.4. STRAIN SENSING MECHANISM IN SAWR

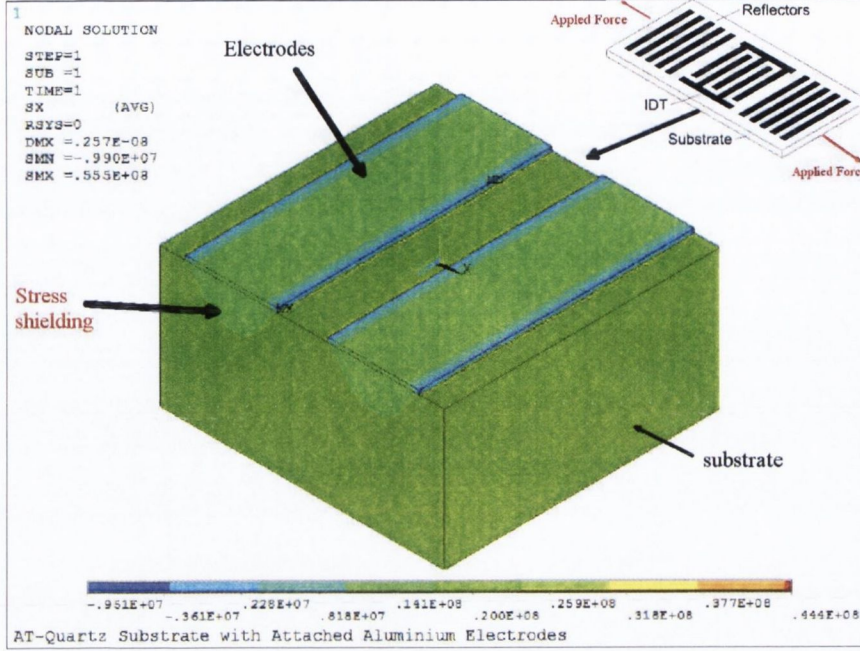


Figure 2.15: Contour plot of the T_{11} stress at the interface between substrate and electrodes for uniaxial strain applied to AT-X Quartz to the direction of SAWR propagation

in the substrate is a function of the longitudinal and transverse stress generated in the substrate as strains are applied. The sensitivity of the v_s can vary dramatically across substrates. The stress generated in the SAW substrate can be calculated using Finite Element methods, to this end an ANSYS v10.0 model was created to illustrate the effects of strain being applied to the surface region of a SAWR. A substrate volume with dimensions λ long, λ wide and $\lambda/2$ deep were chosen. The substrate was generated as a quartz aluminium composite body. Symmetric boundary conditions were applied to the edges of the quartz. A uniaxial displacement was applied in the x_3 direction equivalent to a $250\mu\epsilon$. Figure 2.15 shows a contour plot of the T_{11} stresses (normal to wave propagation) in the surface region of SAWR. The metallised portions of the surface display significantly lower stress state than the free surface regions and the rest of the substrate. The thin electrodes have a negligible effect in the overall stress state in the material. Only moderate stress shielding occurs in the region directly under the electrode of approximately $\lambda/8$.

An applied strain bias leads to an alteration of the elastic constants of the material to form a set of biased elastic constants known as the effective elastic constants [39]

2. GENERAL THEORY OF SAW STRAIN SENSORS

$$c_{ijkl}^* = c_{ijkl} + T_{il}\delta_{jk} + c_{ijklmn}S_{mn} + c_{ijpl}w_{k,p} + c_{ipkl}w_{j,p} \quad (2.4.1)$$

where T_{il} is the static biasing stress, δ_{jk} is Kronecker delta and w_i is substrate deformation due to the applied mechanical bias. From Equation 2.4.1 it can be seen the c_{ijkl}^* values are a combination of the second order c_{ijkl} and the third order coefficients c_{ijklmn} of the material. Furthermore the contribution of the third order coefficients is required to calculate the sensitivity of the substrate to changes in SAW velocity. This is in keeping with the velocity stress-dependency that would be expected with acoustoelasticity effects.

In the next Section the overall strain sensitivity of the project sensors will be calculated based upon a combination of SAW velocity and geometric effects.

2.5 Theoretical Strain Sensitivity of AT-X SAWR strain sensors

Many authors have measured the changes in the velocity of a SAW due to applied static biases [40][41][42][43]. Typically this work has been focused on identifying the effects of strain, pressure, torque and temperature as they vary across substrates and propagation orientations which allowed for the design of bias-insensitive filters and oscillators or bias sensitive sensors. Recently a complete profile of the sensitivity of all quartz cuts to torque has been theoretically determined with some experimental verification [44]. Several high sensitivity quartz substrates have been identified which demonstrate a strain coupling four times higher than conventional cuts with low temperature sensitivities. The sensitivity of the SAW velocity to such external biases is calculated by defining effective material constants which are the constants perturbed by a stress that is introduced into the material by the external biases. While all material constants are bias sensitive for quartz the elastic constants are dominant. These effective elastic constants are then used to calculate a perturbed SAW velocity using the methods described in Section 2.2.

In this section a similar procedure based upon the static deformation of the material constants is implemented to calculate the variation in strain sensitivity of an AT-X quartz at various alignment angles to applied strain as shown in Figure 2.16. Perturbed velocities were calculated using the SAW velocity calculation program [23]. However free software is available, such as VCAL [19], which allows for alteration of the

2.5. THEORETICAL STRAIN SENSITIVITY OF AT-X SAWR STRAIN SENSORS

material constants and can be used to calculate the perturbed velocity. The modelling assumes that the wave mode propagating in the structure is a Rayleigh wave.

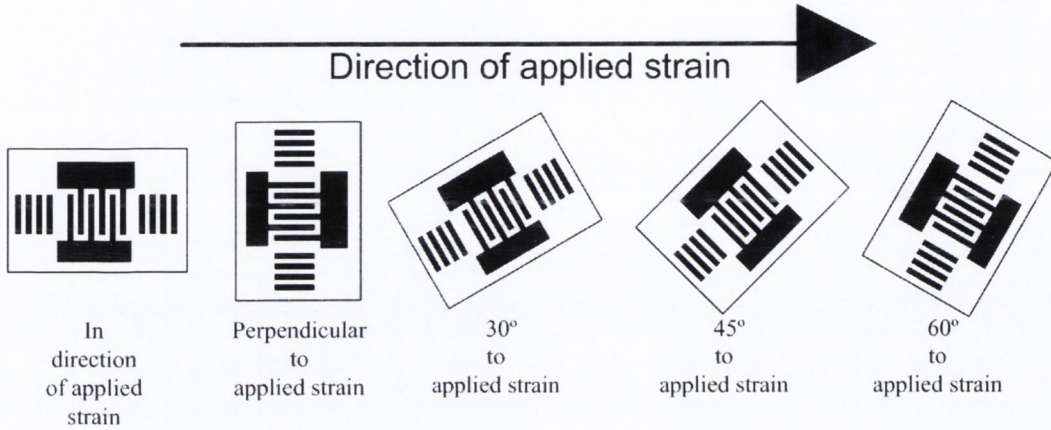


Figure 2.16: Alignment of SAWR to applied strain for calculation of SAW velocity dependency

The f_r of a SAW strain sensor is primarily a function of v_s and λ . However, influences such as electrode reflectivity and wave attenuation will influence the resonance of the SAWR [45] and are sensitive to applied external biases. Static frequency response analysis techniques such as Coupling of Modes (COM) can be adapted to include stress components. However, COM parameters, such as reflectivity, are difficult to calculate accurately when compared to experimentally fitted data. COM values can be measured experimentally on predesigned dies [46]. Such devices were unavailable for this project. Thus the calculation of the variation in f_r was made with reflectivity omitted. This approach is generally used in other research to calculate pressure and torque sensitivities and is acceptable for this sensor model [42][44][47].

Additionally, the nature of the applied biases must be considered prior to the calculation of the perturbed SAW velocity. When homogeneous biases are applied to the SAWR, the c_{ijkl} components remain homogeneous in the propagation zone of the SAWR and can be described as in Equation 2.4.1. However when the applied bias is flexural in nature an inhomogeneous stiffness coefficient occurs in the propagation zone of the SAWR substrate. Thus the SAW velocity will not be uniform. Perturbation procedures can be used to calculate the spatially-changing biasing fields. It has been shown that provided the ratio of substrate thickness to SAW wavelength is significant (≈ 90), ordinary SAW calculations produce almost identical results [48]. Typically,

2. GENERAL THEORY OF SAW STRAIN SENSORS

perturbation procedures are used when the SAWR is fabricated on a thin substrate which is acting as a pressure diaphragm [43]. The propagating SAW is confined to the surface region of the substrate. The substrate is far thicker than the SAW wavelength and is bonded to a thicker beam which is under flexure. Therefore biases can be considered homogeneous. This is a reasonable assumption here. FEM analysis of the surface of the SAW resonator confirmed the stress distribution in the working area of the device was uniform. This is consistent with FEM analysis of SAWR torque sensors with similar geometry [47].

It has been shown that for many substrates the SAW velocity changes will be dominated by the influence of the stresses in the direction and transverse to the SAW propagation, T_{11} and T_{33} respectively. Modelling of the SAW velocity sensitivities confirm that for AT Quartz, stress velocity dependencies are dominated by T_{11} and T_{33} stress components. This is shown in Figure 2.17. The sensitivities for T_{11} and T_{33} were found to be $-1.66542e^{-11} \frac{m^2}{N}$ and $8.0512e^{-12} \frac{m^2}{N}$, respectively for AT-X quartz. For this orientation a compressive T_{11} will increase the SAW velocity. Similarly, $\frac{dv}{vT_{33}}$ is positive thus a positive T_{33} will increase the SAW velocity thus causing an increase in the f_r of the resonator. In the absence of electrode reflectivity and other COM effects the sensitivity of f_r to applied stress can be found in Equation 2.5.1 [23].

2.5. THEORETICAL STRAIN SENSITIVITY OF AT-X SAWR STRAIN SENSORS

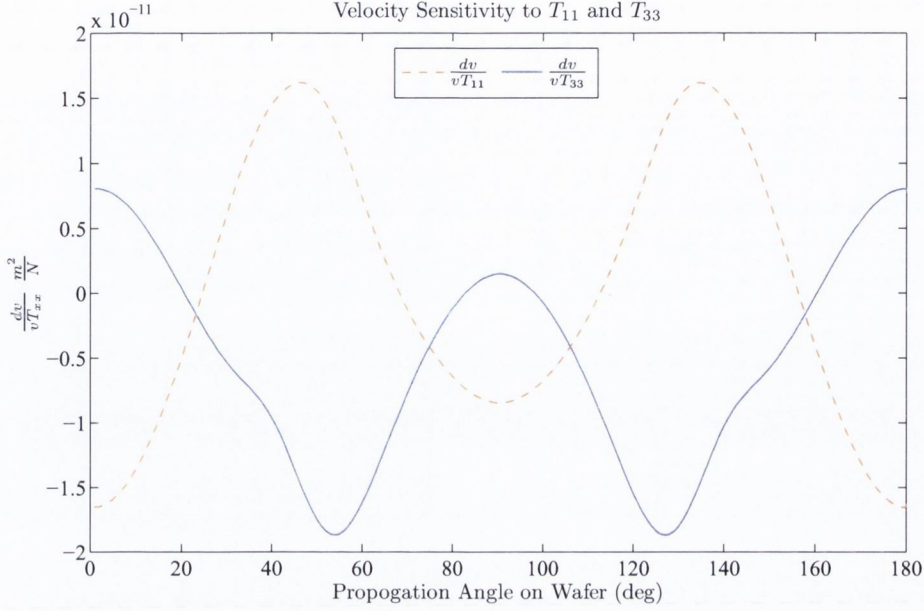


Figure 2.17: Sensitivity of SAW velocity to T_{11} and T_{33} for various AT propagation orientations

$$\frac{\Delta f}{f_0} = \frac{\frac{\Delta v}{v} - S_{11}}{1 + S_{11}} = \frac{(\frac{\Delta v}{vT_{11}})T_{11} + (\frac{\Delta v}{vT_{33}})T_{33}}{1 + S_{11}} \quad (2.5.1)$$

where S_{11} is the strain on the surface of the resonator calculated from the compliances of the rotated quartz substrate.

2.5.1 Strain sensitivity calculation as function of alignment

Once the velocity sensitivity is calculated for AT-X quartz the stress in the surface of the substrate is calculated at various alignments in the applied strain field as shown in Figure 2.16:

- The SAWR was defined in ANSYS v10 as an anisotropic block attached to the measurement area of the SAW calibration beam. The material properties of the attached die were defined as rotated values of the material constants found in [49]. The SAWR was rotated on the SAW calibration beam to the appropriate angle.

2. GENERAL THEORY OF SAW STRAIN SENSORS

Orientation	T_{11} MPa	T_{33} MPa
0°	22.31	-0.68
30°	14.58	4.17
45°	9.07	10.27
60°	4.23	16.25
90°	-1.67	19.39

Table 2.1: Calculated T_{11} and T_{33} at various orientations to applied strain for a consistent loading condition

- The beam and SAWR were then meshed. Boundary conditions were applied constraining the beam in all DOF at the mounted end. A point load was applied to the free end which generated a displacement equal to a loading point defined in the calibration process.
- Stress values were calculated on the surface of the SAWR for a coordinate system relative to the propagation direction of the SAW in the IDT and reflective gratings.
- The relative shift in f_r was calculated from the stress values calculated in the SAWR and the stress dependency of the fractional change in SAW velocity $\frac{dv}{T_{11}v}$ and $\frac{dv}{T_{33}v}$ see equation 2.5.1.
- $\frac{\Delta f}{f_0}$ was converted to S_{sen} using a value of strain for a location parallel to the SAWR in the ANSYS model. The strain value used was found at a distance away from the SAWR where localised effects caused by the stiffness of quartz substrate would not skew results.

The procedure was repeated for orientations of 0°, 30°, 45°, 60° and 90° to the applied strain. The calculated values for stress in the SAW propagation zone on the substrate surface are shown in Table 2.1

The resulting strain-frequency sensitivity for SAWR at various alignment angles can be seen in Figure 2.18. The values are compared to the experimental values determined in Section 6.8

2.5.2 Discussion on Modelling of AT-X SAWR Strain sensors

In order to verify the modelling procedure outlined in Section 2.5 the predicted strain sensitivities were compared to those found experimentally in Section 6.8. The overall

2.5. THEORETICAL STRAIN SENSITIVITY OF AT-X SAWR STRAIN SENSORS

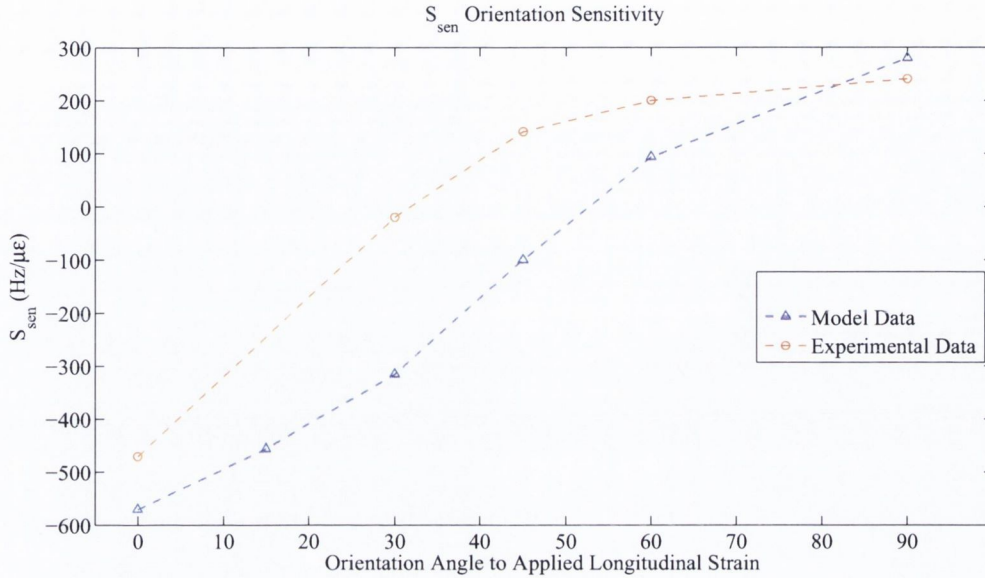


Figure 2.18: Sensitivity of SAWR alignment to applied strain experimental and theoretical

trend of the graph is correct. The sign of the frequency strain sensitivity matches that of the experimental work thus verifying that the wave mode and model set up for the determination of stress sensitivity for a Rayleigh wave mode is correct. For an AT-X sensor aligned to applied strain a value of $-571.2\text{Hz}/\mu\epsilon$ was determined, this represents an over estimation of approximately 21% which is comparable to the over estimation of the strain sensitivity for ST-X Quartz of 30% reported in [44]. The over estimation between experimental and simulation is moderately improved at AT-X aligned at 90° to the applied strain $\approx 15\%$. In simulations of the SAWR strain orientated 30° , 45° and 60° to the applied strain field the results are broadly similar in error. For these alignments, FEM indicated significant shear stress is generated in the surface of the material. While the velocity sensitivity to shear $\frac{dv}{T_{13v}}$ was found to be $9.8617e^{14}\frac{m^2}{N}$, which is several orders of magnitudes lower than the calculated sensitivities $\frac{dv}{T_{11v}}$ and $\frac{dv}{T_{33v}}$ and will have a negligible effect on SAW velocity. Stress shielding effects caused by the inclusion of adhesive layers for the bonding of the SAWR sensor are known to be significant and may result in the offset in measured and theoretical values.

However the results predict the decrease strain sensitivity of the SAWR as orien-

2. GENERAL THEORY OF SAW STRAIN SENSORS

tation to applied strain is changed, the correct sign change was calculated for AT-X orientated at 0° and AT-X orientated at 90° . Thus demonstrating that alignment errors and the effects on SAW performance can be calculated. It also demonstrates that strain insensitivity can be achieved by mounting of the SAWR which could be of benefit for compensation of the SAWR in electronic applications to stress and temperature. The modelling schemes can also be used to predict possible substrate orientations of quartz which could be suitable for strain measurements. From simulation cuts AT- 40° to AT- 46° show strong coupling to T_{11} while simultaneously demonstrating an acceptable K^2 . However reflectivity effects would need to be investigated to ensure suitability. To the author's knowledge this is the first instance of using rotated SAWR strain sensors to validate the modeled response of a SAW strain sensor to experimental data. This novel validation procedure negates the requirement to use a range of substrates to validate theoretical modelling of SAWR strain and torque sensors. Thus decreasing the complexity of sensor validation. The SAWR strain sensor remains at a single propagation direction and the stress states are changing due to changes in the orientation of the SAWR strain sensor. Die design is generally not considered in the design of SAWR strain and torque sensors or at least published literature does not suggest so. This method suggests the strain sensitivities can be controlled by designing the SAWR die into a particular geometry in which an appropriate stress state in the substrate is generated. Such a design approach could be included at the design stage along side substrate selection and design of the IDT structures. This may in fact be a more suitable method for SAWR design and be preferential for creating multi sensor array in the ISM band as strain sensitivities can be controlled rigidly thus limiting full scale sensor bandwidths.

2.5.3 Conclusion

In this chapter a general overview into SAW strain sensor was presented. The basic concepts on the nature of the SAW and the methods used to excite the wave on piezoelectric substrates was presented. Modelling techniques used to calculate the SAW velocity for a given substrate and orientation were detailed as well as methods to calculate the effects of stress and strain on the wave velocity. These methods were then employed to calculate the theoretical response of the SAWR strain sensor. These modelling techniques were expanded to predict the variation in the SAWR strain sensitivity at various alignments to applied strain. The theoretical SAWR response was then com-

2.5. THEORETICAL STRAIN SENSITIVITY OF AT-X SAWR STRAIN SENSORS

pared to experimental measured sensitivities and a novel method for validating SAWR strain sensors was presented. The accuracy of the model was evaluated and the advantages and weakness of this modelling technique were discussed. The possibility of incorporating this modelling technique into SAWR design to create sensors which can retain the advantages of AT-X propagation whilst controlling the strain sensitivity was also discussed.

2. GENERAL THEORY OF SAW STRAIN SENSORS

Chapter 3

Surface acoustic wave sensors

The application of SAW devices to the sensing of physical measurands was first reported over thirty years ago [50]. Over the last fifteen years extensive research has been undertaken to develop the reader technology to interrogate SAW sensors wirelessly. While the advantages of passive wireless sensing are obvious and have the potential for extensive commercialisation, it has only been recently that commercial interrogation units have come to market. The commercialisation of interrogation hardware was a key development which facilitated this work. The availability of commercial hardware will undoubtedly see another surge in SAW sensor development. It is hoped this thesis can facilitate such endeavors.

This chapter discusses the development of SAW sensing over the last three decades. A review of SAW sensors designed for the sensing of physical measurands such as temperature, strain and pressure is provided. Details and an assessment of the sensor used for this project is presented. An overview of the interrogation unit used in this project is also included.

3.1 History of physical SAW sensors

The primary application of SAW devices is to act as electronic components where highly stable performance is essential. This requires that components demonstrate an insensitivity to temperature and strain. During the 1970's investigations were performed to assess the sensitivity of SAW devices to external biases. These early works focused on identifying sources of instability in the performance of electronic SAW based components. This led to the discovery of several temperature and stress insen-

3. SURFACE ACOUSTIC WAVE SENSORS

sitive quartz cuts like the double rotated stress compensated SC cut [51] and the current industry standard ST quartz [52] which exhibits minimal temperature sensitivity in the range around ambient conditions.

As the sensitivity of a SAW device performance to external biases was known, the possibility of utilising SAW device as physical sensors was assessed. One of the earliest reported examples of SAW devices as sensors was performed by Dias and Kerrer in 1974 [50]. They investigated the effects of stress on the delay time of SAWDL (see Section 2.3.3 for a description of SAWDL). A SAWDL was mounted in a cantilever arrangement and the free end displaced, the result was a demonstration of a force and pressure transducer [50]. Further developments were made by Cullen and Reeder when they fabricated a SAWDL on a machined diaphragm to create a SAW pressure sensor in 1976 [41]. As SAW devices become more common in telecommunications systems SAW research focused once more on eliminating SAW sensitivity to external biases in particular to vibration [42] through package design [53] and the identification of other stress and temperature compensated substrate cuts [54].

Research into mechanical SAW sensors slowed during the 1980's mostly due to the robustness of the competing technologies. SAW sensor development became focused on chemical and biological applications. Today SAW chemical sensors are readily available as commercial products [55]. Chemical sensing is the main application area for SAW sensors.

The main attraction of physical sensing with SAW devices is the possibility for wireless passive measurement, which can be achieved with either the SAW delay line (SAWDL) or the SAWR [56]. This is the method by which SAW ID tags operate and indeed the development of SAW sensing is closely related to the development of wireless SAW RFID tags. By 1972 wireless SAW ID tags had been demonstrated. Today passive wireless ID tags are in commercial use. The first reported demonstration of a SAW wireless sensor was made in 1989 when Bao et al [57] demonstrated wireless passive temperature sensing with SAW ID tags. During the 1990's development of wireless passive readers and interrogation units accelerated greatly with two separate groups primarily developing reader technologies for SAWR and SAWDL. A combined research group from Siemens and the University of Technology Vienna focused on SAWDL sensors and developed a number of prototypes for automotive applications. Reader units for SAWDL line devices were developed in tandem and shown to operate in applications such as: tyre pressure monitoring and torque sensing [58].

At the same time research continued with the development of wireless SAWR sen-

3.2. SPECIFICATION OF PROJECT SENSORS

sors. In 1990s patents were filed by A and B Lonsdale demonstrating details on SAW torque sensors [59]. Buff et al at the Technical University of Ilmenau developed SAWR wireless readers and sensors for pressure and temperature applications during the 1990's [60]. During this time differential sensing and temperature compensation for SAW devices was introduced in both SAW delay line and reflective delay line sensor types. Buff implemented differential measurement in SAWR sensors. Differential measurement calculates a strain based upon the difference in response between two or more SAWR on the one die and is commonly used in torque measurements [61]. Differential measurement in SAW sensor greatly lowers the temperature dependency making it ideal for physical sensing. An additional benefit was that this difference is almost independent of influences of the radio channel such as distance [60]. While several research groups left the field, research into SAW sensors and reader technology continued to grow mostly however in a commercial setting. Several companies have commercialised reader and interrogator hardware and currently offer pressure, torque and temperature sensors. Carinithian Tech Research have commercialised SAW delay line sensor for use in measuring pressure temperature and strain [62]. While recently SenSeor have commercialised temperature, pressure, stress and torque SAW sensors [63]. Interrogation units have become available at a competitive price point designed with off the shelf components. Transense Technologies probably the leader in SAW sensing technology have begun to license technology to several companies, SenGenuity currently use such hardware [64] for wireless SAWR temperature sensing. In section 3.5 the interrogator hardware will be discussed. The Transense interrogation hardware has also been commercially licensed to several automotive manufacturers. However these licenses use a custom ASIC which performs signal processing and acts as the Tx/Rx synthesizer. The custom ASIC has been reported to operate with a sensor update rate of 6kHz with one sensor [65]. Currently, however, no major market has adopted SAWR sensors and it seems unlikely that SAW sensing technologies will displace existing technologies. However SAW devices may be best suited to niche operations or open applications previously unsuitable with other commercial technologies, such as strain measurement on rotating shafts.

3.2 Specification of project sensors

At the commencement of this project suitable SAW sensors were unavailable. One port SAW resonators were selected as the device type for this project. For mechanical

3. SURFACE ACOUSTIC WAVE SENSORS

sensing operations SAWR are preferred over delay line devices due to their narrow-band performance, smaller die size and higher Q factor when compared to delay line devices of equal dimension [47]. As will be discussed in Chapter 2 the properties and behaviour of SAW devices can vary significantly depending on the design of the device and selection of the substrate material. Therefore to operate successfully as a wireless sensor a potential SAW device should demonstrate several key characteristics.

Passive wireless operation: For a SAWR to operate wirelessly and passively a high Q-factor is required. SAWR strains sensors are required to store energy from an RF pulse from which to supply a response signal. The Q-factor quantifies how the energy stored in a SAWR dissipates over time.

Strain dependency and temperature independent To operate as a strain sensor, the SAWR strain should operate with a sensitivity to strain which is larger than the sensitivity to temperature. Temperature compensated cuts and stress compensated cuts of quartz have been identified previously. Due to the anisotropic nature of quartz, SAWR sensitivity to strain and temperature can vary depending on substrate and propagation conditions. The strain sensitivity must be such that the f_r remains confined to a known full scale sensor bandwidth during operation to avoid confusion with other sensor types while demonstrating a low temperature sensitivity.

Physical size: One of the virtues of commercial SAW filter technology is the small physical dimensions of the die typically $2.8\text{mm} \times 1.7\text{mm}$. Such dimensions however are too small for manual handling. Physically small dies would also suffer from inconsistent bonding and alignment errors.

Repeatable sensors: The test sensors should form part of a consistent manufactured lot. The strain performance can be separated from inconsistency in manufacturing.

3.2.1 SAWR sensor type

A SAWR strain sensor may be required to operate as part of a wireless passive network which may contain several sensor nodes, or for differential SAWR sensor several resonators forming a single node. In each case the resonant response of each SAWR must be distinguishable in the bandwidth of sensor operation. This is usually achieved by

3.2. SPECIFICATION OF PROJECT SENSORS

separation of f_c . Figure 3.1 shows the S_{11} plot of several absolute measurement sensors acting as a single sensor node. In absolute measurement, compensation of thermal or transmission effects cannot be made.

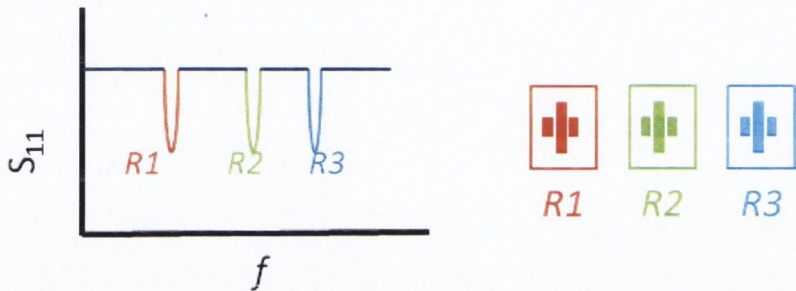


Figure 3.1: Multi SAWR network with several sensor nodes

Figure 3.2 shows a schematic of a differential SAWR sensor. A single sensor node comprises of several resonators. The additional resonators are used for temperature compensation.

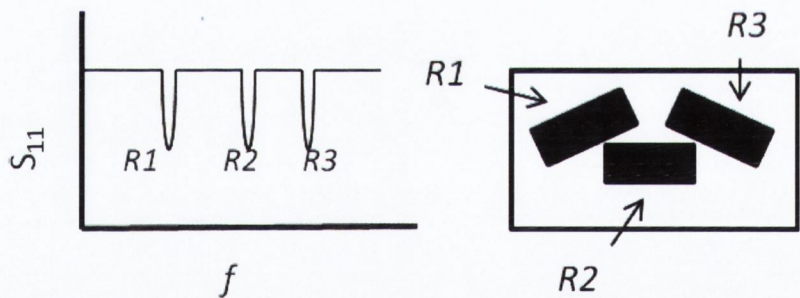


Figure 3.2: A single SAWR node incorporating several resonators for differential measurement

For absolute SAW sensing each node must be separated by a bandwidth sufficiently large to cover the frequency range of operation. It is possible however to implement beam forming techniques on the interrogation signal to measure SAWR which are physically separated [66]. This could facilitate the use of identical sensors in one network. The implementation of such a scheme would be included into the reader electronics and is beyond the scope of this project.

3. SURFACE ACOUSTIC WAVE SENSORS

3.2.2 Sources of SAWR sensors

This project forms part of the second generation of SAW research in Trinity College Dublin. The previous project completed in 2007 used SAWR devices fabricated on ST-Quartz [23]. However the fabricated devices failed to perform effectively. This could be attributed to the complexity in SAWR design and the lack of trial and error in the fabrication processes. For this project fabrication facilities were not available to perform trial and error on the fabrication process and on the design of the SAWR therefore the chances of success were felt to be limited. It was decided to commission a commercial organisation to aid in the design and fabricate the SAWR strain sensor for this project. In most cases commercial SAWR sensor companies license the manufacture to a commercial organisation. This allows for the SAWR sensor to enter into a well defined and optimised process during fabrication which will lead to higher yields. SAWNICS international, a South Korean manufacturer of SAW devices was commissioned to design and fabricate SAWR strain sensors. Based upon details found in the literature, the authors involvement in previous SAW sensors projects [67] as well as recommendations by the manufacturer a design specification was agreed upon and a fabrication run was commissioned. As the manufacturer was located in South Korea traveling to observe the process was not practical and many of the finer details on the manufacture process are propriety knowledge. Details on the sensors specification provided to the SAWNICS is shown in Table 3.1.

The final dies were delivered on a 4 inch wafer which was diced using a quartz dicing saw. The completed wafer is shown in Figure 3.3 and a single sensor is shown in Figure 3.4.

3.2. SPECIFICATION OF PROJECT SENSORS

Electrical Specifications			
	IDT type	TCD	Final Delivered
f_c	Non-Apodized	433.42MHz	$f_c \pm 0.05$ MHz
f_c	Apodized	433.92MHz	$f_c \pm 0.05$ MHz
f_c	Apodized	434.42MHz	$f_c \pm 0.05$ MHz
$ Z $ at f_c		$50\Omega \pm 20\Omega$	$50\Omega \pm 20\Omega$
Q factor		10,000	$> 10,000$
Broadband S_{11}		$-1dB$	$> -1dB$
Spurious S_{11}		$> -2dB$	$> -2dB$
Substrate Specifications			
		TCD	Final Delivered
Material		Quartz	Quartz
Cut Type		ST	AT
Thickness		$350\mu m$	$350\mu m$
Length		5mm	$5mm \pm 0.1mm$
Width		5mm	$5mm \pm 0.1mm$
Bond Pads		$2 \times 2mm$	$2 \times 2mm$

Table 3.1: Specification of SAWR senors

3. SURFACE ACOUSTIC WAVE SENSORS

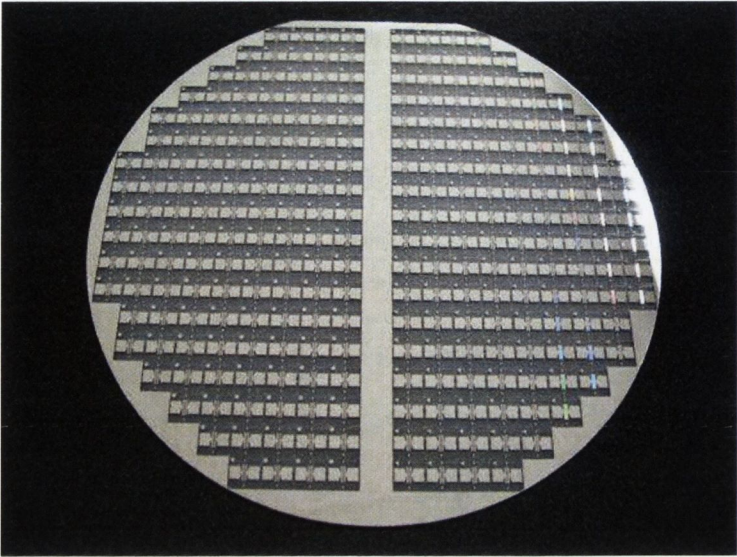


Figure 3.3: Completed SAWR wafer

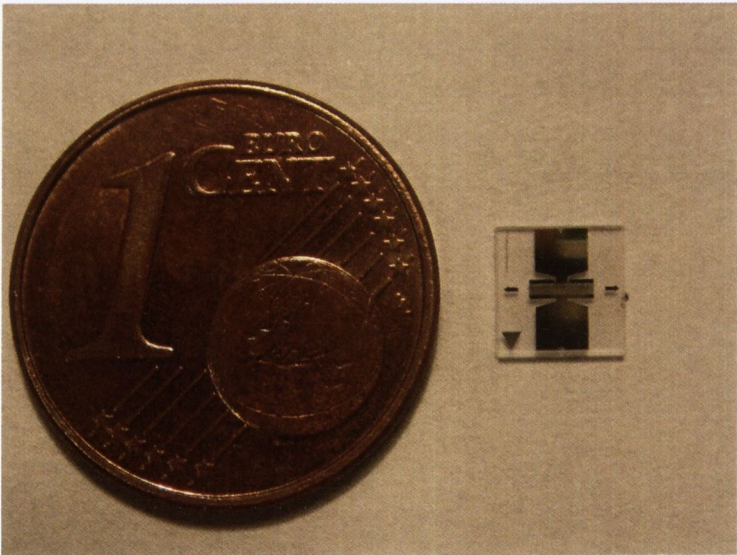


Figure 3.4: Diced SAWR strain sensor

3.3 SAWR Sensor Design

Each completed fabricated wafer contained 280 dies. For this project work was focused on the 434.42 MHz apodized sensor and 433.42 MHz non apodized sensor. This section provides details on the layout of the SAWR.

3.3.1 Non Apodized 433.42MHz

A schematic of the layout of the non apodized SAWR sensor is shown in Figure 3.5. The non apodized structure is the most basic design configuration for the IDT.

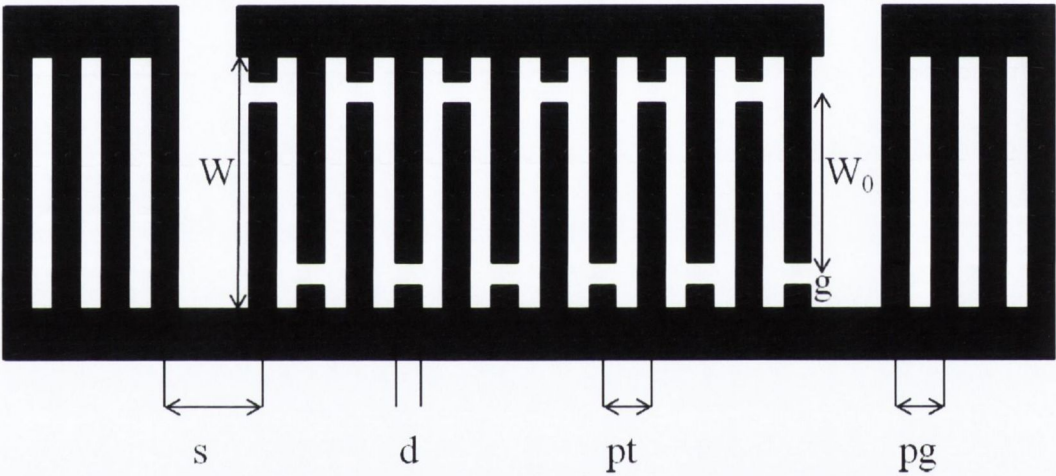


Figure 3.5: Schematic of 433.42MHz non Apodized SAWR

The dimensions of the non apodized SAWR are given in Table 3.2. A magnified image of the IDT is shown in Figure 3.6.

3. SURFACE ACOUSTIC WAVE SENSORS

pt	IDT Electrode pitch	$3.6162\mu m$
pg	Grating Electrode pitch	$3.6162\mu m$
g	Electrode width	$0.35 \times pt$
d	Base of Electrode	pt
Nt	Number of electrodes in IDT	121
Ng	Number of electrodes in Grating	280
s	Grating Spacing	$7/4 \times pt$
h	Deposition thickness	$1100\text{\AA}$
W_0	Aperture	$120 \times pt$
W	Aperture	$W_0 + 2 \times d$

Table 3.2: Non-apodized 433.42MHz SAWR Geometrical Features

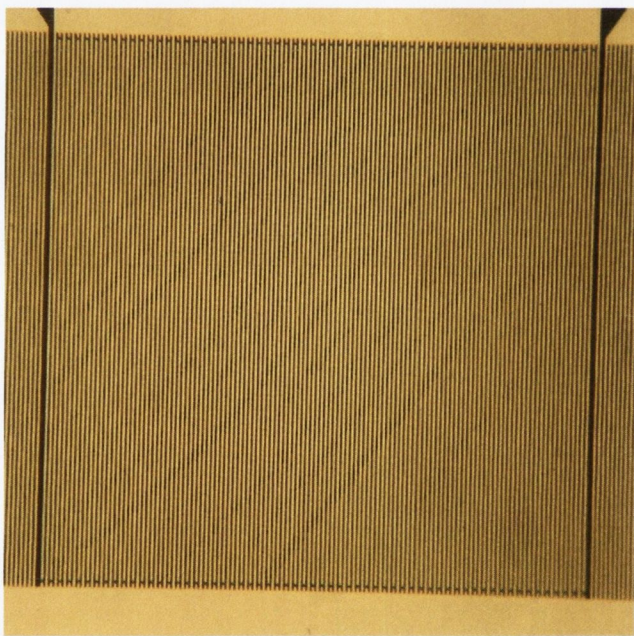


Figure 3.6: Photo of non Apodized 433.42 MHz SAWR at approx. 200x magnification. The lighter regions are deposited aluminum

3.3.2 Apodized 434.42 MHz

The second design incorporated an apodization function. Apodization is commonly used in optics to control the input of an optical system. The intensity of profile of the optical input can be varied through apodization of the input source. In SAW devices apodization is a method whereby the overlap of the active electrodes is varied along the length of the transducer to control the profile of the SAW generated by the IDT. When an impulse response of the transducer is considered, the frequency response of the device can be given by the Fourier transform of its time response which is directly related to the electrode layout. The strength of the time response of the SAWR varies as the SAW passes through the IDT. As the Fourier transform from time domain to frequency and vice versa creates almost identical results, the time response and frequency response of the SAW can be controlled. Apodization can also be used to suppress the unwanted transverse wave modes generated in the reflective gratings [68].

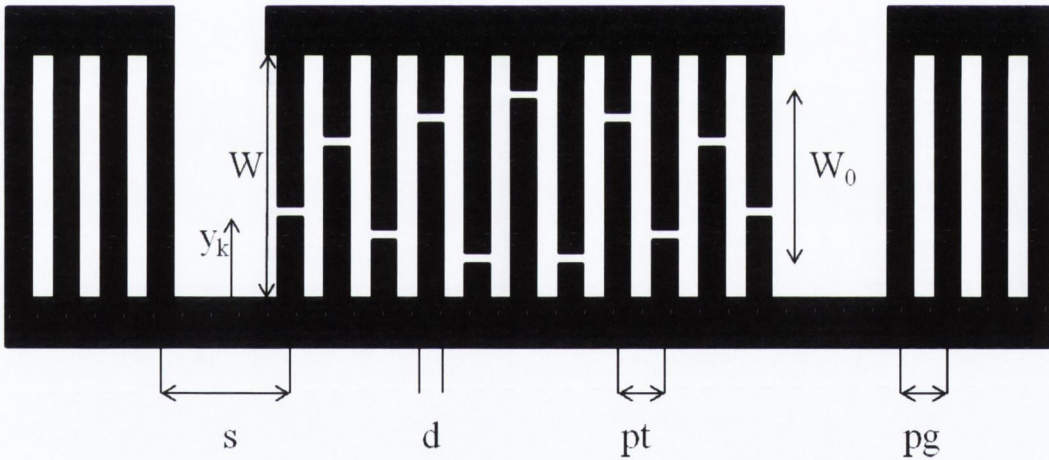


Figure 3.7: Schematic of 434.42MHz Apodized SAWR

A schematic of the IDT layout is shown in Figure 3.7. The apodization function which defines the electrode aperture is given by Equation 3.3.1 and Equation 3.3.2.

$$q_k = (-1)^k \cos(\pi k / (4 \times N)); \quad (3.3.1)$$

$$y_k = \frac{W + g}{2} (1 + q_k) \quad (3.3.2)$$

This results in the overlap of the electrodes varying with position. In Figure 3.8 an image of the IDT of the apodized SAWR is shown under magnification. The apodiza-

3. SURFACE ACOUSTIC WAVE SENSORS

tion function of the IDT is typical of a classical apodization function for a SAW IDT.

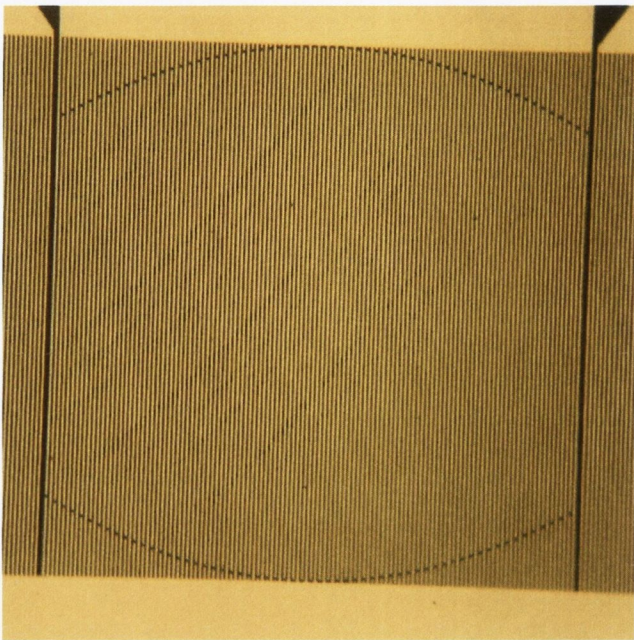


Figure 3.8: Photo of Apodized 434.42MHz SAWR at approx. 200x magnification. Lighter regions are deposited aluminum

pt	IDT Electrode pitch	$3.599\mu m$
pg	Grating Electrode pitch	$3.599\mu m$
g	Electrode width	$0.35 \times pt$
Nt	Number of electrodes in IDT	120
Ng	Number of electrodes in Grating	280
s	Grating Spacing	$7/4 \times pt$
h	Deposition thickness	$1400\text{\AA}$
W_0	Aperture	$120 \times pt$

Table 3.3: Apodized 434.42MHz SAWR Geometrical Features

3.4 Discussion on SAWR Design

All sensors were fabricated on AT-X quartz. AT quartz has a turnover temperature of $\approx 80^\circ$. It is similar in orientation to the substrate used by both SenSeor and Transense for pressure and torque sensor (Y-34 $^\circ$). It is more suitable for strain sensors than conventional ST Quartz as the turnover temperature of ST-X quartz is 24° [69]. The temperature drift of AT quartz is lower than that of ST quartz, for an absolute SAWR sensor low temperature drift is preferable. To the authors knowledge this is the first implementation of SAWR fabricated on AT quartz for physical sensing applications. The frequency response of a SAWR is a function of the design which can be a compromise between substrate properties and the fabrication capabilities. Generally, f_r is a function of the v_s and the tolerances of the photolithographic processes. However other factors can influence the overall frequency response. The presence of surface metallisation introduces mass loading which effectively dampens the amplitude of the SAWR response thus lowering v_s . The propagating wave can be further attenuated by parasitic losses due to bulk wave couplings, mass loading due to the presence of air and acoustic losses due to the propagating wave interacting with the crystalline structures of the substrate [70]. Beam steering and wave diffraction can introduce second and third wave modes in the device response which should be avoided. During the design phase these effects can be simulated, generally with COM [71].

- The resonant frequency of a SAWR is dependent on the reflective gratings [45]. The influence of reflectivity on the f_c can be controlled by the spacing of the reflective gratings. However through design the sensitivity of f_c to the RGs can be eliminated. The IDT and RG layout configurations can be divided into two types described by the spacing between the IDT and reflective gratings. The preferred layout known as the optimal design type, positions the reflective gratings a multiple of the electrode pitch apart i.e ($s = 1.75 \times pt$). This provides that the total phase shift of the SAW within the resonant cavity is a multiple of π [31]. The optimal design increases the magnitude response of the SAWR at resonance and minimise ripples in the frequency response particularly at the low side of the stop band. The second configuration is the synchronous layout where the reflective gratings are located at a position directly related to the periodicity of the IDT ($s = 2 \times pt$ etc). Such designs may result in poorer overall magnitude responses at resonance and introduce ripples in the response at the stopband edges. However such designs tend to be easier to manufacture as the tolerances

3. SURFACE ACOUSTIC WAVE SENSORS

on the position of the reflective gratings is directly related to the periodicity of the IDT and is less critical. The advantage of the synchronous design is the manufacturability as the response of the SAWR becomes effectively independent of reflectivity. Synchronous configurations are generally used in high yield commercial processes with a very low frequency deviation (± 50 kHz) [45].

- In both sensor types for this project optimal spacings configurations were used. For both sensor types equal numbers of electrodes are used in the RG. The pitch of the electrodes in the RG is identical to the IDT while this is common design trait in SAWR, RG in which the electrode pitch is varied can also be used. The RG are very important in device design as their function is to reflect all the energy back towards the IDT thus maximising the Q-factor of the resonator, which is preferable for this project. However long reflective gratings have been shown to generate unwanted *longitudinal* wave modes (sometimes called multimodes). These generally occur in two-port SAWR where resonant cavities are longer than one-port resonators [72]. Beam steering and diffraction of the propagating wave in the RG can cause higher order *transverse* wave modes to be generated. Such transverse waves appear as an unwanted spurious response close to the resonant frequency. Higher order transverse wave modes can severely influence the performance of a wireless SAWR sensor. These wave modes can degrade the Q factor of a one port SAWR and cause a misinterpretation of the f_r in wireless applications.
- Spurious modes may be avoided by splitting up the entire aperture into well separated tracks where each track supports the fundamental mode [68]. This approach, however, requires sufficient space in the transverse direction which often is not available. Alternatively the excitation of spurious modes can be avoided. This can be achieved by overlap weighting or apodization [73]. The disadvantage of apodization is that additional IDT width is required since the maximum excitation strength only applies in the centre of the device. A common method is to control the overlap length of the IDT [74]. This techniques was used in the non apodized sensors.
- In both designs shorted RG were used. This is the preferred configuration for ST-X Quartz [31] and is not surprising that AT-X resonators use the same RG configuration. Other methods can be used to increase the reflectivity of RG such

as varying the polarity of the gratings, however for quartz substrates the low K^2 coefficient would limit any possible success with such techniques.

At the design stage of this project it was decided not to pursue a differential style SAWR i.e multiple resonators on one die. The performance of an absolute SAWR sensor had not been fully validated at this time, which is a key step in the development of a SAWR strain sensor. Implementing several resonators on a single die would complicate the design brief introducing different propagation conditions which may not have the temperature stability of conventional AT-X quartz. Furthermore the iterations required in order to achieve the required electrical specifications of Table 3.1 would increase the cost beyond that permissible for a University research project. Additionally differential measurement can still be implemented using different die. i.e. using a 433.42 MHz and 434.42MHz sensor, which is an acceptable alternative see Section 7.4.4.

3.5 Wireless Sensing

A wireless sensor consists of a sensing element coupled to a micro controller, a radio transceiver and an on board power supply, typically a battery. However, battery-powered transmitting sensors have drawbacks due to their physical size and the requirement for periodic and sometimes frequent battery replacement. Commercial wireless strain sensors which incorporate such an arrangement are available and can be used to measure strain using a foil resistive strain gauge. The SG-Link for Microstrain [75], see Figure 3.9, is a commercially available wireless strain gauge module. Each single sensor node consists of 2.4GHz transceiver completed with on board bridge completion. However wiring from the gauge to sensor node is required and the module has a limited temperature range of $-40^{\circ}\text{C} - 70^{\circ}\text{C}$.

3. SURFACE ACOUSTIC WAVE SENSORS

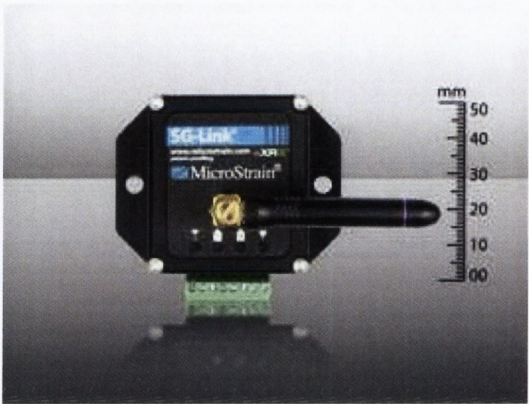


Figure 3.9: SG-Link Wireless Strain Gauge Module

SAW sensors allow for passive wireless sensing and remove the need for a battery allowing for the complete installation to consist of sensor and antenna. While the SAWDL and SAWR can both act as a wireless passive sensor, the required reader electronics and method of interrogation are different [56]. Passive wireless interrogation of SAW devices is possible due to the energy storage mechanism of the SAW propagating on piezoelectric substrate. The resonant frequency of the SAWR strain sensor can be determined wirelessly by time or frequency domain methods. Currently the preferred method to determine f_r of the SAWR device is time domain sampling. For this work the SenGenuity TempTracker shown in Figure 3.10, was used to wirelessly interrogate the SAWR strain sensors using the pulsed interrogation method, which is a time domain method. Phase lock loop methods have been reported [76] and it seems likely such methods will be commercialised in the near future [77].

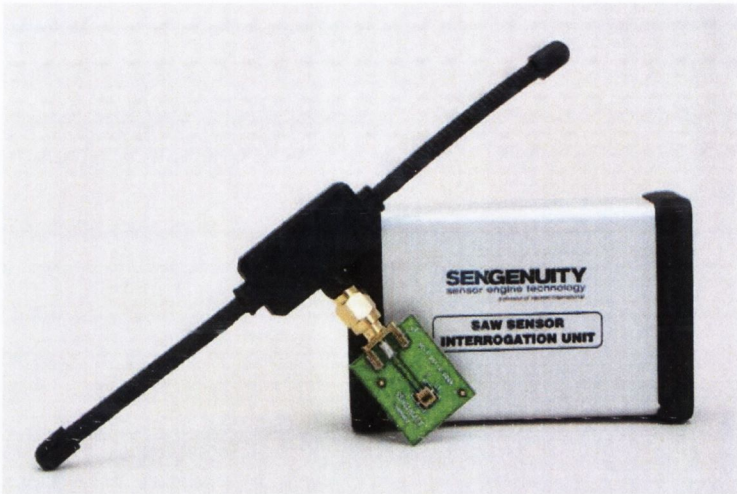


Figure 3.10: Wireless temperature interrogator and SAWR sensor from SenGenuity

In the pulsed interrogation method a series of short RF pulses are transmitted wirelessly to the SAWR. A transmitter is used to load the sensor with an RF pulse which excites the SAWR and generates a mechanical wave in the IDT which propagates between the RG. After the burst has been applied the interrogator enters a listening stage where the SAW is reconverted to the RF signal by the IDT and discharged through the antenna as a decaying sinusoidal response related to the Q factor of the SAWR [78]. This response signal is transmitted to the interrogator where it is sampled and processed. An on board DSP performs a final frequency measurement. Figure 3.11 illustrates the loading and unloading cycle for a SAWR sensors. The decay time of the sinusoidal RF response is typically 6 μ s in duration.

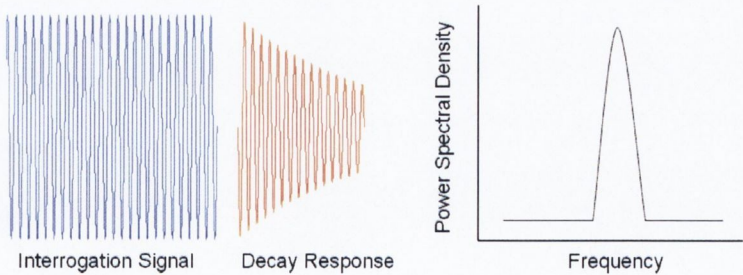


Figure 3.11: Interrogation Method for SAWR sensor a burst RF signal is transmitted to the SAWR sensor.

The f_r is determined by first searching for the SAWR across a band of frequencies where the f_c is expected to be located. This is the search phase of the measurement

3. SURFACE ACOUSTIC WAVE SENSORS

cycle. The bandwidth of operation is divided into frequency bins. The system performs a series of excite and listen cycles at these frequency bins and determines through PSD analysis of the response signal, a rough value for the f_c . A second phase is then undertaken where f_c is determined more precisely by subdividing the bin where the SAW is located. The fine measurement phase is shorter in duration than the search phase. Figure 3.12 shows a schematic of the SAWR interrogation cycle. Each block contains several loading and measurement cycles typically 5-10 μs . These loading cycles are used to improve signal processing in the DSP through coherent accumulation or averaging [79].

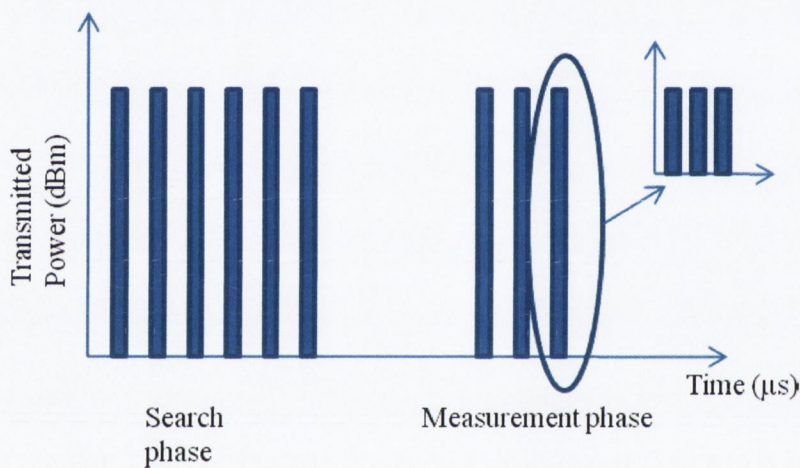


Figure 3.12: Interrogation timing diagram for TempTracker

3.6 Conclusion

In this chapter a review of SAWR sensing and wireless interrogation was presented. SAWR sensors and interrogation hardware have matured to the point where commercial applications can be developed. Unfortunately much of the information associated with these projects is held as proprietary information.

A customised SAWR strain sensor was developed and manufactured specifically for this project. Details on the SAWR design was presented. The design of SAW devices has been on going for 50 years. Several design traits which are commonly used in device design can be identified in the SAWR strain sensor design. The design of SAW devices for sensing is complicated by the requirement for wireless interrogation. The SAWR sensor must provide a strong response at resonance. The SAWR response

3.6. CONCLUSION

should be pure with spurious responses suppressed. The manufactured SAWR sensors were found to operate effectively with the commissioned wireless system. In the next chapter the SAWR strain sensor electrical performance will be investigated.

3. SURFACE ACOUSTIC WAVE SENSORS

Chapter 4

Bare die characterisation

Initial experimental testing of the SAWR strain sensors requires the electrical characteristics and behaviour of the device to be measured on-wafer without the influence of external mechanical biases, thus providing a base line for the sensors performance. This will allow the effects of bonding and packaging to be quantified. The determination of the broadband frequency response of an individual SAWR will determine the device's suitability as a wireless sensor. From the fabrication of commercial quality devices two wafers of devices at 433.42 MHz and 434.42 MHz were available for testing. This section will detail the electrical characterisation of the prototype sensors on wafer and the assessments made to determine the suitability for wireless sensing.

4.1 Microwave Testing Techniques

The on-wafer prototype SAWR strain sensors are designed to operate in the 434 MHz ISM band. Due to the relatively high frequency of the devices circuit analysis techniques that can be applied to DC and low frequency measurements are not applicable. In high frequency testing the wavelength of the applied signal becomes comparable to the length of the transmission line and becomes subjected to transmission effects such as phase changes in the transmitted signal. Microwave analysis techniques are generally used for testing of SAW devices and were utilised for the testing of the SAWR strain sensors. A good introduction to these techniques can be found in [80]. In the analysis of SAW components such as oscillators and resonators, the device under test (DUT) is typically treated as a N-port electrical network. A prototype sensor can be considered as an N-port device in order to determine the broadband electrical response.

4. BARE DIE CHARACTERISATION

While several techniques exist to describe the behavior of linear electrical networks, the scattering matrix (S-Matrix) which contains the S-parameters is most commonly used for the analysis of SAWR devices as many of the electrical properties typically used to quantify the performance of a SAWR device can be found using simple calculations and conversions of these parameters [81].

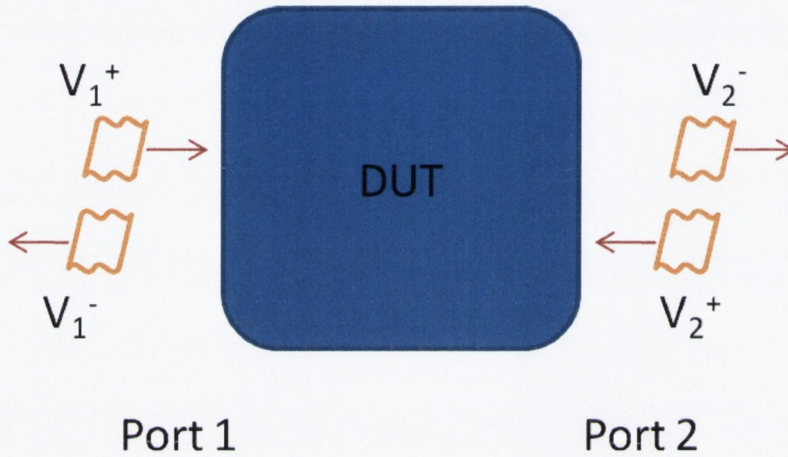


Figure 4.1: An 2-port network

Figure 4.1 shows the typical set up for 2-port electrical network. The behaviour of an electrical network can be described as analogous to a beam of light reflecting or refracting on a surface. When an RF signal is applied to one port of the DUT a fraction of the incident signal is reflected, a portion is scattered and then exits the DUT through other ports. Each individual S-parameters describes a ratio between reflected and incident waves at the ports of the DUT. An advantage of the scattering matrix is that it allows complex system such as the SAWR to be treated as a black box where only behaviour at the ports is analysed. It is important, however, to differentiate between incident and reflected waves in the transmission lines connected to the device for which the microwave theory is applicable and the SAW propagating within the SAWR structures. A two port network ($N=2$) which is described in *S-matrix* notation is shown in Equation 4.1.1.

$$\begin{bmatrix} V_1^- \\ V_2^+ \end{bmatrix} = \begin{bmatrix} S_{11}(f) & S_{12}(f) \\ S_{21}(f) & S_{22}(f) \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^- \end{bmatrix} \quad (4.1.1)$$

Where each element of the S-matrix contains an S-parameter which describes the reflection and transmission characteristics of the DUT for a particular port at a given

4. Bare die characterisation

frequency. V_1^+ and V_2^- is the amplitude of the voltage wave incident on port 1 and 2 respectively, while V_1^- and V_2^+ are the reflected voltage at port 1 and 2 respectively. S_{11} is the voltage reflection coefficient on port 1 which describes the ratio of reflected wave power to incident wave with no incident voltage at port 2 see (Equation 4.1.2) .

$$S_{11} = \frac{V_1^-}{V_1^+} \quad V_2^+ = 0 \quad (4.1.2)$$

Similarly, S_{12} , which is the voltage transmission coefficient at port 1 is described as the ratio of transmitted voltage at port 1 to the incident voltage at port 2 and describes the flow through a DUT is described in 4.1.2

$$S_{12} = \frac{V_1^-}{V_2^-} \quad V_2^+ = 0 \quad (4.1.3)$$

Electrical boundary conditions are achieved by terminating port 2 with a matched characteristic impedance of 50Ω to allow for full transmission into the DUT. Passive devices such as a SAWR will operate with $0 \leq |S_{11}| \leq 1$. Three basic reflection coefficients may be considered.

Open Circuit: $S_{11} = 1$; All the incident waves are reflected back to the source.

Matched Circuit: $S_{11} = 0$; All the incident wave is absorbed by the DUT

Shorted Circuit: $S_{11} = -1$; All the incident wave is reflected back to the source.
However the wave is phase shifted by 90°

At f_r the behaviour of the SAWR can be described as that of a matched circuit where the incident RF signal energy is dissipated into the sensor and very little is reflected. For frequencies off resonance the sensor behaves with characteristics of an open circuit or short circuit and little to none of the energy is dissipated into the sensor.

The impedance (Z) of the SAWR under test can be calculated from the S_{11} values by Equation 4.1.4, where the characteristic impedance of the network Z_0 was 50Ω .

$$Z = Z_0 \frac{1 + S_{11}}{1 - S_{11}} \quad (4.1.4)$$

S_{11} values converted to impedance operate with:

Matched Circuit: $Z = 50\Omega$ Occurs at resonant frequency of the SAWR where ideally all the power is absorbed into the DUT and no reflections occur.

4. BARE DIE CHARACTERISATION

Open Circuit: $Z = \infty$ Occurs typically at off frequencies from resonance. No power is absorbed into the device. SAW are not generated in the IDT.

Shorted Circuit: $Z = 0$ Again occurs at off frequencies, and all the incident wave is reflected.

4.2 Testing Equipment and Set-up

SAWR devices can be analysed using both S_{11} and S_{12} parameters. For this project it was decided to test the S_{11} response of the prototype sensors. The S_{11} response is the industry standard for describing the response of the SAWR device as f_r and impedance can be found readily providing a link to static modelling techniques such as COM [46]. As the SAWR sensors are ultimately going to form a stand alone wireless sensor where it will be configured with one port connected permanently to ground S_{11} testing is the most appropriate method. On-wafer measurements were performed at the facilities in the Microwave Laboratory at the University College Dublin. The experimental set up for the static testing of devices on-wafer is shown in Figure 4.2. An Agilent E8361A PNA vector network was used for S_{11} testing with one port of the SAWR connected to the signal the second to ground. The probe SAWR interface is shown in Figure 4.3. Electrical probing of the die was performed using a set of calibrated probes, GB ECP18-GS/SG-2500-EDP Picoprobes calibrated using a CS-17 calibration substrate. The probes and die were held in a Cascade Microtech Summit 9000 probe station.

4.2. TESTING EQUIPMENT AND SET-UP

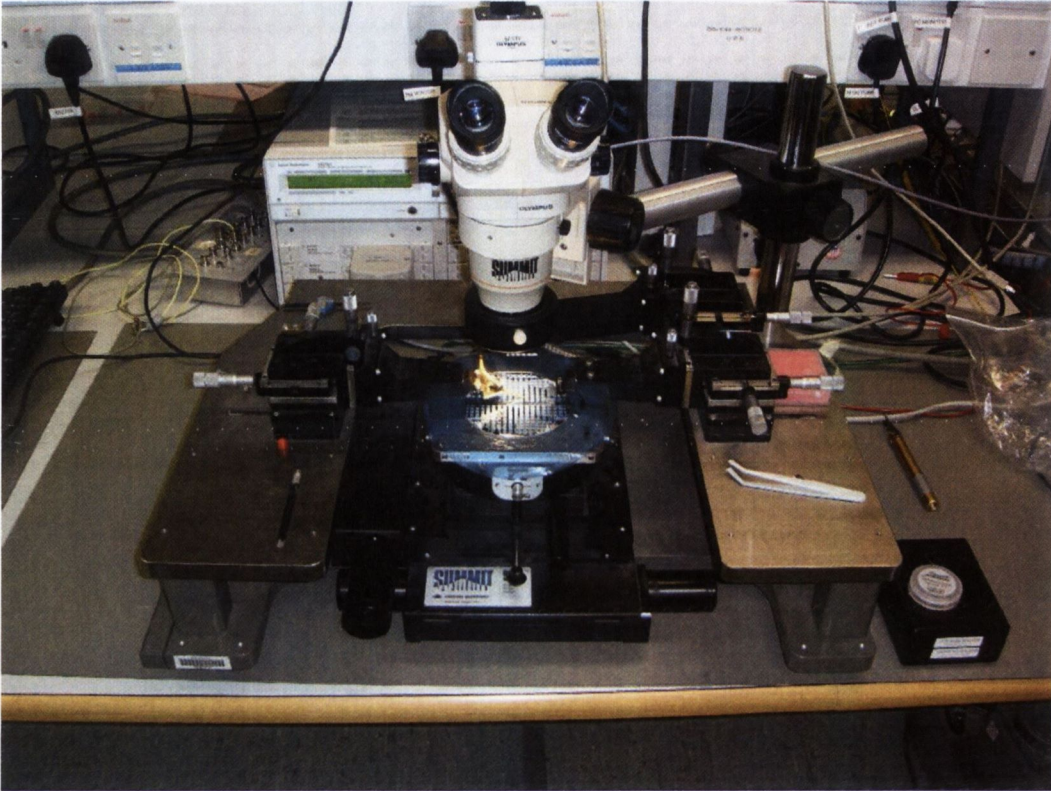


Figure 4.2: Cascade Microtech probe station with Picoprobes installed performing on wafer-open air calibrations of SAWR strain sensors.

For the S_{11} testing of the SAWR sensors a *short-open-load* calibration of the VNA was performed across a 2 MHz bandwidth which covered the expected range of operation of the devices as well as the ISM band. Calibration and internal error correction can provide $\pm 10 \text{ ppm}$ frequency accuracy [82].

4. BARE DIE CHARACTERISATION

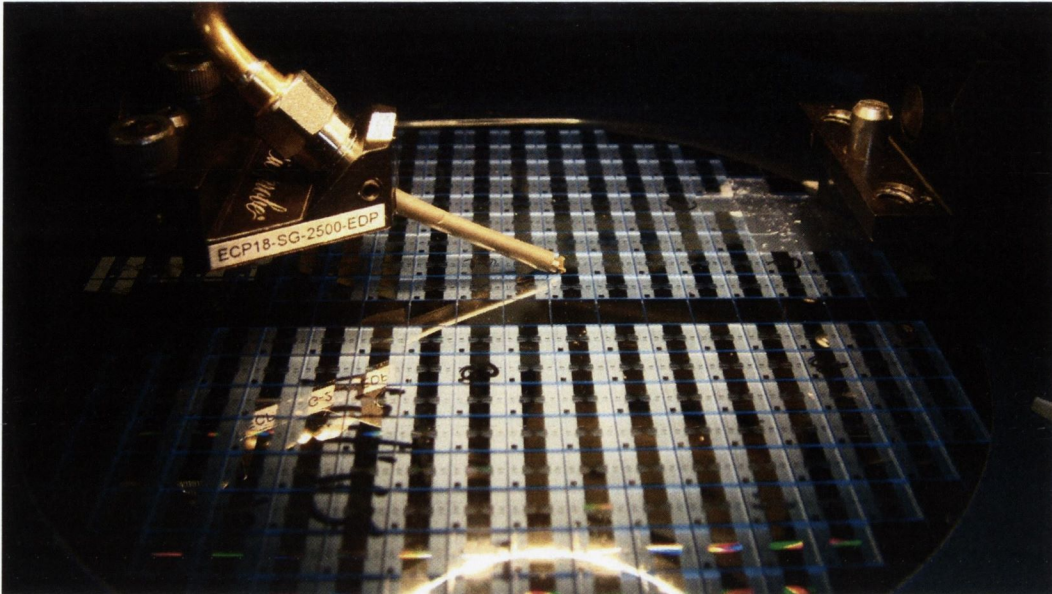


Figure 4.3: Probing and Die Interface.

4.3 Bare Die Testing

The bare die devices were tested to determine both their frequency and magnitude response. S_{11} testing was performed on two sets of wafers with identical devices of nominal frequency 433.42 MHz and 434.42 MHz respectively. A typical S_{11} response for a SAWR can be seen in Figure 4.4. Each wafer layout was identical with 260 devices fabricated on each wafer and was divided into sides A and B each containing 130 dies. The numbering structure is shown in Figure 4.5.

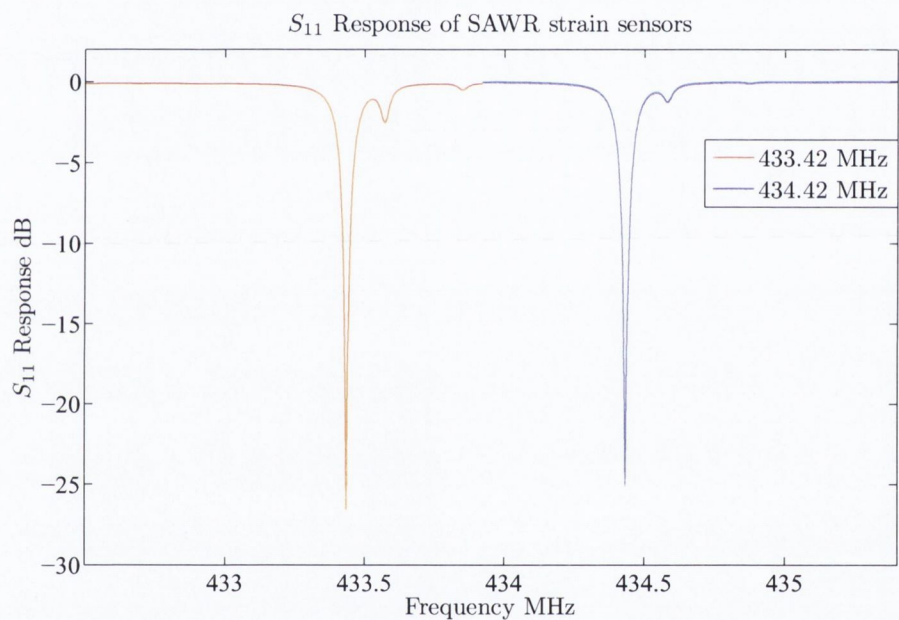


Figure 4.4: Typical S_{11} response of 433.42 MHz and 434.42 MHz SAWR strain sensor measured at the Microwave Research Laboratory UCD

4. BARE DIE CHARACTERISATION

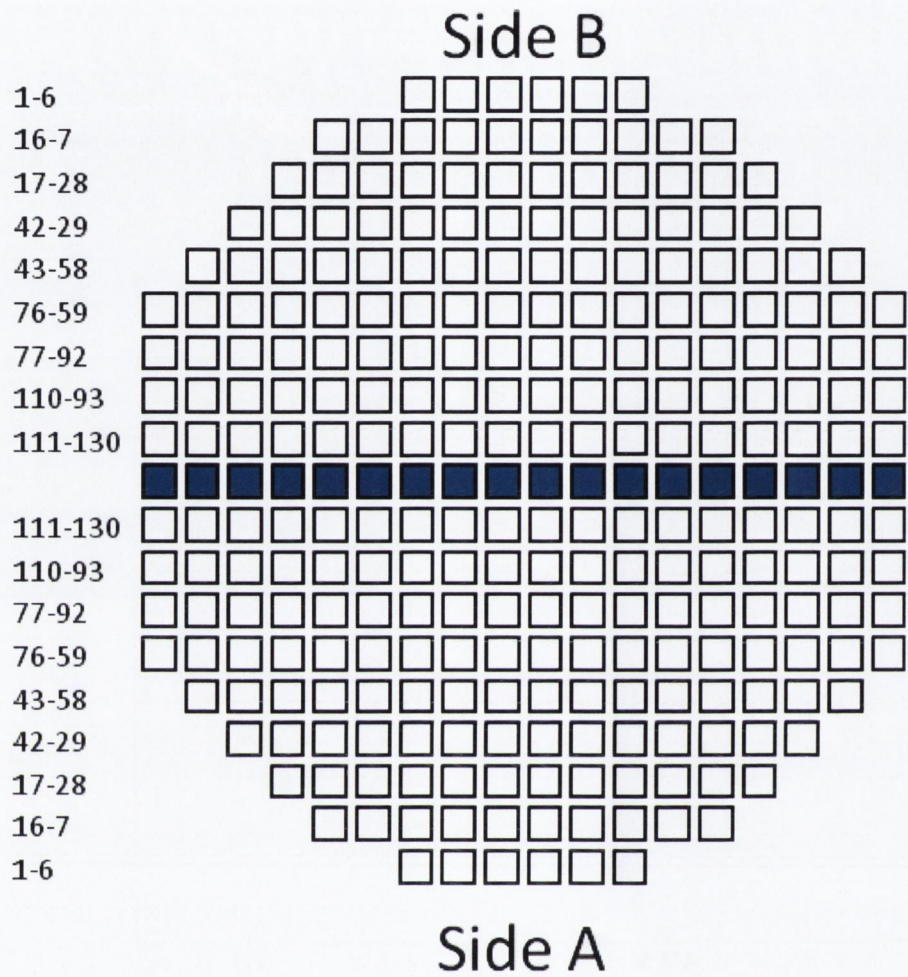


Figure 4.5: Layout of a 4 inch wafer with die numbering shown at the side.

Each device was tested using the process described in Section 4.2. The VNA was calibrated across a bandwidth centred at f_r of the DUT. The goal of on-wafer testing was to determine several key parameters from which individual sensor quality could be evaluated. These parameters were identified as:

Resonant Frequency of Device: The SAWR strain sensors are designed to operate with a resonant frequency located within the 434 MHz ISM-Band which has a bandwidth of 1.39 MHz. Determination of the resonant response on wafer allows for an unbiased response to be determined prior to implementation of the SAWR as a sensor.

Magnitude of the Resonant response Pronounced and defined response at resonance

4.3. BARE DIE TESTING

is required to differentiate the resonant response from the general broadband behaviour of the sensor. The magnitude of the resonant response must be significant for the device to be considered suitable for sensing.

Q-factor For passive wireless sensing the unloaded Q factor provides an indication of the energy storage capabilities of an individual die.

Device Yield General purpose sensing requires that the response of sensors fabricated on the one batch be uniform in nature. Devices demonstrating comparable characteristics across a wafer should be selected for strain calibration. Therefore the yield of devices from a fabricated wafer will require each sensor to meet several criteria simultaneously.

Sensors which displayed a definite incorrect performance were excluded as being defective or damaged and thus were omitted in the calculation of any statistical representation of the test wafers.

4. BARE DIE CHARACTERISATION

4.3.1 Resonant Response of Dies

The test sensors fabricated by SAWNICS were specified to have a centre frequency of $433.42 \text{ MHz} \pm 50 \text{ kHz}$ and $434.42 \text{ MHz} \pm 50 \text{ kHz}$. The variation in the resonant response of SAWR across a wafer can be attributed to the inconsistency in the substrate material and the repeatability of the equipment used in the fabrication process. Typically quartz wafers are artificially grown from seed wafers using hydrothermal growth methods [83]. These wafers tend to show light non uniformity across their surface which results in variations in propagation conditions and wave velocity which could cause moderate variations in f_r of each die. Furthermore, the fabrication of SAWR is a multi step process which introduces possible sources of error at each step. SAWNICS as a commercial organisation were unable to provide complete details on their fabrication processes. However the devices were fabricated using standard photolithographic techniques. Using a photomask with a linewidth tolerance of $2.353 \pm 0.1 \mu\text{m}$ [84] and i-line stepper using light with a wavelength of 365 nm . Slight variations in the dimensions of the device structures should result in an averaging effect with the total variation in response being therefore negligible. However as the devices are identical in geometry, variations due to the location of the device on the wafer are far more likely and therefore one would expect to see a profile in the device response showing a symmetry and predictability across the wafer. Mass loading effects due to variations in the deposition thickness of the surface metallisation could result in variations in the SAW velocity across the wafer, this would result in a predictable variation in f_r with position. This could be caused during the spinning of the wafer during fabrication. Without extensive details on the fabrication process a determination of the source of this behaviour is difficult.

Figure 4.6 and 4.7 shows the resonant response from 433.42 MHz wafer 2 and 434.42 MHz wafer 2. It can be observed that an approximate cyclic variation in the resonant response occurs with on-wafer position. This could be attributed to a variation in SAW velocity due to the proximity of a die to a growth striation which develop during the growth of synthetic piezoelectric crystals [85][83]. However as X-ray topograph of the crystal prior to testing was unavailable this cannot be confirmed. For the 434.42 MHz wafers dies with higher f_r are located towards the centre of the wafers. However the distribution of die across the 433.42 MHz wafer is far more dispersed, see Figure 4.8 and Figure 4.9

4.3. BARE DIE TESTING

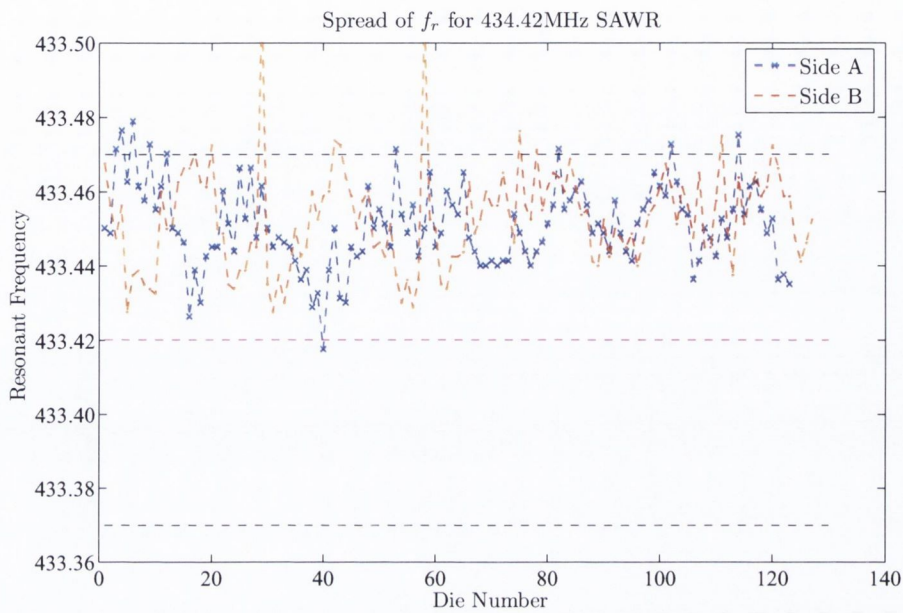


Figure 4.6: Frequency spread of SAWR resonant frequency equal to 433.42MHz, black dashed line indicate upper and lower bands in SAWR specification

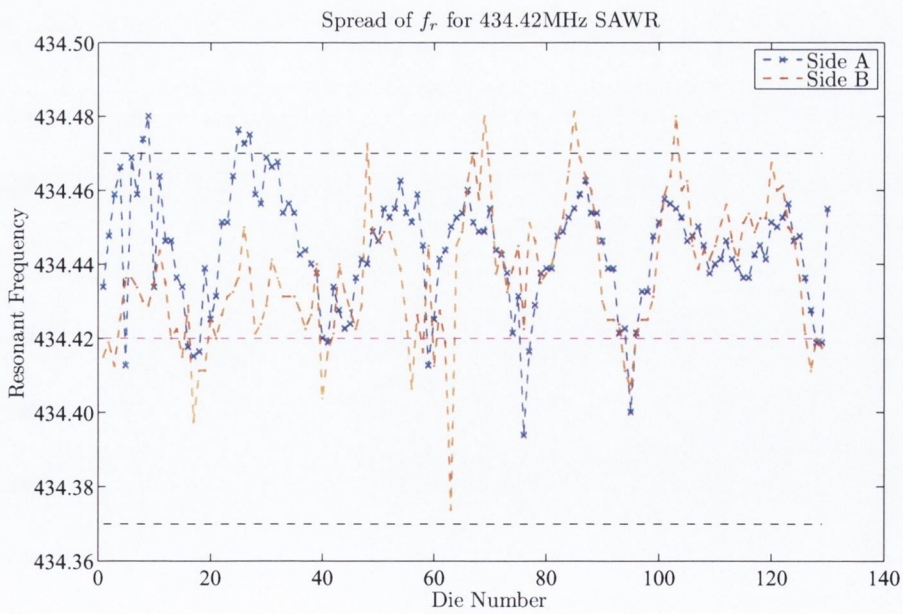


Figure 4.7: Frequency spread of SAWR resonant frequency equal to 434.42MHz, black dashed line indicate upper and lower bands of specified performance

4. BARE DIE CHARACTERISATION

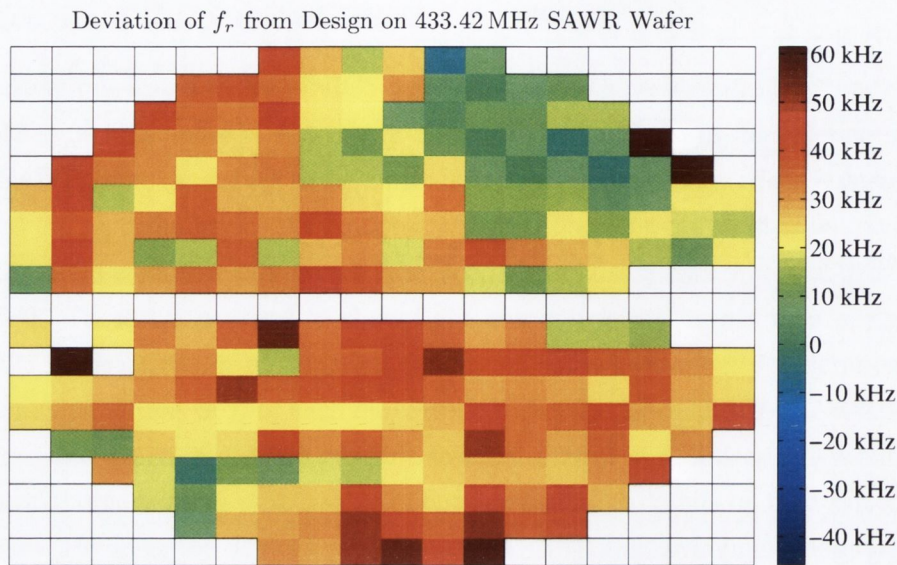


Figure 4.8: Plot of SAWR f_r grouping across 433.42 MHz Wafer

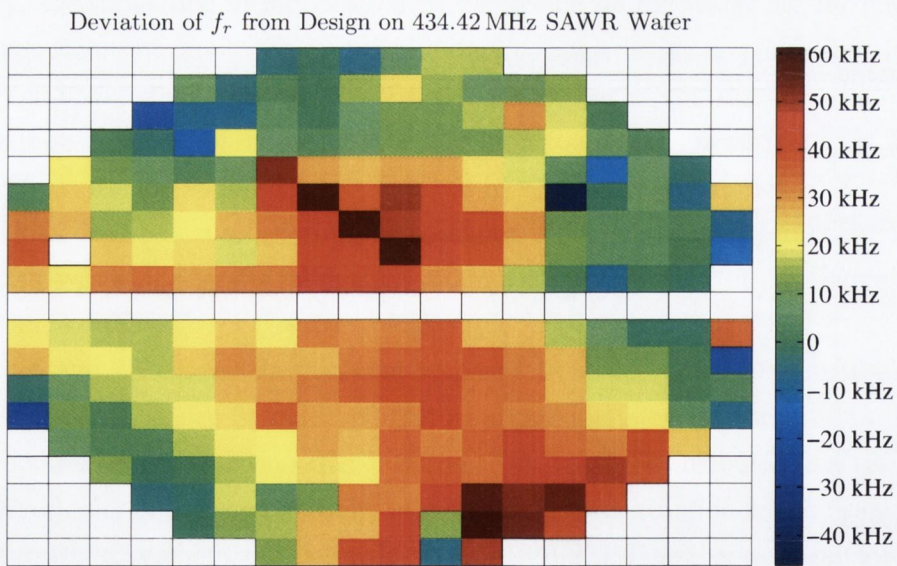


Figure 4.9: Plot of SAWR f_r grouping across 434.42 MHz Wafer

Generally, across each of the wafers tested the fabricated devices were found to show broadly similar results. Table 4.1 shows the results of each wafer tested. Posi-

4.3. BARE DIE TESTING

tional comparison fails to indicate a direction relation i.e similar devices at identical locations on comparative wafers are not generally comparable. While such a relation would be desirable it is unlikely that 100 % repeatability across different wafers could be achieved due to the fabrication process and slight inconsistency in wafer properties.

Frequency	Wafer Number	Mean resonant frequency	Standard Deviation
433.42MHz	(1)	433.447 MHz	7.831 kHz
433.42MHz	(2)	433.451 MHz	11.691 kHz
434.42MHz	(1)	434.420 MHz	2.776 kHz
434.42MHz	(2)	434.434 MHz	2.349 kHz

Table 4.1: Resonant Response of Test Wafer

Figures 4.10 and 4.11 shows histograms of the frequency spread across the tested wafers. Interestingly the 433.42MHz wafers show a similar grouping of f_r for both wafers, the 434.42MHz wafers however, shows an obvious shift in the groupings of the f_r . The majority of die still were located in the nominal threshold specified by the design criterion. As this is a once off manufacturing run the overall quality and repeatability of the dies is unlikely to be as high as a commercial device. Through contact with the manufacturer it seems three trial runs were made in order to achieve an acceptable yield of devices. Commercial devices would be part of a manufacturing run which is far more defined and validated than was practical for this project thus it is reasonable to expect variation across the wafers to be greater [71].

4. BARE DIE CHARACTERISATION

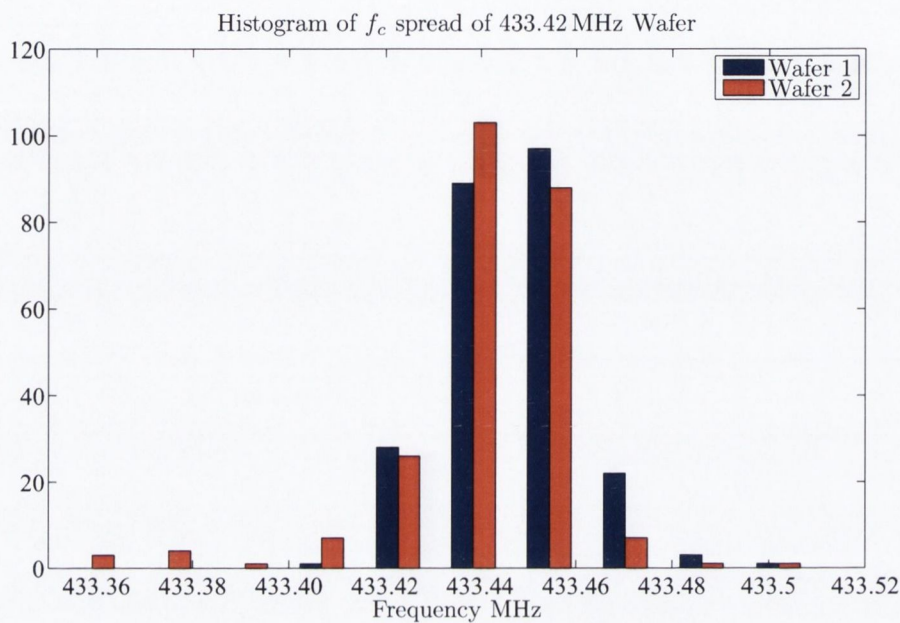


Figure 4.10: Histogram SAWR resonant on wafers designed to have nominal frequency 433.42MHz $\pm$ 50kHz

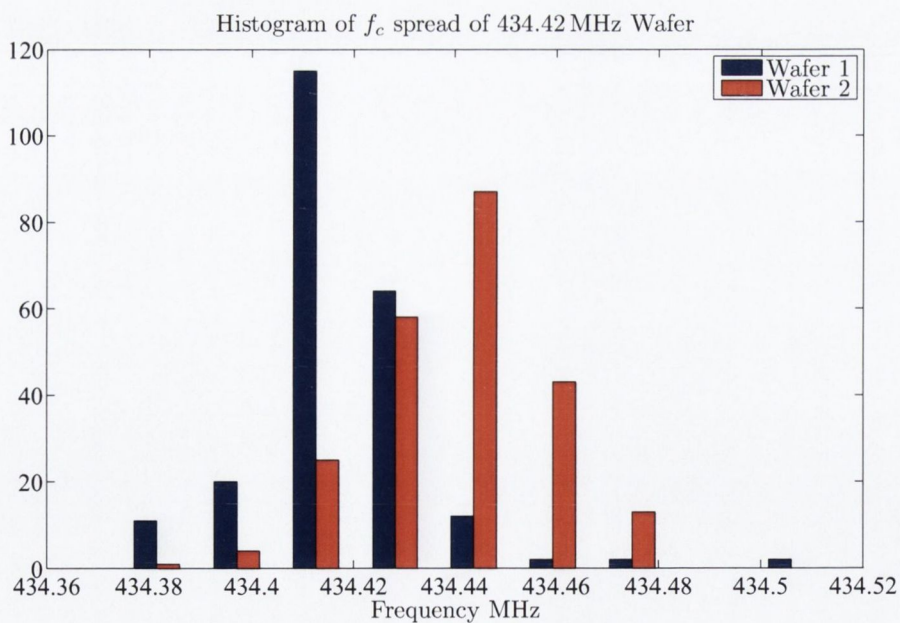


Figure 4.11: Histogram SAWR resonant on wafers designed to have nominal frequency 434.42MHz $\pm$ 50kHz

4.3.2 Magnitude Response of the dies

While the resonant frequency is an important criterion for measuring the quality of a SAWR, the magnitude of $|S_{11}|$ (expressed in dB) at resonance is an equally significant factor in determining the usability of the devices for both electronic or sensing applications. The magnitude of the resonant response will be due to the design of the SAW structures, choice of substrate material and the fabrication processes. While the overall magnitude response of the resonator at resonance is combination of all the design steps involved in reaching a completed device. The response can be primarily attributed to a combination of two factors, the coupling coefficient and the reflectivity of the SAW structures (*IDT and reflective gratings*). In this section the analysis of the magnitude response of the dies will be divided into two separate measurements. The broadband S_{11} response was measured and the maximum value was determined. This will occur at a frequency off resonance. Secondly the magnitude response at resonance, found at the minimum S_{11} value. The broadband frequency response occurs at frequencies off resonance should ideally be 0dB. In SAWR sensor applications a good broadband response will cause the resonant response to appear more distinct. Of the sensors tested 95-100% of the fabricated devices operated with an acceptable broadband response.

At resonance a definitive and pronounced response is required to differentiate the resonant response from broadband behaviour and the response of spurious wave modes. Typically the resonant response between similar wafers show comparable behaviour. The apodized structures demonstrate typically lower resonant response across the wafer however with a greater consistency when compared to the non-apodized 433.42MHz devices. Table 4.2 shows the results from the tested wafers.

Wafer Fre- quency	Number	Broadband S_{11} : Mean (dB)	Standard Deviation (dB)	Resonant S_{11} : Mean (dB)	Standard Deviation (dB)
433.42MHz	(1)	-0.2565	1.1407	-29.8421	7.5138
433.42MHz	(2)	-0.1534	0.7044	-27.1640	7.9051
434.42MHz	(1)	-0.5443	1.9516	-21.5821	5.827
434.42MHz	(2)	-0.1446	0.9544	-23.7942	3.0329

Table 4.2: Broadband and resonant S_{11} response of SAW Resonator

The majority of the devices demonstrate a $|S_{11}|$ lower than the $-10dB$ specified in the design requirements. While several outliers and defective devices are contained within the batch, the majority of the die on the wafer met the requirement of the reso-

4. BARE DIE CHARACTERISATION

nance response.

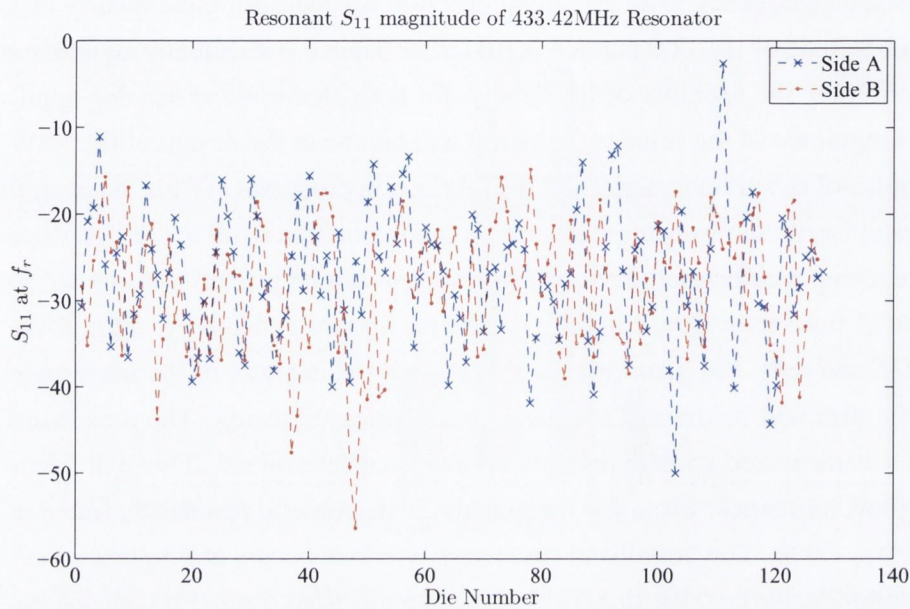


Figure 4.12: $|S_{11}|$ response of 433.42MHz resonators at resonance: wafer 2

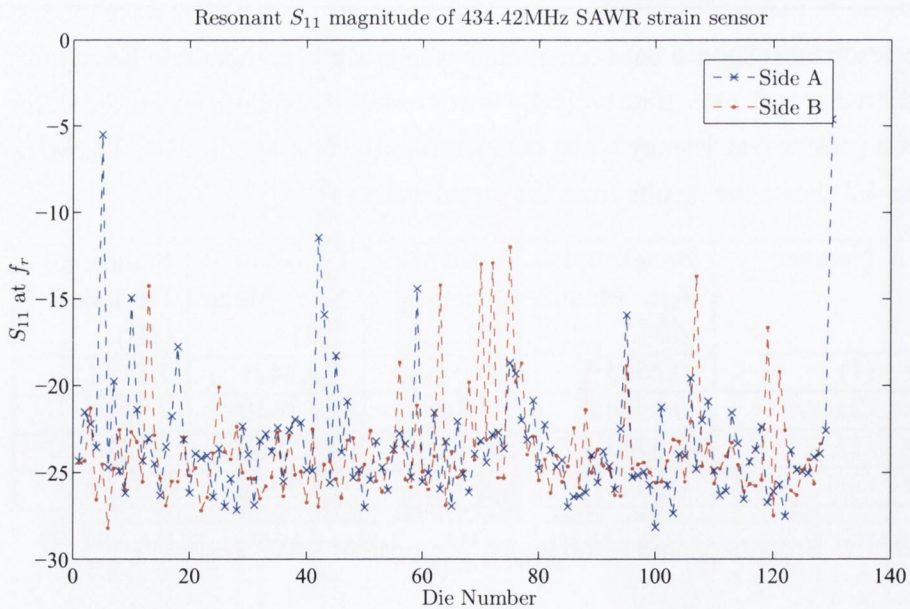


Figure 4.13: $|S_{11}|$ response of 434.42MHz resonators at resonance: wafer 2

4.3.3 Device Impedance and Quality Factor

The Q factor of a SAWR is defined as *the ratio of stored energy to dissipated energy in the half cycle*. The Q factor at resonance (Q_r) provides an important measure of the energy storage capabilities of a die for wireless sensing application. While various methods can be used to calculate Q_r the most convenient method is based upon measurement of the conductance plot, which can be found by converting S_{11} parameters.

The SAWR sensors were specified to operate as a part of a 50Ω network. To achieve maximum load transfer the die should operate with a $|Z|$ of 50Ω at resonance. The impedance response from a pair of "good" 433.42 MHz and 434.42 MHz SAWR which fulfil the specified criteria of Section 4.3.1 and 4.3.2 respectively is shown in Figure 4.14.

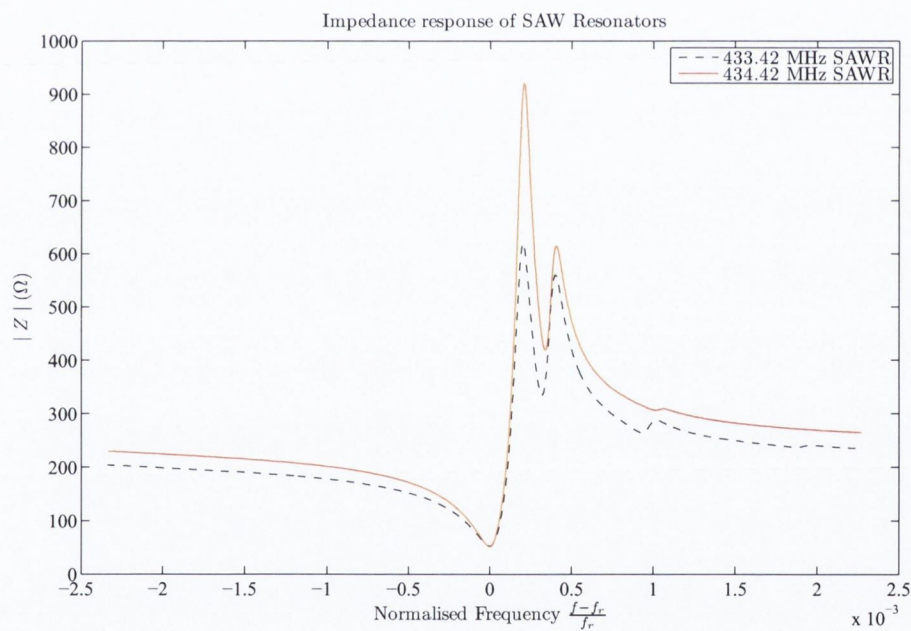


Figure 4.14: Comparison of the Impedance response of 433.42MHz and 434.42MHz Resonator

Most of the device fabricated fulfilled the design criterion of 50Ω at resonance. This is beneficial for load matching to an industrial standard 50Ω antenna. The energy storage capability of a SAWR strain sensor is an important characteristic for the performance of the sensor in wireless measurement chains. In order to determine the energy storage capabilities of each die an algorithm described in [19] was used to cal-

4. BARE DIE CHARACTERISATION

culated the unloaded Q_r this method is based upon the conductance plot and is preferable to methods based upon the S_{11} plot. The SAWR were specified to operate with a $Q_r > 10,000$. Table 4.3 shows the calculated results for the test wafers.

Wafer f_r	Number	Mean Q_r	Standard Devia- tion
433.42MHz non-ap	(1)	10,000	1008
433.42MHz non-ap	(2)	10,100	1247
434.42MHz ap	(1)	9920	1385
434.42MHz ap	(2)	10,552	735

Table 4.3: Q_r for SAW Resonators from Test Wafers

4.4 Analysis of Finished Devices

Table 4.4 shows the results of on-wafer testing. While the response of the sensors can be measured and evaluated, the commercial nature of the fabrication means that minimal details on each of the individual design steps are available. Therefore the correlation between sensor performance and the individual design and fabrication steps cannot be made.

Wafer	Q_r	f_r	$ Z $	$< 10dB$	Yield
433.42MHz	139	238	241	240	138/242
433.42MHz	148	240	249	251	141/252
434.42MHz	145	226	219	227	145/232
434.42MHz	148	240	249	251	141/260

Table 4.4: Die fulfilling Design Criterion

However some key points can be made on the performance of the die measured on-wafer.

- The majority of devices fulfilled the criteria for the f_r , magnitude response and impedance at resonance while only 55% devices tested met the design requirement for a $Q_r > 10,000$. However the average response Q_r on three of the test wafers fulfilled the design requirement. Over 90% of devices however did have a Q factor greater than 9000 which while lower than specified is still acceptable when compared to the Q_r of the wireless sensor see Appendix 8.2.

4.4. ANALYSIS OF FINISHED DEVICES

- Spurious response: The generation of spurious responses can be minimised during the design stage. However in reality the spurious response cannot be fully suppressed, apodized devices have a slightly lower magnitude of the 1st order spurious response which would be preferable for wireless sensing. The lower magnitude response of the apodized devices would be expected [18]. The spurious responses are generally 175kHz greater than the centre frequency and display the same frequency shifts with position that the resonant frequency demonstrates. Generally speaking the form of the response of the devices across the wafer is similar except with a stepped frequency response.
- Figures 4.10 and 4.11 shows that 434.42MHz test sensors demonstrate a similar frequency distribution between wafers. However the 434.42 wafers show a definite shift in frequency distribution, a frequency bias due to testing being performed on different dates mean that changes in cabling, calibration and unseen errors could have introduced a frequency off set in the measurement, this is unlikely. It is possible that the wafers are not completely unbiased prior to fabrication. As-received untreated Quartz wafers can have residual strain of approx. $1400\mu\epsilon$ due to machining process [86]. Lapping of the back surface which is achieved with sandblasting the back surface of the wafer, is a common process in wafer preparations. The process can result in the wafers becoming slightly curved ($Radius > 50m$), introducing stresses into the material, which can gradually relax [87].
- Figure 4.4 contains a typical S_{11} response for a 433.42 MHz SAWR and a 434.42 MHz apodized SAWR. The inclusion of an apodization function in the IDT has succeeded in suppressing the magnitude of the higher order transverse wave mode. The trade however is that the response of the apodized SAWR is lower at resonance than the non apodized SAWR 433.42 MHz SAWR. The magnitude of the apodized SAWR at resonance shows greater consistency than the non apodized sensors across the wafer.

4.4.1 Conclusion

In this chapter the electrical performance of the SAW test sensors was measured. The on wafer response of the SAWR strain sensors was broadly consistent. The majority of the SAW test sensors demonstrate a performance comparable or superior to that of

4. BARE DIE CHARACTERISATION

commercial SAWR temperature sensor see Appendix 8.2 . While the Q_r was slightly lower than was specified in the design brief it will have moderate impact on the development of the wireless strain sensors. Overall the decision to contract devices to a private contractor was deemed justified.

Chapter 5

Testing apparatus and protocol

A calibration data set detailing the response of the SAWR to strain applied at various loading levels across an extended temperature range is vital in the development of SAWR strain sensors and for application development. Experimental data describing the SAWR response to strain has been available since the 1980's [88]. While the sensitivity of SAWR devices to strain and to temperature for specific substrate cuts such as ST-X and $Y - 34^\circ$ Quartz has been documented. Prior to commencement of this project a comprehensive calibration data set for AT-X SAWR sensors was unavailable. A reason for this maybe that the majority of active research into mechanical SAWR sensors now occurs in the commercial rather than the academic sector. The performance of SAWR is dependant on the substrate and electrode configurations implemented during the design and the response of the project sensors to applied strain must be evaluated experimentally. In this project the SAWR strain sensor must be rigourously characterised, initially bare die to determine the design's suitability as a strain sensor and subsequently, packaged to determine the influence of packaging on sensor behaviour.

In this chapter the apparatus and protocol developed for the testing of a SAWR to determine the strain performance characteristics is presented. Details will be provided on the design and development of a customised rig achieved through a combination of the ProEngineer suite and ANSYS 10. The testing apparatus was fully automated to improve robustness of calibration cycle. The methods for treatment of experimental data will also be discussed.

5. TESTING APPARATUS AND PROTOCOL

5.1 Design of Testing Apparatus

The dilemma that arises when characterising a new sensor is defining an appropriate methodology and procedure. No test procedure has been adopted as the preferred method for the calibration of SAWR strain sensors. In the absence of testing standards when calibrating a prototype strain sensors (MEMS, SAWR etc), typically either the British or American standards [89] [90] for the calibration of foil resistive strain gauges is adapted [91]. Both standards suggest similar if not identical testing apparatus and methodology wherein the general procedure requires a sensor to be mounted on a test beam which is then strained. The response of the test sensor is then calibrated against a permanently mounted reference sensor, the performance of which is known. A gauge factor is then determined measuring the normalised fractional change in sensor response at intermediate strains.

ASTM E251-92 standard was selected as the basis in the development of calibration methodology for the SAWR strain sensors as it provides a thorough description of the methodology for sensor calibration. However both methods are largely similar and indeed indistinguishable in some sections. Within the ASTM E251-92 three separate test apparatus for calibrating strain gauges are described.

Constant Bending Moment Test Method: This test method generates a surface strain on a test bar by loading it with a constant moment. The test beam is placed between two dead weights and the beam is loaded until the desired surface strain is generated along the beam

Constant Stress Cantilever Beam Test Method: A cantilever beam is designed to have a constant stress over the major portion of its length. The surface of the beam is strained by deflecting the free end of the cantilever.

Direct Tension or Compression Test Method: This test method produces strain in a test bar by applying direct tensile or compressive loads.

Based upon evaluation of the three suggested methods of the ASTM standard, the constant stress cantilever beam was selected for a SAWR strain sensor calibration rig. The selection of the constant stress cantilever beam method for the calibration for SAWR strain sensors was based upon the following criteria.

- The suggested apparatus can be easily adapted to operate as part of an inclusive strain and temperature test rig.

5. Testing apparatus and protocol

- The loading requirements can be achieved safely using cost efficient methods.
- The dynamic loading capabilities exceed the current SAWR strain sensor interrogation hardware that is available, thus special apparatus is not required for dynamic characterisation.
- The test beam creates an area of constant uniform stress distribution which is advantageous in the modelling of SAWR strain sensors, see Section 2.5.
- Compressive and Tensile strain tests can be preformed in the same cycle without repositioning of the beam.

Unfortunately the suggested apparatus for the constant stress cantilever beam is too cumbersome for a laboratory environment. Due to space constraints the testing apparatus was redesigned to decrease the physical size of the rig and the loading requirements while still generating an appropriate surface strain profile on the calibration beam. To achieve this, 3D CAD design was integrated with FEA. Using the beam configurations suggested in ASTM E251-92 as a basis, refinements in the design were made until space, loading requirements and an appropriate surface-strain profile could be met in one beam geometry. The final geometry beam design was one which is optimised for the calibration of small SAWR strain sensors and provides a reliable test platform for the calibration of SAWR strain sensors. Section 5.1.1 provides details on the optimisation and design process.

5.1.1 FEA Design of Calibration Beam

The calibration beam was designed by integrating FEA into the design of the customised test beam. The design flow consisted of Pro Engineer Wildfire 4.0 generating 3D models of the beam. Potential beam design were similar in geometry to that described in [90] but the dimensions were varied. These were exported to ANSYS 10 in the IGES file format. A load step in the calibration cycle was modeled as a point load applied to the free end of the calibration beam. The cantilever beam was constrained in all degrees of freedom at the mounted end. A region of interest was defined at the mounting location of the SAWR strain sensor and the mesh was refined to have an increased density at that location. The strain profile in the region of interest was optimised by varying the beam dimensions in order to generate an adequate area with a constant strain level. FEA of the SAWR calibration beam is shown in Figure 5.1.

5. TESTING APPARATUS AND PROTOCOL

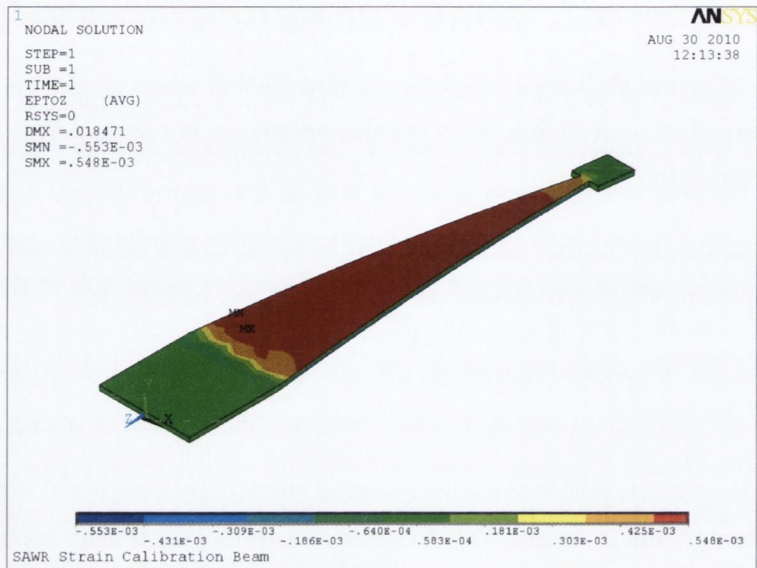


Figure 5.1: Finite Element Analysis of SAWR Strain Calibration beam

The load applied is equivalent to 150N load placed on the free cantilever end with a displacement on the free end of the beam of approximately 14mm. At the location where the SAWR would be attached the strain predicted by FEA was $440\mu\epsilon$. The dimensions of the finalised beam are shown in the Figure 5.2 and the final manufactured beam is shown in Figure 5.3. The final calibration beam was manufactured using EN8 steel. EN8 is a mild carbon steel with a yield strength of $500-800\text{Nm}^2$ and a Young's modulus of 210GPa [92]. EN8 mild steel is suggested in the British Standard as an appropriate material for use in calibration beams. The maximum strain level that can be applied to the calibration sensor is then a function of elastic range of the beam which is suitable to a strain level of $800\mu\epsilon$. The completed beam was mounted upon a steel base to provide stability. Mass of the steel base was 50kg. The overall footprint of the testing apparatus was $1\text{m} \times 0.1\text{m} \times 0.5\text{m}$

5.2. AUTOMATION OF TEST PROCEDURE

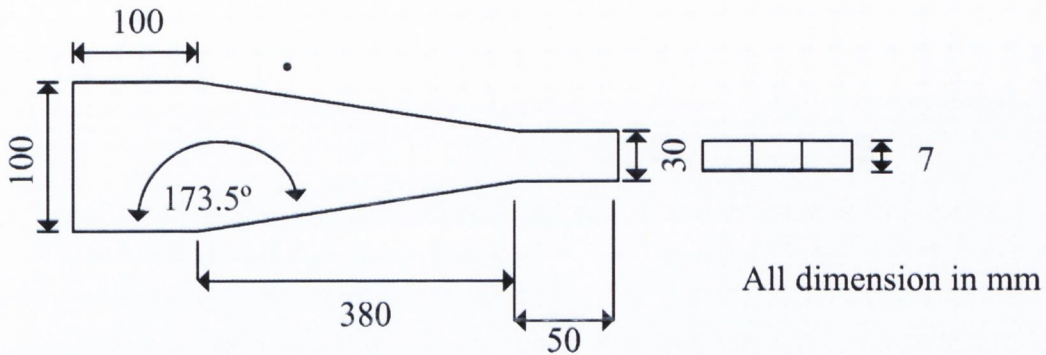


Figure 5.2: Schematic of SAWR calibration beam manufactured on Mild EN-8 steel



Figure 5.3: Finalised SAWR calibration beam manufactured on Mild EN-8 steel

5.2 Automation of test procedure

The strain response of a SAWR requires calibration against a reference strain sensor with known characteristics. A measurement platform was required which was capable of interfacing with the SAWR and several reference sensors which operate across several different interfaces. The design of a customised test rig also created an opportunity to commission a fully automated test bench. Automation decreases the period of each testing cycle thus limiting sources of error, removing the possibility of dropped samples due to human error and increasing repeatability. A loading mechanism was required which could generate the required surface strains on the surface of the calibration beam. A linear Electro-mechanical actuator manufactured by *Intelligent Actuator Incorporated* (part no: IAI-RCP2-RA6C) was mounted horizontally to produce a displacement at the free end of the cantilever beam. The actuator contains a 4mm lead

5. TESTING APPARATUS AND PROTOCOL

screw connected to a modified stepper motor and gearing mechanism to provide linear motion with a positional repeatability of $\pm 0.02\text{mm}$. The actuator is controlled via an external controller (model: P-CON). To aid automation, Intelligent Actuator provided a command set of ModBus serial communication protocols [93].

An automated calibration required control of the actuator and data acquisition from several sources to be combined in an integrated control and measurement platform. As the test apparatus required an interface between several hardware platforms National Instruments LabVIEW v8.6 was selected as the measurement platform. A virtual instrument (VI) written with NI-VISA v4.5 was run on a PXI-1011 chassis with a PXI-8186 embedded controller forming the core of the system. Reference foil resistive strain gauges are connected to an SCXI-1314 strain gauge terminal block, which in turn is attached to an SCXI-1520 input module in the chassis. Wired measurement of the SAWR was performed using an Agilent E5061A vector network analyser (VNA), connected to the controller via the GPIB line. Where possible Sample code from National Instruments and was integrated into the measurement platform. Intelligent Actuator provide a command set of ModBus serial communication protocols. A target position, which is provided as a 12 bit ASCII message frame is sent over the RS-232 interface. A set of customised VI's were written to control the actuator. Temperature measurements were made using two *K-type* thermocouple. Later refinements were made when the PXI chassis and strain modules were replaced with a conventional desktop computer and a USB Strain Gauge module from National Instruments (NI-9237) and a NI-9231 thermocouple module was integrated into the control VI. A schematic of the control interface for the automated test rig is shown in Figure 5.4 showing the interconnectivity.

The availability of commercial interrogation units allowed for a wireless interrogation unit to be integrated into the testing apparatus and measurement platform. A wireless TempTrackr unit from SenGenuity, a division of Vectron International was used for wireless calibration. A command set was provided by the vendor and a set of custom built VI's were integrated into the LabVIEW control platform. The SenGenuity interrogator is controlled by a P-CAN, USB to CAN convertor via a serial command.

The testing apparatus using the National Instruments PXI chassis and instrumentation is shown in Figure 5.5

5.3. REFERENCE SENSOR SELECTION AND BONDING

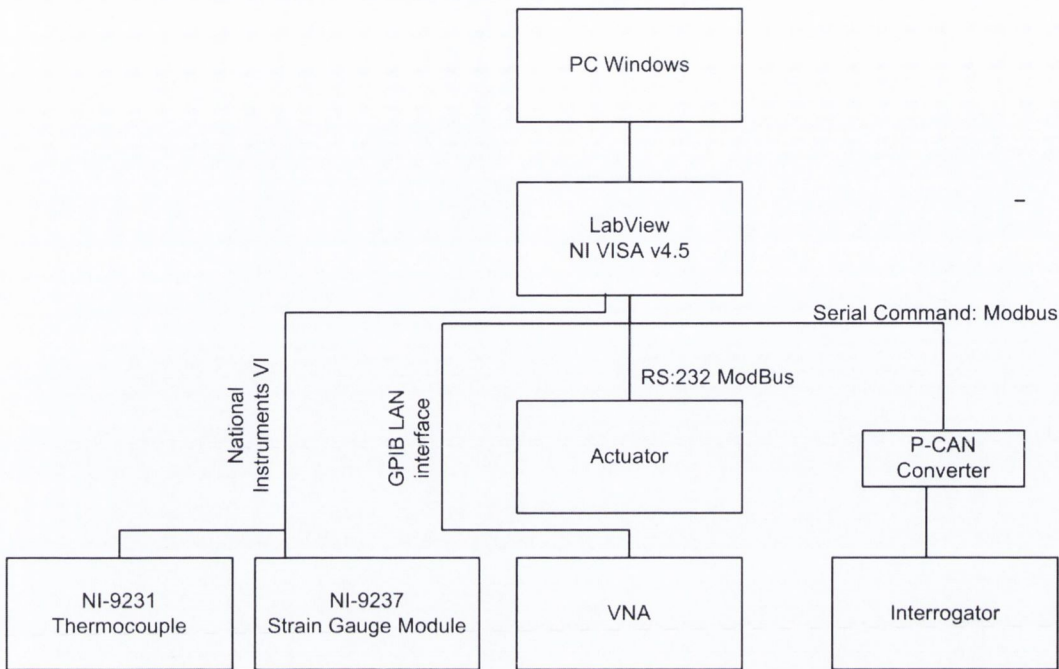


Figure 5.4: Block Diagram of Integrated Measurement and Control VI

5.3 Reference Sensor selection and bonding

The SAWR strain sensors were calibrated against two reference foil resistive strain gauges mounted in parallel with the SAWR strain sensor. While calibrations were performed with a range of Vishay strain gauges the majority were made with a Vishay Micro Measurements self temperature compensating gauge for mild steel strain gauge (Part number L2A-06-125LT-120). The reference strain gauge was connected in a half bridge configuration.

Foil resistive strain gauges require bonding to the test surface. Typically this is done with a polymer adhesive. As the surface finish of the SAW calibration beam was poor after manufacture, the surface of the SAWR calibration beam was prepared with a range of emery papers to provide a polished surface advantageous to successful bonding. The surface was prepared to be clean and defect free. The preparation of the surface was completed as described in the ASTM standard and Vishay recommended procedures [94]. Several epoxy based adhesive, M-Bond 200, M-Bond M82 and a non branded cyanoacrylate epoxy adhesive were investigated for suitability. Reference gauges were mounted using the recommended procedure of the manufacturer. While

5. TESTING APPARATUS AND PROTOCOL

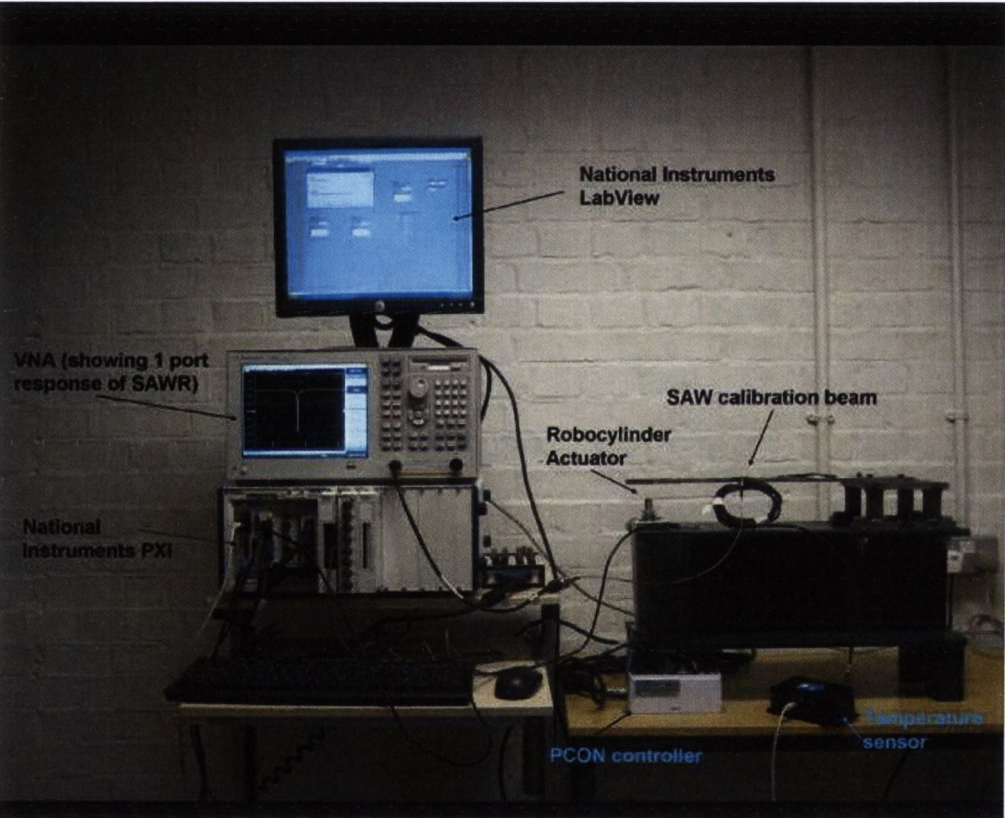


Figure 5.5: Calibration Apparatus; PXI-1011/8186 measurement platform running LabVIEW v8.6.

5.3. REFERENCE SENSOR SELECTION AND BONDING

all adhesives provide a repeatable response to strain at ambient conditions, M-Bond 600 a transducer quality adhesive provided a stable linear response over an extend temperature range when compared to the other adhesives tested. For bare die testing SAWR strain sensors were bonded with M-Bond 600 using the manufacturers recommended attachment procedure with a clamped cure temperature of 120° for 2 hours, see section 6.1.

Electrical connectivity between die and VNA cabling or antenna was made using a small PCB and SMA connector. Electrical connection between the calibration sensors and antenna was made through a double ground plane printed circuit board (PCB) measuring 20mm x 20mm. For bare die testing silver wire and conductive silver paint epoxy provided the electrical connections between SAWR bonding pads and a pair of solder pads located on the PCB. For later tests wire bonding facilities became available. The test PCB is shown in Figure 5.6.

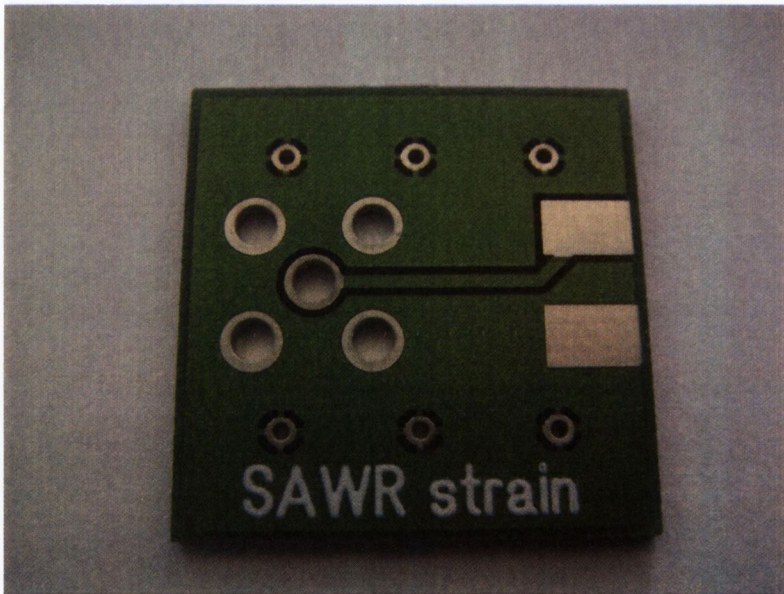


Figure 5.6: PCB for SMA connector: PCB was used for bare die and packaged sensor calibration

For wired testing a co-axial cable was used to connect the SMA connector on the PCB to the VNA. For wireless calibration a dipole antenna of length 16cm was used for both interrogator and sensor. The spacing between the sensor and interrogator antennas was held constant at 10cm. To verify the probing and VNA interface, a S_{11} measurement of a SAWR was made with calibrated probes and subsequently using

5. TESTING APPARATUS AND PROTOCOL

the PCB silver conductive paste method. SAWR was connected to the VNA prior to bonding to the beam using this technique. No variation in the f_r of the SAWR device was measured, however a decrease in sensitivity of the S_{11} magnitude was observed. As sensor performance is evaluated on variations in f_r to applied strain, decreases in the magnitude whilst undesirable are acceptable for calibration tests.

5.3.1 Verification of test beam

Prior to calibration of a SAWR sensor, the FEA of the calibration beam and the installation of the foil resistive gauges were verified. To commission the beam a test gauge was mounted, and strain measurements taken at each calibration step. The gauge was removed and another gauge was mounted and measurements were repeated. The repeatability of the mounting process was then determined. The reliability of the strain readings was then verified against the FEA. The loading curve compared to the FEA is shown in Figure 5.7

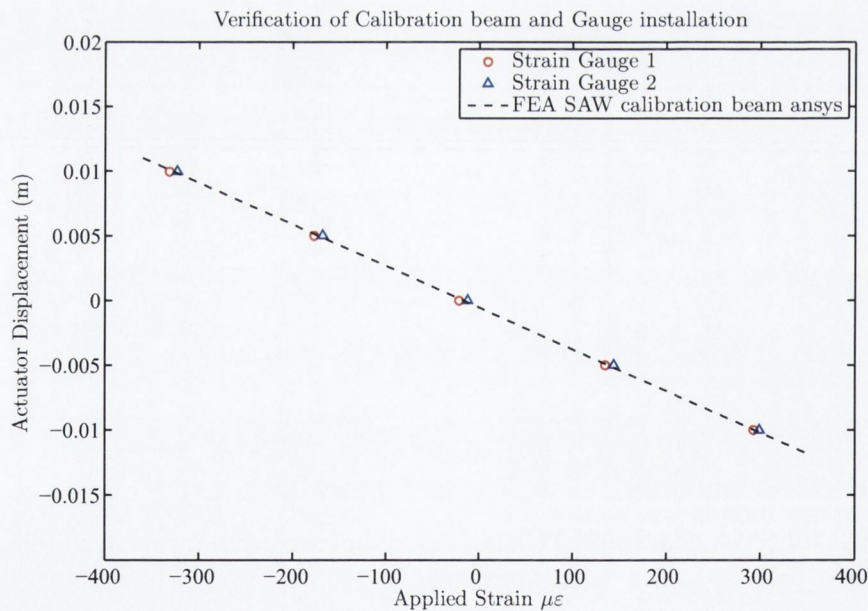


Figure 5.7: Verification of SAW calibration beam and Gauge installation

While slight deviation from linearity was observed, the profile of experimental data and values predicted by FEA at each load step is sufficiently close. As the strain

measurements are taken from gauges bonded with the same procedure but at different times, the repeatability of bonding procedure has also been verified.

5.4 Test Protocol

Once the SAWR had been mounted and connected to the measurement hardware (VNA or interrogator) a reference frequency response was measured to determine the effects of the bonding procedure. The bonding procedure results in a residual stress being generated in the SAWR substrate which causes an apparent strain to be generated.

The following steps were then performed as part of the calibration cycle:

- A reference value for the SAWR strain sensor is determined before the mounting of the sensor on the test beam, preferably on wafer. A second reference value (zero reference value) is determined after the mounting procedure to account for any strain induced in the mounting procedure and to account for any insertion losses due to connection to the VNA.
- The beam is deflected and a strain is applied incrementally in 10 nominally equal steps up to the maximum strain value of $\pm 400\mu\epsilon$.
- The strain level is determined from a strain gauge placed in close proximity to the SAWR devices to form a reference between strain and shift in resonant frequency.
- The strain level is reduced incrementally in ten nominally equal steps down to the zero reference value.
- The procedure is repeated for both tensile and compressive behaviour and is cycled in compression and tension three times for each SAWR sensor tested.

To reduce the effect of random errors and to account for dropped samples caused by transmission effects (in wireless tests). 50 data points were taken at each loading step for wireless calibration. For wired calibration the VNA has internal functions to calculate the maximum and minimum values of a sweep i.e broadband magnitude and resonant frequency respectively. For wired calibration a sweep was performed 10 times at each load point. Due to data transmission rates across the GPIB interfaces the broadband response was only recorded once.

5. TESTING APPARATUS AND PROTOCOL

5.4.1 Elevated Temperature Testing

Similar to the effects of strain on a SAWR, thermal biases alter the properties of the substrate material resulting in a thermal stress being generated in the substrate. The thermal stresses cause a shift in the f_r of the resonator. This change in f_r due to thermal effects represents an apparent thermal strain. Therefore the strain response of the SAWR at elevated temperatures must be investigated. It has been reported that SAWR strain sensor display decreasing S_{sen} at elevated temperatures [47]. The ASTM and British standards describe experimental apparatus to determine gauge factors at elevated temperatures. It was decided to modify the rig set up described in Section 5.1 to facilitate elevated temperature testing. To achieve this the SAWR calibration apparatus was fitted with an oven to encapsulate the beam mounting and beam. Two radiant heaters were fitted in the oven. Thermal insulation superwool 607 max thermal blanket thickness 6mm surrounded the oven to provide sufficient insulation. A diagram of the set up of the experimental rig to allow for calibration at elevated temperature is shown in Figure 5.8.

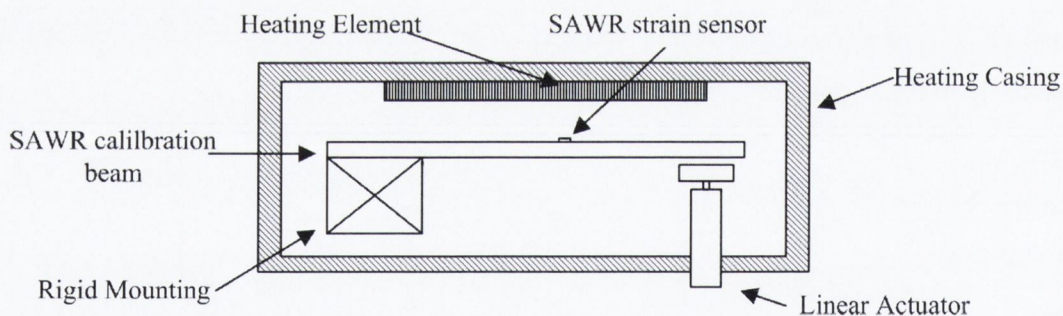


Figure 5.8: Schematic of layout for elevated temperature test rig

The 230V 250W quartz radiant heaters manufactured by Ceramicx Ltd. were selected. Each heater is capable of a maximum surface temperature of 438°C [95]. Initially for bare die testing the heaters were placed in open loop control with a VARIAC transformer connecting the heaters in parallel thus allowing temperature control be achieved by varying the supply voltage. At each incremented step the oven was allowed to enter a steady thermal state by holding the value for 2.5 hours prior to starting a calibration cycle described in section 5.4. Reference temperature was measured using a K type thermocouple. The thermal profile of the oven used for the elevated temperature testing is shown in Figure 5.9.

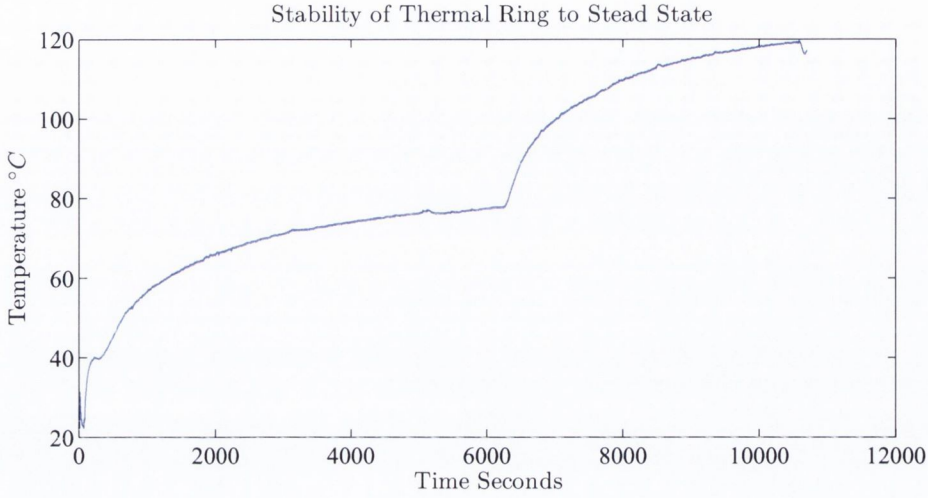


Figure 5.9: Thermal Response of the SAWR test rig to step change in temperature.

Later refinements to the elevated testing apparatus were made by connecting the radiant heaters to an Omega CNi 32 series PID controller. Some bare die sensors and all packaged devices were tested at elevated temperatures using the heaters controlled with the PID controller.

5.4.2 Treatment of Experimental Data

The purpose of the calibration of foil resistive strain gauges is to determine the gauge factor of the test gauge. The gauge factor for a foil resistive strain gauge is defined as: *the ratio between unit change in resistance due to strain and the causing strain* [90].

For SAWR strain sensors we define the gauge factor of a SAWR strain sensor as:

$$K_{gf} = \frac{\Delta f_r / f_0}{\epsilon} \quad (5.4.1)$$

However for SAWR strain sensors the sensitivity of the sensor to applied strain is frequently used:

$$S_{sen} = \frac{\Delta f_r}{\epsilon} \quad (5.4.2)$$

where f_0 is the nominal frequency of the SAWR and Δf_r is the variation in the mounted unstrained resonant frequency as strain is applied as opposed to the on wafer measurements. Thus the effects of thermal mismatch and residual stresses in the adhesives are naturally accounted for. As shown in Figure 5.10 SAWR strain sensors form

5. TESTING APPARATUS AND PROTOCOL

part of a complex systems that includes adhesive, lead wires, instrumentation, packaging, antenna and in the case of SAWR wireless strain sensors transmission effects. A link budget for wireless SAW strain sensors is given in [56] which accounts for losses in a SAWR wireless system.

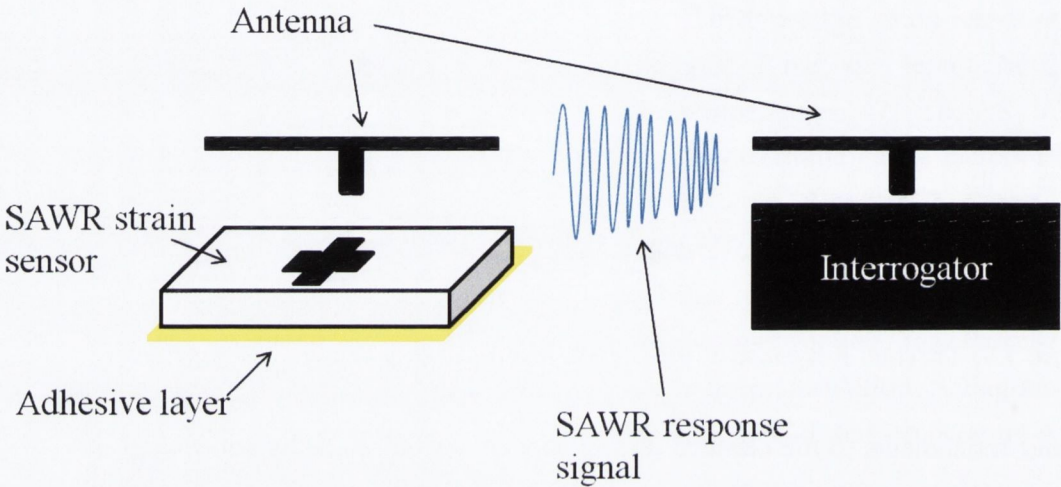


Figure 5.10: SAWR sensor strain system

The performance of a SAWR sensor is sensitive to a number of factors. Repeatability of the sensor must be paramount as was demonstrated in Section 4.3.1 the variation in the f_c and S_{11} magnitudes values across the wafer is small. Therefore the main concern in performing strain calibrations is ensuring that the bond line is repeatable. This requires a well defined methodology for the bonding process to the authors knowledge no optimised bonding procedure is available for SAWR strain sensors. For bare die testing tests were performed using the recommend procedures for M-Bond 600. The nature of the bonding process means that once a SAWR strain sensor has been installed it is not possible to reinstall the sensor at a different location. Due to these factors the calibration data provides only a statistical representation of the performance of an entire manufactured lot. For foil resistive strain gauges the variation across a manufactured lot tends to be negligible as materials are usually isotropic and performances are statistically known to be consistent in a single manufactured lot. Calibrating all the sensors in a entire wafer is an impractical proposition. Therefore only sensors with a S_{11} centre frequency response less than -10db and a spurious transverse wave component response greater than -2.5db were considered for calibration. The presence of a large transverse wave component in the S_{11} response can cause the wireless interrogation

unit to misinterpret this as the dominant wave mode. This can be avoided with careful mounting, providing sufficient grounding for the sensor and avoiding non-uniform stress distributions in the SAWR substrate.

The f_r at each loading point was calculated as the mean value of all measured values. The sensitivity of the SAWR sensor is measured for loading and unloading in both tension and compression. Mean values and 95% confidence intervals are used to provide four values to describe the full cycle. A linear least squares best fit line is fitted to the data and a coefficient of determination (R^2) is calculated to determine the suitability of the linear fit. An average S_{sen} for each test sensor is calculated from the three calibration cycles.

5.4.3 Evaluation of Testing Apparatus and Methodology

The calibration of the SAWR strain sensor requires creating a repeatable methodology. Sensor bonding, electrical connections and the applied strain fields must be repeatable for the calibration of a sample lot of sensors. The absence of a standardised procedure for SAWR strain sensors required the creation of a comparable testing procedure. SAWR sensor calibration particularly calibration performed wirelessly creates its own set of challenges. Transmission effects at RF frequencies can be substantial, environmental propagation conditions and antenna consideration can all dramatically effect the performance of the system particularly at elevated temperatures. Calibration of sensors should always be performed with the best available apparatus which minimise transmission effects thus providing a clear view of actual sensor behaviour. While standard dipole antenna can be used and in many cases were, specialised planar antenna optimised for the 434MHz ISM band provided far greater performance, especially when mounted on the interrogation side [96].

The FEA of the beam demonstrated that the SAWR is subjected to a biaxial strain which is highly dominated by S_{11} strains. The calibration beam developed has a strain profile which is well defined with the SAWR test sensors and reference foil gauge subjected to the same strain state at each load step in the calibration process. An advantage of the constant stress cantilever beam is that an area of almost constant stress is generated. FEA also indicated minimal variation in the surface strains across the beam in the test area. The integration between ProEngineer and FEA allowed for the completion of the design to be achieved within a reasonable time scale without substantial cost. The adopted calibration procedure was tailored to the requirement of this project. While

5. TESTING APPARATUS AND PROTOCOL

retaining many of the recommendations and practices of the standard. The methods and apparatus described within this section describe a customised procedure tailored to SAWR strain sensors which addresses the current lack of a defined procedure.

Quartz is reported to survive to a strain level of $1200\mu\epsilon$ after which brittle failure will occur. Unfortunately testing to failure are not investigated as the test beam is only operational to a maximum stress of 800N/mm^2 and strain level of $800\mu\epsilon$. Thus full scale testing to failure is limited by the testing apparatus. Full scale tests to failure could not be performed without changing the elastic range of the beam through plastic deformation which was undesirable in maintaining beam consistency. Calibration cycles are minimised to negate the impact of creep of the adhesives which is a common feature in many strain sensors.

Automation of the testing procedure decreased the overall testing cycle time, primarily time at each loading point which minimised the effects of creep in the SAWR sensor response. Creep effects are a direct effect of using polymer based adhesive. The effects of adhesives and the lack of purpose designed SAWR strain gauge adhesives prompted the investigation in SAWR strain adhesives in Section 6.4. The overall performance of a foil resistive gauge is built upon characterising a sample of the entire manufactured batch. The calculated value is found to a value at the 95% confidence level. Reported details on the calibration of SAWR Torque sensors have discussed that for many applications, individual calibrations of a completed Torque measurement unit is required to account for variations in sensor performance and bonding inconsistency.

5.4.4 Conclusion

A calibration apparatus has been designed, manufactured and commissioned for the calibration of SAWR strain sensors. The calibration beam is easily repeatable and manufactured from common mild steel components. With simple modifications to the rig the test beam can be encapsulated with thermal insulation and calibrations at elevated temperatures can be performed. Elevated temperature tests can be performed using moderate additions to the control software. The rig design is flexible so that sub ambient temperatures tests would require the adaptation of the rig to contain a refrigeration unit similar to inclusion of the oven. This could be implemented as part of future work.

The calibration rig allows for packaged SAWR sensors to be calibrated on the same rig. Both wireless and wired testing can be performed, However it is preferable to

5.4. TEST PROTOCOL

perform elevated temperature tests with the wireless interrogation unit so as to avoid the effects of temperature on measurement cabling and damage to equipment. The methodology included as well as smaller rig size allows for the rig design to be repeated and adapted for the calibration of other MEMS sensors. The linearity of the reference gauges response suggest that negligible bending strains were introduced during the calibration of the SAWR.

In this section a reliable cost effective and repeatable testing procedure for the calibration of SAWR strain sensors was presented. The testing rig and reference gauges are integrated within the LabVIEW environment. Automation of the rig and wireless interrogator was achieved using command sets supplied by the manufacturer of the actuator and interrogation unit respectively. The rig design allows for the calibration of both bare die and packaged SAWR sensors to be performed on the same rig at a range of temperatures from ambient to 120°C. The design of a customised rig addressed the need for a suitable calibration platform which characterised the performance of SAWR strain sensors in a controlled environment.

5. TESTING APPARATUS AND PROTOCOL

Chapter 6

Bare die experimental testing

To date, limited calibration data has been published for SAWR strain sensors. The most complete set of calibration results details the performance of a SAWR torque sensor fabricated on ST-X quartz and was provided by Beckley [47] of Transense Technologies. Beckley reported that ST-X SAWR Torque sensors can demonstrate significant variation in the strain sensitivity at elevated temperatures. This variation makes sensors fabricated on ST-X unsuitable for general purpose absolute measurement SAWR sensing. This chapter presents calibration data for SAWR strain sensors fabricated on temperature stable AT-X quartz, only the bare die strain performance is reported as sensor packaging tends to alter the performance of a strain sensor [97] [98]. To the authors knowledge, no data exists on the effects of bonding and adhesive selection for SAWR strain sensors.

In this chapter, the performance of the SAWR strain sensor was experimentally examined for a range of adhesives. The merits of the adhesives tested will be discussed. Temperature sensitivities and the apparent strain curve for a bare die SAWR strain sensor is provided. Strain response at a range of temperatures is also examined. The orientation sensitivity of the SAWR strain sensors is also examined. SAWR sensors were all tested wirelessly. Initially a VNA was used to measure the broadband frequency response of the SAWR strain sensor and determine f_r . The wireless interrogation unit was then used to determine f_r wirelessly. The wireless unit and wired VNA showed excellent agreement in the determination of f_r .

6. BARE DIE EXPERIMENTAL TESTING

6.1 Attachment of bare die SAWR sensors

For each calibration test the unpackaged SAWR sensors were bonded to the test beam using adhesive. The surface was prepared to provide an extremely clean and pH-neutral surface, which is conducive to bonding SAWR sensors. The SAWR strain sensor was attached using a modified version of the procedure recommended by Vishay foil gauge manufacturers [94]. The methods outlined by Vishay are designed to provide a consistent and repeatable process which ensures that a clean contaminant free surface is obtained. Such a surface is paramount in achieving the bond quality required between the strain sensor and the measurement area of the calibration beam. The following procedure was developed to clean the surface of the calibration beam to a suitable level.

- Prior to all bonding procedures the surface of the test specimen should be prepared to a surface finish free of voids and features of the machining process such as grooves and scratches. This requires the surface being abraded using a range of papers and emery cloths. Once the surface abrasion has been performed to an suitable level CSM degreaser is used to remove any residues and oils, either organic or from the machining process used in the preparation of the beam. This is crucial in the first preparation of the beam, as the calibration beam will come in contact with coolants and lubricants during fabrication. CSM degreaser is preferred as it is an active compound which can drive contaminants from the surface of the material. However, an isopropyl alcohol cleaner may also be used.
- The next stage of the cleaning process requires the surface be rendered pH-neutral. The surface is wet abraded and rinsed clean with Vishay M-Prep surface conditioner. The surface is dried with surgical gauze. This is a critical step in the procedure and prone to difficulties. The surface should be wiped clean with no M-Prep conditioner allowed to dry on the surface. In practice this can be difficult especially if trying to prepare a large area as the liquid will evaporate leaving residual materials behind which severely damage the adhesive's bond lines. Once the surface has been dried, the surface is wetted again with conditioner and scrubbed with cotton swabs until the swabs are no longer discoloured. The surface is rinsed once more and wiped dry.
- M-Prep neutralizer is then applied liberally to the surface and the area is scrubbed using cotton swabs once more. The surface is rinsed and wiped dry once again.

6. Bare die experimental testing

The surface is now suitable for bonding. At this stage alignment markers can be placed on the surface provided they do not enter the area where the SAWR will be attached. At this stage a visual inspection of the surface will determine the quality of the cleaning procedure. A suitable surface should be contaminant and residual free.

- The SAWR sensor is removed from the wafer using a tweezers. Adhesives are applied to the attachment area either with an applicator brush or adhesive nozzle. Minimal amounts of adhesive are generally required. Typically the applicator brush is brushed against the side of the bottle several times to remove excess liquid. The attachment area is then brushed with adhesive and if possible the underside of the SAWR is coated with a thin layer to wetten the surface. The SAWR is placed in the attachment area and alignment is made. Alignment is finalised by using a standard laboratory microscope to align the sensors to their final position. The SAWR is then held in place until a light tack has been achieved. A layer of teflon sheet covers the SAWR sensor and fixtures are placed over the sensor and held in place with a sellotape or equivalent material. A clamp is placed over the fixtures and the adhesive is ready to be cured.

It is preferable to perform all cleaning under a bright white lamp as the surface contaminants and staining from improper removal of cleaning materials will be more noticeable. Successful steps in the cleaning process will result in the surface appearing cleaner and more polished. The SAWR sensor should enter the cure cycle as soon as possible. Procedures presented in this thesis are for the best results and practices. Many combinations and variations of the surface preparation and bonding methods were attempted with varying degrees of success. For tests using M-Bond 600 and M-Bond 610 a clamped elevated cure is required. To clamp the die successfully the sensors were covered with a sheet of teflon similar to that used to ship diced wafers. Sellotape or similar was used to hold the teflon sheet taut over the die. A washer clamped the bond pads but allowed the IDT to remain untouched is shown in Figure 6.1. Pressure was applied using a clamping fixture.

6. BARE DIE EXPERIMENTAL TESTING

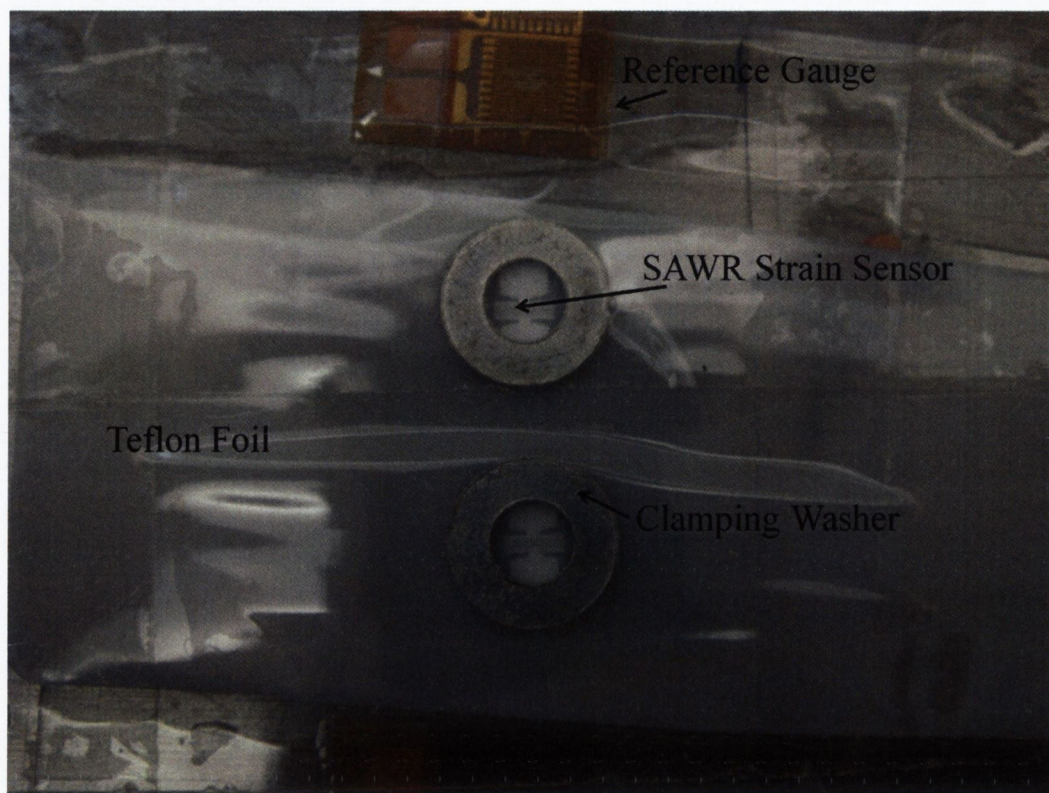


Figure 6.1: Bonding set up of SAWR strain sensor with M-Bond 610

A successful bond of the SAWR strain sensor will result in a residual stress will be induced which causes a change in f_r from the on wafer value. Stresses induced during the mounting process with M-Bond 600 cause a typical reduction in frequency response of 0.02% from on-wafer values see Figure 6.2.

6.2. TEMPERATURE SENSITIVITIES

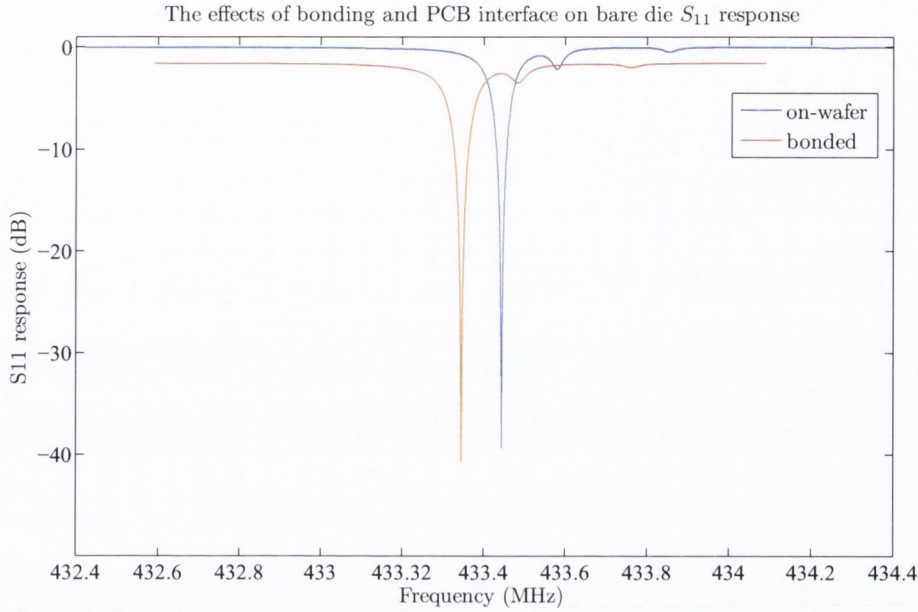


Figure 6.2: Comparison of the mounted and on-wafer S_{11} response of SAWR strain sensor at 20°

6.2 Temperature sensitivities

Temperature is known to affect the majority if not all physical sensors [99]. To negate the effects of temperature several approaches can be implemented including dummy sensors for temperature compensation, additional temperature sensors to measure temperature directly and provide error correction or through careful design of the sensor itself. In a SAWR strain sensor temperature biases cause a shift in f_r which is often referred to as apparent strain. This response of SAW resonators when exposed to thermal biases is a function of the properties of the substrate, the processes used during fabrication, and, critically, the metallization ratio [100]. In an uncompensated strain sensor temperature biases will appear as an apparent strain skewing the results. However, in applications where the strain levels are much larger than the apparent strain compensation may not be required. The temperature profile for a bare die SAWR used in this work is shown in Figure 6.3. The profile of the response reverses at a point of inflection called the turnover temperature [101]. As a linear temperature response is the preferred response to temperature for sensors, the presence of the turnover temperature increases the complexity of calibration equations for the sensors. While the

6. BARE DIE EXPERIMENTAL TESTING

operational temperature range of the SAWR strain sensor can be varied by fabricating on substrates other than quartz, the aluminium depositions used in the fabrication of the majority of SAWR strain sensors has an operational range up to about 200°C after which electrode softening and migration occurs [102].

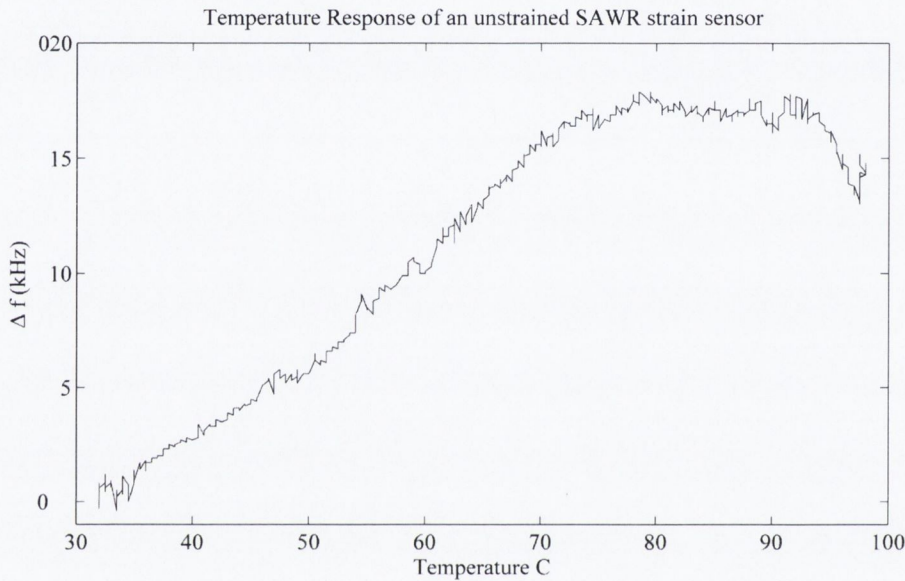


Figure 6.3: The temperature response of an unmounted SAWR strain sensor

Without the adhesive, the temperature sensitivity (T_{sen}) of a the non adhered bare die SAWR strain sensor was recorded at approximately 450Hz/°C over the temperature range 25°C- 70°C. Beyond this, the turnover effect reduces the linearity of the sensors temperature response. This thermal variation of the SAWR sensor tends to generate a requirement of SAWR devices to require some form of temperature compensation as an apparent strain results influences f_r . Using typical strain sensitivity values of ($-470Hz/\mu\epsilon$) an apparent strain curve is plotted against the performance of a self temperature compensation (STC) Vishay foil gauge, see Figure 6.4. The STC foil gauge was thermally matched for steel.

6.3. ACTUATOR LOADING PROFILE

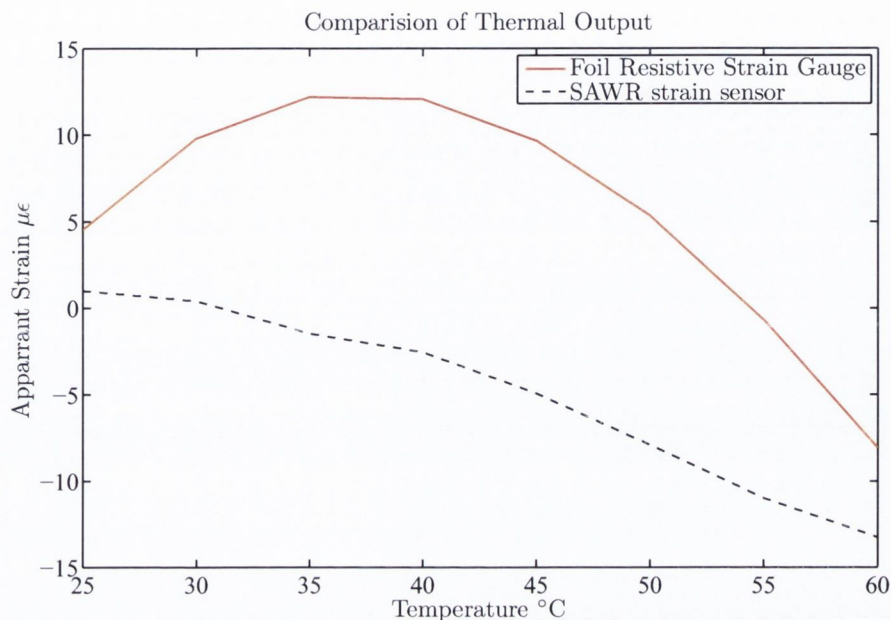


Figure 6.4: Comparison of apparent strain from a SAWR strain sensor to Vishay foil resistive strain gauge

The SAWR strain sensor response is far more linear in the range of ambient to 60°C. However turn over effects can increase the complexity of calibration of the SAWR strain sensors. The choice of AT-X quartz as the substrate material was shown to generate a suitably linear temperature profile. The turnover temperature which is located away from ambient conditions is preferable for many applications and would suggest to be superior to that of ST-X quartz which exhibits a turnover temperature at 20°. In any case the apparent strain profile of the SAWR sensor is comparable to that of industrial grade foil resistive gauges.

6.3 Actuator loading profile

Prior to the commencement of testing the SAWR strain sensors, the performance and linearity of the foil gauge as a reference sensor was evaluated. The linearity and repeatability of the foil resistive strain gauge is paramount to provide a reliable reference sensor. Overall the linearity of the foil gauge is consistent in both tensile and compressive loading, with the maximum hysteresis across an entire calibration found to be $(0.003 \pm 0.04)\mu\epsilon$. This high performance is indicative of the optimisation of both foil gauge design, installation procedures and adhesive. Figure 6.5 shows the variation in

6. BARE DIE EXPERIMENTAL TESTING

the strain level at the measurement area of the beam with regards to variations in the actuator position and beam deflection.

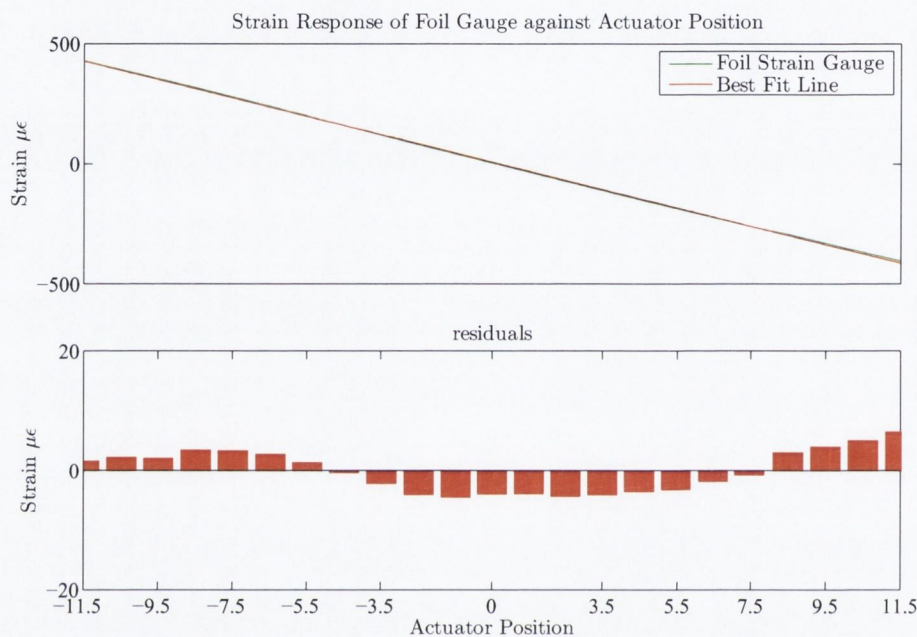


Figure 6.5: Strain Gauge Response to variations in Actuator Position

Hysteresis levels are consistent in tensile and compressive loading. The full scale sensitivity of the strain gauge across the full range of the testing cycles is consistent although some variation is observable in the repeatability of the sensors at various loading position across the three cycle of a calibration procedure. Such variations may be caused by a residual stresses. Variations are most likely due to the positional accuracy of the actuator ($\pm 0.2\text{mm}$). The performance of the strain gauges applied with M-Bond 610 and M-Bond 600 was found to be excellent, as would be expected. Figure 6.6 shows the performance of the actuator at various loading positions and the strain response of the SAWR. The profile of the residual is similar to that of Figure 6.6 suggesting the non linearity of the loading curve is a function of the loading profile of the beam.

6.3. ACTUATOR LOADING PROFILE

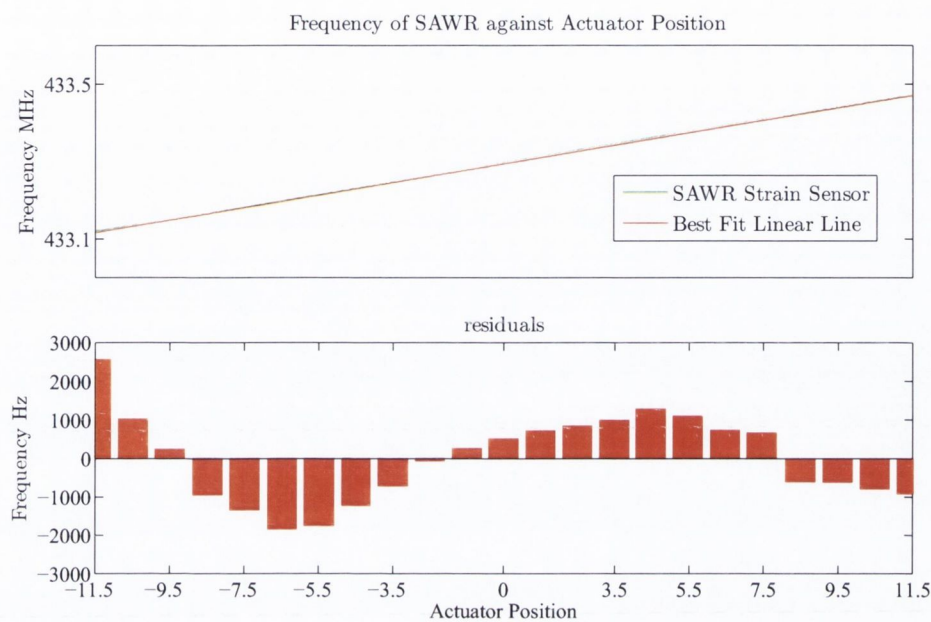


Figure 6.6: Strain Gauge Response to variations in Actuator Position

6. BARE DIE EXPERIMENTAL TESTING

6.4 Calibration results

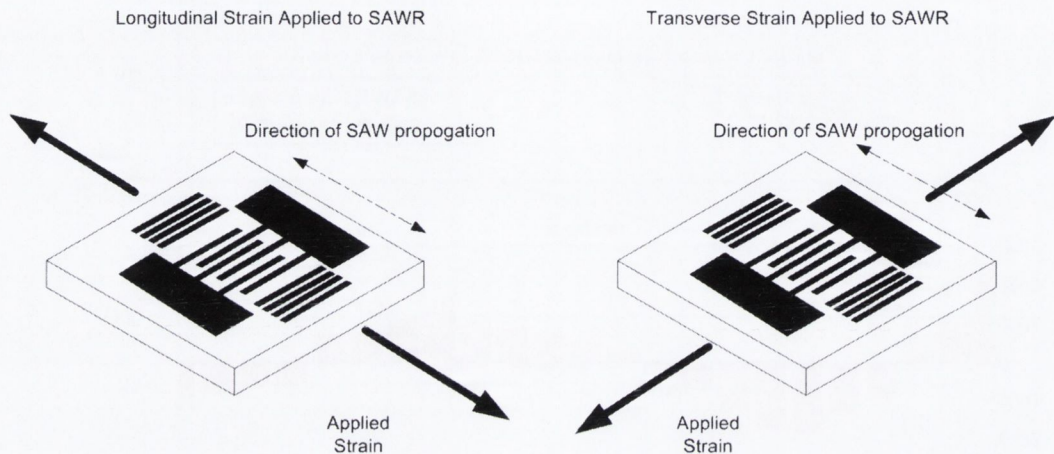


Figure 6.7: Orientation of strain applied to SAWR strain sensors for calibration for longitudinal and transversely applied strain

In this section SAWR strain sensors were mounted and calibrated using the protocol described in Section 6.1 and 5.4. The longitudinal and transverse strain sensitivity of the SAWR strain sensor as shown in Figure 6.7 are of particular interest. To evaluate the performance of the test sensors the following sensor parameters were defined.

S_{sen} The sensitivity of f_r to applied strains. Five values are defined for each calibration cycle. Four values can describe the sensitivity of the SAW strain sensor in loading and unloading for both tensile and compressive portions of the load cycle. A fifth value describes the average sensitivity of the SAWR strain sensor for the entire test.

Max hysteresis The hysteresis value is calculated as maximum variation in the f_r or the SAWR sensor at an identical loading points in the loading and unloading phase of a test cycle. The maximum hysteresis is expressed as a percentage of the full scale sensor value.

Best fit line A linear least squares best fit line is fitted to the experimental data.

Linearity While several definitions of linearity exist [103] for this work linearity will taken as the independent linearity definition i.e the maximum deviation of any of the calibration points from least squares best fit line expressed as a percentage full scale value [99].

6.5. CALIBRATION RESULTS WITH M-BOND 200

R^2 The coefficient of determination for a linear least squares best fit line is used to provide a measure of the suitability of a linear approximation of the test data.

6.5 Calibration results with M-Bond 200

Initial calibration tests were performed using M-Bond-200 [104]. This cyanoacrylate adhesive is widely available as super glue and requires a low temperature cure. As a widely available low temperature adhesive it was selected as the initial candidate for investigations into the performance of SAWR strain sensors.

M Bond 200 requires a cure at temperatures slightly elevated above ambient. The cure is aided by the inclusion of a catalyst agent. For general bonding of foil gauges the best practices recommended by Vishay suggest a cure cycle that is enhanced by the inclusion of temperature and pressure generated by the applicators thumb. However due to the fragility of the SAWR strain sensor this was not feasible so the initial tests performed in Section 6.5.1 used a cure cycle aided only by pressure applied to the bond pads of the SAWR while avoiding the IDT and reflectors. In section 6.5.2 adhesives were cured using an elevated temperature cure of 50° for a period of thirty minutes. Once bonded the SAWR strain sensors were allowed to post cure for a period of 24 hours.

6.5.1 Ambient M-Bond200

All test sensor were calibrated using the testing protocol outlined in section 5.4. The reference foil gauges for these tests were attached using M-Bond 600 and covered with a protective silicon coating. Ambient conditions were measured at 20°C. Nulling values was used to remove any bridge offset. A three cycle calibration curve for a SAWR strain sensor is shown in Figure 6.8. The strain sensitivity of the 433.42 MHz non apodized SAWR sensors in loading and unloading for compressive and tensile loading cycles are shown in Table 6.1. The full cycle values are shown in Table 6.2.

6. BARE DIE EXPERIMENTAL TESTING

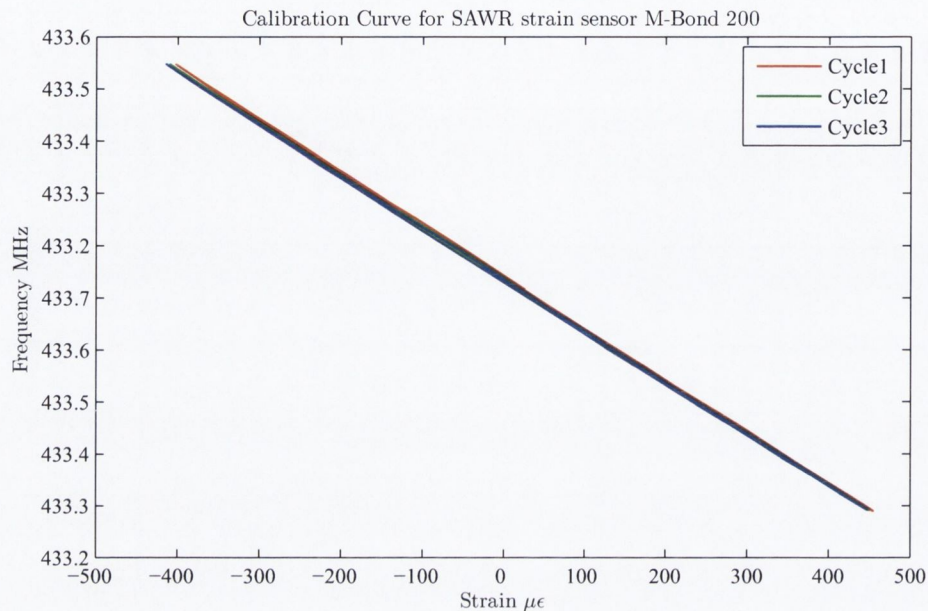


Figure 6.8: Strain Frequency Response of 433.42MHz SAWR bonded with M-Bond 200 at 20°C

Sensor	Load.Tens	Unoad.Tension	Load.Comp	Unload.Comp
1	-420.41 ± 3.81	-439.54 ± 3.21	-428.56 ± 1.94	-446.23 ± 3.90
2	-413.21 ± 1.49	-418.21 ± 2.41	-431.44 ± 1.20	-438.22 ± 1.91
3	-426.31 ± 0.58	-419.24 ± 6.04	-429.11 ± 2.68	-426.07 ± 5.71
4	-434.35 ± 7.09	-438.72 ± 7.09	-443.65 ± 2.83	-443.56 ± 3.40

Table 6.1: M-Bond200 strain sensitivities (Hz/ $\mu\epsilon$) at 20°C

Sensor	Full cycle
1	-425.01 ± 2.45
2	-420.52 ± 2.41
3	-417.11 ± 4.04
4	-432.08 ± 5.71

Table 6.2: M-Bond 200 Full cycle strain sensitivities (Hz/ $\mu\epsilon$) at 20°C

6.5. CALIBRATION RESULTS WITH M-BOND 200

Sensor	Equation	R^2	FS Hysteresis %
1	$f = -421.94e^6 \times \varepsilon + 433.31e^6$	0.9999	2.44
2	$f = -419.58e^6 \times \varepsilon + 433.32e^6$	0.9999	1.29
3	$f = -414.31e^6 \times \varepsilon + 433.56e^6$	0.9999	2.43
4	$f = -430.32e^6 \times \varepsilon + 433.47e^6$	0.9999	1.51

Table 6.3: Best Fit Line for M-Bond 200 sensors at 20°C

Best fit least squares line approximations were used to calculate the final calibration curve for all data is shown in Table 6.3. Full scale max hysteresis values are shown as well as the coefficient of determination (R^2).

6.5.2 Elevated Temperature Testing with M-Bond 200

The performance of the M-Bond 200 at ambient conditions is quite linear, elevated temperature tests were performed using the apparatus described in Section 5.4.1. The testing range was from 30°C to 80°C. Figure 6.9 shows the calibration results for a 433.42MHz die mounted using M-Bond 200. For clarity calibration curves presented are for cycle 2 of all tests. The sensor results are consistent across all three cycles of the calibration curve. Table 6.4 provides the experimental performance of the sensors.

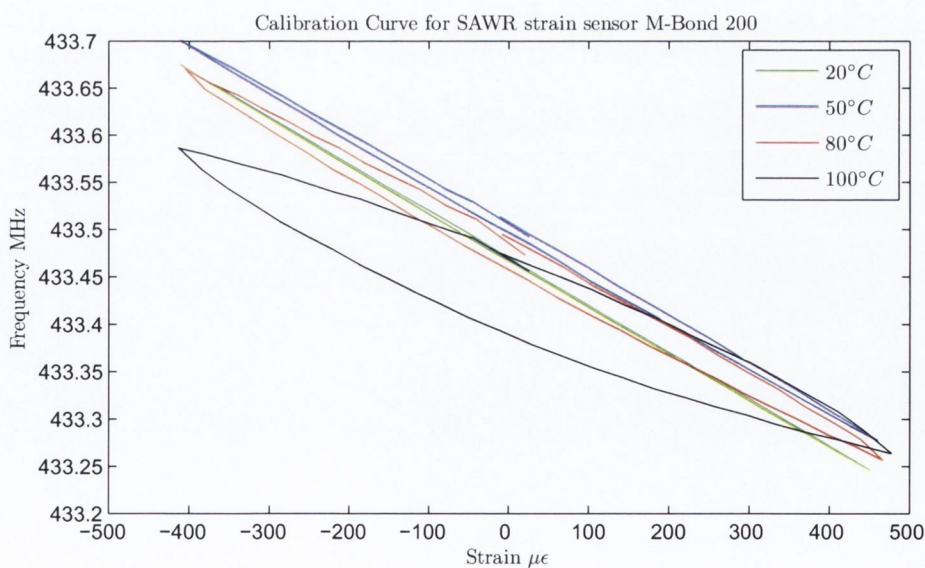


Figure 6.9: Frequency Strain Response of 433.42MHz SAWR with M-Bond 200 at elevated temperatures

6. BARE DIE EXPERIMENTAL TESTING

While M-Bond 200 demonstrates adequate performance at ambient conditions strain sensitivities become skewed at elevated temperatures. Hysteresis becomes extremely pronounced at these temperatures which is not surprising as the working temperature range for M-Bond 200 provided a foil strain gauge is used is -185°C to 95°C. It is reasonable to assume the mismatch of thermal expansions coefficients and the softening of the adhesive are major factors in the deterioration of the strain response.

Temp	S_{sen}	Best Fit Line Equation	R^2	FS Hysteresis %
20°	-496.12 ± 3.93	$f = -496e^6 \times \epsilon + 433.47e^6$	0.9999	0.64
50°	-487.55 ± 7.14	$f = -483e^6 \times \epsilon + 433.51e^6$	0.9999	2.87
80°	-482.45 ± 28.14	$f = -464e^6 \times \epsilon + 433.48e^6$	0.9998	6.86
100°	-366.15 ± 37.78	$f = -349e^6 \times \epsilon + 433.43e^6$	0.9997	26.51

Table 6.4: Best Fit Line for M-Bond 200 SAWR strain sensors

6.6 Calibration results with M-Bond 600

A standard epoxy resin was selected as a strain gauge adhesive for the SAWR strain sensors. M-Bond 600 requires a cure temperature of 120°C and a working range of -452°C to 260°C for standard strain gauge [105]. The test sensors were bonded using the cleaning and surface preparation methods outlined in section 6.1. The dies were clamped and bonded using a cure cycle of 130°C for 2 hours clamped and 2 hours unclamped. To avoid thermal shock the gauges were cycled to 130°C over a period of thirty mins. Once bonded the sensors should be allowed post cure at ambient conditions for a minimum period of 24 hours.

Both 433.42 MHz non apodized and 434.42 MHz apodized SAWR strain sensors were calibrated. Table 6.5 shows the S_{sen} for 433.42MHz sensors while the S_{sen} for 434.42MHz sensors is shown in Table 6.6.

Sensor	Load.Tens	Unoad.Tension	Load.Comp	Unload.Comp
1	-443.22 ± 5.66	-450.15 ± 8.71	-443.20 ± 5.66	-452.40 ± 5.96
2	-454.75 ± 2.75	-458.81 ± 1.43	-421.13 ± 2.01	-435.06 ± 1.89

Table 6.5: 433.42 MHz SAWR M-Bond 600 strain sensitivities (Hz/ $\mu\epsilon$) at 20°C

Sensor	Load.Tens	Unoad.Tension	Load.Comp	Unload.Comp
1	-483.35 ± 2.93	-494.90 ± 5.54	-455.48 ± 4.19	-476.91 ± 4.09
2	-472.35 ± 5.63	-475.10 ± 5.54	-447.48 ± 5.00	-442.91 ± 6.20
3	-464.27 ± 3.48	-477.00 ± 8.27	-434.74 ± 4.58	-448.48 ± 1.31
4	-416.62 ± 9.64	-459.01 ± 1.58	-432.45 ± 3.45	-466.48 ± 1.31
5	-414.20 ± 8.64	-462.12 ± 11.58	-432.45 ± 3.45	-435.28 ± 4.16

Table 6.6: 434.42 MHz M-Bond 600 strain sensitivities (Hz/ $\mu\epsilon$) at 20°C

Overall the strain sensitivities are consistent between the two SAWR types. A three cycle calibration curve for a 433.42MHz sensor is shown in Figure 6.10.

6. BARE DIE EXPERIMENTAL TESTING

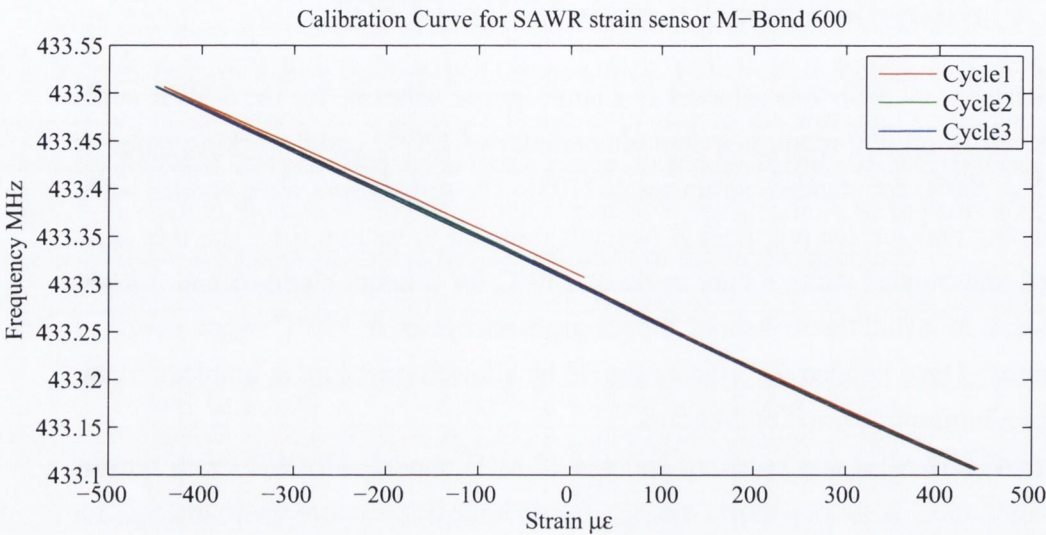


Figure 6.10: Frequency Strain Response of 433.42 MHz SAWR with M-Bond 600 at 20°

Full cycle strain sensitivities for both 433.42 MHz and 434.42 MHz strain sensors are given in Table 6.7

433.42MHz	Full cycle
1	−433.99 ± 3.66
2	−435.06 ± 1.89
434.42MHz	Full cycle
1	−471.19 ± 4.26
2	−471.29 ± 3.21
3	−433.99 ± 3.66
4	−438.57 ± 5.10
5	−425.11 ± 3.66

Table 6.7: M-Bond 600 full cycle strain sensitivities at 20°C

6.6. CALIBRATION RESULTS WITH M-BOND 600

Sample	Equation	R^2	FS Hysteresis %
433.42 MHz			
1	$f = -454.33e^6 \times \varepsilon + 433.3e^6$	0.9999	0.57
2	$f = -435.06e^6 \times \varepsilon + 433.16e^6$	0.9999	1.25
434.42 MHz			
1	$f = -471.19e^6 \times \varepsilon + 434.29e^6$	0.9999	1.83
2	$f = -477.29e^6 \times \varepsilon + 434.29e^6$	0.9999	2.80
3	$f = -438.19e^6 \times \varepsilon + 434.27e^6$	0.9999	1.19
4	$f = -436.57e^6 \times \varepsilon + 434.37e^6$	0.9999	4.81
5	$f = -426.63e^6 \times \varepsilon + 434.31e^6$	0.9999	5.34

Table 6.8: Best Fit Line for M-Bond 600 sensors at 20°C

The strain sensitivity is slightly higher with M-Bond 600 adhesives compared to that of M-Bond 200. Full scale hysteresis levels are considerably lower. Overall M-Bond 600 offers improved performance at ambient conditions when compared to M-Bond 200.

6.6.1 Elevated Temperature Testing with M-Bond 600

Elevated temperature tests were performed to assess the performance of the SAWR strain sensors and M-Bond 600 adhesive. M-Bond 600 was expected to show improved performance at elevated temperature when compared to M-Bond 200. The higher cure temperature and therefore higher glass transition temperature are typically associated with greater bond stability at elevated temperature. A calibration graph is shown in Figure 6.11. The best fit calibration lines are shown in Table 6.9.

6. BARE DIE EXPERIMENTAL TESTING

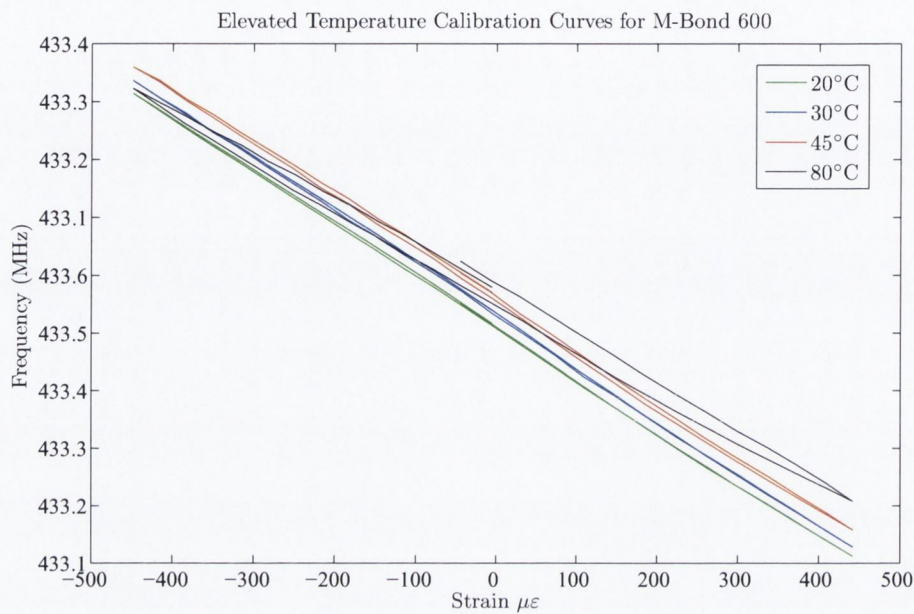


Figure 6.11: Frequency Strain Response of 433.42MHz SAWR with M-Bond 600 at elevated temperatures

Temp.	S_{sen}	Best Fit Line Equation	R^2	FS Hysteresis %
20°	-454.99 ± 3.76	$f = -454e^6 \times \epsilon + 433.31e^6$	0.9999	0.64
30°	-453.54 ± 7.67	$f = -458e^6 \times \epsilon + 433.31e^6$	0.9999	0.899
45°	-457.24 ± 28.14	$f = -460e^6 \times \epsilon + 433.32e^6$	0.9998	0.934
80°	-407.12 ± 37.78	$f = -407e^6 \times \epsilon + 433.33e^6$	0.9999	4.23

Table 6.9: Best Fit Line for M-Bond 600 433.42 MHz sensor

Comparing Figures 6.11 and 6.9 it is clear that M-Bond 600 performs better than M-Bond 200 with lower hysteresis. Hysteresis effects account for a difference in loading and unloading of approximately $4\mu\epsilon$ at 20°C , this increases to $40\mu\epsilon$ at 80°C . The increase in hysteresis is most likely caused by degradation in the bonding interface caused by the elevated temperature. For the mounted SAWR a frequency shift of 34 kHz over a 40°C temperature range was observed. This equates to a temperature sensitivity of $926\text{Hz}/^\circ\text{C}$ for a mounted sensor. This value is approximately twice that for the unmounted SAW temperature response and could be attributed to stress effects influencing the turnover temperature [106]. The temperature drift for an unstrained mounted sensor is $2\mu\epsilon/^\circ\text{C}$. The stability of S_{sen} for resonators fabricated on AT-X

6.6. CALIBRATION RESULTS WITH M-BOND 600

quartz is also far superior than that reported for ST-X cuts [47]. Before the turnover effects of the piezoelectric substrate and hysteresis influences due to the adhesive, the variation in S_{sen} is 1.4%, however, at 80°C this variation increases to 11%.

6.6.2 Transverse Strains

SAWR strain sensors were mounted with the IDT perpendicular to the applied longitudinal strain as shown in Figure 6.7. Calibration was performed with the same procedure as that used for longitudinal strain calibration. Transverse sensitivities are expressed as a function of the longitudinal applied strain in Table 6.10 with the calibration curve shown in Figure 6.12. When mounted with the IDT perpendicular to applied strains the response of the SAWR is the opposite of a SAWR mounted in the direction of the applied strain. For a transversely mounted SAWR fabricated on AT-X quartz, tensile strains result in an increase in resonance frequency while compressive strains show a decrease. The slight variation in typical hysteresis is most likely due to variations in the repeatability of the bonding between sensors and test beam. Hysteresis values are comparable to those reported for longitudinally mounted strain sensors. The S_{sen} of the transversely mounted sensor is also stable across a 60°C range with a variation of 4%. The presence of the turnover temperature causes a decrease in sensor sensitivity of 20%.

6. BARE DIE EXPERIMENTAL TESTING

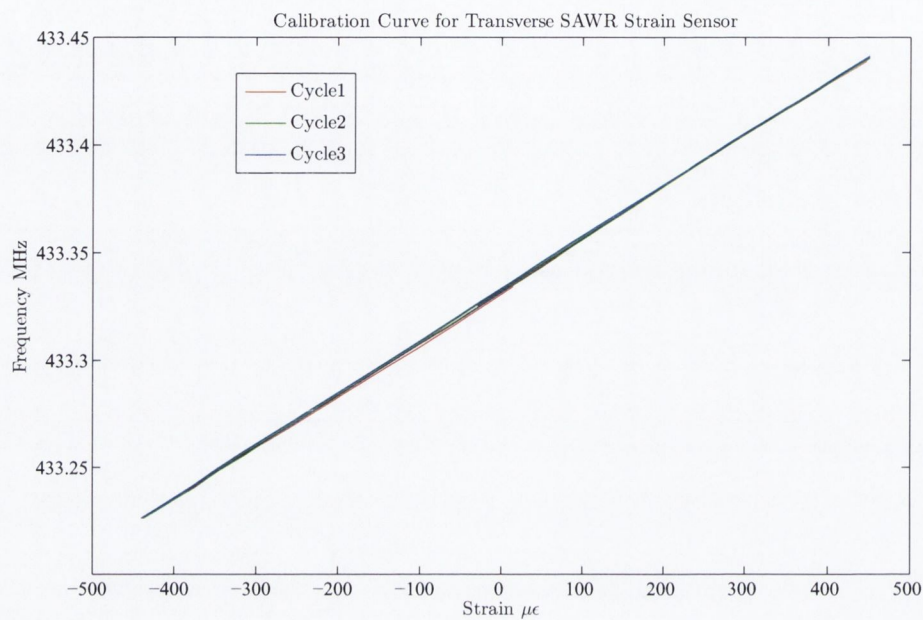


Figure 6.12: Transverse Strain Frequency response of a 433.42 MHz SAWR strain sensor with M-Bond 600 at 20°

Temp.	S_{sen}	Best Fit Line Equation	R^2	FS Hys-teresis %
20°	-240.12 ± 1.96	$f = -241.5e^6 \times \epsilon + 433.332e^6$	0.9999	1.68
35°	-247.18 ± 10.60	$f = -246.6e^6 \times \epsilon + 433.316e^6$	0.9999	1.68
45°	-245.72 ± 4.67	$f = -245.7e^6 \times \epsilon + 433.354e^6$	0.9999	2.78
60°	-236.10 ± 6.59	$f = -234.2e^6 \times \epsilon + 433.352e^6$	0.9998	5.15
80°	-176.45 ± 9.15	$f = -170.9e^6 \times \epsilon + 433.354e^6$	0.9999	6.11

Table 6.10: Transverse temperature performance of SAWR strain sensor with M-Bond 610

6.7 Calibration results with M-Bond 610

As elevated cure temperatures are known to improve the temperature stability of foil gauge adhesives over an extended temperature range a higher temperature cure epoxy resin was selected as a test adhesive. M-Bond 610 is the highest quality adhesive supplied by Vishay with the highest working temperature range (-269°C to 370°C) and the thinnest glue line (3-5μm) [107]. Bare die specimens were cured at a temperature

6.7. CALIBRATION RESULTS WITH M-BOND 610

of 140°C for a period of two hours while clamped. The sensors were unclamped and post cured for 2 hours at 140°C. Table 6.11 shows the S_{sen} of the calibrated sensors. The tested sensors were found to under go a more repeatable residual stress induced frequency shift than other test adhesives.

Sensor	Load.Tens	Unoad.Tension	Load.Comp	Unload.Comp
1	-407.2 ± 3.5	-421.2 ± 1.7	-421.1 ± 2.3	-430.5 ± 2.9
2	-507.3 ± 4.6	-511.1 ± 7.4	-521.4 ± 5.3	-524.7 ± 2.9
3	-492.8 ± 4.3	-511.1 ± 7.4	-492.8 ± 4.3	-496.3 ± 5.1

Table 6.11: M-Bond610 strain sensitivities at 20°C

Sensor	Full cycle
1	-420.1 ± 3.5
2	-516.2 ± 6.8
3	-503.1 ± 4.7

Table 6.12: M-Bond 610 full cycle strain sensitivities at 20°C

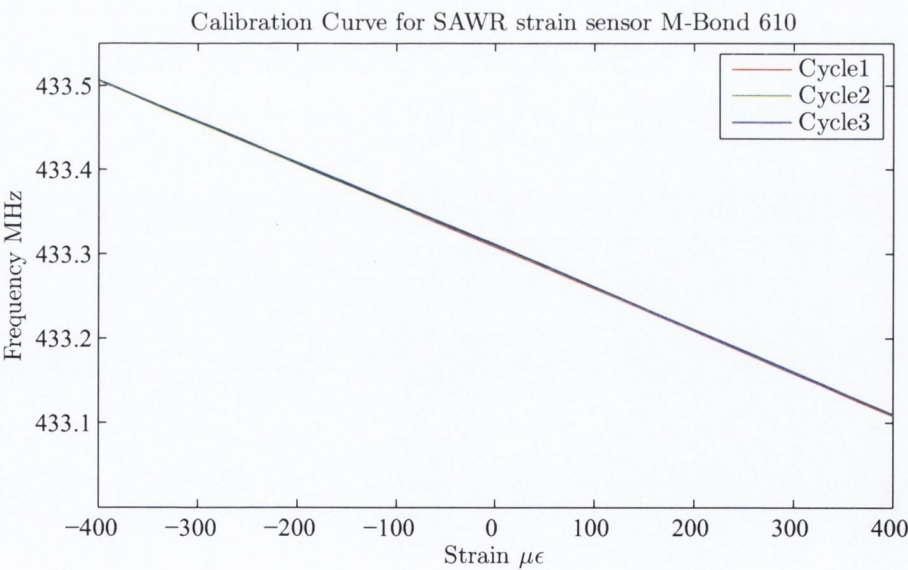


Figure 6.13: Strain Frequency response of a SAWR with M-Bond 610 at 20°C

6. BARE DIE EXPERIMENTAL TESTING

Sample	Equation	R^2	FS Hysteresis %
1	$f = -420.3e6 \times \varepsilon + 433.302MHz$	0.9999	1.78
2	$f = -519.2e6 \times \varepsilon + 433.310MHz$	0.9999	1.28
3	$f = -503.3e6 \times \varepsilon + 433.308MHz$	0.9999	0.37

Table 6.13: Best Fit Line for M-Bond 610 sensors at 20°C

6.7. CALIBRATION RESULTS WITH M-BOND 610

6.7.1 Elevated Temperature Testing with M-Bond 610

Elevated temperature tests were performed to assess the performance of the SAWR strain sensors and M-Bond 610 adhesive. With a higher cure temperature and greater working range than both M-Bond 600 and M-Bond 200 it is to expected that hysteresis levels and decreases in strain sensitivity with increasing temperature would be lower. Calibration data for elevated temperature tests are shown in Table 6.14 and 6.15.

Temp.	S_{sen}	Best Fit Line Equation	R^2	FS Hys- teresis %
20°	-454.29 ± 7.10	$f = -451.12e^6 \times \epsilon + 433.325e^6$	0.9999	1.61
40°	-440.12 ± 5.27	$f = -438.93e^6 \times \epsilon + 433.331e^6$	0.9999	1.61
50°	-434.73 ± 6.45	$f = -432.63e^6 \times \epsilon + 433.3334e^6$	0.9999	2.09
60°	-428.89 ± 7.09	$f = -428.07e^6 \times \epsilon + 433.336e^6$	0.9998	3.26
70°	-418.99 ± 8.19	$f = -417.19e^6 \times \epsilon + 433.329e^6$	0.9999	4.14
90°	-348.00 ± 29.19	$f = -342.66e^6 \times \epsilon + 433.311se^6$	0.9999	8.75

Table 6.14: Elevated temperature performance of SAWR strain sensor

Table 6.14 contains data for what would be considered a poorly performing sensors i.e sensor 1 in Table 6.13. The results for elevated temperature calibration for a good performing sensor is shown in Table 6.15 and in the Figure 6.14.

Temp.	S_{sen}	Best Fit Line Equation	R^2	FS Hys- teresis %
45°	-529.71 ± 9.27	$f = -527.67e^6 \times \epsilon + 433.368e^6$	0.9999	0.3584
55°	-533.32 ± 3.4	$f = -532.65e^6 \times \epsilon + 433.356e^6$	0.9999	0.4606
65°	-535.33 ± 4.02	$f = -535.33e^6 \times \epsilon + 433.358e^6$	0.9998	0.4339

Table 6.15: Elevated temperature performance of SAWR strain sensor

6. BARE DIE EXPERIMENTAL TESTING

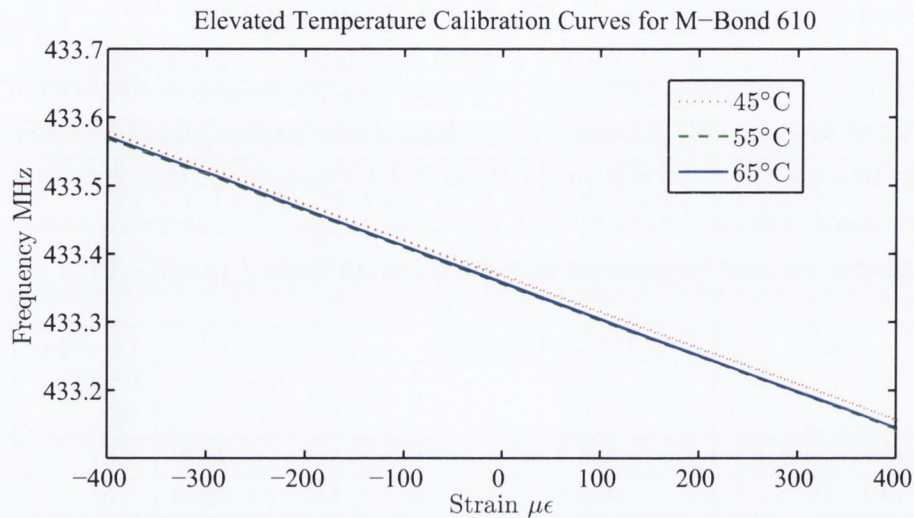


Figure 6.14: Strain Frequency response of a SAWR with M-Bond 610 at Elevated Temperatures

It is clear that bond line repeatability is a key issue effecting the performance of the SAWR strain sensor. In the best case M-Bond 610 offers the best bond line of all adhesives tested. Repeatability of the bond is poor. Overall low level hysteresis was obtained for a large temperature range with minimal reduction in strain sensitivity. Further enhancements to the performance of the SAWR strain could be achieved through the introduction of packaging and will be discussed in section 7.3.

6.8 Orientation sensitivity of SAWR strain sensors

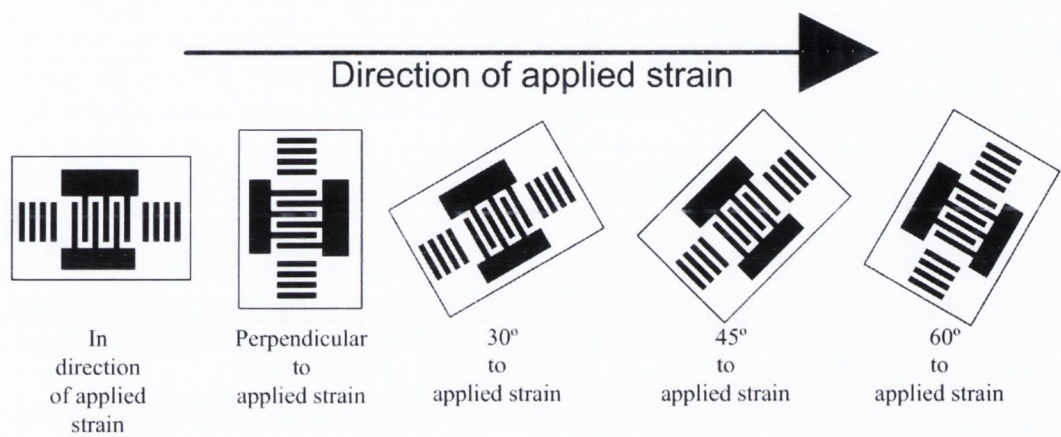


Figure 6.15: Alignment of SAWR strain sensors to measure alignment sensitivity

Comparing the profile of Figure 6.10 and Figure 6.12 it can be observed that the orientation of the SAWR strain sensors relative to the applied strain has an influence on the strain sensitivity of the SAWR. To investigate this relationship the SAWR strain sensor was mounted at a range of alignments relative to the dominant strain component in the SAWR calibration beam as shown in Figure 6.15. The test sensors were bonded to the testing beam using M-Bond 600 and the methodology described in sections 6.1 and 6.6. The same testing protocol was used as in the previous sections. The result is shown in Figure 6.16. The strain sensitivity of the SAWR to strain was found to be minimised at an orientation of approximately 30° to the applied strain field. At this orientation the sensitivity is approximately $-20\text{Hz}/\mu\epsilon$ or 4% of the sensitivity of the longitudinal strain sensitivity. In section 2.5 this will be compared to theoretically predicted values of strain sensitivity.

6. BARE DIE EXPERIMENTAL TESTING

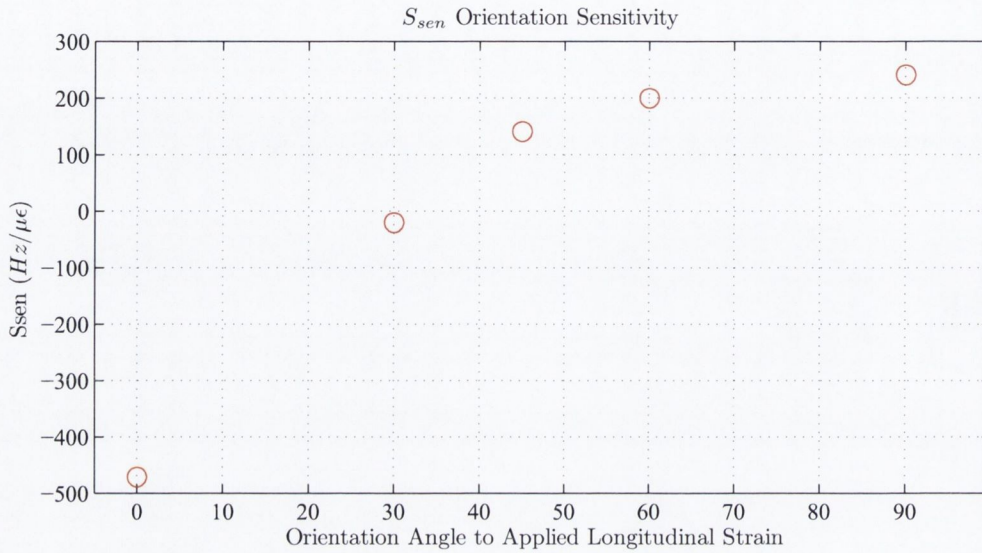


Figure 6.16: Experimental S_{sen} as function of alignment to applied strain

6.9 Discussion on Experimental Testing

In all bare die calibrations commercial strain gauge adhesives were used. Strain gauge adhesives demonstrate a greater ability to transmit strain effectively with reduced creep and brittle failures compared to many structural adhesives. Provided the required surface preparations were performed correctly as described in Section 6.1 the SAWR strain sensors were found to undergo a distinct and repeatable response to applied strains. The sensors show a frequency shift of approximately 450Hz/ °C which is far lower than the sensitivity to applied strain and comparable to self temperature compensating strain gauges.

Some general comments can be made on the bare die strain tests:

- All strain gauges used to evaluate the SAWR strain sensors demonstrated good linearity and repeatability with actuator position. The mounting position for the test sensors was constant across all the experimental testing as was the installation procedures. The loading profile of the beam was verified in Section 5.3.1. The performance of the strain gauge is revisited briefly. The strain gauge sensitivity to actuator position and residual plot of the best fit line is shown in Figure 6.5. The maximum deviation of the strain gauge from linearity is approximately

6.9. DISCUSSION ON EXPERIMENTAL TESTING

$14\mu\epsilon$ while the maximum hysteresis was measured at 0.26% of full scale. The worst case hysteresis values of the foil gauge remains superior to that of the best SAWR strain sensor, however the difference is lower than was expected. For these tests a half bridge configuration (National Instruments Half Bridge: type I [108]) was used, as bending effects are already minimal and this bridge configuration is suitable for cantilevers. Full bridge configurations could also be used for elevated temperature testing. However tests were all performed using constant temperatures and bridge nulling to remove offsets prior to the commencement of all tests. Deviation from the linear approximation appears more pronounced in compression and than in tension. This is surprising as the calibration beam is designed to behave the same in tension and compression. Non linearity of a constant voltage bridge circuit is generally taken to be a percentage of the strain level, which would be 0.04% at $400\mu\epsilon$ [109]. In most cases nonlinearity errors in conventional strain gauge circuits are small enough to ignore when measuring modest strain levels as done in this project. The deviation from the linearity at the full scale value in compression across all calibration beams would suggest that the behaviour is a feature of the beam loading profile and suggest that bending strains are being generated in the testing apparatus by the actuator loading. In any case limiting the loading profile to $\pm 400\mu\epsilon$ will avoid the introduction of significant bending components and avoid plastic deformation of the beam. Not surprisingly the SAWR strain sensor follows an almost identical loading profile with actuator position as the foil gauge see Figure 6.6.

- The SAWR sensors demonstrate similar linearity to that of the foil resistive strain gauge illustrating a linear approximation is valid. At ambient conditions for all adhesives tested the R^2 value of the best fit line in excess of 0.9999 which validates the linear approximation of the best fit line. Elevated temperature tests result in a decrease in this value, which is visible with the increase in hysteresis and the curvature of the strain frequency response curves.
- For longitudinal tests the S_{sen} of the SAWR sensor is negative. Therefore a compressive strain results in an increase in f_r and tensile results in a decrease in f_r . Transverse strains result in a positive S_{sen} . The changes in strain sensitivity at various alignments to a dominant strain can be attributed to the varying stress states in the anisotropic substrate. The strain sensitivity of the sensors in all adhesives shows moderate variation in the different loading stages of each cycle.

6. BARE DIE EXPERIMENTAL TESTING

In general SAWR sensors tend to be more sensitive in unloading than in loading. This is the trend for all adhesives tested and would suggest a stress relaxation of the adhesive is occurring. However, no-load values recorded for three consecutive test cycles with the same sensor and M-Bond 610 found no residual effects as the pre and post no-load values remained consistent.

- There is considerable variation in the S_{sen} between dies bonded with different adhesives. M-bond 200 cured at an elevated temperature was found to have significantly better performance compared to ambient cures. Post cure and allowing the bond to strengthen over an extended period further enhanced the bond strength for the bare dies.
- Table 6.5 and Table 6.6 illustrate that S_{sen} between SAWR types is comparable for a given adhesive. This is not surprising as SAWR layout and reflective grating configurations are consistent for both devices bar the inclusion of apodization in the 434.42 MHz SAWR IDT. The non apodized devices were found to be more prone to spurious measurements possibly due to the greater magnitude of the spurious response. However the susceptibility of the interrogation hardware to spurious measurements can be minimised by sufficient grounding of the SAWR sensor and by optimisation of interrogation parameters such as sensors bandwidth and measurement energy level thresholds. In the treatment of the experimental data dropped samples due to transmission effects and spurious measurements were treated as outliers [110] and removed.
- The S_{11} magnitude response of the SAWR strain sensor does not appear to change significantly with applied load. A general linear relationship however can be observed between magnitude response and applied load. Tensile strains appear to cause a decrease in the magnitude of the response while compressive strains result in the opposite behaviour. This behaviour was observed for both wired and wireless strained testing. For dies bonded using a wire bonding machine it was more apparent. In dies where it was observed the general trend of this behaviour was consistent across the test cycle. The changes in the magnitude response of the sensors under applied loads can be attributed to changes in reflectivity of the reflective gratings and changes in separation between IDT and reflective gratings resulting in the phase of the reflected wave being altered which causes changes in the magnitude response. Similar variation in the mag-

6.9. DISCUSSION ON EXPERIMENTAL TESTING

nitude of the spurious response with respect to applied strains in tension and compression was observed.

- SAWR sensors fabricated on quartz are typically reported to have a working range of $-40\text{ }^{\circ}\text{C}$ to $160\text{ }^{\circ}\text{C}$. A correlation exists between the glass transition temperature range of the adhesive and the working temperature range of the adhesive. Thermal mismatch and contraction of the adhesive as it cools results in the frequency offset caused by the adhesive. For those adhesives reported in this section the offset is modest and tested sensors remain in the ISM 434 MHz band. Structural filled epoxies were tested and they resulted in a frequency shift of f_r outside the ISM band by over 2 MHz. The magnitude of the residual stress resulted in the magnitude response of the sensor being completely degraded and several spurious modes being generated thus suggesting permanent device damage. It is clear the requirements for strain sensor adhesive differs to those for a structural adhesive and will be discussed in Section 7.3.2.
- For each load step of the calibration cycle 50 measurements were made. For the purpose of this analysis the response was averaged. In general the standard deviation at each measurement point for a double dipole antenna at 5cm was found to be 180 - 260 Hz for full scale values (equivalent to a $0.35 - 0.5\text{ }\mu\epsilon$). The standard deviation of the measurement points was found to increase as distance between interrogator antenna and SAWR antenna increased which was to expected [111]. While transmission effects have been shown to greatly influence the performance of a wireless SAW strain sensor and would need to be considered in the design of a SAW strain sensor based application. Based upon a 95% confidence level the wireless bare die SAWR sensor resolution of $2.5\mu\epsilon$ can be achieved without optimisation of the antenna.
- In general, the inclusion of temperature results in a decrease in the performance of the sensors as hysteresis increases and strain sensitivity decreases. Changes in the gauge factor of foil resistive gauges with temperature is a known performance characteristic of foil resistive gauges and is usually accounted for in elevated temperature applications. Of the adhesives tested, M-Bond 610 demonstrated the best overall performance with higher strain sensitivities and lower hysteresis levels for all temperatures tested. While surface preparation was carefully monitored, bond line repeatability is difficult to control. Residual stresses and the

6. BARE DIE EXPERIMENTAL TESTING

resulting SAWR frequency shift can be used to evaluate the possible strain sensitivity of the dies however an exact relationship to S_{sen} is not clear. Application of the adhesives is typically performed using a squeeze nozzle or application brush. Due to capillary action an excessive use of adhesive can flow over the edge of the SAW substrate and damage IDT and reflective gratings especially with viscous adhesives such as M-Bond 200. Cleaning of the IDT tends to result in a surface becoming further contaminated and is highly undesirable. While surface cleaning can be used on the attachment area, bare dies were untreated. It is possible that contaminants remain from the photolithographic process which may decrease bond strength. Due to the size of the die it was not possible to clean the underside of the die due to the wetness of the cleaning process surface cleaning was not possible due to wetness of the processes. Ideally ion beam cleaning could be used prior to dicing to provide a highly clean surface.

- The alignment sensitivity of the SAWR strain sensor is shown in Figure 6.15. It is clear the orientation of the IDT to applied strains has an effect on the response of the SAWR strain sensor. Changes in alignment of the SAWR changes the orientation of the IDT and consequently the direction of the propagating SAW relative to the applied strain. The results in the variation in S_{sen} as a function of orientation can be seen in Figure 6.16. The shifts in resonant frequency of the SAWR strain sensors are canceled at an orientation of approximately 30° to the applied strain. At an orientation of 30° the S_{sen} is approximately 20Hz or 4% of the strain sensitivity for longitudinal strains. The possibility of removing strain sensitivity may be beneficial for future works when strain insensitive temperature compensation is required. It could be possible to rigidly control the full scale working range of the SAWR sensor within the ISM band by specific dicing of the SAWR die.

6.10 Conclusions

In this chapter bare-die-one-port SAWR strain sensors have been calibrated wirelessly using a commercially available SAWR interrogation unit. The SAWR strain sensors were bonded using a polymer adhesive traditionally used in the attachment of foil resistive strain gauges. Good linearity can be observed up to approximately 60°C with suitable adhesive, beyond which however creep effects, hysteresis and changes in sen-

6.10. CONCLUSIONS

sitivities reduce sensor response to applied strain considerably. This was attributed to a decrease in the strain coupling between the stiff SAWR strain sensor substrate and the measurement surface, and the effects of the turnover temperature. The temperature stable strain sensitivity of this particular quartz cut makes it highly suitable for strain sensing applications. The results indicate that over a moderate temperature range uncompensated strain measurement is possible. The results also indicate that the strain sensitivities of SAWR strain sensors are highly sensitive to orientation of the sensor as well as to crystal cut and propagation direction of the SAW relative to applied strain. As SAWR strain sensors require specialised packaging this has implications for the design of customised packaging for SAWR strain sensors which will be discussed in Chapter 7. To the authors knowledge, the results within this chapter provide the most detailed and complete data set on the calibration of SAWR strain sensors for a range of loading conditions and temperatures. AT-X quartz has been identified as a substrate orientation which combines good strain sensitivity with minimal temperature dependency.

6. BARE DIE EXPERIMENTAL TESTING

Chapter 7

Packaging and calibration of SAWR strain sensors

SAWR and filters are fragile components made of thin film structures. The IDTs and RGs as well as propagation paths are prone to damage and contamination from foreign particles. Foreign materials contaminating key features of the SAW component can cause shorting, wave attenuation or permanent damage and therefore must be avoided. In this chapter packaging of the SAWR will be examined. Commercial filter and sensor packaging will be discussed. Details on packaging and adhesives will be presented including the calibration of packaged sensors at a range of temperatures.

7.1 Commercial filter packaging technology

For electronic and sensing applications, packaging of the SAW component is required. In electronic applications packaging is required to shield the SAW component from damage whilst providing an environment that allows for highly stable output. While stable output can be achieved by device design, shielding the SAW die from stress and temperature which occur either externally or are generated by the presence of the package itself remains a primary consideration in the selection of a package for electronic applications.

A commercial SAWR or filter is supplied in a standard metallic, plastic, or at high operational frequencies ($> 1\text{GHz}$) ceramic cavity packaging with input and output pins available [112]. Electrical connection between package and die is then usually made with conventional techniques such as ultrasonic wedge or ball bonding. A cap is

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

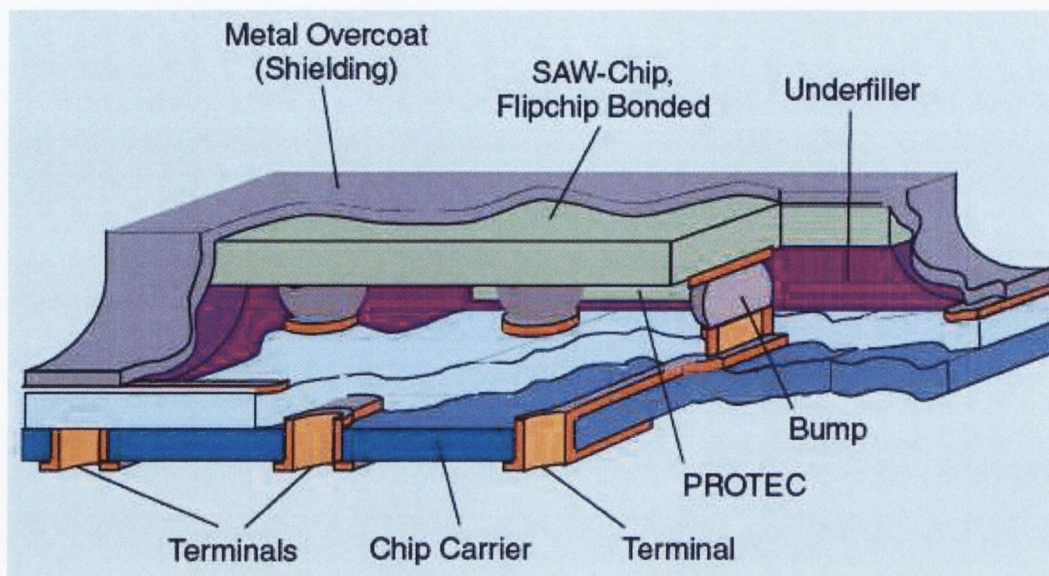


Figure 7.1: SAWR packaged in commercial Epcos packaging [113].

placed over the cavity of package and sealed hermetically.

As a key component in telecommunications devices continual emphasis is placed on reducing package size as well as that of the die. Recently, flip chip assemblies have allowed for greater reductions in footprint. For flip chip assemblies bump studs are deposited on bonding pads of the die. A die is mounted on the lid of the package and contact between the bump studs and external connections completes electrical connectivity thus removing the need for wire bonding to the die. Most commercial manufacturers have developed proprietary packaging technologies. Epcos, for example, have developed a variation on the traditional flip chip design which uses a proprietary passivation layer to protect (*PROTEC*) the SAW structures [113]. The Epcos solution is a multi layer solution with the individual layers chosen to match thermal expansion coefficients of the substrate thus limiting stress caused by the expansion of the package see Figure 7.1.

Impressive reductions in size of the SAW filter technology have recently been achieved through the use of wafer level package techniques. Wafer level packaging uses a second wafer to cover the device wafer. The second wafer will cap the SAW device. The second wafer may have preprepared drilled vias and if required photolithographically fabricated interconnections. The capped wafer is then diced into individual devices. Using this technique packaged SAW devices as small $1\text{mm} \times 0.8\text{mm} \times$

7.2. COMMERCIAL SAW SENSOR PACKAGING

0.25mm can be realised [114]. Both wafer level and chip scale packaging has been successfully implemented for various MEMS sensor types such as gyroscopes, pressure and temperature, it is possible that in development of future SAW sensors, integrating sensor fabrication and packaging at the wafer level may allow for the realisation of extremely small SAW sensors.

7.2 Commercial SAW sensor Packaging

The packaging of a SAW component for sensing applications will be designed based upon the target application. SAWDL bio-sensors for example have been developed for liquid sensing with a machined cavity to isolate the sensing area from the IDT [115].

For temperature sensing applications substrates such as lithium niobate, langastite and gallium nitrate are preferred over quartz and have documented as operating at temperatures up to 900°C with several high temperature substrates shown to be stable in the range of 800°C – 1000°C for a period of several months [116]. However, challenges remain in developing suitable packaging and antenna solutions which remain functional at high temperatures [117]. Commercial SAWR temperature sensors manufactured by SenGenuity use standard surface mount ceramic packages allowing for an operational range 0 – 100°C [118]. At such temperatures packaging for SAW temperature sensors is chosen to minimise thermal stresses caused by poor matching of the thermal expansion coefficients of both the package and substrate. However at moderately high temperatures of 400°C additional factors must be considered in packaging SAW temperature sensors. Surface effects such as chemical boundary reactions, crystal decomposition and metallisation dewetting can occur. Low temperature measurement can be limited by the dew point of the cavity gas. Generally high temperature SAW devices have been packaged primarily in air. However recent investigations suggest that operation at high temperatures is significantly influenced by the cavity gas. A trade off exists between the long term stability and performance of a SAW temperature in a high temperature environment [119].

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

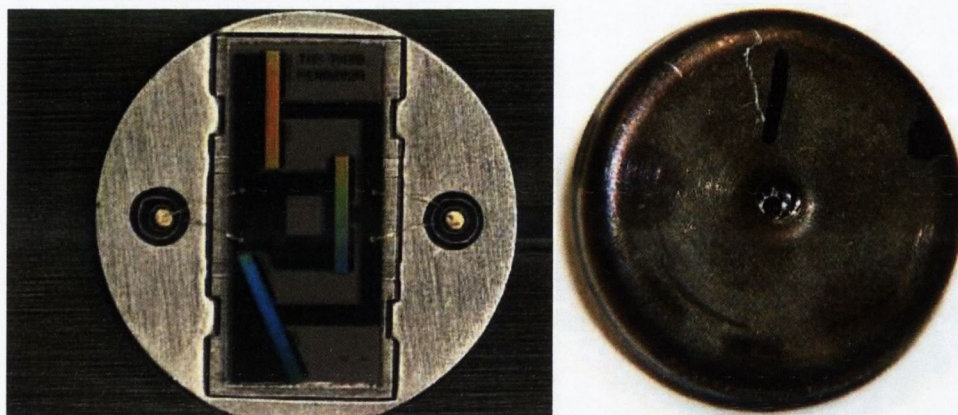


Figure 7.2: Differential SAW TPMS button sensor [78]

The most common measurand for physical measurements with SAWR components is pressure. Pressure sensors require a specialised packaging solution to generate a physical bias to act upon the SAW device from which a pressure can be inferred. Reported devices fall into two categories, the first case is the dimple package type [78]. The SAWR is encapsulated in a package, the package contains a machined dimple which is in contact with the underside of the SAWR. An external pressure will displace the dimple, deflecting the SAWR substrate and introducing a stress into the SAWR substrate. In the second case, the SAW device substrate acts as a diaphragm [120] and the pressure measurand directly deforms the substrate. Typically SAW pressure sensors use multiple resonators to provide differential frequency measurement and temperature compensation on one die, as shown in Figure 7.2. Usually pressure sensors are combined with additional packaging for a final assembly, For example, the Tire Pressure Monitoring System (TPMS) by Transense Technologies is based upon the dimple package which is incorporated into a tyre valve assembly.

Packaging should not negatively impact the performance of the SAWR sensor. The dimple package generates non-uniform stress fields in the propagation zone of the SAWR sensor. The stress biased SAW velocity will be varied across the propagation zone of the SAWR. This has been shown to generate higher order spurious responses in the S_{11} response of the SAWR which may be attributed to out of phase reflections occurring in the RG [121]. Packaging design should therefore minimise the generation of a non uniform stress distribution especially if the sensor is to be interrogated wirelessly. Recently an all quartz wafer level packaging of SAW sensors has been demonstrated for SAW pressure sensors using a SAWR fabricated a ST-Quartz. The pressure

7.2. COMMERCIAL SAW SENSOR PACKAGING

sensing resonator was fabricated directly onto a portion of the die which had been pre-fabricated to form a micro machined diaphragm suitable for measuring pressure [63]. Torque sensors with a differential SAWR torque sensor are currently available commercially. SAWR die are directly bonded to mechanically weakened shafts with post attachment encapsulation to protect and seal the sensor shown in Figure 7.3. In both cases the SAWR die is bonded to the shaft or the base of the package with an adhesive. While the adhesive is most likely an epoxy, exact details are unknown. Adhesives will be discussed in greater detail in Section 7.3.2.

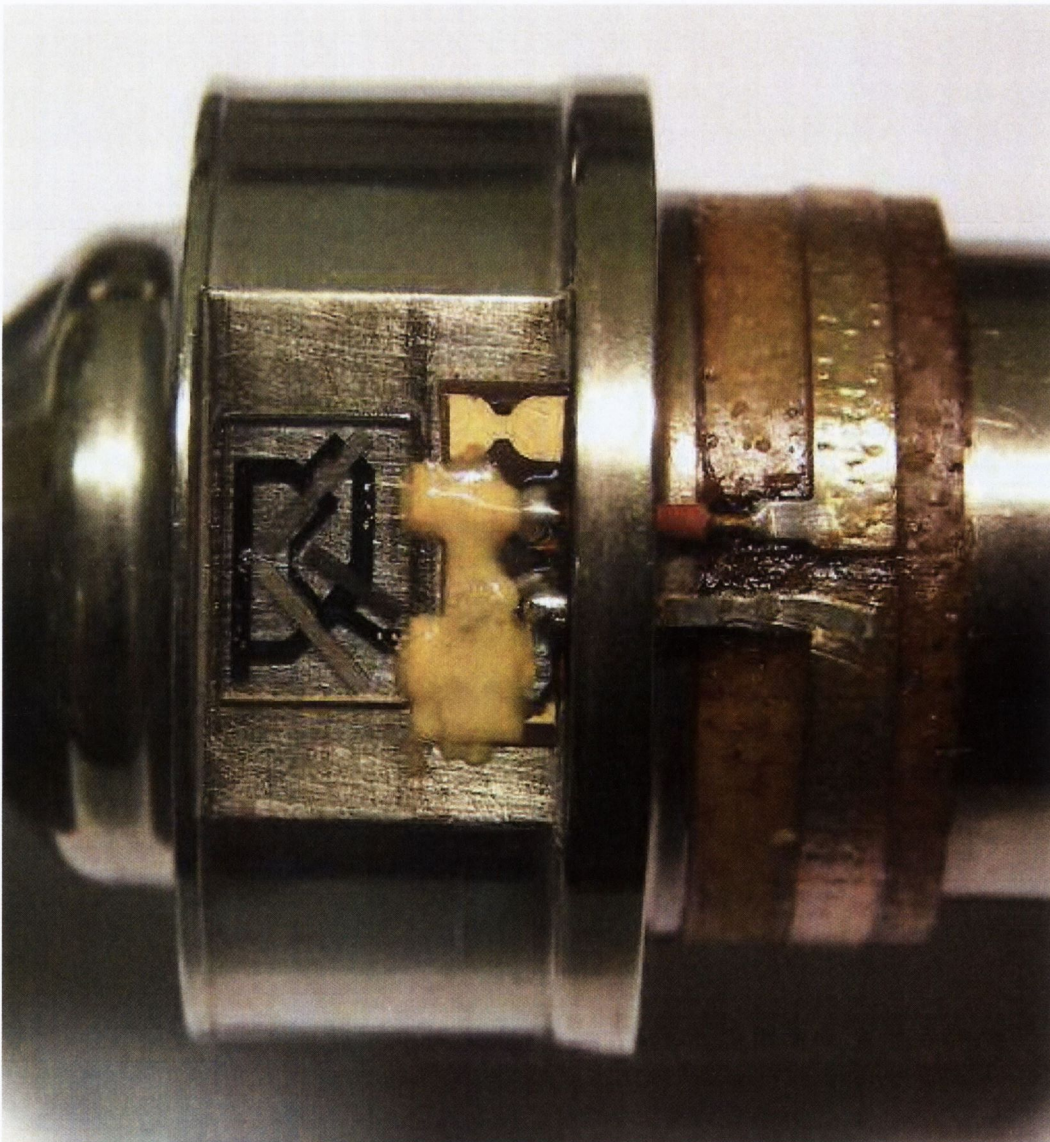


Figure 7.3: Directly bonded SAWR torque sensor for automotive applications [122]

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

Transense technologies in collaboration with Schott, a micro packaging manufacturer have developed a steel purpose built package for the house of SAWR torque sensor within a machined steel package with glass fritted electrical connections see Figure 7.4.



Figure 7.4: High elastic limit purpose built Transense and SCHOTT torque sensor and package consisting of three parts: a base, a ring and a cover [123]

7.3 Packaging of SAWR strain sensor

As discussed in Section 7.2 a sensor package is required to be application and measurand specific. For strain sensing a suitable package is required to meet the following requirements:

Hermetic Sealing of the SAWR: Sealing and isolation of the device from foreign particulates is a key requirement. Hermetic vacuum sealing of the devices may also slightly reduce the attenuation of the propagating SAW caused by mass loading due to air. The effects of acoustic losses are more prevalent in delay line devices. In resonators acoustic losses are dominated by propagation effects in the crystal which is dependent on substrate properties therefore improvements in sensor response due to hermetic sealing may be minimal [31].

Electrical Connections: Wire bonding techniques can be used to make electrical connections between the SAWR bond pads and package. I/O pins on the package can then be used to provide connections to additional PCB or antenna.

Provide interface between SAWR sensor and measurement area : The package must allow for strain biases to be transferred from the measurement area to the sensor without excessive shielding of the sensor from the strain field, thus retaining measurand sensitivity. Package pins should be oriented to avoid interference with the measurement zone

Matched Thermal Expansion: Ideally the thermal expansion of the package should be close to that of the sensor to avoid the generation of thermal stresses across the sensor operational temperature range.

Footprint: Package size should be minimised and not excessively larger than the die. Excessive footprint size may have a negative impact on the measurement zone.

The addition of a packaging will improve the S_{11} response of the SAWR compared to the silver paste connections used in section 6.1. For wireless measurements improved connections to the SAWR will increase the reliability of the wireless measurements and extended the readout distance. Sealing the package and isolating the SAWR will minimise the possibility of damage during handling and bonding.

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

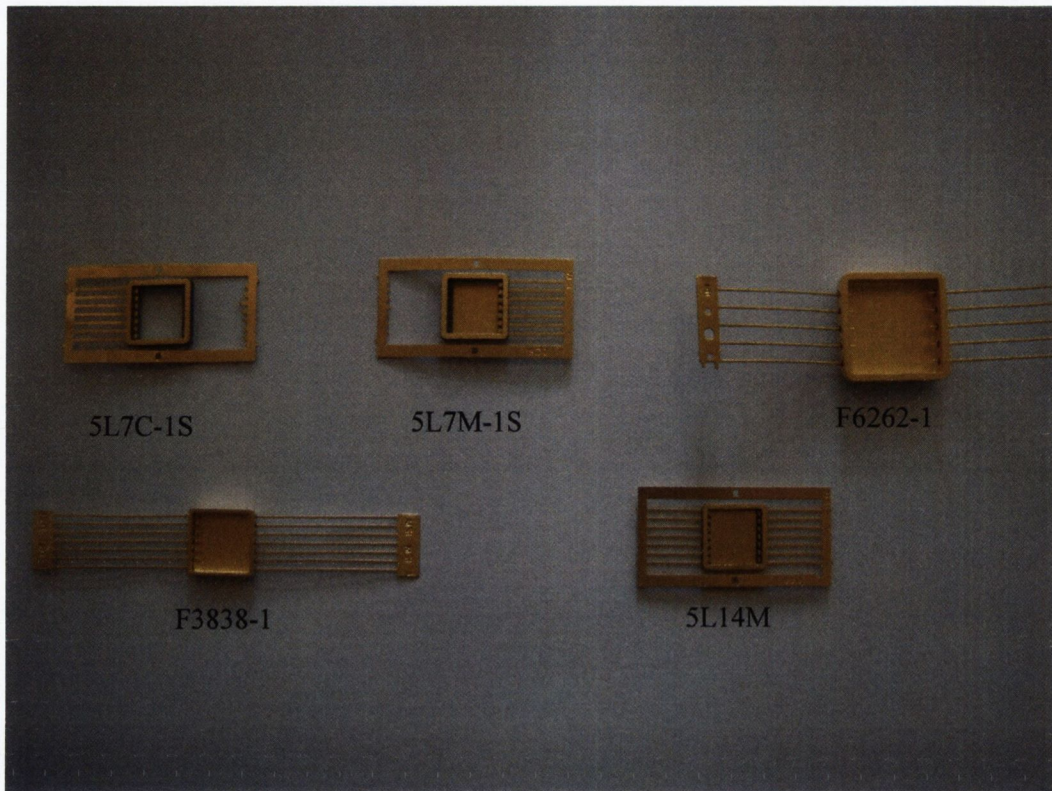


Figure 7.5: Packages selected for development of a packaged SAWR strain sensor.

7.3.1 Selection of Packaging for the SAWR

Development of a customised package was not feasible with the facilities available for this project. Set up costs required to commission a customised package with a commercial manufacturer were also prohibitive. As an alternative method packaging of the SAWR strain sensors was performed with standard off the shelf flat pack packages. Several package types were procured from the supplier Mini-Systems Electronic Packaging based in the United States [124]. The selected packages are shown in the Figure 7.5.

The packages consisted of sidewalls made from a combination of alumina/glass attached to a base material, or full metal packages made of kovar (ASTM-F15) with glass fritting isolating the I/O pins. All packages were sealed with kovar lids. The dimensions and a description of the packages selected can be found in Table 7.1. Kovar is a material traditionally used in electronic packages and has a Young's Modulus of 159 GPa and thermal expansion coefficient of $5.5 \times 10^{-6} K^{-1}$. While the thermal expan-

7.3. PACKAGING OF SAWR STRAIN SENSOR

sion of kovar is poorly matched to quartz ($5.5 \times 10^{-7} K^{-1}$) it is moderately better than that of conventional steel ($13 \times 10^{-6} K^{-1}$).

Package	Sidewall	Footprint	Height	Base Material
5L7C-1S	Alumina-Glass	$3.57mm^2$	2.54mm	Ceramic
5L7M-1S	Alumina-Glass	$3.57mm^2$	2.54mm	Kovar
5L14M	Alumina-Glass	$3.57mm^2$	1.52mm	Kovar
F3838-1	Metal	$3.66mm^2$	2.54mm	Kovar
F6262-1	Metal	$9.92mm^2$	4.19mm	Kovar

Table 7.1: Packages

7.3.2 Adhesives

An adhesive provides the mechanism by which stress and strain from the measurement zone is transferred to the SAWR strain sensor. An adhesive is defined as the substance capable of holding at least two surfaces together in a strong permanent manner. Modern adhesives are manufactured by compounding a base resin material with various fillers, pigments, stabilizers, plasticisers and other additives to form the desired end product. While the development of an adhesive optimised for SAWR strain sensors is outside the scope of this project an investigation into the suitability of commercially available adhesives is an appropriate step in the development of SAWR strain sensors.

To act as an adhesive for a SAWR strain sensor a suitable adhesive should have the following characteristics:

- They must flow like a liquid at some point during the course of the bond formation so to flow over the and *wet* the substrate they make contact with.
- They must harden from a liquid to a solid to carry sometimes continuous loads during the life cycle.
- They must transfer and distribute loads and not shield the sensor from the measurand.

No general theory of adhesion has been universally adopted. Adhesion is attributed to several forces acting simultaneously. Generally speaking adhesion is predominately

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

caused by two forces, adhesive and cohesive. Adhesive forces hold two materials together at their surfaces while cohesive forces occur internally within a material caused by intermolecular attraction between molecules of the same material. Failure of a bondline can occur due to adhesive and cohesive failure acting simultaneously or independently. An adhesive failure occurs when the adhesive interface between adherend and adhesive fails.

Cohesive failure typically occurs due to a stress fracture in the material and can be identified if a layer of adhesive remains on both of the adherend. A common cause of this failure is due to poor surface preparation and contaminants such as oil and grease causing weak bond lines resulting in the formation of stress concentrations. The bondline then fails with a combination of adhesive and cohesive failure identifiably as areas of adhesive remain on the underside of the packages.

The strength of an adhesive bond is determined by two factors. The shear strength of the bond, a measure of the holding strength of the bond and the peel strength which is the resistance of a bond line from being peeled away. Bond strengths can be decreased significantly if voids, cracks, air bubbles, inclusions or surface defects are present which can cause localised stress concentrations [125]. Thus the minimisation of stress in the adhesive layer is paramount to the success of the bond. The most common cause of stress formation in the bond line is due to the mismatch of the thermal expansion coefficients of the substrate or the adhesive. Solidification of the adhesive generally occurs at the glass transition temperature (T_g) and is typically above room temperature. Generally speaking, for good bond strength and creep resistance the T_g of the adhesive should be well above the maximum operating temperature. The requirement for a high cure temperature results in residual stresses being generated upon cooling as significant differences in the thermal expansion coefficients of substrates and adhesives can exist. For illustrative purposes, we can assume quartz has a linear thermal expansion coefficient of 0.5ppm/K [126] while epoxy adhesives have values between 40ppm/K and 200ppm/K . The adhesives chosen for this project are typically designed to have a thermal expansion coefficient close to that of constantan alloy (40ppm/K) [127], a material commonly used for foil resistive strain gauges. Thus upon cooling significant thermal stresses will be generated in the substrate material.

Additional stresses also occur due to the shrinkage of the adhesive during solidification as solvent evaporates during curing. Epoxy resins typically undergo 4 – 5% shrinkage as the solid polymerises and the adhesive occupies lower space than the liquid reactants. The combination of both shrinkage and thermal expansion can result in

7.3. PACKAGING OF SAWR STRAIN SENSOR

significant stress concentrations being formed post cure. This is evident in the variation between in f_r between on-wafer and bonded sensors. The disadvantage when using a foil gauge polymer adhesive on quartz is that the strain coupling between the stiff sensor substrate and the polymer adhesive is poor [91]. The M-Bond adhesives when used with foil resistive strain gauges demonstrate excellent strain coupling. However, when used with SAWR strain sensors a bonding mismatch occurs between the stiff SAWR strain sensors and the polymer adhesive causing a slight decrease in strain sensitivity. A creep effect in the sensor response can also be observed due to this mismatch.

7.3.3 Selection of adhesives

In this project, several adhesives were examined for their suitability to bond SAW strain sensors. The requirements for an adhesive in strain sensing applications are slightly different for structural bonding. For strain sensing the bondline must be rigid so to adhere the substrate yet demonstrate a flexibility which can transfer the strain measurement to the sensor. The cure temperatures of some adhesives makes them unsuitable for SAW components as they require high cure temperature ($300 > ^\circ\text{C}$) which may result in damage to the SAWR. The majority of testing was performed with commercial strain adhesives, due to their availability, price point and low toxicity.

7.3.3.1 Cyanoacrylate

A well known adhesive commonly known as "*superglue*". This thin film adhesive is solvent free and cures rapidly at room temperature. Cyanoacrylate adhesives can exhibit a shear strength of 13 MPa after ten minutes which increases over time. Unfortunately cyanoacrylates are thermoplastic and will creep on exposure to high temperature and stress. M-Bond 210 a commercial strain gauge cyanoacrylate adhesive was used in bare die testing, see section 6.5.

7.3.3.2 Epoxy resin adhesives

Epoxy adhesives are probably more versatile than cyanoacrylates. They bond well to many substances and cure at room temperature or at elevated temperatures. Commercial epoxy resins are composed primarily of an epoxy resin, a curing agent, and other modifiers and additives. In this project two part epoxy resins were used. The first part is an adhesive resin, the second is a curing agent. Pot life once mixed is signifi-

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

cantly lower than M-Bond 200 ranging from 10 minutes for AE-10 to three weeks for M-Bond 610.

7.3.3.3 Addition of fillers to epoxy resin adhesives

The mismatch in the thermal expansion coefficient is a serious issue in the bonding of SAWR strain sensors with epoxy resin adhesives. In order to address this issue and improve the bonding characteristics of the adhesive, *fillers* were added to the epoxy. A filler is a relatively non adhesive material added to improve properties of the adhesive. By judicious selection of the filler the properties of the adhesive can be altered: thermal expansion coefficients and shrinkage effects can be significantly changed. An aluminium filled epoxy adhesive, EP-950 Gray was selected to assess the suitability of structural adhesives in SAWR strain sensor design. This is an aluminium filled one part rubber modified adhesive [128] with a minimum cure temperature of 113°, primarily used for structural bonding.

7.3.3.4 Adhesive used for this project

The properties of the various adhesives are shown in Table 7.2. Performance can vary significantly between adhesives. Generally an adhesive is defined as either structural or nonstructural depending on the shear strength of the adhesive and peel strength of the bondline. Commercial strain gauges adhesives however, are not evaluated on shear strength or peel strength but as a function of elongation capabilities of the adhesive. The selected adhesives transfer strain with varying degrees of capability which is dependant on temperature. For strain gauges the elongation capabilities are primarily a function of the shear strength of the adhesive bond. Many strain gauge adhesives will operate to elongations of 50,000 $\mu\epsilon$ while still being quite easily peeled from the surface [107]. The commercial adhesives performed with varying degrees of success see section 6.4.

7.3. PACKAGING OF SAWR STRAIN SENSOR

Adhesive	Cure Time	Cure Temp (°C)	Temp Range (°C)	Elongation Capabilities
M-Bond 200	2mins	20	-30-60	2%
M-Bond 600	2hrs	125	-269-175	3%
M-Bond 610	2hrs	150	-269-175	3%
M-Bond AE10	24hrs	20	-269-95	6-10%
M-Bond AE15	24hrs	60	-269-95	10-15%
EP 950	45mins	135	-40-175	2%

Table 7.2: Adhesives used in calibration of SAWR strain sensors

7.3.4 Completed packaged SAWR strain sensors

A total of five packages (see Section 7.3.1) were selected for the development of a packaged SAWR strain sensor. The influence of bonding and packaging on the performance of the SAWR strain sensor can then be compared to bare die results, and the effects quantified. Packaging was performed at two sites, the initial packaging attempts were carried out in the Tyndall Institute as part of a National Access Program Grant. Subsequent work was carried out at the Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN) Trinity College Dublin.

In the Tyndall facilities the process flow involved the SAWR strain sensors being bonded to the packages using Vishay M-Bond 610. The dies were clamped in place with a special fixture. A machined steel holder was placed over the bonding pads of the die and held in place with an EAS sealing clip, model 3711 [129]. The clips are typically used for lid/package sealing operations similar to those used for clamping foil resistive strain gauges. The clip delivers a minimum pressure of 3.5kPa. The clamped sensors were placed in an oven at 150°C for a period of two hours. The clamping fixtures were then removed and the sensors were post cured at 160°C for a duration of two hours.

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

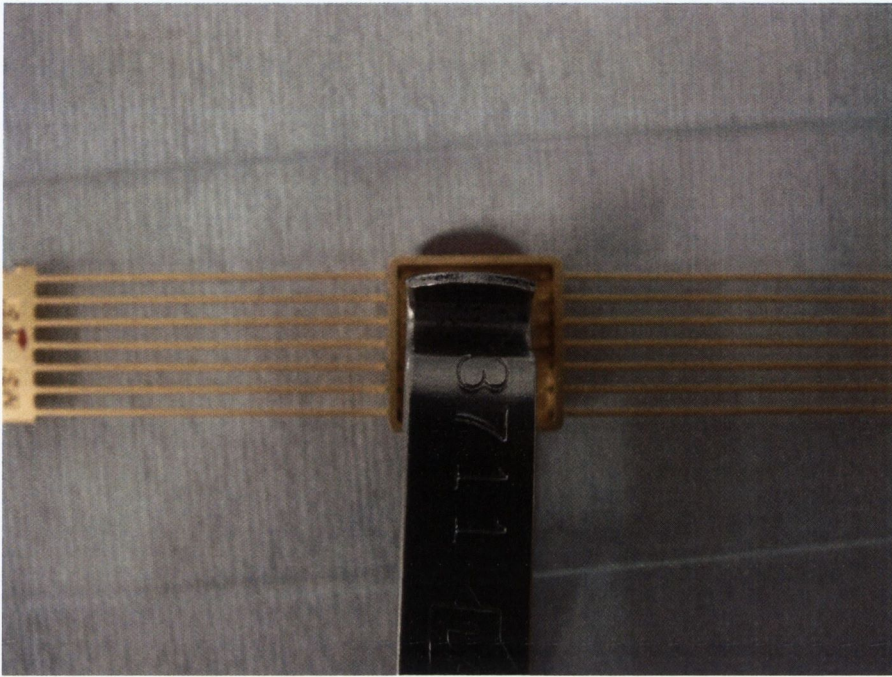


Figure 7.6: SAWR package clamped prior to elevated temperature cure

Post curing, the packages were allowed to cool to room temperature. Electrical connections were made between bonding pads of the die and the I/O pins of the package with an ultrasonic wedge bonder and 25 micron aluminium wire. The lids of the packages were hermetically sealed using glue. An unsealed packaged sensor is shown in Figure 7.7. The completed sealed sensor is shown in Figure 7.8

7.3. PACKAGING OF SAWR STRAIN SENSOR

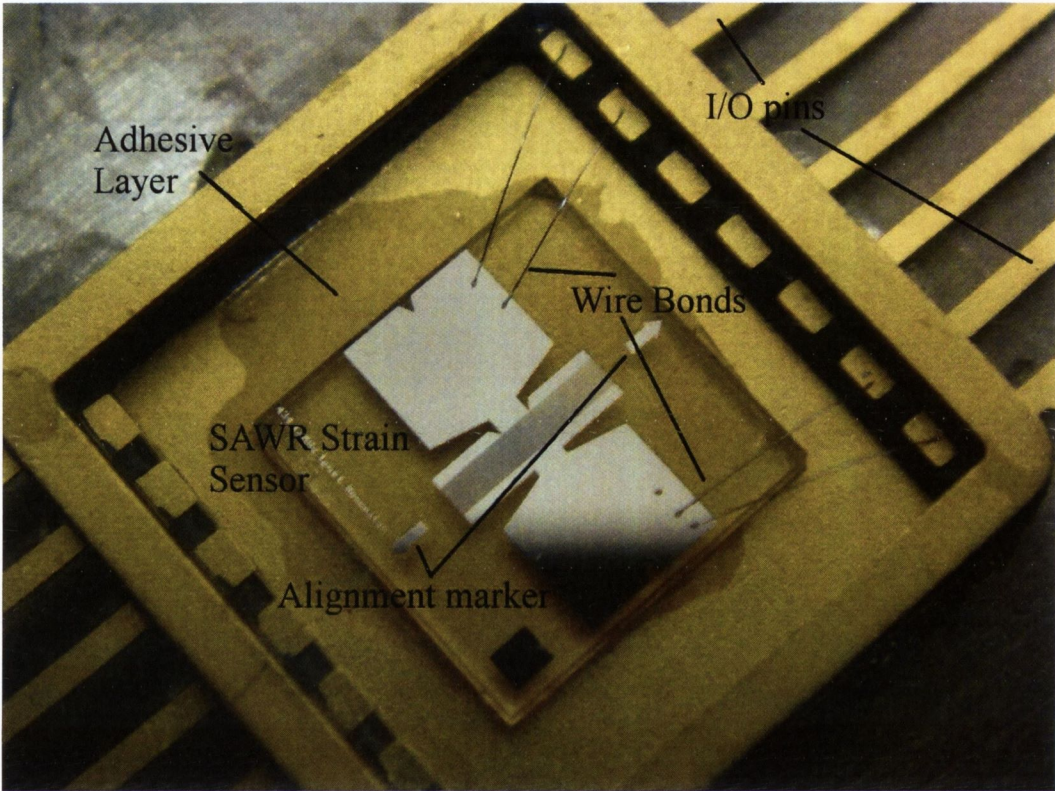


Figure 7.7: SAWR strain sensor bonded in a package with wire bonding to the I/O pins prior to sealing with lid

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

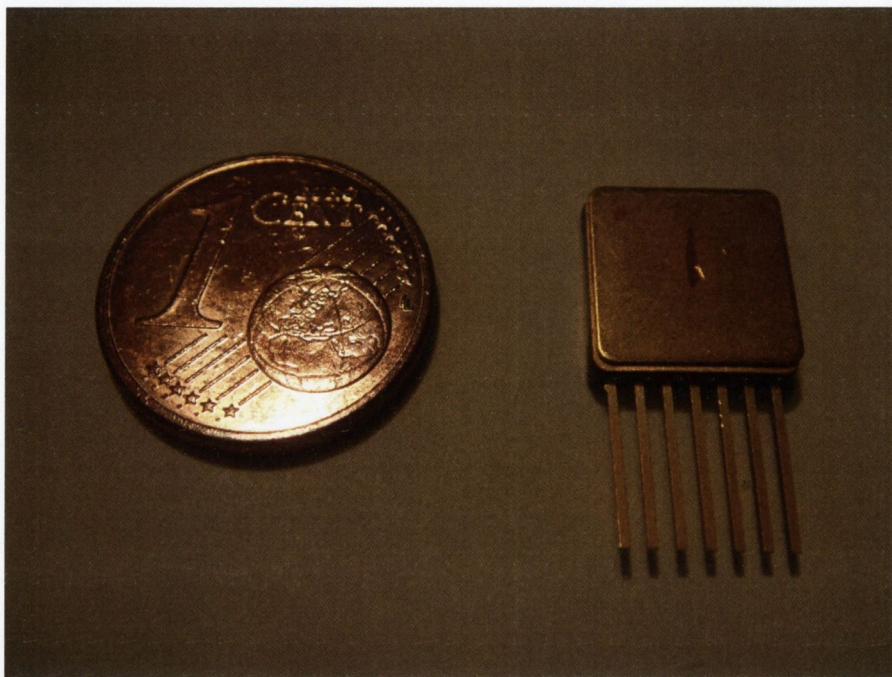


Figure 7.8: Completed packaged SAWR strain sensor

Within the CRANN facilities additional packaging was performed, this included cleaning of the packages with ion-beam cleaning in an argon environment at 500eV for 5 minutes. SAWR die were then bonded to the interior of the package using M-Bond 610, AE15, H-Cement and EP-950 adhesive.

Unfortunately the M-Bond 610 packaged sensors failed due to misalignment of the die during clamping causing the clamp to damage the IDT. This was a disappointing result and was not possible to rectify within the time scale of the project. Test packages in which dies were bonded with H-Cement and EP950 underwent extreme shifts in f_r resulting in the sensor operating outside the ISM band. While shifts in f_r due to bonding process were expected the magnitude (4 MHz for EP-950) was surprising and resulted in the response being degraded and becoming unsuitable for wireless sensing.

7.4 Calibration of packaged sensors

The addition of packaging may alter the performance of the SAWR strain sensor. The electrical S_{11} response may be sensitive to the inclusion of packaging and additional connectors, antenna and PCB's. The SAWR strain sensitivity may be diminished by additional layers of adhesive and packaging. The adhesion of the dies will also induce

7.4. CALIBRATION OF PACKAGED SENSORS

a stress into the material resulting in a shift of the bare die frequency measurements. This is attributed to a residual thermal stress resulting from the bonding processes. Bondline thickness will also have an effect on the residual stresses generated [61]. The bondline thickness will also vary depending on the type of adhesive used, Ferri et al measured the bondline thickness for M-Bond 600 at $6 - 7\mu\text{m}$ and M-Bond 200 at $20\text{-}30\mu\text{m}$ [130]. The performance of the packaged sensors vary depending on the glues and cure cycle used. All die were bonded in the packages with M-Bond 610 at an elevated cure of 150°C . The packaged sensors initially were bonded firstly to the beam with M-Bond 610 cured at 150°C . SAWR sensors packaged with F3838-1 demonstrated a failure mechanism shown in Figure 7.9. Initially the packaged sensor demonstrated moderately good strain coupling. However after several cycles the response degraded and a mixture of cohesive and adhesive failure occurred in the external package bond. A second package was then mounted on the beam with additional surface cleaning to the underside of the package with an isopropyl cleaner and M-Prep Neutraliser and Conditioner. While this improved the performance moderately, failure occurred after several cycles. As a result all packaged sensor calibration test required the underside of the package to be cleaned and prepared. Calibration data presented within this chapter is based upon the sensor being cycled through the calibration procedure three times.

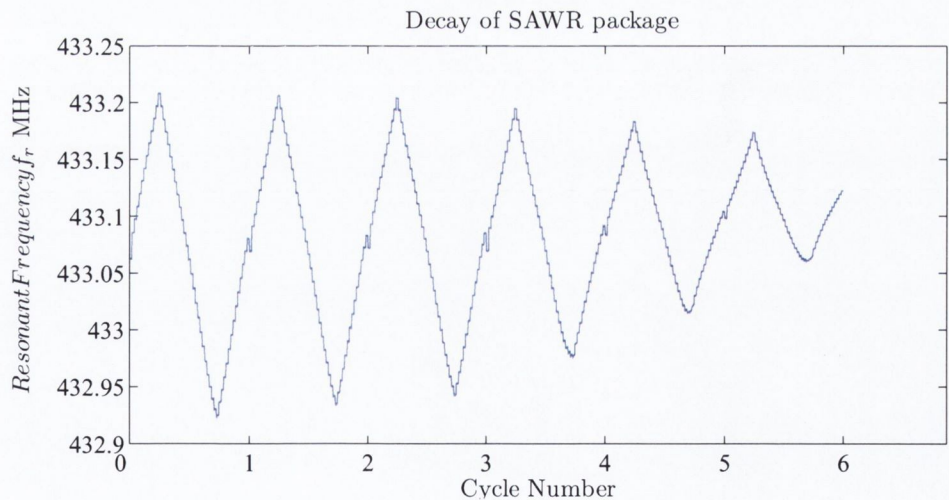


Figure 7.9: Packaged SAWR strain sensor showing degrading response over cycles

In this section, calibration data presented is based upon experimental work performed using packaged sensors from Tyndall. The sensors were calibrated wirelessly using the same PCB and antenna configurations used in bare die testing. For consistency M-bond 610 was used for the adhesive layer between package and test beam with

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

a cure at a temperature lower original cure temperature of 150°C. This was to prevent damage to the internal package bondlines due to additional thermal stresses.

7.4.1 Calibration results for 5L7C-1S ceramic base SAWR strain sensor

A 434.42 MHz ceramic package sensor was bonded to the beam using M-Bond 610 and a cure cycle of 2.5 hours clamped, 3 hours unclamped, at a temperature of 140°C. Packaging of the sensor and subsequent mounting caused a reduction in f_r of over 1.5 MHz moving the SAWR sensor outside the ISM 434 MHz band. However, the working bandwidth of the interrogator was sufficient to interrogate the mounted sensor. Before testing, the bonded package sensor was allowed to post cure for a period of over 48 hours. The three cycle calibration curve is shown in Figure 7.10 S_{sen} for loading and unloading are shown in Table 7.3

Load.Tens	Unoad.Tension	Load.Comp	Unload.Comp
-110.43 ± 2.86	-114.81 ± 3.39	-134.67 ± 6.51	-141.29 ± 11.61

Table 7.3: 5L7C-1S strain sensitivities (Hz/μϵ) at 20°C

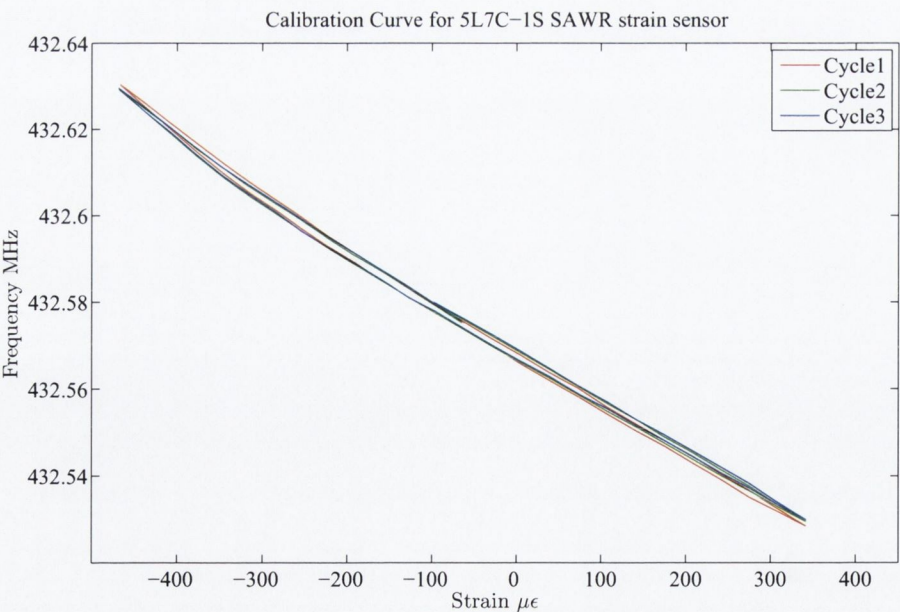


Figure 7.10: Calibration curves for 5L7C-1S SAWR strain sensor at 20°C

7.4. CALIBRATION OF PACKAGED SENSORS

7.4.1.1 Elevated temperature calibration results for 5L7C-1S SAWR strain sensor

The 5L7C-1S ceramic base SAWR strain sensor was subjected to the elevated temperature testing. The calibration data for elevated temperature tests is shown in Table 7.6.

Temp.	S_{sen}	Best Fit Line Equation	R^2	FS Hys-teresis %
20°	-124.23 ± 4.88	$f = -119.62e^6 \times \epsilon + 432.568e^6$	0.9999	2.93
40°	-125.10 ± 7.23	$f = -119.47e^6 \times \epsilon + 432.541e^6$	0.9999	2.45
60°	-130.81 ± 7.89	$f = -125.41e^6 \times \epsilon + 432.526e^6$	0.9999	3.53
80°	-133.17 ± 8.04	$f = -128.70e^6 \times \epsilon + 432.488e^6$	0.9998	4.01
90°	-132.58 ± 8.41	$f = -129.19e^6 \times \epsilon + 433.458e^6$	0.9999	4.23

Table 7.4: 5L7C-1S strain sensitivities for elevated temperature calibration

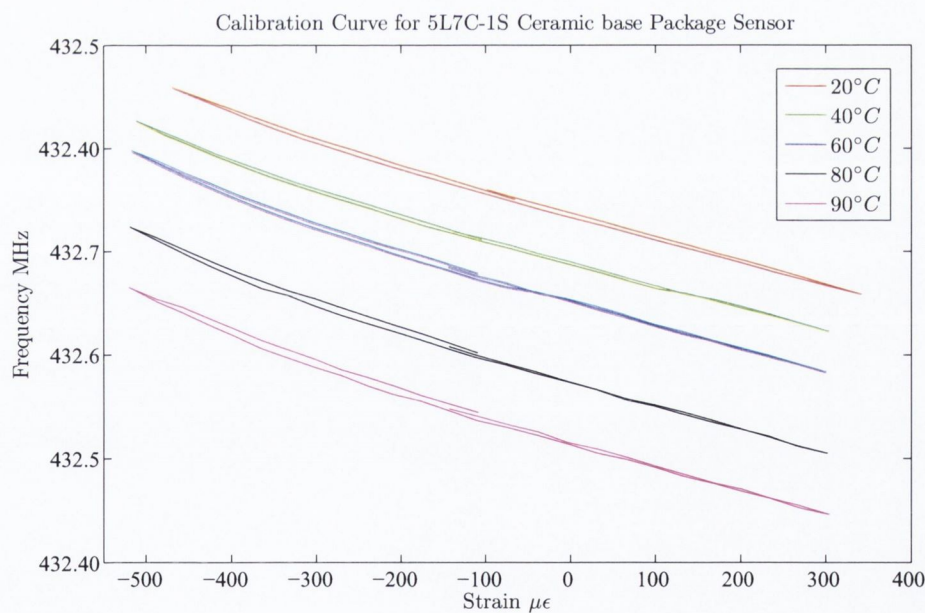


Figure 7.11: Elevated temperature calibration curves for 5L7C-1S SAWR strain sensor

Elevated temperature calibration curves are shown in Figure 7.11, it is clear that the thermal drift in the packaged sensor is substantial. The profile and sensitivity of the sensor remain consistent across the complete temperature range. Hysteresis levels

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

appear to be lower in tension, at the end of each calibration cycle the lower tensile strain sensitivity causes the f_r to be lower than the value measured at the beginning of the cycle.

7.4.2 Calibration results for 5L7M-1S kovar base SAWR strain sensor

The base material of the 5L7M-1S package is made from kovar and has identical dimensions to the 5L7C-1S package. The SAWR sensor was bonded to the beam with a cure of 125°C for a period of 2 hours clamped, 2 hours unclamped. Post cure, the sensor was allowed to sit for a period of 48 hours prior to the commencement of any testing. S_{11} testing found the f_r of the bonded packaged SAWR sensor to be 434.2932 MHz which was a reduction of 0.127 MHz. The S_{sen} of the sensor for loading and unloading is shown in Table 7.5, while the calibration curves are shown in Figure 7.12.

Load.Tens	Unoad.Tension	Load.Comp	Unload.Comp
-304.05 ± 11.39	-318.98 ± 10.14	-310.70 ± 11.84	-331.38 ± 18.47

Table 7.5: 5L7M-1S strain sensitivities (Hz/μϵ) at 20°C

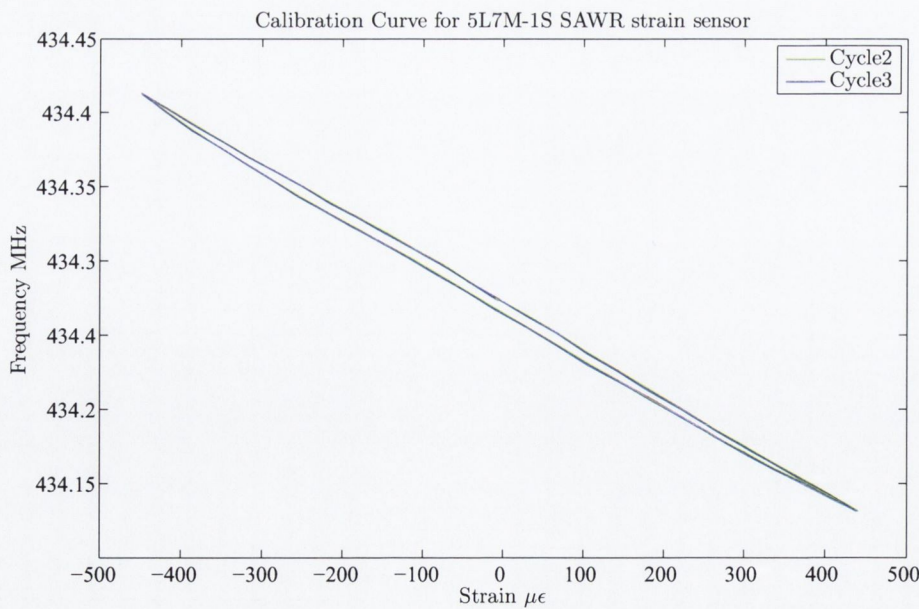


Figure 7.12: Calibration Curves for 5L7M-1S SAWR strain sensor at 20°C

7.4. CALIBRATION OF PACKAGED SENSORS

7.4.2.1 Elevated temperature calibration results for 5L7M-1S SAWR strain sensor

The 5L7M-1S kovar base SAWR strain sensor was subjected to the elevated temperature testing. The calibration data for elevated temperature tests is shown in Table 7.5.

Temp.	S_{sen}	Best Fit Line Equation	R^2	FS Hys- teresis %
20°	-316.16 ± 6.72	$f = -314.78e^6 \times \varepsilon + 434.269e^6$	0.9999	2.62
40°	$-317.59 \pm 5.82f$	$f = -316.36e^6 \times \varepsilon + 434.272e^6$	0.9999	2.43
60°	-319.03 ± 6.30	$f = -317.84e^6 \times \varepsilon + 434.269e^6$	0.9999	2.62
80°	-319.33 ± 7.42	$f = -318.33e^6 \times \varepsilon + 432.261e^6$	0.9999	3.15
110°	-302.58 ± 8.41	$f = -300.10e^6 \times \varepsilon + 434.237e^6$	0.9999	6.45

Table 7.6: 5L7M-1S strain sensitivities for elevated temperature calibration

The calibration curves for the elevated temperature calibration tests are shown in Figure 7.13. Strain sensitivities and hysteresis values are broadly consistant over the temperature range 20°C - 80°C. In the temperature range 80°C - 110°C strain sensitivities decreases by 7% and full scale hystereses increases by 50%.

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

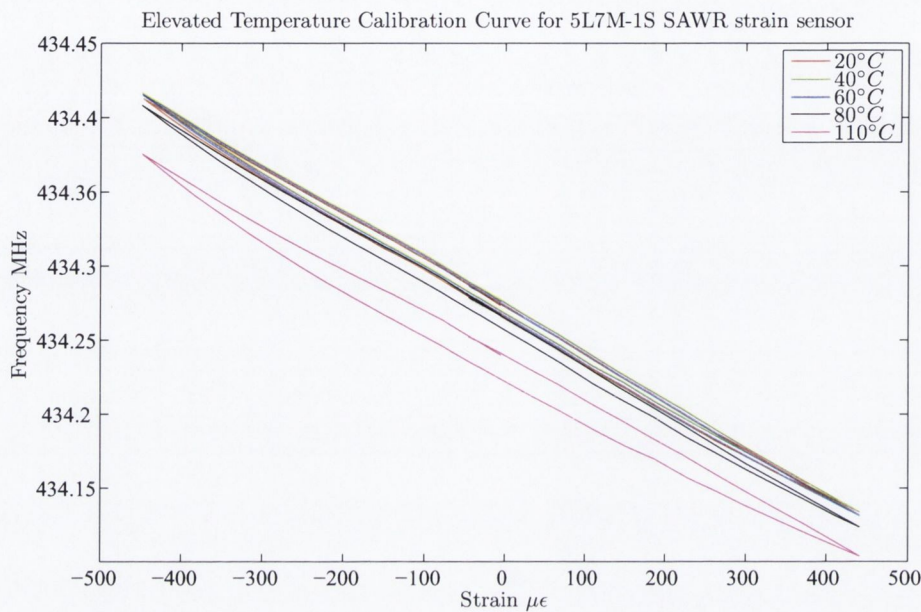


Figure 7.13: Elevated Temperature Calibration Curves for 5L7M-1S SAWR strain sensor

7.4.3 Calibration results for 5L14M SAWR strain sensor

The 5L14M kovar base SAWR strain sensor was subjected to the calibration testing. A 434.42MHz SAWR was bonded internally in the package with M-Bond 610 and a cure cycle that was slightly modified to be incrementally raised to 120°C in two steps, the first step raised the oven to 90°C for a period of the twenty minutes then to 125°C. The cure cycle for this package was 2.5 hours at 125°C clamped and 2.5 hours unclamped at 125°C. The staggered cure cycle was implemented to avoid thermal shock in the adhesive which is known to cause excessive creep to occur in foil gauges. The bonded sensor was then allowed to cool to ambient over an hour and then allowed to sit for a period of 24 hours. The packaged sensor underwent a shift of f_r of 0.2 MHz due to bonding of the package and an additional 0.6 MHz due to adhesion of the package to the beam. The S_{sen} for the 5L14M SAWR strain are shown in Table 7.7.

Load.Tens	Unoad.Tension	Load.Comp	Unload.Comp
-448.39 ± 9.34	-448.13 ± 7.41	-433.34 ± 5.36	-437.48 ± 6.92

Table 7.7: 5L14M strain sensitivities ($Hz/\mu\epsilon$) at 20°C

The calibration curves for a 5L14M SAWR strain sensor are shown in Figure 7.14.

7.4. CALIBRATION OF PACKAGED SENSORS

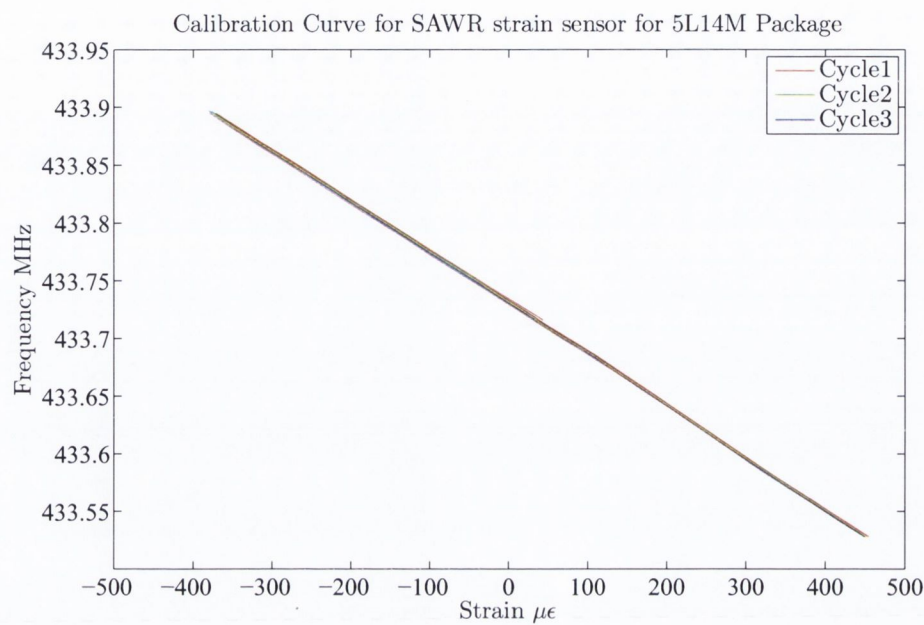


Figure 7.14: Calibration curves for 5L14M SAWR strain sensor at 20°C

7.4.3.1 Elevated temperature calibration results for 5L14M SAWR strain sensor

The elevated temperature calibration curves for the 5L14M packaged sensor are shown in Figure 7.15. Table 7.8 contains the results for the elevated temperature tests.

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

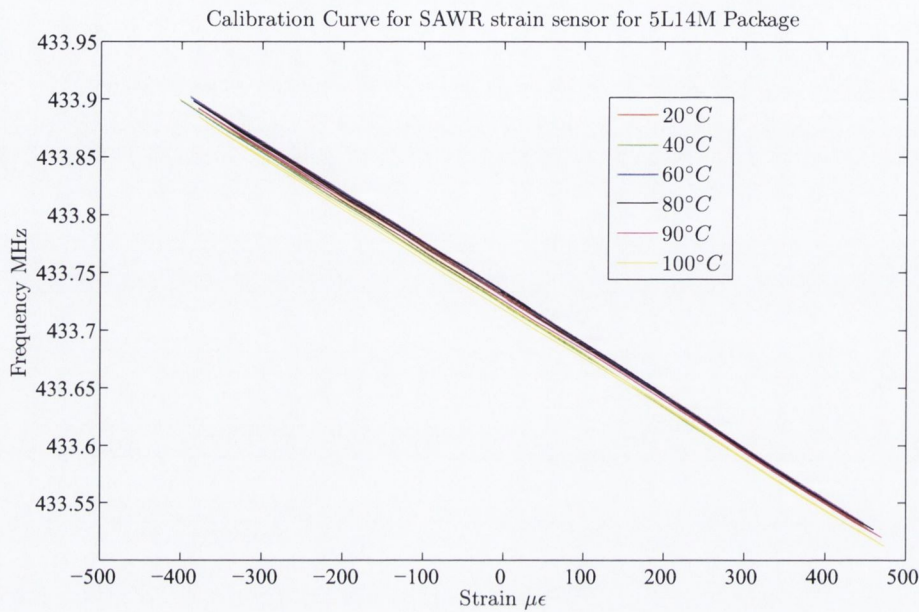


Figure 7.15: Elevated temperature calibration curves for 5L14M SAWR strain sensor

Temp.	S_{sen}	Best Fit Line Equation	R^2	FS Hys-teresis %
20°	-442.29 ± 4.16	$f = -442.75e^6 \times \epsilon + 433.729e^6$	0.9999	0.75
40°	-442.65 ± 4.21	$f = -443.36e^6 \times \epsilon + 433.723e^6$	0.9999	0.67
60°	-430.81 ± 7.89	$f = -440.70e^6 \times \epsilon + 432.731e^6$	0.9999	0.71
70°	-439.11 ± 4.21	$f = -438.02e^6 \times \epsilon + 433.729e^6$	0.9999	0.76
80°	-438.91 ± 4.83	$f = -439.90e^6 \times \epsilon + 433.730e^6$	0.9999	0.93
90°	-437.29 ± 4.98	$f = -437.46e^6 \times \epsilon + 433.726e^6$	0.9999	0.88
100°	-439.28 ± 4.84	$f = -435.51e^6 \times \epsilon + 433.719e^6$	0.9999	0.91

Table 7.8: 5L14M SAWR strain sensitivities for elevated temperature calibration

In Figure 7.16 the apparent strain due to thermal biases is plotted, the inflection in the thermal profile is caused by the turnover temperature of the substrate at approximately 60°C. This is lower than the bare die results (see Figure 6.3). This is most likely due to thermal stresses from the package and bonding processes.

7.4. CALIBRATION OF PACKAGED SENSORS

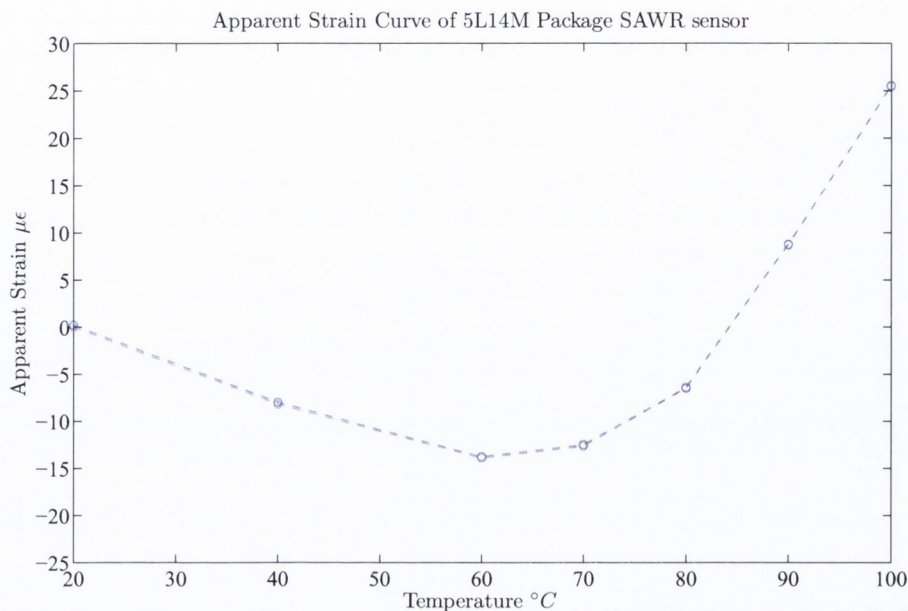


Figure 7.16: Apparent Strain Curve for 5L14M SAWR Strain sensor

7.4.3.2 Long term sensitivity stability of 5L14M SAWR strain sensor

The calibrated SAWR strain sensors were placed into a continues cycling calibration to determine the degradation of the sensors due to continuous cycling. The sensors was cycled to $\pm 300\mu\epsilon$ for $\approx 13,500$ calibration runs. The 5L7M-1S pacakge was also tested however the S_{sen} varied during the testing, the full scale f_r underwent also under went significant variation.

Negligible loss in S_{sen} was measured and hysteresis levels and full scale values remained constant for the complete duration of the testing over 5 days.

The stability of the bondline of M-Bond 610 adhesive layer shows promise for long term installations.

7.4.4 Differential SAWR strain sensor

The F6262-1 package is similar to the F3838-1 package but with a large cavity. SAWR sensors operated with an on wafer value of 433.42 MHz and 434.42 MHz were bonded in the F6262-1 package using M-Bond 610. The sensors were oriented so one SAWR would be sensitive to longitudinal strains the other mounted perpendicularly to be sensitive to transverse strains. External bondlines with M-Bond 610 demonstrated a sim-

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

ilar failure mechanism to the F3838-1 package. As a result several different methods of attachment were attempted:

EP-950: This adhesive resulted in extreme shift in f_r , the magnitude of the SAWR response became degraded, and substantial parasitic modes were introduced into the SAWR response.

Conventional Welding Welding introduced massive thermal gradients into the pack- age which critically damaged the SAWR strain sensors inside.

Soldering Package temperatures were lower than welding however not sufficiently lower to avoid damage to the internal SAWR.

A somewhat satisfactory bondline was formed with AE-15, the S_{11} plot is shown in Figure 7.17. The sensors operate outside the ISM band and the working range of the interrogator. The response has been shifted over 2 MHz from the on wafer values. Furthermore, the frequency response is less defined and the transverse response has been incorporated in the main resonant mode, thus suggesting permanent damage to the SAWR.

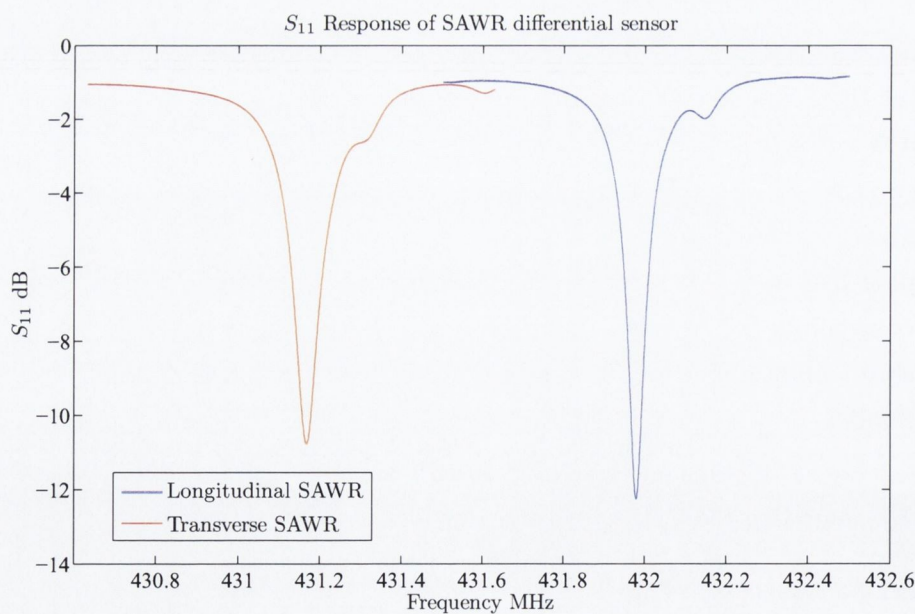


Figure 7.17: S_{11} Response of a Differential SAWR strain sensor at 20°C

The bonded SAWR sensors were connected to two separate PCB’s and interrogated using a VNA. The calibration curves are shown are each SAWR strain sensor is shown

7.4. CALIBRATION OF PACKAGED SENSORS

in Figure 7.18. Unfortunately it was not feasible to perform elevated temperatures due to the possibility of damage to the VNA so test temperautres were limited to $\approx 20^{\circ}\text{C}$.

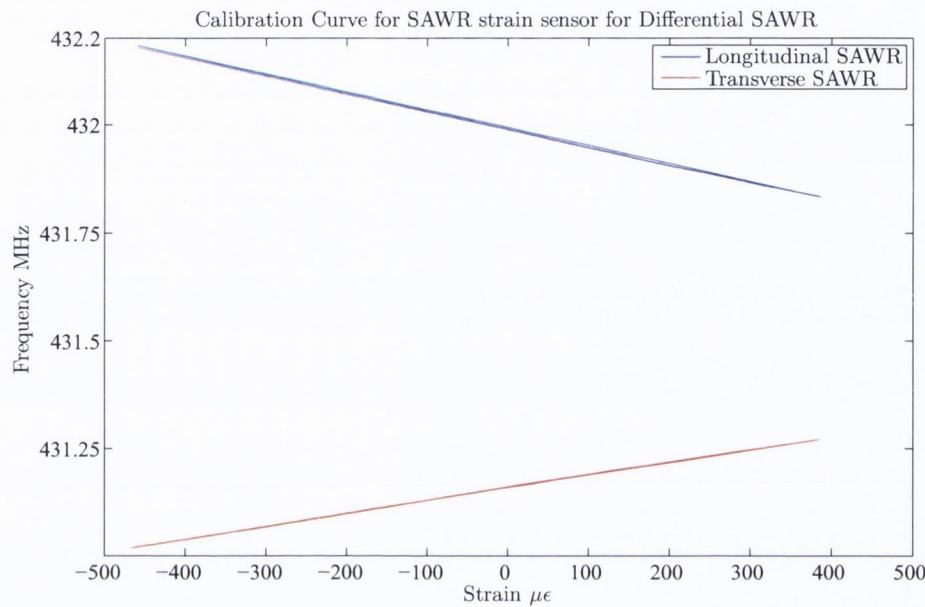


Figure 7.18: S_{11} Response of a differential SAWR strain sensor at 20°C

The total measured response from the Differential SAWR strain sensor is defined as:

$$\Delta f_{diff} = f_l - f_t \tag{7.4.1}$$

where Δf_{diff} is the total response of the differential SAWR strain which is a function of the resonant frequency of the longitudinal and transversely aligned SAWR f_l and f_t respectively.

Sensor	S_{sen}	FS Hysteresis %
Longitudinal	-408.18 ± 4.26	1.16
Transverse	-298.90 ± 3.81	0.97
Differential	-709.91 ± 3.53	0.87

Table 7.9: Differential SAWR strain sensitivities at 20°

The performance of the final calibration sensor is shown in Figure 7.19.

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

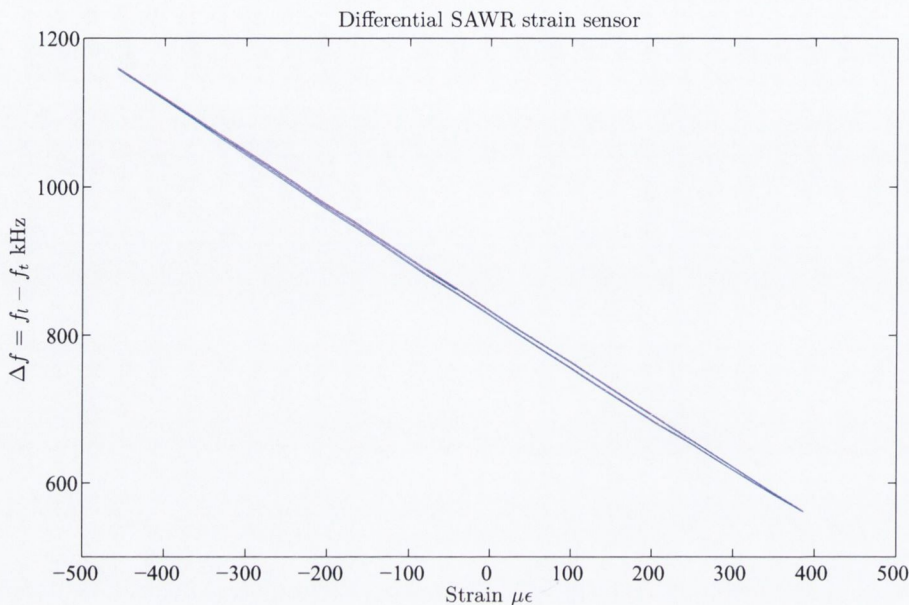


Figure 7.19: Calibration curve for a differential SAWR strain sensor at 20°C

7.5 Evaluation of the packaged SAWR sensor

The role of packaging was to provide a hermetic environment to protect the SAWR strain sensor from environmental damage and increase the robustness of the sensor. As a fragile component the SAWR strain sensor requires packaging. However it is crucial packaging doesn't isolate the sensor from the strain field it is measuring. Several key points can be made in the evaluation of the packaging of the SAWR strain sensor.

- All sensors were calibrated against longitudinal strains. The S_{sen} of the packaged sensors were found to be negative, therefore a compressive strain will result in an increase in f_r and a tensile strain has the opposite effect. However there is a marked difference between the packages in the magnitude of the S_{sen} . Undoubtedly the 5L14M packaged sensor offers the best overall strain sensitivity at -442 Hz/ $\mu\epsilon$ which is a reduction of 15 % from the bare die sensitivity (see Table 6.11). The package effectively creates a composite body consisting of the calibration beam, the adhesive layers, package base and SAWR, resulting in a completely heterogeneous interface between the sensor and the strain field. The strain transfer across the package to the sensor itself will then be influenced highly by both packaging and cure conditions applied to the adhesive. This can be seen in the el-

7.5. EVALUATION OF THE PACKAGED SAWR SENSOR

evated temperature performance of the 5L7M-1S compared to the 5L7C-1S. The strain sensitivity and thermal stability of the metal base package is far superior to that of the ceramic base. There is scope, therefore, for additional packaging optimisation.

- It is apparent that curing stresses can influence greatly the performance of the packaged SAWR strain sensor. Bonding a packaged SAWR sensor and maintaining the f_r within the ISM band appears to be highly dependent on the adhesive choice and the cure conditions. Curing stresses are well known to be significant in epoxy systems, particularly in structural applications. In bare die testing SAWR remained within the ISM bandwidth. It is reasonable to assume that bonding of the package is introducing additional stresses which are transferring to the SAWR. There is a possibility for optimisation of both the cure temperature and clamping forces.
- The S_{sen} of the packaged sensors shows slightly different behaviour in tension than in compression. As with the bare die tests, the results suggest that this remains an adhesive issue rather than a characteristic of the sensor. As shown in Table 7.8, temperature stability, S_{sen} , full scale hysteresis the residual stress generated are all interrelated and can indicate the success of a bondline.
- The effects of packaging can have a significant influence on the thermal response of the SAWR sensor. Thermal drift in the sensor response becomes extreme for the ceramic based packages, probably due to the thermal mismatch in the package causing additional stresses to be generated which overwhelm the natural behaviour of the quartz crystal. No turnover behaviour can be observed within the expected range for the ceramic base package. For the 5L7M-1S package the thermal profile is similar to the bare die performance with the turnover point $\approx 40^\circ\text{C}$. In Figure 7.16 the apparent strain curve for the 5L14M is shown. The turnover temperature is reduced to the 60°C the curve shows more similarity to the natural unbonded SAWR behaviour (see Figure 6.3). Before and after the turnover point the apparent strain due to temperature behaves linearly; however after the turnover temperature the sensitivity to temperature increases. In the temperature range $20^\circ\text{C} - 60^\circ\text{C}$ the apparent strain is $\approx 0.25\mu\epsilon/^\circ\text{C}$. This is above the turnover temperature however the apparent strain response is $\approx 1.15\mu\epsilon/^\circ\text{C}$.

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

- It is unfortunate that the residual stress formed during bonding caused the SAWR differential strain sensor to operate outside of the ISM band and the operational range of the interrogator. It should be noted, however, that a S_{11} measurement was performed 24 hours prior to the commencement of the tests and both sensors were operating with the ISM band. After an additional 24 hours the sensors had been shifted to their final frequency which suggests that additional curing effects are occurring over time, possibly strength hardening of the adhesive, shrinkage strain or indeed hygroscopic stress [131]. The combination of package and adhesive could be controlled to a greater extent to ensure the packaged sensor remains within the ISM band. The overall strain sensitivity becomes the sum of the S_{sen} for the longitudinal and transverse strain sensor. The strain sensitivity of the die is a function of the individual sensors performance.
- Post cure cycling can improve the temperature response of the stresses introduced into the sensors. In experimental testing of certain epoxy laminates a temperature can be determined in which the material shows no stress effects due to the adhesive. This is usually due to the thermal expansion coefficients causing the material to harmonise to the conditions at which cure occurred. This should be close to the cure temperature. Elevated testing of the die to the cure temperature failed to return the die to on wafer values or to the post package attachment. In fact such temperature gradients resulted in the sensor performance degrading. This highlights the differences between a strain gauge and structural adhesive.
- The long term stability of the 5L14M packaged sensor was tested to $\pm 300\mu\epsilon$ for 13,500 continuous cycles. The 5L14M package performed exceptionally well with little to no reduction in the S_{sen} . In future work accelerated life testing could be used to determine the number of cycles to failure.

7.6 Dynamic performance of the system

In chapter 7 the strain sensitivity of a packaged SAWR strain sensor was determined at a range of temperatures. In practice however, strain fields will vary dynamically. The ability of a sensor to measure dynamic measurand is often limited by the first order time constant of the sensor. However for a SAWR strain dynamic measurement is currently limited by the update rate of the interrogation equipment. A single measurement of the SAWR sensor requires several interrogation pulses that excite the

7.6. DYNAMIC PERFORMANCE OF THE SYSTEM

SAWR to different levels. The interrogator calculates the resonant frequency of the SAWR by a PSD analysis of the response signals. All these measurements are made sequentially, requiring spacing in the time domain, which increases interrogation time. This is the major bottleneck which limits SAWR sensor wireless update rates. Introducing dynamic measurement strategies could increase the update rates. The SAWR interrogation hardware contains several measurement algorithms. Such algorithms can vary the interrogation scheme, removing the search phase for the SAWR and iteratively changing the frequency bin spacing in the measurement phase to dynamically track the sensor [132]. These measurement techniques would improve sensor update rates for dynamic applications. Measurement rates can also be increased by reducing the resolution of the measured f_r [133]. The highest reported update rate for a wireless SAWR sensor is 4kHz for OEM automotive interrogation units which are not commercially available [122].

7.6.1 SAWR sensor system dynamic performance

To evaluate the suitability of the SAWR sensor for dynamic measurements, the TempTracker interrogator settings were optimised to improve the update rate. Firstly search phases to locate the SAWR strain sensor were performed only once, to initially locate the SAWR strain sensor within the ISM band. Measurement bandwidths were then minimised to cover the dynamic range of the sensor. This assumed that the dynamic range of the sensor is small, i.e. strain loading will not exceed a couple of $\mu\epsilon$. Lastly the magnitude threshold of the sensor was set at 20dB (in arbitrary units as per [132]) to minimise dropped samples. The experimental set up consisted of the SAWR strain sensor being bonded to the SAW calibration beam with M-Bond 600. The sensors were statically calibrated as described in Section 5.4. The S_{sen} was taken as the best fit value of $-450\text{Hz}/\mu\epsilon$. The loading actuator was removed from the testing apparatus, the calibration beam was subjected to an impulse at the free end of the beam, the dynamic strain field resulting from the oscillation of the beam was then measured using the SAWR strain sensor with a foil resistive strain gauges in parallel acting as a reference. The dynamic response of the vibrating beam is shown in Figure 7.21

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

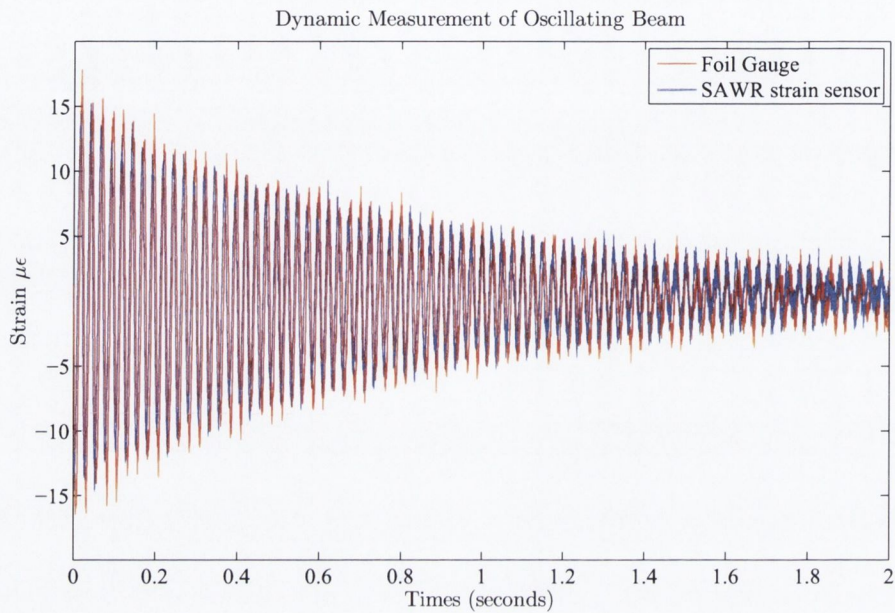


Figure 7.20: Impulse response of SAW calibration beam measured with SAWR strain sensor at 20°C

A FFT of the SAWR response was calculated which determined the fundamental frequency of the beam as shown in Figure 7.21. The experimentally measured value was found to be 38Hz for both SAWR and foil gauge measurements.

7.7. APPLICATION OF SAWR STRAIN SENSOR

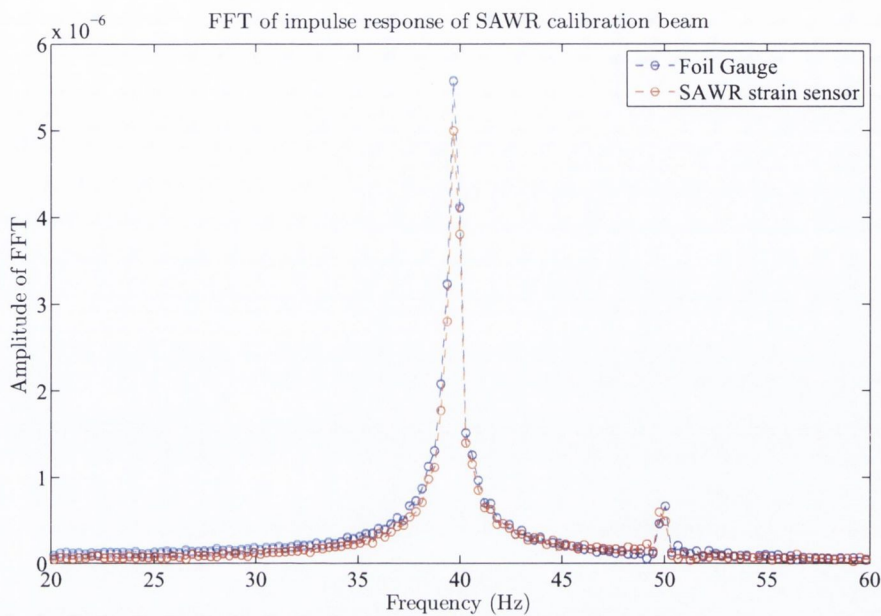


Figure 7.21: FFT of impulse response of SAW calibration beam measured with a SAWR strain sensor

Using Pro Engineer tool box, the natural frequency of the calibration beam was calculated at 40Hz, this correlates closely to the experimentally determined values. The maximum update rate achieved with the interrogation hardware was 500Hz, which is a sufficient sampling rate to cover the Nyquist sampling criterion [134].

7.7 Application of SAWR strain sensor

A goal of this project was to develop a modular SAWR strain sensor. Modular capability would allow the completed package to be integrated with various other packages or in other applications to form transducers. Foil resistive strain gauges have shown extremely high versatility in this regard and act as transducers in torque measurement systems, weigh stations and load cells. A good example of the integration of foil gauges into transducers is the standard commercial load cell [135]. The strain gauge is bonded at specific location in a predefined mechanically weakened structure so a compressive or tensile load will deform the cell in a specific way. A commercial load cell is shown in Figure 7.22.

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

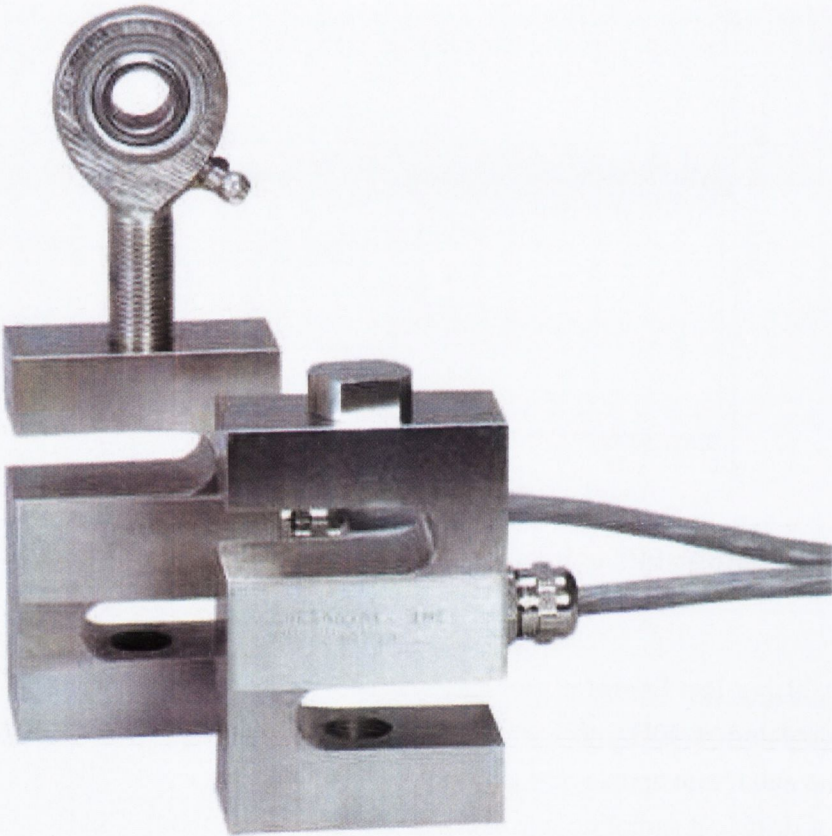


Figure 7.22: Commercial Omega S-Beam load cell adapted from [135]

Load cells are typically made from aluminium, steel or titanium at relatively low cost. As a demonstration of the capabilities of the SAWR strain sensor as a modular unit a SAWR load cell was designed, manufactured and calibrated. To date, SAWR strain sensors have not been integrated into load cells.

While many physical configurations for load cells can be used [99] in commercial products S-beam and binocular load cells are generally preferred. A load cell was designed in ProEngineer using the Mechanica tool box so an applied load would generate a surface strain detectable by the SAWR strain sensor. The dimensions of the load cell are shown in Appendix 8.2. The final load cell was manufactured from aluminium. FEA of the load cell found that a 10N load on the surface portion of the load cell

7.7. APPLICATION OF SAWR STRAIN SENSOR

produces a strain level of approximately $15\ \mu\epsilon$ well above the threshold level for the SAWR sensor.

The SAWR strain sensor was packaged in the 5L7C-1S package using M-Bond 610 adhesive. The packaged SAWR sensor was then bonded to the load cell using AE-15 adhesive. The SAWR sensor was clamped and cured at 75°C for 2 hours with a post cure of two hours. The completed load cell is shown in Figure 7.23.

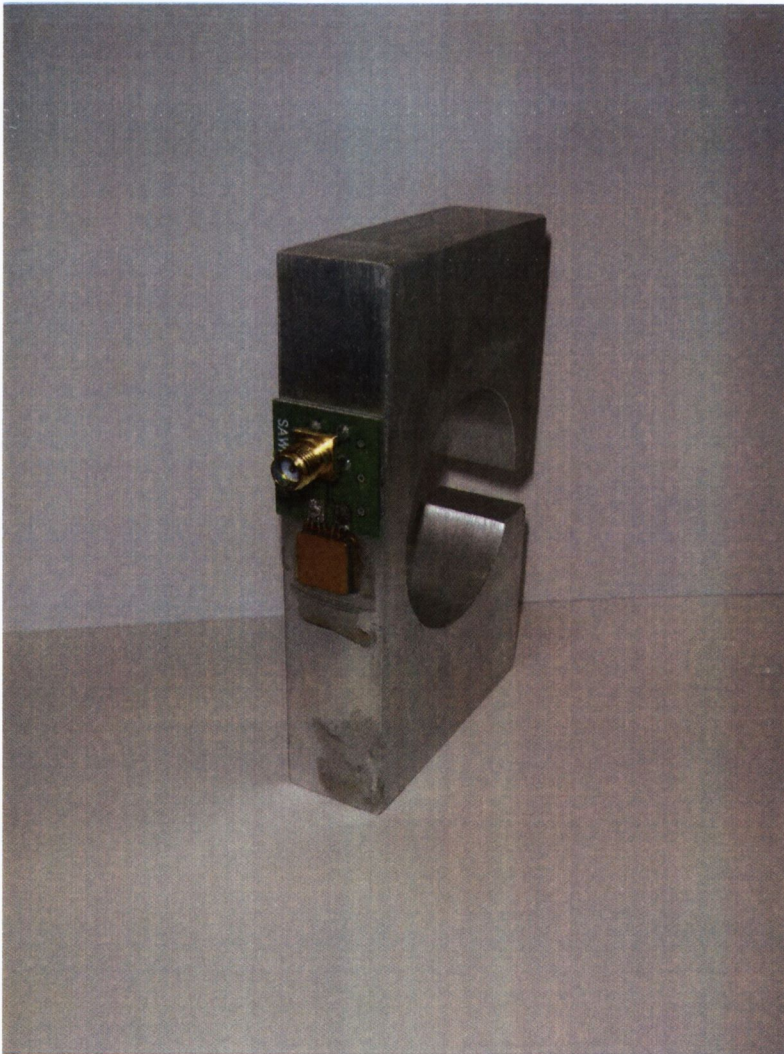


Figure 7.23: The prototype SAWR load Cell

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

7.7.1 Experimental measurement of load cell

The load cell was loaded using free weights from 0-60N in compression only with an interrogation distance of 15cm. As the SAWR package was orientated longitudinally to the generated strain field a compressive strain will cause a decrease in f_r . The measured calibration curve of the SAWR load cell is shown in Figure 7.24.

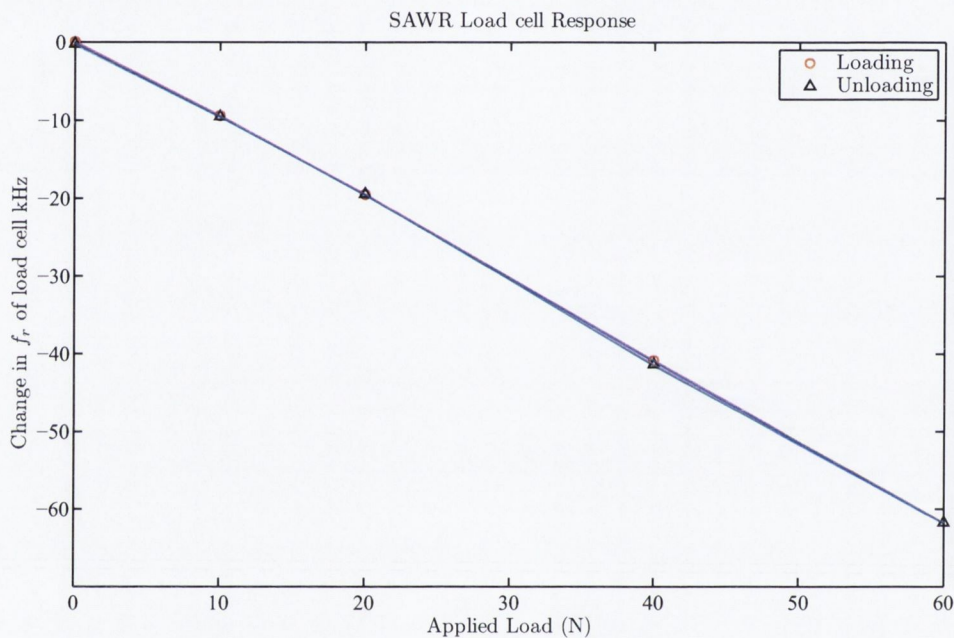


Figure 7.24: Loading profile for SAWR load cell at 20°C

The load cell was shown to have a sensitivity to the applied load of 1.029 kHz/N, hysteresis values were measured at 0.3% of the full scale. Sensor readout distance was found to be stable up to 0.5m. Interference increased as loading increased. This was attributed to the load arrangement and interference due to the use of iron dead weights. As a demonstration application the SAWR load cell illustrates the flexibility of the strain sensor developed during this thesis.

7.8 Conclusion

In this chapter the packaging requirements for a SAWR strain sensor were presented. With SAWR strain sensors the influence of packaging on the performance of the sensor must be taken into consideration. As with bare die testing thermal mismatch between

7.8. CONCLUSION

adhesive, package and sensor can result in the formation of significant residual stresses, which depending on cure conditions can be sufficient to shift the f_r of the sensor outside the ISM band. It is apparent that optimisation of the bonding procedure could will improve the overall package performance. The dynamic capability of the SAWR sensor was assessed and an update rate of 500Hz was obtained. However the reliability of the system at these sample rates can be poor and depending on environmental conditions dropped samples can be prevalent. A sample rate of 300Hz was found to be more reliable. The system was shown to measure dynamic strain quite accurately when compared to a foil resistive strain gauge. Low level dynamic measurement was shown to be feasible with the current hardware technology. As interrogation technologies improve it is highly probable the update rates and measurement reliability will increase. The modular nature of the SAWR strain sensor was demonstrated with the development of a wireless SAWR load cell. The performance of the load cell was assessed and found to operate with low hysteresis and good sensitivity in ambient temperature conditions. In the next chapter the project as a whole will be assessed.

7. PACKAGING AND CALIBRATION OF SAWR STRAIN SENSORS

Chapter 8

Conclusion and future work

In this thesis the operation of surface acoustic wave resonators as strain sensors has been investigated. Through an understanding of the nature of the SAW effect combined with piezoelectricity a simple photolithographic structure can be made bias sensitive to a range of measurands whilst simultaneously being made bias insensitive to others. As a result of the energy storage capabilities of the SAW propagating on a piezoelectric substrate. A SAW sensor can operate wirelessly and passively, thus making SAW sensors ideal for long term installations and in applications with dynamic or rotating components. This thesis has investigated the application of SAW devices as strain sensors with an emphasis placed upon both theoretical and practical implementation of the SAWR as a strain sensor. While highly application specific SAW sensors are available, this project addresses the need for modular SAW sensors that can be integrated into applications with the same flexibility as foil resistive strain gauges.

8.1 Contribution of the thesis

In this thesis the implementation of SAWR's as general purpose strain sensors was investigated. This included sensor specification, calibration, packaging and development of a wireless measurement chain. To the author's knowledge this work is the first instance of a SAWR developed as general purpose strain sensors as opposed to the highly application specific sensors. The major research topics addressed within this thesis are:

- Specification and design of a SAWR strain sensor.
- Integration of a SAWR sensor in a wireless measurement chain.

8. CONCLUSION AND FUTURE WORKS

- Correlation between theoretical SAWR strain sensor response and experimental performance through a novel validation method.
- A calibration and testing platform and methodology for SAWR strain sensors has been developed.
- Packaging, calibration and implementation of SAWR strain sensors as a modular sensor including an investigation into the suitability of a range of adhesives for SAWR strain sensors

8.1.1 Specification and design of a SAWR strain sensor

In Chapter 3 a specification was presented for the SAWR strain sensors used in this project. The SAWR was designed through collaboration with an industrial manufacturer of SAW components. The sensor specification was based upon fabricating a highly reproducible device which would demonstrate suitable performance characteristics in a wireless environment. This required the sensor to operate with a strong suppression of the transverse wave modes and with a high Q-factor. In a wireless environment the SAWR sensors performed with an electrical response comparable to that of commercial temperature sensors (see Appendix 8.2) thus allowing integration into commercial interrogation hardware to form a wireless measurement chain. The wireless measurement chain was found to be robust. However several key points can be made:

- For wireless measurement transverse wave mode suppression is crucial to avoid an incorrect measurement; careful design of the device is required to achieve this. The pulsed interrogation method determines the f_r of a SAWR through PSD analysis of the response signal. Correct power threshold levels and bin spacing in the measurement bandwidth can all aid in avoiding incorrect measurement. It may be possible that the interrogator is susceptible to gain saturation especially for low distance measurements. Control of the transmitted signal power may help to further interrogation susceptibility to transverse wave mode measurement.
- In wireless measurements the SAWR strain sensor is a passive low power device. Applications based upon wireless measurement of the SAWR should reflect this.

Read out distance and attenuation due to environmental factors will require tuning of the antenna for optimal performance. As a SAWR operates passively it is unlikely to perform as robustly as other wireless sensor networks.

As interrogation hardware improves it is highly probable sensor update rates will increase. With the current technology available for this project an update rate of 500Hz was achieved. The complete, packaged, SAWR sensor was shown to operate successfully in low level dynamic processes see section 7.6.1.

8.1.2 Correlation between SAWR strain sensor theoretical and experimental performance through a novel testing method

Quartz is a highly anisotropic material and the properties of the material can vary dramatically for different substrate cuts. A direct result of this is that the sensitivity of the SAW velocity can vary drastically even on given substrate. Depending on the cut, quartz substrates can either be stress sensitive or insensitive. The validation of experimental modelling will aid the SAW sensor designer in future design of high strain sensitivity SAWR sensors.

In section 2.5 the SAWR strain sensor theoretical performance was evaluated. The SAWR strain sensor will demonstrate a sensitivity to applied strain due to a geometric effect which changes the pitch of the IDT and reflective gratings, simultaneously the stress generated in the substrate of the sensors causes a change in the SAW velocity through the acoustoelastic effect. The combination of these factors results in a linear measurable change to the f_r . In section 2.5.1 a novel method for experimental verification of SAWR sensors is introduced. It is probable that stress shielding is occurring within the adhesive. This is apparent through hysteresis effects and the variation in bondline effects. Therefore 100 % accuracy of the model is unlikely. However, as was shown in Figure 2.18 the overall trend is correct.

8.1.3 Calibration and testing methodology for SAWR strain sensors

In Chapter 5 a testing method for the calibration of SAWR strain sensors was developed based upon the American standard for testing foil resistive strain gauges. The testing

8. CONCLUSION AND FUTURE WORKS

method addresses the lack of a standardised procedure for the calibration of SAWR strain sensors. The testing apparatus was fully automated which facilitates long term cyclic testing of the sensor and increases test reliability and repeatability. The testing apparatus was fully integrated with both wired and wireless tested equipment. Elevated temperatures test can be performed on the same rig as part of a fully inclusive test bench. The testing procedure reflects the specific sensor under calibration, the SAWR strain sensors primarily is calibrated wirelessly with constant transmission conditions, antenna configuration distance etc. For elevated temperature RF effects were taken into consideration during the design of the oven, where possible heaters and metallic elements were positioned to avoid excessive interference.

In Chapter 6 commercially manufactured bare die SAWR strain sensors were calibrated at a range of loading conditions and temperatures. A selection of adhesives were investigated which demonstrate various levels of performance. A relationship between hysteresis and S_{sen} was observed. At elevated temperatures, increases in hysteresis generally occur with decreases in S_{sen} . While sensor performance can vary drastically between adhesive types, for a given adhesive cure and post cure cycles can cause dramatic changes in the performance of a bondline. Residual stresses generated during the adhesive curing cycle can offer some indication to the success of the bonding process, however scope for optimisation of the process still remains. Provided that the SAWR strain sensor is bonded correctly the hysteresis levels can be lower than 1% of full scale across a temperature range of 20°C- 100°C with a S_{sen} greater than -500Hz/ $\mu\epsilon$ this is slightly greater than results for commercial torque sensor strain sensitivity [47]. The apparent strain drift of the AT-X SAWR strain sensor is 1-2 $\mu\epsilon$ and with a higher turnover temperature than traditional ST-X quartz. The profile temperature remains linear to 80°C. The effects of alignment to applied strain are also investigated in section 6.8. It was found that significant variation in the performance of the SAWR strain sensor S_{sen} can exist with changes in stress distribution in the substrate relative to SAW propagation. This result could allow limits to be placed upon the operational bandwidth of the SAWR strain sensor. It is clear that die design should be considered alongside substrate selection in order to optimise S_{sen} .

8.1.4 Evaluation of packaged SAWR sensors

Standard off the shelf components were used to package the bare die SAW strain sensor. The complete prototype consisted of a kovar alumina composite package with

8.2. FUTURE WORK AND FINAL THOUGHTS

the SAWR sensor bonded in the cavity of the sensor with an epoxy strain gauge adhesive. The completed package was then bonded to the test specimen with a strain gauge adhesive. As with the bare die sensor performance of the packaged sensor varied significantly depending on the adhesive used and the cure cycle. For the 5L14M packaged SAW sensor a reduction of strain sensitivity of under 35% was achieved. The full scale hysteresis remained less than 1% for the temperature range of 20°C-100°C see section 7.4.3. As packaging of the SAWR strain sensor results in the sensor becoming a composite body, the adhesive layers, packaging material and geometry of the SAW substrate may be optimised in the future to improve strain transfer characteristics and temperature stability. Integration of the SAWR into an application such as load cell (see section 7.7.1) demonstrate the packaged sensor as a modular component fulfilling one of the main motivations of the research. The wireless measurement chain was capable of a strain resolution of 1-2 $\mu\epsilon$. Improvement may be possible by increasing the S_{sen} of the packaged sensor through optimisation of package adhesive and sensor substrate.

8.2 Future work and final thoughts

As a core engineering component the measurement of strain has been of interest to engineers for centuries. This thesis has developed a strain sensor which can measure strain wirelessly and passively. Both the bare die and packaged SAWR strain sensor demonstrate good strain coupling with a low temperature dependency. Optimisation of the adhesive interface and packaging will improve the performance of future SAWR strain sensor. A recommendation for future work is the optimisation of the adhesive interfaces to improve SAWR strain sensor performance. While the 5L14M package operated successfully demonstrating good performance characteristics across a range of temperatures, scope exists for the design of a customised packaging solution possibly through the optimisation of physical design and material selection.

SAWR sensing over the past fifteen years has been curtailed by the lack of wireless interrogation hardware. Practical considerations in the use of SAWR strain sensors has been for the most part neglected. It is hoped this thesis contributes to future work by providing testing methodology and a full calibration data set for AT-X SAWR strain sensors with a rigorous investigation into the practical implementation of SAWR as strain sensors. This thesis has addressed some of the key points in the development of

8. CONCLUSION AND FUTURE WORKS

SAWR strain sensor and it is hoped it will enable future researchers to develop high performing SAWR strain sensors.

Measurement of commercial SAWR

sensor

The performance of a commercial SAWR sensor was measured thus providing a comparison between the electrical performance of the project sensor and a commercial wireless SAWR sensor. The comparison device was a one port SAWR temperature sensor shipped with the SenGenuity TempTrackr. The TFSS433D SAW temperature sensor is a one-port SAW resonator designed to have a f_c of 433.778MHz at a temperature of 50°C with a linear frequency versus temperature profile with the specification sheet reporting the response of the sensor to be $(7028\text{Hz}/^\circ\text{C})$ [118].

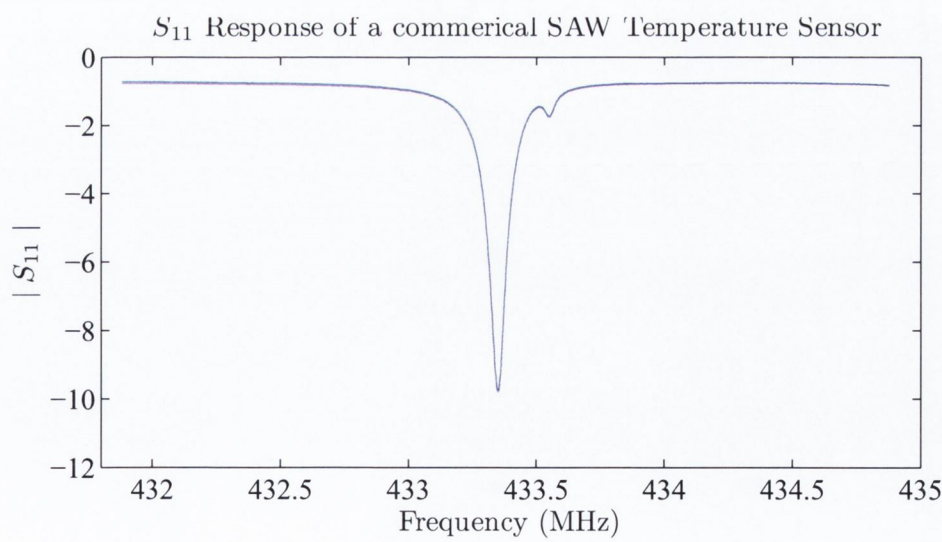


Figure 1: $|S_{11}|$ response of a commercial SAW temperature sensor measured at ambient conditions

APPENDIX . MEASUREMENT OF COMMERCIAL SAWR SENSOR

Using the protocol described in Section 4.2 the temperature sensor was connected directly to the transmission line of the VNA. The S_{11} response is shown in Figure 4.4 while the impedance response is shown in Figure 2. As the sensor was packaged it was not possible to preform S_{11} testing directly at die level. Packaging and connectors will have a degrading effect on the SAW performance, thus the S-parameter testing provides only an indication of die performance and direction comparisons are not comparable to die level testing which was performed on the project sensor. The commercial sensor was found to have an S_{11} response of -9dB at resonance and an impedance at resonance of 10Ω . The Q_r was calculated at 7000. The spurious wave modes in the commercial SAWR sensor are suppressed to a greater extent than the project sensor.

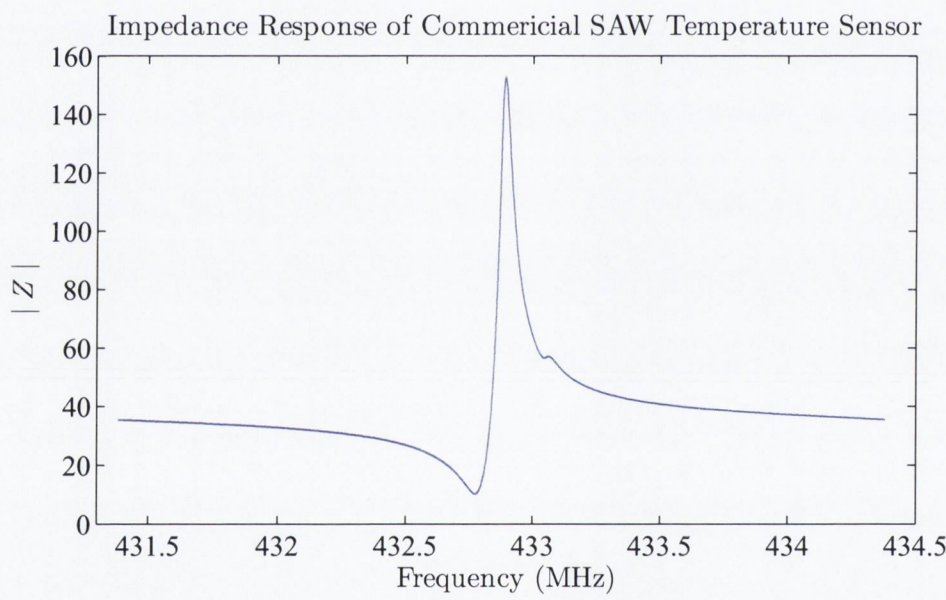
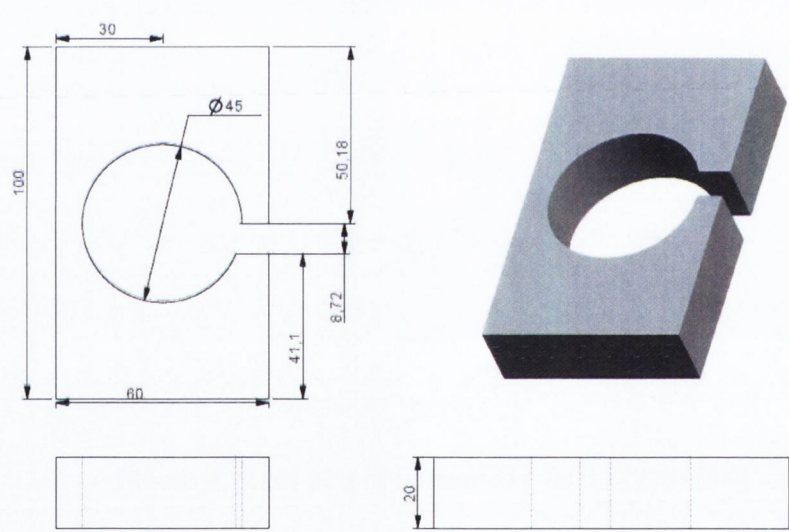


Figure 2: Impedance Response of a Commercial SAW temperature sensor measured at ambient conditions

SAWR load cell

Dimension of SAWR load cell are shown in Figure 3.



SAWR Load Cell: All dimension in mm

Figure 3: SAWR Load Cell

APPENDIX . SAWR LOAD CELL

Euler rotations

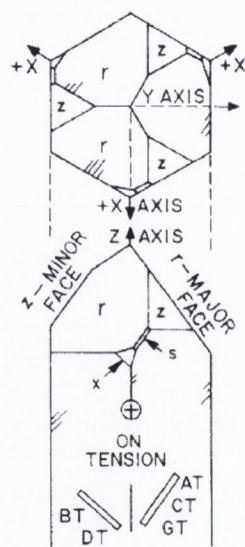


Figure 4: Axes of a right handed quartz crystal [14]

For crystalline materials the convention is reference material to a set of axes defined by the convention put forward in [136]. The accepted method for defining substrate orientations for SAW devices is based upon an Euler rotation. The axes of the crystalline structure are denoted by the uppercase symbols X Y, Z. The orientation of device axis are defined by x, y, z Initially prior to any rotations the x, y, z and X, Y, Z axis are the same. A complete Euler rotation is defined by three rotations. The initial planes are defined by the X Y Z axes, additional planes of reference are created by rotating the x, y, and z through an angle of λ about the z axis to form new axis set (x_1,y_1,z_1) where z_1 is the same as z and Z. A second rotation is then applied to rotate the axes x_1, y_1, z_1 about x_1 through an angle of ϵ to form a second axes set (x_2,y_2,z_2) a third and final rotation through an angle of θ about z_2 is then applied to form the final axes (z_3,y_3,z_3) . In the final orientation of the substrate, z_3 is the surface normal and x_3 is

APPENDIX . EULER ROTATIONS

the propagation direction. The AT quartz is a rotated Y cut has a rotation $\lambda=\theta=0$; with an anticlockwise rotation $\varepsilon=\psi-90$, where $\psi = 36^\circ$.

References

- [1] J. M. Gere and S. P. Timoshenko, *Mechanics of Materials*. Cheltenham: Stanley Thornes, 1999.
- [2] W. M. Murray and W. R. Miller, *The Bonded Electrical Strain Gage: An Introduction*. New York: Oxford University Press, 1992.
- [3] M. Johnson, M. Healy, P. van de Ven, M. Hayes, J. Nelson, T. Newe, and E. Lewis, "A comparative review of wireless sensor network mote technologies," in *Proc. IEEE Sensors*, 2009, pp. 1439–1442.
- [4] J. W. S. L. Rayleigh), "On waves propagated along the plane surface of an elastic solid," *Proceedings of the London Mathematical Society*, vol. 17, pp. 4–11, 1885.
- [5] M. P. da Cunha, "Pseudo and high velocity pseudo SAWs," *International Journal of High Speed Electronics and Systems*, vol. 10, no. 4, pp. 1069–1109, 2000.
- [6] J. L. Bleustein, "A new surface wave in piezoelectric materials," *Applied Physics Letters*, vol. 13, no. 12, pp. 412–413, 1968.
- [7] Y. V. Gulyaev, "Electroacoustic surface waves in solids," *Soviet Physics JETP Letters*, vol. 9, pp. 37–38, 1969.
- [8] A. E. H. Love, *Some Problems of Geodynamics*. Cambridge: Cambridge University Press, 1911.
- [9] A. P. Borezi and K. P. Chong, *Elasticity in Engineering Mechanics*, 2nd ed. New York: Wiley-Interscience, 2000.
- [10] B. A. Auld, *Acoustic Fields and Waves in Solids*. New York: John Wiley and Sons, 1973, vol. 1 and 2.

REFERENCES

- [11] G. W. Farnell, *Properties of elastic surface waves*.
- [12] W. Voigt, *Lehrbuch der Kristallphysik*. Berlin: Teubner, 1910.
- [13] J. A. Cross, *Electrostatics: Principles, Problems and Applications*. Bristol: Adam Hilger, 1987.
- [14] *IEEE Standard on Piezoelectricity*, IEEE Std. 176-1987, 1987.
- [15] D. P. Morgan, *Surface Acoustic Wave Filters with applications to electronic communications and signal processing*. United Kingdom: Academic Press, 2007.
- [16] J. Curie and P. Curie, “Développement, par pression, de l’électricité polaire dans les cristaux hémihédres à faces inclinées,” *Comptes Rendus Acad. Sci. Paris*, vol. 91, pp. 294–295, 1880.
- [17] A. Ballato, “Basic material quartz and related innovations,” in *Piezoelectricity*, W. Heywang, K. Lubitz, and W. Wersing, Eds. Berlin: Springer, 2008.
- [18] D. P. Morgan, “History of SAW devices,” in *Proc. IEEE International Frequency Control Symposium*, 1998, pp. 440–460.
- [19] K. Hashimoto, *Surface Acoustic Wave Devices in Telecommunications: Modelling and Simulation*. Berlin: Springer, 2000.
- [20] J. J. Campbell and W. R. Jones, “A method for estimating optimal crystal cuts and propagation directions for excitation of piezoelectric surface waves,” *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*.
- [21] A. J. Slobodnik, E. D. Conway, and R. T. Delmonico, “Microwave acoustics handbook volume 1A: Surface wave velocities,” Air Force Cambridge Research Laboratories, Tech. Rep. AFCRL-TR-73-0597, 1973.
- [22] T. C. T. Ting, *Anisotropic Elasticity: Theory and Applications*. New York: Oxford University Press, 1996.
- [23] B. Mc Cormack, D. Geraghty, and M. O’Mahony, “Design and manufacture of surface acoustic wave sensors for real-time weigh-in-motion,” in *Proc. IEEE Instrumentation and Measurement Technology Conference*, 2005, pp. 1360–1364.

REFERENCES

- [24] A. Slobodnik and T. Szabo, "New technique for measuring acoustic-surface-wave propagation loss," *Electronics Letters*, vol. 8, no. 25, pp. 617–618, 14 1972.
- [25] D. P. Morgan, *Surface-Wave Devices for Signal Processing*. Amsterdam: Elsevier, 1985.
- [26] M. Yamaguchi, K. Hashimoto, and H. Kogo, "Effects of surface metallisation on ssbw and bgw propagation in quartz," *Electronics Letters*, vol. 17, no. 17, pp. 602–603, 20 1981.
- [27] L. Reindl, C. C. W. Ruppel, S. Berek, U. Knauer, M. Vossiek, P. Heide, and L. Oréans, "Design, fabrication and application of precise SAW delay lines used in an FMCW radar system," *IEEE Transactions on Microwave Theory and Techniques*.
- [28] R. M. White and F. W. Voltmer, "Direct piezoelectric coupling to surface elastic waves," *Applied Physics Letters*, vol. 7, pp. 314–316, 1965.
- [29] H. Matthews, *Surface Wave Filters: Design, Construction and Use*. New York: John Wiley & Sons, 1977.
- [30] R. H. Tancrell and M. G. Holland, "Acoustic surface wave filters," *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, vol. 59, pp. 393–409, 1971.
- [31] C. K. Campbell, *Surface Acoustic Wave Devices for Mobile and Wireless Communications*. San Diego: Academic Press, 1998.
- [32] E. A. Ash, "Surface wave grating reflectors and resonators," in *Proc. IEEE Symposium on Microwave Theory and Techniques*, 1970, pp. 385–386.
- [33] J. Helmick, C.N., D. White, and K. Lakin, "Deep-bulk-acoustic-wave (dbaw) devices utilizing interdigital transducers," in *Proc. IEEE Ultrasonics Symposium*, 1981.
- [34] B. Fleischmann and H. Skeie, "Higher harmonic surface transverse wave filters," in *Proc. IEEE Ultrasonics Symposium*, vol. 1, 1989, pp. 235–239.

REFERENCES

- [35] D. S. Hughes and J. L. Kelly, "Second-order elastic deformation of solids," *Physical Review*, vol. 92, no. 5, pp. 1145–1149, 1953.
- [36] T. M. Reeder, D. E. Cullen, and M. Gilden, "SAW oscillator pressure sensors," in *Proc. IEEE Ultrasonics Symposium*, 1975, pp. 264–268.
- [37] B. K. Sinha and H. F. Tiersten, "On the influence of uniaxial biasing stresses on the velocity of piezoelectric surface waves," in *Proc. IEEE Ultrason. Symp.*, 1976, pp. 475–479.
- [38] A. L. Nalamwar and M. Epstein, "Propagation of surface acoustic waves in strained media," in *Proc. IEEE Ultrasonics Symposium*, 1975, pp. 484–487.
- [39] B. K. Sinha, W. J. Tanski, T. Lukaszek, and A. Ballato, "Influence of biasing stresses on the propagation of surface waves," *Journal of Applied Physics*, vol. 57, no. 3, pp. 767–776, 1985.
- [40] A. L. Nalamwar and M. Epstein, "Surface acoustic waves in strained media," *Journal of Applied Physics*, vol. 47, no. 1, pp. 43–48, 1976.
- [41] D. E. Cullen and T. M. Reeder, "Measurement of SAW velocity versus strain for YX and ST quartz," in *Proc. IEEE Ultrasonics Symposium*, 1975, pp. 519–522.
- [42] B. K. Sinha and S. Locke, "Acceleration and vibration sensitivity of SAW devices," *Journal of Ultrasonics, Ferroelectrics and Frequency Control*, vol. 34, no. 1, pp. 29–38, Jan. 1987.
- [43] R. Taziev, E. Kolosovsky, and A. Kozlov, "Extreme pressure-sensitive cuts for surface acoustic waves in alpha-quartz," in *Proc. IEEE International Frequency Control Symposium*, Jun. 1994, pp. 345–351.
- [44] A. Shevtsov, S. Zhgoon, A. Lonsdale, and S. Sandacci, "Deformation sensitive cuts of quartz for torque sensor," in *Proc. IEEE Ultrasonics Symposium*, 2010.
- [45] P. V. Wright, "A review of SAW resonator filter technology," in *Proc. IEEE Ultrasonics Symposium*, 1992, pp. 29–38.
- [46] V. Plessky and J. Koskela, "Coupling-of-modes analysis of SAW devices," *International Journal of High Speed Electronic Systems.*, vol. 10, no. 4, pp. 867–947, Dec. 2000.

REFERENCES

- [47] J. Beckley, V. Kalinin, M. Lee, and K. Voliansky, "Non-contact torque sensors based on SAW resonators," in *Proc. IEEE International Frequency Control Symposium and PDA Exhibition.*, 2002, pp. 202–213.
- [48] B. K. Sinha and H. F. Tiersten, "On the influence of a flexural biasing state on the velocity of piezoelectric surface waves," *Wave Motion*, vol. 1, pp. 37–51, 1979.
- [49] R. N. Thurston, H. J. McSkimin, and P. Andreatch, "Third-order elastic coefficients of quartz," *Journal of Applied Physics*, vol. 37, no. 1, pp. 267–275, 1966.
- [50] J. F. Dias and H. E. Karrer, "Stress effects in acoustic surface-wave circuits and applications to pressure and force transducers," in *Proc. IEEE International Solid-State Circuits Conference (Digest)*, 1974, pp. 166–167.
- [51] E. EerNisse, "Quartz resonator frequency shifts arising from electrode stress," in *29th Annual Symposium on Frequency Control*. 1975, 1975.
- [52] M. B. Schulz and J. H. Matsinger, "Rayleigh wave electromechanical coupling constants," *Applied Physics Letters*, vol. 20, pp. 367–369, 1972.
- [53] J. Greer and T. Parker, "Improved vibration sensitivity of the all quartz package surface acoustic wave resonator," in *Proc. Frequency Control Symposium*, Jun. 1988, pp. 239–251.
- [54] E. Bigler and S. Ballandras, "Experimental study of saw quartz cuts with low sensitivity to dynamical thermal effects," *Electronics Letters*, vol. 27, no. 15, pp. 1343–1345, 1991.
- [55] D. S. Ballantine, R. M. White, S. J. Martin, A. J. Ricco, E. T. Zellers, G. C. Frye, and H. Wohltjen, *Acoustic Wave Sensors: Theory, Design and Physico-Chemical Applications*. San Diego: Academic Press, 1997.
- [56] A. Pohl, "A review of wireless SAW sensors," *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, vol. 47, no. 2, pp. 317–332, Mar. 2000.
- [57] X. Bao, W. Burkhard, V. Varadan, and V. Varadan, "Saw temperature sensor and remote reading system," in *Proc. IEEE Ultrasonics Symposium*, 1987, pp. 583–586.

REFERENCES

- [58] A. Pohl and F. Seifert, "Wirelessly interrogable surface acoustic wave sensors for vehicular applications," *IEEE Journal of Instrumentation and Measurement*, vol. 46, no. 4, pp. 1031–1038, 1997.
- [59] A. Lonsdale and B. Lonsdale, "Surface acoustic wave sensor," European Patent 5,189,00, 1990.
- [60] W. Buff, M. Rusko, E. Goroll, J. Ehrenpfordt, and T. Vandahl, "Universal pressure and temperature saw sensor for wireless applications," in *Proc. IEEE Ultrasonics Symposium*, vol. 1, 1997, pp. 359–362.
- [61] V. Kalinin, R. Lohr, and A. Leigh, "Development of a calibration procedure for contactless torque and temperature sensors based on saw resonators," in *Proc. IEEE Ultrasonics Symposium*, 2008, pp. 1865–1868.
- [62] R. Fachberger, G. Bruckner, G. Knoll, J. Biniasch, L. Reindl, and R. Hauser, "LiNbO₃, langasite and GaPO₄ as substrates for SAW sensing beyond the GHz range," in *Piezoelectric Resonators for Sensor Applications Workshop*, 2003.
- [63] S. Ballandras, R. Lardat, L. Penavaire, P. Menage, L. Chommeloux, H. Huet, C. Lestrat, T. Pastureaud, F. Haon, W. Steichen, and G. Heider, "P1i-5 micro-machined, all quartz package, passive wireless saw pressure and temperature sensor," in *Proc. IEEE Ultrasonics Symposium*, 2006, pp. 1441–1444.
- [64] <http://www.sengenuity.com>, *TempTrackr Wireless Temperature Measurement Solution*, 2009.
- [65] V. Kalinin, "Wireless resonant saw sensors for automotive applications," in *Proc. Wireless SAW Sensor Symposium - Villach*, 2010.
- [66] R. Feger, S. Schuster, S. Scheiblhofer, and A. Stelzer, "Sparse antenna array design and combined range and angle estimation for fmcw radar sensors," in *Proc. of the IEEE Radar conference*, May 2008, pp. 1–6.
- [67] B. Mc Cormack, "Design, manufacture, modelling and testing," Ph.D. dissertation, University of Dublin, Dublin, 2007.
- [68] G. Martin, B. Wall, and M. Weihnacht, "An alternative method for suppressing undesired transverse modes in longitudinally coupled saw resonator fil-

REFERENCES

- ters,” *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, vol. 42, no. 6, pp. 1099–1101, Nov. 1995.
- [69] M. B. Schulz, B. J. Matsinger, and M. G. Holland, “Temperature dependence of surface acoustic wave velocity on alpha quartz,” *Journal of Applied Physics*, vol. 41, no. 7, pp. 2755–2765, 1970.
- [70] D. P. Morgan, “Cascading formulas for identical transducer P-matrices,” *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, vol. 43, no. 5, pp. 985–987, 1996.
- [71] S. Kondratiev, SAWNICS Corporation, 2009, private communication.
- [72] W. H. Haydl, D. Dischler, and P. Hiesinger, “Multimode SAW resonators - a method to study the optimum resonator design,” in *Proc. IEEE Ultrasonics Symposium*, 1976, pp. 287–296.
- [73] H. A. Haus, “Modes in SAW grating resonators,” *Journal of Applied Physics*, vol. 48, pp. 4955–4961, 1977.
- [74] Y. Yamamoto and S. Yoshimoto, “Saw transversely guided mode spurious elimination by optimization of conversion efficiency using w/w0 electrode structure,” in *Ultrasonics Symposium, 1998. Proceedings., 1998 IEEE*, 1998.
- [75] MicroStrain, “SG-Link wireless sensor,” <http://www.microstrain.com/wireless-sensors.aspx>, March 2011.
- [76] A. Pohl, G. Ostermayer, and F. Seifert, “Wireless sensing using oscillator circuits locked to remote high-Q SAW resonators,” *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, vol. 45, no. 5, pp. 1161–1168, 1998.
- [77] C. Droit, G. Martin, S. Ballandras, and J.-M. Friedt, “Note: A frequency modulated wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement,” *Review of Scientific Instruments*, vol. 81, no. 5, pp. 056 103–056 103–3, May 2010.
- [78] B. Dixon, V. Kalinin, J. Beckley, and R. Lohr, “A second generation in-car tire pressure monitoring system based on wireless passive saw sensors,” in *Interna-*

REFERENCES

- tional Frequency Control Symposium and Exposition, 2006 IEEE*, june 2006, pp. 374 –380.
- [79] V. Kalinin, G. Bown, J. Beckley, and R. Lohr, “Pulsed interrogation of the saw torque sensor for electrical power assisted steering,” in *Proc. IEEE Ultrasonics Symposium*, vol. 3, 2004, pp. 1577 – 1580 Vol.3.
- [80] D. M. Pozar, *Microwave Engineering*, 2nd ed. New York: Wiley, 1998.
- [81] ———, *Microwave Engineering 3^d Edition*. Hoboken, New Jersey: John Wiley & Sons, 2005.
- [82] Agilent, “Applying error correction to network analyzer measurements,” Agilent Technologies, Application Note AN 1287-3, 2002.
- [83] K. Byrappa and P. Capper, *Bulk Crystal Growth of Electronic, Optical and Optoelectronic Materials*. Hoboken, New Jersey: John Wiley & Sons, 2005.
- [84] B. Park, SAWNICS Corporation, 2010, private communication.
- [85] R. Fachberger, E. Riha, E. Born, W. Ruile, P. Pongratz, and S. Kronholz, “Homogeneity of langasite and langatate wafers,” in *Proc. IEEE International Frequency Control Symposium and PDA Exhibition.*, 2002, pp. 311 – 319.
- [86] W. R. Broughton, A. T. Fry, D. A. Mendels, and C. J. Chunnillall, “Near surface strain measurements on quartz wafers and devices,” National Physical Laboratory, Tech. Rep. MATC (MN) 52, 2003.
- [87] P. M. Adams, “Curvature measurements of stressed surface-acoustic-wafer filters using bragg angle contour mapping,” The Aerospace Corporation, Tech. Rep., 2003.
- [88] U. T. Zwicker, “Strain sensor with commercial SAWR,” *Sensors and Actuators*, vol. 17, pp. 235–239, 1989.
- [89] *British Standard Methods for Calibration of Bonded Electrical Resistance Strain Gauges*, British Standards Institute Std. BS6888:1988, 1988.
- [90] *Standard Test Methods for Performance Characteristics of Bonded Resistance Strain Gages*, American Society for Testing and Materials Std. E251-2003, 2003.

REFERENCES

- [91] C. Hautamaki, L. Cao, J. Zhou, S. Mantell, and T. S. Kim, "Calibration of mems strain sensors fabricated on silicon: theory and experiments," *Microelectromechanical Systems, Journal of*, vol. 12, no. 5, pp. 720 – 727, 2003.
- [92] N. M. Zarroug, R. Padmanabhan, B. J. MacDonald, P. Young, and M. S. J. Hashmi, "Mild steel (En8) rod tests under combined tension-torsion loading."
- [93] www.intelligentactuator.com, *Modbus Control Manual* v., 2009.
- [94] "Surface Preparation for Strain Gauge Bonding: Application Note B-129-8:2005," Vishay Precision Group.
- [95] Ceramicx, "Quartz Heater: Data Sheet ," <http://www.ceramicx.com/en/fqe-full-quartz-element>, September 2010.
- [96] Taoglas, "FXP240.07.0100A: Data Sheet," www.taoglas.com, September 2009.
- [97] X. Zhang, S. Park, R. Navarro, and M. Judy, "Accurate assessment of packaging stress effects on mems devices," in *Thermal and Thermomechanical Phenomena in Electronics Systems, 2006. ITherm '06. The Tenth Intersociety Conference on*, June 2006, pp. 1336 –1342.
- [98] R. Krondorfer and Y. Kim, "Packaging effect on mems pressure sensor performance," *Components and Packaging Technologies, IEEE Transactions on*, vol. 30, no. 2, pp. 285 –293, June 2007.
- [99] E. O. Doebelin, *Measurement Systems; Application and Design*. Boston: McGraw Hill, 2004.
- [100] K. Snook, J.-Z. Zhao, C. Alves, J. Cannata, W.-H. Chen, J. Meyer, R.J., T. Ritter, and K. Shung, "Design, fabrication, and evaluation of high frequency, single-element transducers incorporating different materials," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 49, no. 2, pp. 169 –176, 2002.
- [101] J. F. Dias, H. E. Karrer, J. A. Kusters, J. H. Matsinger, and M. B. Schulz, "The temperature coefficient of delay-time for X-propagating acoustic surface-waves on rotated Y-cuts of alpha quartz," *IEEE Transactions on Sonics and Ultrasonics*, vol. SU-22, no. 1, pp. 46–50, 1975.

REFERENCES

- [102] M. Hamidon, V. Skarda, N. White, F. Krispel, P. Krempl, M. Binhack, and W. Buff, "High-temperature 434 mhz surface acoustic wave devices based on gapo/sub 4/," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 53, no. 12, pp. 2465 –2470, 2006.
- [103] J. Webster, *The Measurement, Instrumentation and Sensors HandBook*. Boca Raton: CRC Press, 1999.
- [104] "Strain Gauge Installations with M-Bond 200 Adhesive: Instruction Bulletin B-127-14," Vishay Precision Group.
- [105] "Strain Gauge Installations with M-Bond 43-B,600 and 610 Adhesive Systems: Instruction Bulletin B-130," Vishay Precision Group.
- [106] L. Reindl, G. Scholl, T. Ostertag, H. Scherr, U. Wolff, and F. Schmidt, "Theory and application of passive saw radio transponders as sensors," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 45, no. 5, pp. 1281 –1292, Sep. 1998.
- [107] A. Chitney, SAWNICS Corporation, 2010, private communication.
- [108] (2007) National Instruments Corporation. [Online]. Available: <http://www.ni.com>
- [109] "Errors Due to Wheatstone Bridge Nonlinearity: Tech Note TN-507-1," Vishay Precision Group.
- [110] J. R. Taylor, Ed., *An Introduction to Error Analysis*, 2nd ed. California: University Science Books, 1997.
- [111] W. Buff, S. Klett, M. Rusko, J. Ehrenpfordt, and M. Goroll, "Passive remote sensing for temperature and pressure using SAW resonator devices," *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, vol. 45, no. 5, pp. 1388–1392, 1998.
- [112] P. Selmeier, R. Grunwald, A. Prządka, H. Kruger, G. Feiertag, and C. Ruppel, "Recent advances in saw packaging," in *Ultrasonics Symposium, 2001 IEEE*, 2001.

REFERENCES

- [113] C. C. W. Ruppel, L. Reindl, and R. Weigel, "SAW devices and their wireless communications applications," *IEEE Microwave Magazine*, pp. 65–71, June 2002.
- [114] J. hyuk Lim, J. sik Hwang, J. Kwon, S. jin Ham, W. Kim, T. H. Kim, W. K. Jeung, S. J. Yang, S. M. Choi, and J. H. Park, "6b-6 an ultra small saw rf filter using wafer level packaging technology," in *Ultrasonics Symposium, 2006. IEEE*, 2006, pp. 196–199.
- [115] L. E. Fissi, J.-M. Friedt, B. Belgacem, F. Chicrioux, V. Luzet, and S. Ballandras, "Fabrication and packaging technologies of love-wave-based microbalance for fluid analysis," in *Proc. of the Eurosensors XXIII conference*, vol. 1, no. 1, 2009, pp. 52–55.
- [116] M. da Cunha, R. Lad, T. Moonlight, G. Bernhardt, and D. Frankel, "High temperature stability of langasite surface acoustic wave devices," in *Ultrasonics Symposium, 2008. IUS 2008. IEEE*, 2008, pp. 205–208.
- [117] R. Hauser, R. Fachberger, G. Bruckner, R. Reicher, and W. Smetana, "Ceramic patch antenna for high temperature applications," in *Electronics Technology: Meeting the Challenges of Electronics Technology Progress, 2005. 28th International Spring Seminar on*, 0 2005.
- [118] <http://www.sengenuity.com>, *Wireless Temperature Sensor SAW Temperature Resonator:TFSS433D*, 2009.
- [119] J. Bardong, G. Bruckner, M. Kraft, and R. Fachberger, "Influence of packaging atmospheres on the durability of high-temperature saw sensors," in *Ultrasonics Symposium (IUS), 2009 IEEE International*, 2009, pp. 1680–1683.
- [120] H. Scherr, G. Scholl, F. Seifert, and R. Weigel, "Quartz pressure sensor based on saw reflective delay line," in *Ultrasonics Symposium, 1996. Proceedings., 1996 IEEE*, vol. 1, Nov. 1996, pp. 347–350 vol.1.
- [121] V. Kalinin and A. Leigh, "Influence of non-uniform strain on characteristics of one-port SAW resonators," in *Proc. IEEE Ultrasonics Symposium*, 2003, pp. 1412–1415.
- [122] V. Kalinin, "Wireless resonant saw sensors for automotive applications," in *Wireless SAW Sensor Symposium, 2010*, 2010.

REFERENCES

- [123] Schott, "SAW Torque sensor package," http://www.us.schott.com/magazine/english/sol209/sol209_10_saw_sensor.html, November 2009.
- [124] I. E. P. D. Mini-Systems, "Mini-systems electronic flatpack packages," Website: www.mini-systemsinc.com, November 2010.
- [125] D. M. Mauder, "Thin-film adhesion and adhesive failure - a perspective," *American Society for Testing and Materials*, vol. 640, pp. 54–62, 1978.
- [126] A. Ballato, "Elastic properties of crystalline quartz," in *Handbook of Elastic Properties of Solids, Liquids and Gases*, L. Moises, H. E. Bass, and R. R. Stern, Eds. San Diego: Springer, 2001.
- [127] J. R. Davis, *ASM Speciality HandBook: Copper and Copper Alloys*. ASM International, 2001.
- [128] "Technical Data Sheet EP 950 G Gray," Resinlab: An Ellsworth Adhesive Company.
- [129] "Eas sealing clips: Ap20-3711: Data sheet," Electro Assembly Source, Inc.
- [130] M. Ferri, S. Crisitiani, A. Roncaglia, Y. Kobayashi, and K. Soga, "A packaging technique for silicon mems strain sensors on steel," in *Sensors, 2008 IEEE*, 2008, pp. 1524–1527.
- [131] Y. Yu, I. Ashcroft, and G. Swallowe, "An experimental investigation of residual stresses in an epoxy-steel laminate," *International Journal of Adhesion and Adhesives*, vol. 26, no. 7, pp. 511–519, September 2005.
- [132] V. Kalinin, R. Lohr, A. Leigh, and G. Bown, "Application of passive saw resonant sensors to contactless measurement of the output engine torque in passenger cars," in *Frequency Control Symposium, 2007 Joint with the 21st European Frequency and Time Forum. IEEE International*, june 2007, pp. 499–504.
- [133] V. Kalinin, B. Dixon, and J. Beckley, "Optimization of resonant frequency measurement algorithm for wireless passive saw sensors," in *Frequency Control Symposium, 2009 Joint with the 22nd European Frequency and Time forum. IEEE International*, 2009, pp. 90–95.
- [134] N. Nise, *Control Systems Engineering, 4th Edition*. USA: Wiley, 2004.

REFERENCES

- [135] Omega, “Omega Load Cell,” <http://www.omega.com/Pressure/pdf/LC101.pdf>, January 2011.
- [136] T. R. Meeker, “Publication and proposed revision of ANSI/IEEE Standard 176-1987 “ANSI/IEEE Standard on Piezoelectricity”,” *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, vol. 43, no. 5, pp. 717–718, 1996.