UNCOOLED INFRARED DETECTION BASED ON ALUMINIUM NITRIDE PIEZOELECTRIC RESONATOR

ANG WAN CHIA

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

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Executive Summary

Infrared (IR) radiation is an electromagnetic radiation with wavelength ranging from 0.75 µm to 1,000 µm and photon energy from 1.24 meV to 1.7 eV. IR sensors can be generally categorized into either photon detectors or thermal detectors. Traditionally, IR detection was mainly employed in the fields of astronomy, military and surveillance using photon detectors. Thermal detectors (also called uncooled detectors) were comparatively less explored due to their unsatisfactory performance. Since the emergence of micromachining technologies in the early 1990s, the sensing performance of micro-electro-mechanical systems based thermal IR detectors have been boosted up, which is sufficient for some low-end applications in the field of civilian, medical, spectroscopy, etc.

Among all available thermal IR sensing technologies, resonant detectors appeared to be the promising candidates that are competitive with photon detectors because of their low noise characteristic and highly accurate frequency readout. In this thesis, thermal IR detectors based on aluminium nitride (AlN) piezoelectric resonators have been successfully fabricated, characterized and evaluated.

A brief introduction to IR radiation and currently available IR detection technologies are first given, thereby providing a motivation to evaluate the thermal AlN resonant detectors in this project. An overview of AlN piezoelectric resonators is provided, followed by the working principle and theory of IR detection. Detailed design considerations of AlN resonant detectors are described. A fully CMOS compatible
fabrication process is developed to enable the integration between the detectors and CMOS readout circuits. The detectors in up-side-down design with optimized thermal isolation structure are successfully fabricated.

Resonant and thermal behaviour of the fabricated AlN resonant detectors are characterized using network analyzer in a vacuum prober equipped with temperature chuck and radio frequency feedthroughs. IR sensing characterization of the detectors is accomplished using blackbody source and optical filter in the same vacuum prober. The measurement data is then fitted with modified Butterworth van Dyke equivalent circuit model. The measured performance of the detectors is presented along with figure-of-merits including responsivity, noise performance, and noise-equivalent-temperature-difference. The sensing response as a function of IR radiant power, operating temperatures, and structural design parameters is also illustrated.

It is experimentally proven that the AlN resonant detectors are responsive to the IR range of 0.5 – 20 µm. The anchors dimension does not have significant effect on resonant characteristic of the IR detectors due to high acoustic impedance of molybdenum (Mo). However, the longer and narrower anchors give longer response time with improved responsivity. The optimum interdigitated transducer electrode metallization ratio is chosen based on the resonant characteristic and IR absorption. It is worth noting that the devices with less number of electrode fingers give better sensitivity due to improved temperature coefficient of frequency.

The best performing devices operating at resonant frequency of 388 MHz has anchor dimensions of 12.5 µm × 31.5µm × 200 nm, interdigitated transducer electrode metallization ratio of 0.75 µm with 12 electrode fingers, IR sensing area of 150 µm
× 166 μm, and edge reflector distance of quarter-wavelength of the operating resonant frequency. The peak absorption of at least 90 % (responsivity of 6.0 W⁻¹) is achievable with resonant quality factor of > 1000, anti-resonant quality factor of > 1200 and effective coupling coefficient of 0.8 %. With the low noise characteristic, a noise-equivalent-temperature difference of about 20 mK is obtained at room temperature operation. It is also demonstrated that the AlN resonant detectors are working well at elevated temperatures up to 300 °C. Although the device quality factor and sensitivity degrade with temperature due to material softening and increasing thermal noise, the noise-equivalent-temperature-difference of about 45 mK is achievable with response time of 3.20 ms.
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# Table of Contents

**Executive Summary** ................................................................. i

**Acknowledgements** ....................................................................... iv

**Table of Contents** ........................................................................... vi

**List of Figures** ................................................................................ xi

**List of Tables** ................................................................................ xvi

**CHAPTER 1: INTRODUCTION** .......................................................... 1

1.1 Motivations .............................................................................. 1

1.2 Objectives .............................................................................. 4

1.3 Major Contributions .................................................................. 5

1.4 Thesis Organization .................................................................. 9

**CHAPTER 2: BACKGROUND OF INFRARED** ................................. 11

2.1 Infrared Radiation .................................................................... 11

2.1.1 Discovery of Infrared ........................................................... 11

2.1.2 Classification of Infrared ....................................................... 12

2.1.3 Thermal Radiation and Atmospheric Transmission .............. 13

2.1.4 Infrared Technology for Sensing Applications ....................... 16
2.2 Infrared Detectors ........................................................................................................ 18
  2.2.1 Photon Detectors ...................................................................................................... 20
  2.2.2 Thermal Detectors .................................................................................................... 21
2.3 Uncooled Infrared Detectors .......................................................................................... 24
  2.3.1 Infrared Absorption ..................................................................................................... 24
  2.3.2 Figure-of-merits ......................................................................................................... 27
  2.3.3 Theoretical Limit ........................................................................................................ 32
2.4 State-of-the-art and Future Trends ................................................................................... 36
  2.4.1 Outlook and Commercial .......................................................................................... 36
  2.4.2 Future Trends ............................................................................................................ 38

CHAPTER 3: ALUMINUM NITRIDE RESONANT UNCOOLED INFRARED DETECTOR ......................................................... 39

  3.1 Piezoelectric Resonators ............................................................................................... 39
    3.1.1 Piezoelectricity ........................................................................................................ 39
    3.1.2 Acoustic Wave Excitations ....................................................................................... 41
    3.1.3 Lamb Wave Resonator ........................................................................................... 42
  3.2 Resonant Infrared Detectors based on Piezoelectric Devices ................................. 48
    3.2.1 Operating Principle .................................................................................................. 48
    3.2.2 Material Selection .................................................................................................... 50
  3.3 Device Design Consideration based on Simulation ................................................. 54
### Table of Contents

3.3.1 Effects of SiO\(_2\) Passivation Layer ........................................... 58
3.3.2 Effects of Anchor Design .......................................................... 61
3.3.3 Effects of Edge Reflection, ER .................................................... 65
3.3.4 Effects of IDT Metallization Ratio ............................................. 67
3.3.5 Effects of Bolometric Size .......................................................... 68

**CHAPTER 4: Device Fabrication** ......................................................... 71

4.1 Overall Process Flow ........................................................................ 71
  4.1.1 Phase-one Fabrication ............................................................... 71
  4.1.2 Phase-two Fabrication ............................................................... 73
  4.1.3 Phase-three Fabrication ............................................................. 75
4.2 Silicon (Si) Deposition and Etching .................................................. 77
  4.2.1 LPCVD Poly-Si Deposition ......................................................... 77
  4.2.2 XeF\(_2\) Isotropic Dry Etching ...................................................... 78
  4.2.3 Si CMP ..................................................................................... 80
4.3 Silicon Dioxide (SiO\(_2\)) and Silicon Nitride (SiN) Deposition and Etching 81
  4.3.1 CVD SiO\(_2\) Deposition and Thermal Oxidation ......................... 81
  4.3.2 PECVD SiN Deposition ............................................................. 83
  4.3.3 SiO\(_2\) and SiN ICP-RIE Anisotropic Etching ............................ 83
  4.3.4 VHF Isotropic Dry Etching ....................................................... 84
  4.3.5 SiO\(_2\) CMP ............................................................................. 85
4.4 Molybdenum (Mo)/ Aluminium Nitride (AlN) Deposition and Etching ... 86

4.4.1 Deposition of Mo and AlN ................................................................. 86
4.4.2 AlN RIE Anisotropic Etching .......................................................... 88
4.4.3 Mo RIE Anisotropic Etching .............................................................. 92

4.5 Titanium Nitride (TiN) Deposition ....................................................... 93

4.6 Aluminium (Al) Deposition and Etching .............................................. 94

CHAPTER 5: Characterization of Resonant Behavior .........................96

5.1 Experiment Setup ............................................................................ 96
5.2 Equivalent Electrical Circuit Model .................................................. 100
5.3 Root Mean Square Frequency Noise ................................................. 107
5.4 Network Analyzer Parameter ............................................................ 108
5.5 Results and Discussion ................................................................... 111
  5.5.1 Effects of SiO$_2$ Passivation Layer ............................................. 112
  5.5.2 Effects of Anchor Design .............................................................. 113
  5.5.3 Effects of the Edge Reflector, ER ................................................. 115
  5.5.4 Effects of IDT Metallization Ratio ................................................. 116
  5.5.5 Effects of the Pixel Size ............................................................... 117
  5.5.6 Effects of Pressure and Temperature ........................................... 119

CHAPTER 6: Infrared Sensing Characterization .........................124

6.1 Experiment Setup ............................................................................ 124
Table of Contents

6.2 Infrared Absorption Characterization ........................................ 126
   6.2.1 Three-layer Film Stack Interferometric Absorption ..................... 126
   6.2.2 Fourier Transform Infrared (FTIR) Spectroscopy ........................ 129
6.3 Infrared Sensing Characterization ............................................. 130
   6.3.1 Temperature Coefficient of Frequency .................................... 130
   6.3.2 Steady State Response ..................................................... 132
   6.3.3 Transient Response ......................................................... 133
6.4 Results and Discussion .......................................................... 134
   6.4.1 Effects of SiO$_2$ Passivation Layer .................................... 134
   6.4.2 Effects of Anchor Design .................................................. 140
   6.4.3 Effects of IDT Metallization Ratio ..................................... 141
   6.4.4 Effects of Pixel Size ....................................................... 142
   6.4.5 Effects of Ambient Temperature ....................................... 144
6.5 Noise-equivalent-temperature-difference (NETD) .......................... 146

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS ....150

7.1 Conclusion .............................................................................. 150
7.2 Recommendations for Future Work ........................................... 153

Author’s Publications ......................................................................160

References ....................................................................................161
List of Figures

Figure 2-1: Experiment setup of IR radiation discovery. ........................................ 11

Figure 2-2: The full range of EM spectrum [30]. .................................................. 12

Figure 2-3: Radiation intensity emitted by a blackbody at different temperatures [32]. .......................................................... 13

Figure 2-4: Atmospheric transmission window in IR radiation range [34]. .......... 15

Figure 2-5: The IR-based sensing system. ............................................................... 16

Figure 2-6: (a) The 2D and (b) 3D schematic of a photo-interrupter integrates an emitter and detector in a single package. (c) A market available product of a photo-interrupter................................................................. 17

Figure 2-7: Reflective type photosensors detect light reflected by a target object... 17

Figure 2-8: Classification of infrared detectors. ...................................................... 18

Figure 2-9: (a) A general uncooled IR detector structure [42] and (b) the schematic flow of its working principle................................................................. 24

Figure 2-10: Cross-sectional view of two designs of resonant optical cavities to enhance IR absorption [2]. ................................................................. 27

Figure 2-11: Detectivity of thermal IR detector with different bolometric sizes in relation to (a) detector temperature and (b) effective thermal conductance, limited by temperature fluctuation noise [63]. ................................................................. 34

Figure 2-12: Detectivity of thermal detectors in relation to detector temperature, \( T_D \) and background temperature, \( T_B \) for FOV of \( 2\pi \) and \( \eta \) of 1, limited by temperature fluctuation noise [63]. ................................................................. 35

Figure 2-13: (a) Commercial VO\(_x\) bolometer with single-level of 28 μm × 28 μm pitch from BAE [65] and (b) VO\(_x\) bolometer in umbrella structure with 17 μm × 17 μm pitch from DRS [67]. ................................................................. 37

Figure 3-1: Schematic of (a) thickness excitation, (b) lateral field excitation, and (c) combination of both excitation schemes......................................................... 41

Figure 3-2: General schematic structure of (a) BAW and (b) SAW resonator........ 43
Figure 3-3: LWRs with acoustic reflection achieved by (a) reflector grating and (b) suspended free edges of the piezoelectric thin film. ......................................................... 44

Figure 3-4: (a) Symmetric and (b) asymmetric Lamb wave modes. ..................... 45

Figure 3-5: Different electrode configurations for Lamb wave devices. (a) Type-A: single-sided IDT. (b) Type-B: single-sided IDT with metallized backside. (c) Type-C: double-sided IDT. ................................................................. 46

Figure 3-6: (a) The phase velocity dispersion of S0 and A0 modes for the different electrode configurations of AlN LWR, and (b) the corresponding electromechanical coupling coefficients [80]. ......................................................... 47

Figure 3-7: Schematic diagram of resonant IR detector. ................................. 48

Figure 3-8: Schematic of the simulated (a) 2D and (b) 3D structure with labelled boundary conditions................................................................. 56

Figure 3-9: The illustration of parameters involved in the simulation. ............... 58

Figure 3-10: Simulated frequency response of AlN LWRs with different SiO2 passivation layer thicknesses. ................................................................. 59

Figure 3-11: Simulated displacement profile of AlN LWRs with different SiO2 passivation layer thicknesses. ................................................................. 60

Figure 3-12: Simulated resonant frequency shift of AlN LWRs with temperature at different SiO2 passivation layer thicknesses. ......................................................... 60

Figure 3-13: The 3D simulation structure of AlN LWRs (a) with AlN/Mo and (b) Mo anchors. The structure bottom view is shown in (c). ................................. 61

Figure 3-14: Comparison of resonant behavior for AlN LWRs with AlN/Mo and Mo anchors in (a) COMSOL and (b) ANSYS 3D simulations with the insets enlarging the frequency response at resonance. ......................................................... 62

Figure 3-15: The effect of anchor design on the thermal behaviour of AlN LWRs. The inset shows the temperature profile of the devices. ............................................. 62

Figure 3-16: The effect of anchor design on frequency response of AlN LWRs. (a) \( W_{\text{anc}} \) is first fixed at 10 \( \mu \text{m} \) and \( L_{\text{anc}} \) is varied. The value of \( L_{\text{anc}} \) is then fixed at 31.25 \( \mu \text{m} \) and \( W_{\text{anc}} \) is varied in (b) arbitrary integers and (c) different multiples of quarter-wavelength. The insets enlarge the frequency response at resonance. ............................................. 64

Figure 3-17: The effect of anchor design on frequency response of AlN LWRs. The inset shows the temperature profile of the AlN LWR. ............................................. 65

Figure 3-18: The COMSOL 2D simulated frequency response of AlN LWRs in (a) odd and (b) even number of IDT fingers with different values of \( d_{\text{ERS}} \). The displacement profiles of the devices are shown at the bottom of each graph. ............ 66
Figure 3-19: (a) COMSOL 2D and (b) ANSYS 3D simulation results show the effect of metallization ratio on frequency response of AlN LWRs. 67

Figure 3-20: The effect of N on frequency response of AlN LWRs with d_{ER} of (a) quarter-wavelength (b) 1.5*quarter-wavelength, and (c) 2*quarter-wavelength where N varies from 2 to 12. 69

Figure 3-21: The effect of L_{AL} on frequency response of AlN LWRs. 70

Figure 4-1: The phase-one AlN resonant IR detector. 72

Figure 4-2: Overall fabrication process flow of the phase-one AlN resonant IR detectors. 72

Figure 4-3: The phase-two AlN resonant IR detector. 73

Figure 4-4: Overall fabrication process flow of the phase-two AlN resonant IR detectors. 74

Figure 4-5: The phase-three AlN resonant IR detector. 75

Figure 4-6: Overall fabrication process flow of the phase-three AlN resonant IR detectors. 76

Figure 4-7: Step coverage of the deposited film by (a) PECVD and (b) LPCVD. 78

Figure 4-8: SEM image of XeF_{2}-released structure of phase-one device. The inset clearly shows the XeF_{2} released pit. 79

Figure 4-9: Formation of release isolation wall in phase-three devices. 80

Figure 4-10: Comparison of SiO_{2} step coverage deposited using (a) PECVD, (b) HDP-CVD and (c) thermal oxidation. 82

Figure 4-11: SiO_{2} and SiN etching for (a) contact and (b) release window opening. 84

Figure 4-12: The SEM image of the VHF-released structure of phase-three device. 85

Figure 4-13: SiO_{2} CMP on Mo IDT electrodes to flatten the surface topology prior to AlN deposition. 85

Figure 4-14: XRD patterns for a 1 μm AlN film deposited on 200 nm thick Mo IDT electrodes (a) without and (b) with 20 nm thick AlN seed layer. 87

Figure 4-15: Illustration of AlN etching with PR as the masking layer in phase-one fabrication. 88

Figure 4-16: AlN etching profile in the first approach with PR as masking layer. 89
Figure 4-17: AlN etch profile using modified recipe with only PR as masking layer. ................................................................. 90

Figure 4-18: AlN etching with SiO₂ as hardmask and stop on SiO₂ or Mo surface. 91

Figure 4-19: SEM images of the patterned AlN at different stages in (a) phase-one and (b) phase-two fabrications using optimized recipe. ......................................................... 92

Figure 4-20: Illustration of Mo etching in the fabrication of AlN resonant IR detectors. ................................................................................................................................. 93

Figure 4-21: Mo etching profile with PR as the masking material.................. 93

Figure 4-22 : SEM images of Al etching results using (a) the standard etch recipe and (b) the combined standard and modified recipe in phase-one device. ............ 95

Figure 4-23: SEM images of Al etching results using the combined standard and modified etch recipe in phase-three devices. ................................................................. 95

Figure 5-1: Experiment setup for resonant characteristic and noise analysis of the AlN resonant IR detectors................................................................. 96

Figure 5-2: Schematic of a two-port network with signals in and out............. 97

Figure 5-3: The GSG probe for high frequency measurements..................... 98

Figure 5-4: Planarization of GSG probe tips. (a) Only two tips are in contact with the Contact Substrate. (b) All three tips are in contact with the Contact Substrate but one tip makes a deeper scratch than another. (c) Probe tips are in-plane: all three tips leave an even scratch on the Contact Substrate. ..................................................... 98

Figure 5-5: Different configurations of SOLT calibration on the dedicated ISS..... 99

Figure 5-6: The conventional BVD circuit model. ....................................... 100

Figure 5-7: The modified BVD circuit model. ............................................. 101

Figure 5-8: (a) The one-port and (b) two-port MBVD circuit models............ 104

Figure 5-9: Mason lumped circuit model for piezoelectric resonators. .......... 105

Figure 5-10: The simplified Mason lumped circuit model. ......................... 106

Figure 5-11: RMS noise measurement of a two-port resonator................. 107

Figure 5-12: Illustration of stepped frequency sweep................................. 109

Figure 5-13: (a) The measured frequency response and (b) RMS value of $S_{21}$ phase of the AlN resonant IR detector at different IF BWs........................................ 109

Figure 5-14: (a) The measured frequency response and (b) standard deviation of $S_{21}$ phase of the AlN resonant IR detector at different driving powers .......... 110
Figure 5-15: The measured frequency response of AlN LWRs with different SiO$_2$ thicknesses. ................................................................. 112

Figure 5-16: The measured and fitted frequency response of the AlN LWRs with support anchors of (a) AlN/Mo and (b) Mo. ................................................................. 113

Figure 5-17: The measured frequency response of AlN LWRs with $W_{\text{anc}}$ fixed at 12.5 μm and varying $L_{\text{anc}}$. ................................................................. 114

Figure 5-18: The measured frequency response of the AlN LWRs with (a) odd and (b) even numbers of IDT fingers with different values of $d_{\text{ER}}$. The $Q$-factor and $k_t^2$ of the device with $d_{\text{ER}}$ of quarter-wavelength are also included in the graphs .......... 115

Figure 5-19: The measured frequency response of AlN LWRs with different metallization ratios. .................................................................................. 116

Figure 5-20: The measured frequency response of AlN LWRs with different values of $L_{\text{AL}}$. .................................................................................. 117

Figure 5-21: The effect of $N$ on the frequency response of the AlN LWRs with $d_{\text{ER}}$ of (a) quarter-wavelength, (b) 1.5*quarter-wavelength and (c) 2*quarter-wavelength. The insets magnify the frequency response at the resonances .......... 119

Figure 5-22: (a) The measured frequency response, (b) resonant characteristic and (c) standard deviation of $S_{21}$ phase of AlN LWRs at different operating pressure levels. .................................................................................. 120

Figure 5-23: (a) The stability of the resonant frequency and (b) standard deviation of $S_{21}$ phase of AlN LWRs at elevated temperatures before and after annealing. ...... 121

Figure 6-1: Experiment setup for IR sensing and thermal characterization of the AlN resonant IR detectors. .................................................................................. 124

Figure 6-2: The wavelength dependent transmission of (a) ZnSe optical filter and (b) edge-pass optical filter. .................................................................................. 125

Figure 6-3: (a) The IR spectral irradiance and (b) radiant power density incidents on the AlN resonant IR detector at different blackbody source temperatures. .............. 126

Figure 6-4: Estimated absorption spectral for different values of (a) $R_t$ and (b) $T_d$. 128

Figure 6-5: Schematic illustration of FTIR system .................................................................................. 129

Figure 6-6: Comparison of absorption spectral between theoretical and measurement for (a) $T_d = 985$ nm and (b) $T_d = 1.45$ μm. .................................................................................. 129

Figure 6-7: Relation between resonant frequency and temperature of the AlN resonant IR detector before and after annealing. ................................................................. 131

Figure 6-8: Frequency response of an AlN resonant IR detector upon IR illumination at steady state. .................................................................................. 132
Figure 6-9: Illustration of transient sensing response and estimation of response time of AlN resonant IR detectors. ................................................................. 133

Figure 6-10: (a) Transient response and (b) temperature-dependent resonant frequency shift of AlN resonant IR detectors with different SiO₂ thicknesses. 135

Figure 6-11: (a) Frequency response and (b) steady-state IR response of the AlN resonant IR detector with 1 μm thick SiO₂ passivation layer (device P2-5). 136

Figure 6-12: The $S_{21}$ magnitude shift at resonance in relation to absorbed IR power for AlN resonant IR detectors with different SiO₂ thicknesses. 136

Figure 6-13: Comparison of IR response under ambient and vacuum conditions for AlN resonant IR detector with 1 μm thick SiO₂ passivation layer (device P2-5). 137

Figure 6-14: Capacitance variation of AlN resonant IR detector under ambient and vacuum condition for a device with a 1 μm thick SiO₂ passivation layer (device P2-5). The highlighted regions indicate the IR exposure period. 137

Figure 6-15: Transient response with the steady-state responsivity and response time for devices having different anchor designs. 140

Figure 6-16: (a) Transient response, (b) steady-state responsivity and response time for devices with different anchor lengths, $L_{\text{anc}}$. 141

Figure 6-17: Transient response for devices with different anchor widths, $W_{\text{anc}}$. 141

Figure 6-18: (a) Absorption spectrum; (b) transient response; (c) steady-state response and response time for AlN resonant IR detectors having different metallization ratios. 142

Figure 6-19: Transient response, steady-state responsivity and response time of AlN resonant IR detectors with different $L_{\text{ALS}}$. 143

Figure 6-20: Transient response, steady-state responsivity and response time of AlN resonant IR detectors with different IR absorbing areas ($W_{\text{AlN}} \times L_{\text{AlN}}$). 143

Figure 6-21: Absorption spectrum of AlN resonant IR detectors at elevated temperatures. 144

Figure 6-22: Frequency fluctuation with operating temperature. 145

Figure 6-23: Transient sensing response of AlN resonant IR detectors (a) before and (b) after annealing at elevated temperatures. (c) Steady-state responsivity and (d) response time of the devices during temperature cycling. 146

Figure 6-24: Transient response of AlN resonant IR detectors in the IR detection range of (a) 0.5 – 20 um and (b) 5.5 – 20 um. (c) The shift of resonant frequency in relation to the absorbed IR power. 147
Figure 6-25: Measured $S_{21}$ phase Allan variance of an AlN resonant IR detector at $f_0$ of 377 MHz and $d\phi/df$ of $1.24 \times 10^{-4}$ deg/Hz.......................... 148

Figure 6-26: Relation of NETD of AlN resonant IR detectors with (a) device effective thermal conductance, $G_{th}$, (b) IR absorbing area, $A_D$, and (c) operating temperature. ................................................................. 149

Figure 7-1: Schematic illustration of (a) three-layer film stack interferometric absorption structure and (b) metamaterial-structured absorption system. ............... 155

Figure 7-2: AlN resonant IR detectors with the TCF enhancer (a) deposited on top of the device and (b) embedded within the upper portion of AlN. ....................... 157

Figure 7-3: The 2D axisymmetric model in the finite-element analysis for TCF simulation................................................................. 158

Figure 7-4: The stimulated TCF of AlN resonator with and without Al TCF enhancer. ........................................................................ 158
List of Tables

Table 2-1: IR radiation wavelength divisions [31].......................... 12
Table 2-2: The pros and cons for different types of IR detectors [1]........ 19
Table 2-3: Commercial thermal IR detectors arrays are based on semiconductor resistive bolometers [68]................................................................. 37
Table 3-1: Domain settings for resonant and thermal behavior simulations. ........ 55
Table 3-2: Boundaries settings for the 2D and 3D simulations ...................... 56
Table 3-3: Material properties of AlN and Mo used in the simulation study [80, 117-126] ........................................................................................................... 57
Table 3-4: The device structural parameters studied in COMSOL 2D simulation... 59
Table 3-5: Geometry specifications of devices in 3D simulation with different anchor designs................................................................. 61
Table 4-1: Recipe of the poly-Si CMP using the Ebara CMP tool............... 81
Table 4-2: Recipe of the SiO₂ CMP process using an AMAT CMP tool......... 86
Table 4-3: Al etching recipes used by Centura Metal Etching tool............... 94
Table 5-1: Geometry specification of phase-two devices............................. 111
Table 5-2: Resonant characteristics of AlN LWRs with different SiO₂ thicknesses. .................................................................................................................. 113
Table 5-3: The resonant characteristic of AlN LWRs with different IDT fingers number at δER of quarter-wavelength.................................................. 118
Table 5-4: The resonant characteristics of the AlN LWRs before and after annealing at elevated temperatures................................................................. 122
Table 6-1: The estimated IR response of AlN resonant IR detectors with different SiO₂ thicknesses................................................................................. 135
CHAPTER 1: INTRODUCTION

1.1 Motivations

Ever since astronomer Sir William Hershel in April 1800, announced the discovery of infrared (IR), development of IR engineering progressed in tandem with IR detectors. IR detectors can be grouped into two main groups: photon detectors and thermal detectors. Photon detectors convert the incoming photons into the detectable photocurrents while thermal detectors absorb the incoming radiation energy and convert it into heat energy, which changes certain material properties that are measurable. In the early days, the major applications of IR detection were based on photon detectors in the field of military, defence, astronomy and aerospace. However, they are too costly and bulky for domestic and industry applications because of the cryogenic cooling system.

With the advancements in micromachining technologies, micro-electro-mechanical systems (MEMS) based thermal detectors have gained wide attention since the early 1990s due to their advantages of wide spectral response and uncooled operation [1, 2]. They are low weight, low power consumption, high reliability, low operating and manufacturing costs. Therefore, MEMS-based thermal detectors are playing an increasingly important role in miniaturized and portable thermal imaging applications such as firefighting, automotive night vision, surveillance, industrial inspection, energy conservation and medical diagnosis [3-6].
Along with the discovery of interesting applications of IR thermography, radiometric and spectroscopy including non-destructive testing (NDT), building structural health monitoring, printed circuit board (PCB) evaluation, gas sensing and element identification, many types of thermal detectors based on different temperature sensing principles have been developed: thermoelectric [7, 8], pyroelectric [9, 10], resistive [11-16] and thermomechanical [17, 18]. Among these, only resistive bolometer and pyroelectric detectors have found commercial success. However, the sensitivity of thermal detectors still needs to be improved to the performance level of photon detectors in order to attain success in the competitive IR detector market.

The most successful uncooled IR detectors in thermal imaging applications are semiconductor-based resistive microbolometers because they are relatively easy to fabricate compared with pyroelectric detectors and have a better detectivity than thermoelectric detectors. Nonetheless, this IR detection technology is facing bottleneck in detectivity enhancement. In addition to the fundamental noise sources (temperature fluctuation and background fluctuation noise), their performance is limited by flicker (1/f) and Johnson noise (or thermal noise). Furthermore, they are not suitable to operate under high temperature (>85 °C) conditions as the sensing resistance drop significantly. When the sensing resistance drops to the same order of magnitude with the series system resistance, the readout of the response signal will be a great challenge. Therefore, there is a perceived need for alternative novel techniques in uncooled IR detection technologies that could achieve a significant enhancement of sensitivity over the established one.
Resonant IR detectors appear to be a convincing candidate for uncooled IR detection. It draws much less power with controllable self-heating in comparison with a resistive microbolometer because no direct current (DC) is flowing through the sensing materials. The $1/f$ noise of resonant IR detector could be ignored due to high frequency operation (> 100 MHz). In addition, it can potentially achieve higher sensitivity as frequency shift can be measured with high accuracy, compared with resistance readout. The feasibility of bulk acoustic wave (BAW) quartz resonators as the thermal IR sensor was first reported in 1985 [19], followed by a detailed analysis of sensing properties for thermal imaging applications in 1994 [20]. Quartz-based film bulk acoustic resonators (FBAR) as microbolometers could potentially achieve a very good noise-equivalent-temperature-difference (NETD) of less than 5 mK [21]. However, they are not compatible with CMOS technology and not scalable to sub-micron size, rendering them impossible for mass production.

Effort has been made to explore different piezoelectric materials including gallium nitride (GaN) [22, 23], zinc oxide (ZnO) [24] and AlN [25, 26] for IR sensing applications. Among these materials, thin AlN piezoelectric films with high quality and uniformity can be deposited at low temperature (~200 - 400 °C) by sputtering process on silicon substrates enabling post-CMOS integration processes [27, 28]. This thesis will therefore focus on AlN resonant IR detectors. A CMOS compatible fabrication flow is developed, followed by careful design considerations. Resonant, thermal and sensing properties of the fabricated AlN resonant detectors are systematically characterized both at room temperature and elevated temperatures. IR sensing mechanism is studied and discussed using fitted equivalent circuit.
1.2 Objectives

This project focuses on the design and fabrication of resonant IR detectors based on sputtering AlN piezoelectric thin film, and investigating their sensing properties and underlying IR sensing mechanisms that govern the performance of the sensors. The main objectives of the thesis are broadly classified as follows:

a) Structural design of AlN resonators by simulations

For any MEMS-based sensor, structural design is of particular importance to achieve the ultimate sensing performance. The 2D COMSOL Multiphysics and ANSYS simulation tools were first employed to study the effect of AlN piezoelectric thin film geometry, passivation layers, excitation electrodes configuration and metallization ratio on the device resonant characteristic. Furthermore, the support anchor design directly reflects the efficiency of device thermal isolation, which can also be estimated by 3D simulation.

b) Development of CMOS-compatible fabrication process for AlN resonant IR detectors

The CMOS-compatible fabrication process for AlN resonant IR detectors has been developed in three phases. In the first and second phases, different excitation electrodes configurations were fabricated and tested. Accumulating the measurement results from previous phases, the fabrication process and device structural design were optimized in the third phase with minimum number of mask layers and process steps. Defect review-scanning electron microscope (DR-SEM), energy dispersive (EDX) and X-ray diffraction (XRD) were employed for surface
morphology inspection, elemental analysis and crystallinity study, respectively, in certain process steps throughout the fabrication process.

c) Characterization of resonant properties and noise analysis of AlN resonant detectors

Upon successful fabrication of AlN resonant IR detectors, their resonant properties and noise analysis were performed using network analyzer in a vacuum prober equipped with RF feedthroughs. The effect of annealing, operating temperature, pressure level, measurement parameter and structural design were investigated.

d) Characterization of thermal properties and IR sensing performance of AlN resonant IR detectors

Fourier transform infrared (FTIR) was firstly employed to study the IR absorption spectrum of the fabricated AlN resonant IR detectors. Blackbody source and optical filter were installed externally at a vacuum prober equipped with temperature chuck for characterization of thermal properties and IR sensing performance of the detectors. The measurement data was fitted by an equivalent electrical circuit for detail study of the sensing mechanism. The effect of operating temperature and structural design were then explored.

1.3 Major Contributions

With reference to the four objectives outlined in the last section, few major research contributions have been achieved throughout this project.
a) Integrated the three-layer film stack interferometric absorption system with the piezoelectric resonator

The three-layer film stack interferometric absorption system has been successfully integrated on the AlN piezoelectric resonators as the resonant IR detectors for the first time. The previous reported works on resonant IR detectors were mainly based on the passive IR absorbing layer deposited directly on the resonators. The thick passive IR absorbing (few hundreds nm) induces serious mass loading to the resonators, giving rise to the degradation of the resonators’ $Q$-factor and hence the decrease in detectors’ IR detectivity. Furthermore, the IR absorbing layer increases the system heat capacity, which in turn, slows down the sensing response. This thick absorbing layer also potentially imposes film stress issues on the overall IR detectors.

In this three-layer film stack interferometric absorption system, only an additional ultra-thin titanium nitride (TiN) layer (< 10 nm) is added to the conventional AlN/Mo piezoelectric resonators. The 10 nm thick TiN layer has insignificant mass loading and film stress effect on the 1 μm/200 nm AlN/Mo resonators. Absorption peaks of more than 90% were achieved. It was also demonstrated that the absorption peaks can be designed by changing the thickness of AlN. This is of particular importance when only a certain range of IR wavelengths is to be detected.

b) Fabricated the AlN resonant IR detectors using the CMOS-compatible process

The CMOS-compatible process flow has been successfully developed for the AlN resonant IR detectors. The structural parts of the devices were fabricated at temperature less than 250 °C. Among all the piezoelectric materials, only AlN can be deposited on silicon wafer at such low temperature and yet exhibit good
crystalline structure. This enables the monolithic integration between the IR detectors and the readout circuits. Therefore, the process yield can be significantly improved and the fabrication costs can be reduced.

c) Characterized the IR detecting operation of the AlN resonant detectors at elevated temperatures

The fabricated AlN resonant IR detectors have been demonstrated to operate at elevated temperatures up to 300 °C. This is the highest operating temperature reported for thermal IR detectors. The IR absorption spectrum of the devices was examined at different temperatures and negligible shift was observed. The $Q$-factor and IR detectivity were slightly degraded with increasing temperature because of the material softening and increasing thermal noise. Nevertheless, the NETD of about 36 mK was estimated with response time of 3.20 ms at temperature of 300 °C. The demand on ruggedized sensors network is greatly increased with the advancements in the field of automotive, aerospace, geothermal, oil and gas exploration. This achievement could benefit these industries that have extreme operating environment (high temperature, high pressure, corrosive, etc).

d) Studied the effects of various design parameters on the IR sensing properties of the AlN resonant IR detectors

Different types of resonant IR detectors have been reported elsewhere but there are no detailed evaluations on the effects of design parameters. In this thesis, simulations was firstly employed to predict the resonant and IR sensing properties of the AlN resonant IR detectors based on various structural design factors include
anchor dimensions, edge reflector distance, electrode metallization ratio, and pixel size. Experiments were then carried out to verify the findings of simulations.

It was worth noting that the resonant behaviour of the device is insensitive to the anchor dimensions, which contradicts the literature. This could be attributed to the anchors that only consist of Mo rather than AlN/Mo. Since Mo has high acoustic impedance, the acoustic loss to the substrate is minimized. Eliminating the AlN from the anchor design also improves the thermal isolation of the sensing device and hence enhances the IR detectivity.

The effects of Mo electrode metallization ratio on the AlN resonant IR detectors were inspected and reported in detail for the first time. It was found that the optimum metallization ratio is critical for the AlN resonant IR detectors to ensure both the resonant characteristics and the sensing performance. The higher metallization ratio is desired for the better IR absorption but this increases mass loading and acoustic loss to the electrodes.

e) Proposed the optimum operating frequency for the AlN resonant IR detectors

One of the major contributions of this thesis is the proposal of optimum operating frequency for the AlN resonant IR detectors. It was observed that there is a downshift of $S_{21}$ magnitude when the device was exposed to IR radiation. This phenomenon aligned with the capacitance measurement of the devices, whereby an increase in AlN capacitance was observed upon to IR exposure. The fitting of equivalent electrical circuit model confirmed that the downshift of $S_{21}$ magnitude was caused by the increase of AlN capacitance. However, this IR-induced $S_{21}$ shift phenomenon was only observed for devices operating at resonant frequency higher
than 800 MHz. After verification with the equivalent electrical circuit model, the small change in AlN capacitance can only shift the $S_{21}$ in a significant magnitude at high operating frequencies. Therefore, the AlN resonant IR detectors were suggested to operate at a few hundred MHz frequencies to eliminate the undesired noise induced by the $S_{21}$ magnitude shift.

1.4 Thesis Organization

The thesis is organized into seven chapters and the flow is structured as below:

Chapter 1 provides the introduction of the thesis, encompassing the motivation for this project, objectives, major contributions and organization of the thesis.

Chapter 2 presents a comprehensive introduction of IR radiation and its implications including the basic IR sensing technologies and thermally IR absorption mechanisms. A review of the figure-of-merit (FOM) and theoretical limits is made, followed by state-of-the-art and future trends in uncooled IR detector technology.

In chapter 3, detailed working principle of AlN resonant uncooled IR detector is described. The background theory of AlN piezoelectric resonator is first provided. Next, the temperature sensing mechanism and material selection criteria for the IR detector are explained. The device structural design consideration is then delineated with the help of simulation results.

Chapter 4 delineates the fabrication flow for the AlN resonant IR detector. Three phases of fabrication are experienced before achieving the device with optimized performance. Process challenges and possible solutions are described with the DR-SEM images.
Chapter 5 shows experimental results of frequency response and noise performance of the fabricated devices. The setup and equipment used are outlined. Detailed explanation of the equivalent electrical circuit modelling is given, followed by noise analysis. Resonant characteristics and noise levels of the detectors are elaborated, by emphasising the effect of operating ambient, measurement parameter and structural design.

Chapter 6 reports the thermal characteristics and sensing properties of the AlN resonant IR detectors. The IR absorption spectra of the detectors are depicted analytically using FTIR. Next, the steady-state IR sensing response is studied using the equivalent electrical circuit modelling. The transient IR sensing response is performed for the device response speed. The effects of ambient temperature and device structural design are also discussed in detail.

Finally, Chapter 7 concludes the thesis report and proposes recommendations for future direction of this research project.
CHAPTER 2: BACKGROUND OF INFRARED

2.1 Infrared Radiation

2.1.1 Discovery of Infrared

In the year of 1800, Sir Frederick William Herschel conducted an experiment to investigate his hypothesis that different colours of visible light might contain different levels of heat [29]. In the experiment (Figure 2-1), sunlight was directed through a glass prism to create a rainbow spectrum and temperature of each colour region was measured. Thermometer placed in the colour regions was always found to have higher temperature than the control and the temperature was increasing from violet to red region. To his surprise, the region just beyond the red colour region had the highest temperature of all. These “calorific rays” were later renamed as infrared (IR) radiation. Today, IR technology has many exciting and useful applications as mentioned previously.

Figure 2-1: Experiment setup of IR radiation discovery.
2.1.2 Classification of Infrared

Figure 2-2: The full range of EM spectrum [30].

Table 2-1: IR radiation wavelength divisions [31].

<table>
<thead>
<tr>
<th>Type of IR</th>
<th>Wavelength (µm)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-infrared (NIR)</td>
<td>0.75 – 1.4</td>
<td>Fiber optic telecommunication and remote sensing</td>
</tr>
<tr>
<td>Short-wavelength</td>
<td>1.4 – 3.0</td>
<td>Long distance telecommunication</td>
</tr>
<tr>
<td>infrared (SWIR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-wavelength</td>
<td>3.0 – 8.0</td>
<td>Guided missile technology and gases detection</td>
</tr>
<tr>
<td>infrared (MWIR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long-wavelength</td>
<td>8.0 – 15.0</td>
<td>Thermal imaging</td>
</tr>
<tr>
<td>infrared (LWIR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Far-infrared (FIR)</td>
<td>15 – 1000</td>
<td>FIR laser in fusion plasma physics diagnostics</td>
</tr>
</tbody>
</table>

IR is an electromagnetic (EM) radiation with photon energy from 1.24 meV to 1.7 eV and wavelengths from 0.75 µm to 1000 µm. Figure 2-2 shows the whole range of EM spectrum whereby IR light lies between visible light and microwaves. Objects at
room temperature emit thermal radiation whereby a large portion is included in the IR wavelength range. However, only a certain range of the spectrum is of interest because most of the IR sensors detect only a specific bandwidth of the radiation. Thus, IR radiation is usually categorized into smaller sections that have different practical significances as summarized in Table 2-1.

2.1.3 Thermal Radiation and Atmospheric Transmission

![Graph showing radiation intensity emitted by a blackbody at different temperatures](image)

Figure 2-3: Radiation intensity emitted by a blackbody at different temperatures [32].

Every object is composed of continually vibrating atoms and thus generates EM waves. The atoms gain more energy and vibrate stronger to emit a higher radiant intensity when object is at a higher temperature. The radiant intensity varies with wavelength and temperature as given by Planck’s radiation law (Equation 2-1). An ideal blackbody in thermodynamic equilibrium absorbs the entire radiation that falls
on it and emits EM energy at different temperatures as shown in Figure 2-3. The emitted EM energy increases with temperature. According to Wien’s displacement law (Equation 2-2), the peak emission wavelength, $\lambda_{\text{max}}$ decreases with object temperature.

$$M_{\lambda}(T, \lambda) = \frac{2\pi h c^2}{\lambda^5 \left[ \exp \left( \frac{hc}{\lambda k T} \right) - 1 \right]} \text{ (in } W \cdot \text{m}^{-3} )$$ \hspace{1cm} \text{Equation 2-1}

$$\lambda_{\text{max}} \cdot T = 2898 \text{ (} \mu \text{m} \cdot \text{K} )$$ \hspace{1cm} \text{Equation 2-2}

where $M_{\lambda}$ is the spectral radiant emittance, $\lambda$ is the emitted wavelength, $T$ is the object temperature, $h$ is the Planck’s constant, $c$ is the light velocity, and $k$ is the Boltzmann’s constant.

In real case applications, IR radiation is encountering attenuation due to gas molecules scattering when transmitting through air. Scattering occurs because of the absorption and subsequent re-radiation of energy by floating particles, causing the radiation beam direction to change. Scattering by larger particles does not dependent on wavelength. For wavelengths longer than 2 $\mu$m, scattering by gas molecules is insignificant. In addition, IR radiation can penetrate through smoke and light mists particles because they are considered small in comparison to IR wavelengths [33].

Figure 2-4 shows the earth’s atmospheric transmission spectrum through 2 km of atmosphere as a function of radiation wavelength. Atmospheric transmission is restricted to 3 – 5 $\mu$m (MWIR) and 8 – 14 $\mu$m (LWIR) because of specific absorption bands of oxygen, carbon dioxide and water. Methane, carbon monoxide and nitrous oxide do absorb IR radiation but are less important as their compositions in atmosphere are relatively small.
A blackbody radiates at the highest intensity in the wavelength range of around 10 μm when its temperature being around 300 K, which coincide with the atmospheric transmission window of LWIR band. This explains why most of the IR sensors are operating in this wavelength range for thermal imaging applications. IR sensing utilizing MWIR wavelength range is also possible, particularly for hot targets, or applications where contrast is the main specification. It has advantages of lower ambient and background noise (Figure 2-4). Additionally, optics with smaller diameter is needed to obtain a certain resolution compared to the LWIR band.

Overall, IR sensing in MWIR and LWIR bands differ noticeably on the aspect of atmospheric transmission, temperature contrast, scene characteristics, and background flux under various weather conditions. Factors that favour MWIR applications are superior clear-weather performance, higher resolution, higher contrast, and higher transmission. LWIR band sensing is more appropriate for imaging in fog and dust conditions, winter haze, atmospheric turbulence, solar glints and fire flares.
2.1.4 Infrared Technology for Sensing Applications

In addition to thermal imaging and target tracking, IR detection technology is utilized in a broad variety of wireless applications, particularly in the areas of sensing [35-37]. In IR sensing systems (Figure 2-5), there is no direct interaction between the sensing material and the measurands, thereby avoiding the systems to get corroded or poisoned by reactive measureands. They can also be designed to be easily dismantled for maintenance and hence has a longer life span. Nowadays, IR-based sensing systems are widely used in industries that have harsh environment including combustible and hazardous gas monitoring, concrete and piping quality assurance. In addition to remote control and communication modules, products take advantage of several IR technologies below to address a variety of sensing applications:

**Figure 2-5: The IR-based sensing system.**

**IR emitters:** An IR emitter is a light emitting diode (LED) which provides IR source in desired bandwidth. Different types of IR LEDs are available to cater for different packaging.

**IR receivers (or IR detectors):** IR receivers are also called sensors or detectors. They detect the emitted radiation from IR emitter. IR receivers can be customized
according to the requirement of packaging, optic features, and some dedicated circuitries include wide viewing angle, ambient light filter, and so on.

**Photo-interrupters**: A photo-interrupter generally consists of an IR emitter and detector which are packaged in a U-shaped holder. Emitter and detector are located face-to-face in a transmission type photo-interrupter (Figure 2-6). The holder shape and size differentiate different types of photo-interrupter.

![Figure 2-6](image)

Figure 2-6: (a) The 2D and (b) 3D schematic of a photo-interrupter integrates an emitter and detector in a single package. (c) A market available product of a photo-interrupter.

**Photo-reflectors**: A photo-reflector is a reflective type of photo-interrupter. Photo-reflectors detect the reflected beams as shown in Figure 2-7. The main electrical
Chapter 2

characteristics include: sensor collector current vs. IR LED current, response switching time, transfer gain rate, and detection wavelength.

2.2 Infrared Detectors

![Classification of infrared detectors](image)

With the increasing number of aforementioned IR sensing and wireless applications, a variety of IR detectors has been invented and developed. The existing IR detection technologies can basically be grouped into two major categories: photon detectors and thermal detectors. Photon detectors depend on the photon absorption of specific wavelengths of the EM spectrum while thermal detectors depend on the heating effect due to the phonon absorption and further change a certain parameters of the device. The photon and thermal detectors can be further split into different categories as summarized in Figure 2-8.
Table 2-2: The pros and cons for different types of IR detectors [1].

<table>
<thead>
<tr>
<th>Detector</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photon:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrinsic</td>
<td>IV-VI materials</td>
<td>IV-VI materials</td>
</tr>
<tr>
<td></td>
<td>- Easier to prepare</td>
<td>- Very high thermal expansion</td>
</tr>
<tr>
<td></td>
<td>- More stable materials</td>
<td>- Large permittivity</td>
</tr>
<tr>
<td>II-VI materials</td>
<td>- Easy bandgap tailoring</td>
<td>II-VI materials</td>
</tr>
<tr>
<td></td>
<td>- Multicolor detectors</td>
<td>- Non-uniformity over large area</td>
</tr>
<tr>
<td>III-V materials</td>
<td>- Possible monolithic integration</td>
<td>- High cost in fabrication</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Surface instability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>III-V materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Large lattice mismatch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Long wavelength cut-off limited to 7 μm (at 77 K)</td>
</tr>
<tr>
<td>Extrinsic</td>
<td></td>
<td>High thermal generation</td>
</tr>
<tr>
<td></td>
<td>- Very long wavelength operation</td>
<td>Extremely low temperature operation</td>
</tr>
<tr>
<td></td>
<td>- Relatively simple technology</td>
<td></td>
</tr>
<tr>
<td>Free carriers</td>
<td>Low-cost, high yields</td>
<td>Low quantum efficiency</td>
</tr>
<tr>
<td></td>
<td>Large &amp; close packed 2D array</td>
<td>Low temperature operation</td>
</tr>
<tr>
<td>Quantum well</td>
<td>Type I</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Matured material growth</td>
<td>Type I</td>
</tr>
<tr>
<td></td>
<td>- Good uniformity</td>
<td>- High thermal generation</td>
</tr>
<tr>
<td></td>
<td>- Multicolor detectors</td>
<td>- Complicated design and growth</td>
</tr>
<tr>
<td></td>
<td>Type II</td>
<td>Type II</td>
</tr>
<tr>
<td></td>
<td>- Low Auger recombination rate</td>
<td>- Complicated design and growth</td>
</tr>
<tr>
<td></td>
<td>- Easy wavelength control</td>
<td>- Sensitive to the interfaces</td>
</tr>
<tr>
<td></td>
<td>- Multicolor detectors</td>
<td></td>
</tr>
<tr>
<td><strong>Thermal:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistive</td>
<td>Small thermal capacity</td>
<td>Slow response</td>
</tr>
<tr>
<td></td>
<td>- Large temperature coefficient</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Rugged</td>
<td></td>
</tr>
<tr>
<td>Pyroelectric</td>
<td>Fast response</td>
<td>Required chopper</td>
</tr>
<tr>
<td>Thermoelectric</td>
<td>Reliable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low cost</td>
<td>Low detectivity</td>
</tr>
<tr>
<td>Thermomechanical</td>
<td>High fill factor</td>
<td>Bulky optical readout system</td>
</tr>
<tr>
<td></td>
<td>Fast response</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large focal plane array</td>
<td></td>
</tr>
<tr>
<td>Gas expansion</td>
<td>High detectivity</td>
<td>Slow response</td>
</tr>
<tr>
<td>Resonant</td>
<td>Fast response</td>
<td>Large pixel size</td>
</tr>
<tr>
<td></td>
<td>High detectivity</td>
<td></td>
</tr>
</tbody>
</table>
Before 1990s, photon detectors are preferred over thermal detectors because of their superior sensing performance. With the advances in micromachining techniques, it is now possible to fabricate thermal detectors with comparable sensitivity with that of photon detectors. Each type of detector has its own characteristics, giving the pros and cons when applied in different fields and applications (Table 2-2).

2.2.1 Photon Detectors

In photon detectors, IR is absorbed by the sensing material through the interaction of photons and electrons inside the material, which giving rise to the change of electronic energy distribution and thus the electrical output. Generally, the sensitivity of photon detectors depends on the spectral absorption and photo-excitation, which is determined by the energy bandgap of the sensing material. Operation of photon detectors generally requires cooling system to avoid the thermal-generated charge carriers from competing with the optical ones so that the desired signal-to-noise ratio is attainable [1]. The cooling system makes the semiconductor-based photon detectors expensive, heavy, bulky and inconvenient to use.

The market of photon detectors has been dominated by photodiodes and quantum well infrared photodetectors (QWIPs) [38]. In photodiodes, incoming photons are absorbed and generate electron-hole pairs, resulting in a photocurrent. The bandgap of the sensing material must be lower than the photons’ energy, $E$ given by Equation 2-3 where $\lambda$ is the wavelength to be absorbed by the photodiode. The sensing materials can be categorized into intrinsic, extrinsic and free carriers. The most common material for LWIR detection and thermal imaging is mercury cadmium
telluride (HgCdTe or MCT) [38], belongs to intrinsic material. The bandgap of these materials can be engineered to correspond to various wavelengths.

$$E(\text{eV}) = \frac{1.24}{\lambda(\mu\text{m})}$$

In QWIPs, multilayer materials (normally III-V materials) are used to create quantum wells. The energy levels are engineered so that the energy of infrared photons can excite electrons from those quantum wells into the conduction band. These electrons are then collected as photocurrent. The performance of QWIPs is not as good as photodiodes but they have the advantages of high operability, good uniformity, high yield in fabrication, and thus lower cost [38].

### 2.2.2 Thermal Detectors

Thermal detectors first convert photons into heat before the induced temperature is measured. They are also called uncooled detectors because of their operation at ambient temperature. Until the mid-1990s, sensitivity levels of most thermal detectors were considered low. At room temperature, a radiant power intensity of 1 mW/cm² gives to a temperature rise of 1 K at equilibrium [33]. The heat transfer mechanism of the thermal detectors is a relatively slow process compared with the photon absorption in photon detectors, and thus gives a slow response. However, it is sufficient for applications that using video frame rate of 30 Hz. Nevertheless, they are widely employed in the applications, which require only modest sensing performance, due to their high reliability, low manufacturing cost, and ease of operation. With the increasing advances in MEMS technology, thermal detectors are able to achieve the performance comparable to photon detectors. Many different
temperature sensing principles have been studied for IR detection purpose and some of them are discussed as below:

Gas expansion: Upon IR absorption, the gas inside a closed environment will expand and cause a chamber wall displacement. The displacement can be detected either electrically [39] or optically [40]. In 1974, Golay published a paper presenting an improved version using light deflection from a flexible mirror as a way to detect the gas expansion [41]. This type of detector is known as “Golay Cell” and they are still commercially available.

Thermoelectric: IR detectors that using the thermoelectric temperature sensing mechanism are generally named as thermopiles, which consist of an array of miniaturized thermocouples junctions connected in series as differential pairs. These differential pairs make up the cold junctions and hot junctions, creating a Seebeck effect between the junctions. The electromotive force, $\Delta V$ appearing across a thermopile made of $n$ thermocouples is given by Equation 2-4, where $S_a$ and $S_b$ are the Seebeck coefficients of the two materials that form the thermocouples, $T$ is the detector temperature and $\Delta T$ is the temperature rise of the detector.

$$\Delta V = n \int_{T}^{T+\Delta T} S_a(T) - S_b(T) dT$$

Equation 2-4

Pyroelectric: Pyroelectric detectors consist of a pyroelectric material sandwiched by two electrodes. Pyroelectric materials are characterized by having spontaneous electric polarization, which response with temperature changes upon IR illumination. This polarization change gives rise to a voltage difference across the sensing material. Pyroelectric detectors can only operate in alternating current (AC) mode as
free charges will cancel the obtained polarization in DC mode. The current, \( I \) flowing through a pyroelectric detector is given by Equation 2-5, where \( A_e \) is the area of the electrodes, \( p \) is the pyroelectric coefficient and \( dT/dt \) is the rate of change of temperature.

\[
I = A_e p \frac{dT}{dt}
\]

Equation 2-5

**Thermomechanical:** Thermomechanical IR detectors are based on the mechanical motion of the bimaterial cantilever made of two materials having different coefficients of thermal expansion (CTE). The deflection at the end of the cantilever, \( \Delta z \) can be expressed in Equation 2-6, where \( C \) is the material dependent constant, \( L \) is the length of the cantilever, \( \alpha_1 \) and \( \alpha_2 \) are the CTE of material 1 and material 2 respectively.

\[
\Delta z = C \cdot L^3 (\alpha_1 - \alpha_2) \Delta T
\]

Equation 2-6

**Resistive:** Resistive detectors or more commonly called bolometers are the most commercially successful thermal detectors. They are based on a thermistor, which has a highly temperature dependent resistance. The temperature-induced resistance change, \( \Delta R \) resulting from IR illumination, can be characterized by Equation 2-7,

\[
\Delta R = \alpha_r R \Delta T
\]

Equation 2-7

where \( R \) is the resistance before IR exposure, \( \alpha_r \) is the temperature coefficient of resistance (TCR) and \( \Delta T \) is the temperature rise of the detector as a result of the absorbed IR radiation.
2.3 Uncooled Infrared Detectors

Figure 2-9: (a) A general uncooled IR detector structure [42] and (b) the schematic flow of its working principle.

A typical uncooled IR detector has a bolometric structure as depicted in Figure 2-9 (a) and its operation principle is illustrated in Figure 2-9 (b). Anchors are to mechanically support the sensing material and thermally isolate it from the substrate. The sensing material is electrically connected to the readout circuit through metal studs. An IR reflector is placed under the sensing material to enhance IR absorption. Upon IR illumination, the sensing material absorbs the radiation and gets heated up, inducing a temperature increase. This temperature rise is then translated into the radiant power absorbed by the sensing material through measurable parameters. Different temperature sensing principles can be applied to measure this temperature change as described in Section 2.2.2.

2.3.1 Infrared Absorption

For uncooled detectors, IR absorption can be achieved by active or passive absorption or both. Detectors that using active absorption will have the electrical
active part directly interact with the IR beam. For passive absorption, a passive IR absorbing layer is deposited on top of the detectors. There is a great variety of IR absorbing coatings available [43-47]. When IR radiation strikes on the surface of a medium, it experiences reflection, absorption and transmission as characterized by [48]

\[ r + \eta + \zeta = 1 \]  \hspace{1cm} \text{Equation 2-8}

where \( r \), \( \eta \), and \( \zeta \) are the reflection, absorption, and transmission coefficient, respectively. By decreasing \( r \) and \( \zeta \), \( \eta \) will be increased. For a metal of thickness above threshold value, \( \zeta \) can always be ignored due to high \( r \). When IR radiates from medium 1 to medium 2, the reflection, \( r \) can be calculated using [49]

\[ r = \frac{|R_{s1} - R_{s2}|}{R_{s1} + R_{s2}} \]  \hspace{1cm} \text{Equation 2-9}

where \( R_{s1} \) and \( R_{s2} \) are the sheet resistance of medium 1 and 2, respectively. If the IR detector is operating in vacuum environment, a metal thin film should have a sheet resistance, \( R_s \) close to the free space impedance, which is about 377 \( \Omega/\Box \), in order to optimize the IR absorption. The sheet resistance, \( R_s \) of a material can be calculated using

\[ R_s = \frac{\rho_R}{d} \]  \hspace{1cm} \text{Equation 2-10}

where \( \rho_R \) is the electrical resistivity and \( d \) is the film thickness.

**Free standing metal thin film:** A free standing metal thin film with \( R_s \) of half of the free space impedance can achieve the most 50% of absorption, with 25% of reflection and another 25% of transmission [50-52]. Thicker films tend to have high
reflection because of the high electron mobility and the fading in-plane electric field. Thinner films are transparent because there is insufficient amount of electrons for the interaction with the IR radiation. At the critical thickness (with optimum $R_s$), the maximum absorption is attainable when the electrons interact with the incoming IR beam but cannot move freely. A 17 nm thick evaporated gold (Au) film [53] and a 8 nm thick of nichrome (NiCr) film [54] have proven to have good IR absorption and have been employed in commercial thermal IR detectors.

**Interferometric absorption:** To enhance the metal thin film absorption to $> 50 \%$, resonant optical cavity or Fabry-Perot structures can be employed by placing an IR mirror or reflector at the back of the metal thin film by a separation distance, $d$ to enable multiple absorptions as illustrated in Figure 2-10 (a) [2]. This interferometric enhancement can also be achieved by a three-layer film stack that is composed of a metal thin film with $R_s$ of 377 $\Omega/\square$ on the side facing IR radiation, a dielectric film (with refractive index, $n$ and thickness, $T_{diele} (= \lambda_{max}/4n)$, and an IR mirror on another side, forming a Fabry-Perot structure (Figure 2-10 (b)). It has been shown that such structures are capable of $> 95 \%$ absorption at $\lambda_{max}$. The value of $R_s$ of the metal thin film at the front surface is experimentally shown not to be critically important. Absorption of $> 95 \%$ is achievable within the range of 300 – 600 $\Omega/\square$ [55]. The absorption drops significantly at the wavelength range outside the $\pm 2.5 \mu m$ bandwidth, particularly for the shorter wavelength range.

The interferometric absorption design in Figure 2-10 (a) is more commonly employed in commercial IR detectors since it allows thinner sensing materials that have a lower heat capacity. This allows the minimization of thermal conductance to enhance device sensitivity and speed (see Section 2.3.2 for explanation).
Figure 2-10: Cross-sectional view of two designs of resonant optical cavities to enhance IR absorption [2].

**Porous metal film:** In addition, porous films absorb better than their corresponding well-ordered films. A thermally evaporated Au film under nitrogen (N\textsubscript{2}) atmosphere with pressure of 100 Pa shows conglomerate of very fine needles with linear dimensions of around 25 nm [53]. These films achieve absorption close to 100 % at an area density of 250 to 500 µg/cm\textsuperscript{2}, and about 70 % at about 40 µg/cm\textsuperscript{2}. Similarly, silver (Ag) films show a higher absorption than Au films at the same mass, which is > 99 % at 80 µg/cm\textsuperscript{2} [53].

### 2.3.2 Figure-of-merits

Performance of an uncooled IR detector is normally evaluated in two stages: thermal characterization and sensing properties analysis. The thermal behaviour of the system that determines the IR-induced temperature rise is firstly characterized. Then, this increase in temperature results in the change of some material parameters, which is the sensing properties, that is further being used to indicate the absorbed radiant power. The calculations involved at the first stage are common to all thermal IR detectors, but the analysis at the second stage differs for different types of detector. In this section, thermal characterization is discussed in detail while the second stage evaluation will be covered in Section 3.2.1 for resonant IR detectors.
The important parameters to describe the thermal behaviour of an uncooled IR detector are heat capacity, $C_{th} \ (J/K)$ and thermal conductance, $G_{th} \ (W/K)$. The heat capacity of an IR detector is given as [56, 57]

$$C_{th} = V_1 \rho_1 c_1 + V_2 \rho_2 c_2 + \cdots$$  \hspace{1cm} \text{Equation 2-11}$$

where $V_x \ (m^3)$, $\rho_x \ (kg/m^3)$ and $c_x \ (J/kg \cdot K)$ are the volume, mass density and mass specific heat capacity of each material that makes up the detector, respectively. The effective thermal conductance between a detector and its surrounding ambient is governed by [56, 57]

$$G_{th} = G_{rad} + G_{anchor} + G_{gas} + G_{conv}$$  \hspace{1cm} \text{Equation 2-12}$$

where $G_{rad}$, $G_{anchor}$, $G_{gas}$ and $G_{conv}$ are the thermal conductance between detector and its surrounding through heat radiation, support anchors, gas conduction and convection. Assuming that the temperature difference between the detector and its surrounding is insignificant, the thermal conduction due to heat radiation from both the upper and lower surfaces of the bolometer membrane can be expressed as [57]

$$G_{rad} = 2 \cdot 4 \sigma \delta \beta A_D T^3$$  \hspace{1cm} \text{Equation 2-13}$$

where $\sigma \ (W/K^4 \cdot m^2)$ is the Stefan-Boltzmann constant, $\delta$ is the effective emissivity, $\beta$ is the fill factor, $A_D \ (m^2)$ is the bolometric area, and $T \ (K)$ is the temperature of the detector. $G_{rad}$ can always be neglected compared with $G_{anchor}$, which can be expressed by [57]

$$G_{anchor} = n \cdot \left( \frac{\kappa_{anchor,1} A_{anchor,1}}{l_{anchor}} + \frac{\kappa_{anchor,2} A_{anchor,2}}{l_{anchor}} + \cdots \right)$$  \hspace{1cm} \text{Equation 2-14}$$
where \( n \) and \( l_{\text{anchor}} \) are the number and length of the support anchors, \( \kappa_{\text{anchor},x} \) (W/K-m) and \( A_{\text{anchor},x} \) are the thermal conductivity and cross sectional area of each support anchor material. Under vacuum environment, \( G_{\text{gas}} \) and \( G_{\text{conv}} \) can be ignored and \( G_{\text{th}} \) is dominated by \( G_{\text{anchor}} \). If a detector is operating under atmospheric conditions, \( G_{\text{gas}} \) contributes significantly to \( G_{\text{th}} \). Practically, \( G_{\text{conv}} \) is negligible compared with \( G_{\text{gas}} \) [56]. If the distance, \( d \) between the detector bottom surface and substrate is relatively small (~ 2 – 3 μm) compared with the distance between the detector upper surface and the optical window of the detector package, and the thermal conductance between neighbouring detectors is negligible, \( G_{\text{gas}} \) can be expressed by [56, 57]

\[
G_{\text{gas}} = \kappa_{\text{gas},p} \cdot \left( \frac{\beta A_D}{d} \right)
\]  
Equation 2-15

where \( \kappa_{\text{gas},p} \) is thermal conductivity of the gas at a fixed gas pressure, \( p \).

Upon IR radiation, the temperature change of the detector can be characterized using the thermal differential equation [58]:

\[
C_{\text{th}} \frac{d(\Delta T)}{dt} + G_{\text{th}}(\Delta T) = P_{\text{abs}}
\]  
Equation 2-16

where \( \Delta T \) is the temperature change of the detector, \( d(\Delta T)/dt \) is the rate of temperature change, \( P_{\text{abs}} \) (W) is the absorbed IR power. \( P_{\text{abs}} \) can be related to the IR incident radiant, \( P_{\text{IR}} \) by a factor of IR absorption coefficient, \( \eta \) as given by

\[
P_{\text{abs}} = \eta \cdot P_{\text{IR}}
\]  
Equation 2-17

If the IR radiation is modulated, \( P_{\text{IR}} \) can be expressed as
\[ P_{IR} = P_o \exp(j\omega t) \quad \text{Equation 2-18} \]

where \( P_o \) is the peak power amplitude of the modulated IR radiation and \( \omega \) is the modulation frequency. Equation 2-16 assumes that the power dissipation due to biasing is negligible. Thus, the solution to the thermal differential equation is shown below [1, 58]:

\[
\Delta T_{max} = \frac{\eta P_o}{G_{th} \sqrt{1 + \omega^2 \tau_{th}^2}} \quad \text{Equation 2-19}
\]

where \( \tau_{th} \) is the thermal time constant as expressed by [1, 58]

\[
\tau_{th} = \frac{C_{th}}{G_{th}} \quad \text{Equation 2-20}
\]

A number of FOMs have been developed to describe the sensitivity of uncooled microbolometers such as detectivity, \( D^* \), responsivity, \( \mathcal{R} \), noise equivalent power (NEP) and noise equivalent temperature difference (NETD).

**Responsivity, \( \mathcal{R} \):** Responsivity, \( \mathcal{R} \) (W\(^{-1}\)) is a basic FOM of IR detector and it is defined as the ratio of the electrical output signal to the incident IR radiant power, \( P_{IR} \) on the detector as described by [58]

\[
\mathcal{R} = \frac{\text{electrical output signal}}{P_{IR}} \quad \text{Equation 2-21}
\]

Depending on the temperature detecting mechanism and readout circuit, the output can be any electrical signal including voltage, current, capacitance, or frequency signal. Low responsivity is not itself an insurmountable problem. It is always
possible to increase signal levels by adding amplifiers to the signal processing. A limitation that cannot be overcome with additional gain is the presence of noise.

**Signal-to-noise ratio (SNR):** Noise refers to an electrical output other than the desired signal. The ability of an IR detector to detect an incoming IR radiation is limited by the intrinsic fluctuations, or noise, both of the incoming IR source itself and of the background electrical signal fluctuations generated by the detector. Once noise enters the output, it can obscure or completely overtake the output signal. The SNR is a simple way to describe the “cleanliness” of a given signal level. It is simply defined as the desired electrical signal divided by the root mean square (RMS) of the noise signal.

**Detectivity, \( D^* \):** SNR alone does not determine the performance of a detector as it can be easily raised just by applying a higher incidence level. The most commonly used parameter to characterize a detector is the specific detectivity, \( D^* (\text{m}\sqrt{\text{Hz/W}}) \) which is defined by the output SNR of a detector per unit incident IR radiant power per square root of detector area, as given by [58]

\[
D^* = \frac{\Re \cdot \sqrt{BA_D}}{\sigma_N}
\]

where \( B \) (Hz) is the measurement bandwidth, \( \sigma_N \) is the noise signal and \( A_D \) is the detector bolometric area.

**Noise-equivalent-power (NEP):** NEP (W) is a measure of the ultimate sensitivity of a given detector. It gives the IR incident radiant power needed to generate the electrical output signal so that the SNR equals to 1. NEP is determined by [58]
\[ NEP = \frac{\sigma_N}{\mathcal{R}} \quad \text{Equation 2-23} \]

**Noise-equivalent-temperature-difference (NETD):** NETD (K) indicates the resolution of an IR imaging system. It can be defined as the smallest temperature change on an object that a detector can measure. To be more specific, NETD is the temperature difference between two side-by-side blackbodies which results in the output SNR of 1. NETD can be related to NEP, \( D^* \) and \( \mathcal{R} \) as shown from Equation 2-24 to Equation 2-26 [58-60].

\[ NETD = NEP \frac{4F^2 + 1}{\zeta A_D (\frac{\Delta P}{\Delta T})_{\lambda_1 - \lambda_2}} \quad \text{Equation 2-24} \]

\[ NETD = \frac{(4F^2 + 1)\sqrt{B}}{D^* \zeta \sqrt{A_D (\frac{\Delta P}{\Delta T})_{\lambda_1 - \lambda_2}}} \quad \text{Equation 2-25} \]

\[ NETD = \frac{(4F^2 + 1)\sigma_N}{\mathcal{R} \zeta A_D (\frac{\Delta P}{\Delta T})_{\lambda_1 - \lambda_2}} \quad \text{Equation 2-26} \]

where \( F \) is the F-number of the IR optics, \( \zeta \) refers to the transmittance of the overall optics, \( \frac{\Delta P}{\Delta T} \) gives the temperature contrast in the wavelength interval from \( \lambda_1 \) to \( \lambda_2 \). \( \frac{\Delta P}{\Delta T} \) has a value of 0.21 W/m\(^2\)-K and 2.62 W/m\(^2\)-K in 3 – 5 μm and 8 – 14 μm spectral interval, respectively at 300 K [61].

### 2.3.3 Theoretical Limit

The major noises incurred by any uncooled IR detector are Johnson noise and flicker noise [62]. Johnson noise is caused by the thermal agitation of the charge carriers in
any system causing a small yet detectable current to flow. Flicker noise is due to the non-crystalline structure of the electrical active part. Depending on the temperature sensing mechanism, Johnson noise can be characterized in different ways. Another two unavoidable fundamental noise sources involved in all type of thermal IR detectors are thermal fluctuation noise and background fluctuation noise [1, 61].

**Thermal fluctuation noise:**

There is a certain extent of temperature fluctuation within the freestanding detector due to the variation in heat conduction between the detector and its surrounding. Under this condition, the temperature fluctuation noise limited detectivity, $D_t^*$ is given by [61]

$$D_t^* = \sqrt{\frac{\eta^2 \cdot A_D}{4kT_D^2G_{th}}}$$  \hspace{1cm} \text{Equation 2-27}

where $k$ is Boltzmann’s constant, and $T_D$ is the detector temperature. Figure 2-11 shows the thermal fluctuation limited detectivity in relation to the device temperature and effective thermal conductance for different bolometric sizes. Noticeably, increasing thermal isolation improves the performance of thermal IR detectors.
Figure 2-11: Detectivity of thermal IR detector with different bolometric sizes in relation to (a) detector temperature and (b) effective thermal conductance, limited by temperature fluctuation noise [63].

**Background fluctuation noise:**

The device detectivity is limited by background fluctuation noise, $D_b^*$, when the dominant heat exchange mechanism is radiant power exchange [61].

$$
D_b^* = \sqrt{\frac{\eta}{8k\sigma(T_D^2 + T_B^2)}}
$$

Equation 2-28
where $T_B$ is the background temperature. In many practical instances, $T_B$ is equal to room temperature, 290 K. The background fluctuation noise limited detectivity of an ideal thermal detector operated at 290 K and lower, in relation to $T_B$ is plotted in Figure 2-12.

![Graph showing detectivity of thermal detectors in relation to detector temperature, $T_D$ and background temperature, $T_B$ for FOV of 2π and $\eta$ of 1, limited by temperature fluctuation noise [63].](image)

Due to the thermal and background fluctuation noise, a thermal detector operating at room temperature is expected to have the highest possible $D^*$ of $1.98 \times 10^{10}$
cm√Hz/W. The value of $D^*$ would improve only by square root of two even though the detector was cooled to absolute zero. Photon detectors have higher background limited detectivities because of their limited spectral responses [63].

### 2.4 State-of-the-art and Future Trends

#### 2.4.1 Outlook and Commercial

In 1978, the first uncooled IR detector employed ferroelectric temperature sensing principle with barium strontium titanate (BST) as the sensing material. At the same time, MEMS-based bolometers that make use of micromachining technology were developed [64]. In the early 1990s, the research into BST was less advanced while vanadium oxide (VO$_x$) technology was developing at a very fast pace because of its advantages of high reliability, ruggedness and stability over BST [64]. Amorphous silicon (α-Si) has drawn an increasing interest in the mid-1990s because it is CMOS compatibility. Nowadays, VO$_x$ is the dominating technology in bolometer arrays in competition with other technologies such as α-Si and Si diodes. Most commercially available uncooled detector focal plane arrays (FPAs) make use of standard single-level bolometric designs (Figure 2-13 (a)) [65]. FPAs in two-layer (umbrella structure) bolometric designs (Figure 2-13 (b)), which have very small pixel sizes (17 μm × 17 μm pitch), are also available in market since 2009 [66].
Figure 2-13: (a) Commercial VO\textsubscript{x} bolometer with single-level of 28 \(\mu\text{m} \times 28 \mu\text{m}\) pitch from BAE [65] and (b) VO\textsubscript{x} bolometer in umbrella structure with 17 \(\mu\text{m} \times 17 \mu\text{m}\) pitch from DRS [67].

Table 2-3: Commercial thermal IR detectors arrays are based on semiconductor resistive bolometers [68].

<table>
<thead>
<tr>
<th>Company</th>
<th>Bolometer Type</th>
<th>Pixel pitch ((\mu\text{m}))</th>
<th>Detector NETD (mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>[(f/1, 20 \text{ – } 60 \text{ Hz})]</td>
</tr>
<tr>
<td>L-3 (USA)</td>
<td>VO\textsubscript{x}</td>
<td>37.5 30 17</td>
<td>50 50 30 - 50</td>
</tr>
<tr>
<td></td>
<td>(\alpha)-Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\alpha)-Si/(\alpha)-SiGe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAE (USA)</td>
<td>VO\textsubscript{x}</td>
<td>28 17</td>
<td>30 50</td>
</tr>
<tr>
<td>DRS (USA)</td>
<td>VO\textsubscript{x} (standard) VO\textsubscript{x} (umbrella)</td>
<td>25 17</td>
<td>35 50</td>
</tr>
<tr>
<td>Raytheon (USA)</td>
<td>VO\textsubscript{x} (standard) VO\textsubscript{x} (umbrella)</td>
<td>25 17</td>
<td>30 - 40 50</td>
</tr>
<tr>
<td>ULIS (France)</td>
<td>(\alpha)-Si</td>
<td>25 17</td>
<td>(&lt; 60 ) (&lt; 60 )</td>
</tr>
<tr>
<td>SCD (Israel)</td>
<td>VO\textsubscript{x}</td>
<td>25 17</td>
<td>50 35</td>
</tr>
<tr>
<td>NEC (Japan)</td>
<td>VO\textsubscript{x}</td>
<td>23.5</td>
<td>(&lt; 75 )</td>
</tr>
</tbody>
</table>

During the past decade, thermal IR detector technology has continued developing and achieves dramatic improvement in resolution and performance. The demonstrated devices have been proved to perform closer to the theoretical limit and
hence have a smaller performance gap with photon detectors. Table 2-3 summarizes the important suppliers and specifications for the current uncooled IR detectors and those in R&D stage.

### 2.4.2 Future Trends

Despite successful commercialization of uncooled microbolometers the community is still searching for a platform for uncooled detectors that combine affordability, convenience of operation, and excellent performance. There is a high demand in reducing the detector pixel size to achieve several potential benefits include low power consumption and high speed. In addition to the improvement in overall system size, weight and portability, reduction in pixel size can also reduce the system cost by having a smaller lens and enable significantly larger FPAs to be fabricated on a single wafer. However, the NETD is inversely proportional to the pixel area (see Equation 2-24 to Equation 2-26).

Near future high performance uncooled thermal imaging will be dominated by VO$_x$ bolometers. However, their sensitivity limitations and the still significant prices will encourage many research teams to explore other IR detection technologies with the potential for improved performance with reduced detector costs. Moreover, value-added R&D work is on-going to discover interesting sensing and communication related applications using single pixel or small array IR detectors. Therefore, novel detection technologies (even though with large pixel size) with significant improved sensitivity are always welcome.
CHAPTER 3: ALUMINUM NITRIDE RESONANT UNCOOLED INFRARED DETECTOR

3.1 Piezoelectric Resonators

3.1.1 Piezoelectricity

The piezoelectric effect is the ability of a crystalline material to generate electric charge in the presence of external mechanical stress. Piezoelectricity is bidirectional and reversible. In the converse piezoelectric effect, an applied electric field induces a mechanical strain in the material. Piezoelectric devices have shown success as a high volume product among other mechanical resonators due to their ease of fabrication and remarkably low motional resistance (10s of ohms) [69, 70]. Motional resistance is the mechanical motion induced equivalent electrical resistance. Low motional resistance of these devices gives opportunity to work with single transistor circuits where the circuit phase noise and selectivity improves significantly.

A crystalline material is comprised of atoms, molecules or ions, which are arranged in a highly ordered microscopic structure, sharing the electron density in some manners, e.g. ionic and covalent bonds. Because of this sharing, the electron density is not uniform throughout the crystal and there are periodic electric dipoles that reflect the periodic atomic arrangement of the crystal. In most crystals, the constituent atoms are distributed such that the effective dipole of the crystal is zero,
although a ferroelectric has a nonzero dipole sum at equilibrium. When an applied stress creates a strain in the crystal, there is a small change in the bond lengths between the atoms. This causes a shift in the positions or directions of the individual dipoles. Many crystals are centrosymmetric and even under the applied stress the sum of the dipoles is zero. In most non-centrosymmetric crystals, however, the stress results in the formation of a nonzero dipole — a manifestation of piezoelectricity.

The piezoelectric effect can be expressed mathematically using Equation 3-1 to Equation 3-4 that describe the electric and structural behaviours of a material. Electric displacement, $D_i$ is defined as

$$D_i = \varepsilon_0 \varepsilon_{ij} E_j$$  \hspace{1cm} \text{Equation 3-1}$$

where $\varepsilon_{ij}$ is the permittivity matrix of the material, $E_j$ is the applied electric field. Similarly, Hooke’s law for mechanical strain, $S_{ij}$ is

$$S_{ij} = s_{ijkl} T_{kl}$$  \hspace{1cm} \text{Equation 3-2}$$

where $s_{ijkl}$ is the elastic compliance tensor of the material and $T_{kl}$ is the mechanical stress. In a piezoelectric, the above two equations are combined to yield the coupled constituent equations:

$$S_{ij} = s_{ijkl}^E T_{kl} - d_{klj} E_k$$  \hspace{1cm} \text{Equation 3-3}$$

$$D_i = d_{ijk} T_{jk} + \varepsilon_0 \varepsilon_{ij}^T E_j$$  \hspace{1cm} \text{Equation 3-4}$$

where $d_{ijk}$ is the strain-charge form of the piezoelectric coefficient tensor, $s_{ijkl}^E$ is the compliance at constant electric field, $\varepsilon_{ij}^T$ is the permittivity at constant stress [71].
3.1.2 Acoustic Wave Excitations

An acoustic wave can be generated within a piezoelectric thin film through the two main excitation schemes as illustrated in Figure 3-1.

**Figure 3-1**: Schematic of (a) thickness excitation, (b) lateral field excitation, and (c) combination of both excitation schemes.

**Thickness Excitation (TE)**: In the TE scheme, the piezoelectric thin film is sandwiched between metal electrodes. An electric field is applied across the piezoelectric film in the Z-direction and induces the propagation of an acoustic wave. When the frequency of the applied electric field is equal to a natural resonance frequency of the structure, the resonance mode is excited. The targeted mode-shape...
can be designed by alternating the electrode patterns and the location of the suspension elements. One of the most commonly employed resonance modes in piezoelectric devices is the thickness longitudinal mode (determined by $d_{33}$) in which the strain field is in the same direction as the applied electric field.

In addition to $d_{33}$, there are also other non-zero piezoelectric coefficients in the material, which induces strain fields in other directions. The coefficient $d_{31}$ is responsible for length extensional mode whereby the strain field is orthogonal to the electric field and in parallel with $X$-direction. The thickness shear mode can be excited by the shear coefficient, $d_{15}$ which relates the deformation in the $X$-$Y$ direction when the electric field is applied in the $Y$-$X$ direction.

**Lateral Field Excitation (LFE):** In the LFE scheme, the metal electrodes are patterned into an interdigitated transducer (IDT) structure where the electrode pitch plays an important role to determine the resonance. Longitudinal, extensional and thickness shear modes are also possible with the LFE scheme. Similar with the TE scheme, different piezoelectric coefficients are responsible for different resonance modes. One can also combine both the TE and LFE scheme as shown in Figure 3-1 (c) for certain applications.

### 3.1.3 Lamb Wave Resonator

In addition to small form factors and low losses for filter applications and noise frequency sources, the low noise characteristic renders the radio frequency (RF) electroacoustic devices being employed in various high resolution sensing applications. The two common types of electroacoustic devices, bulk acoustic wave (BAW) and surface acoustic wave (SAW) resonators (Figure 3-2), are currently
utilized in commercial communication applications, especially in communication devices and oscillators.

![Diagram of BAW and SAW resonators]

Figure 3-2: General schematic structure of (a) BAW and (b) SAW resonator.

A BAW resonator is a simple structure with a piezoelectric film sandwiched between two plate electrodes, which utilizing the TE excitation scheme [72-75]. SAW devices employ high electromechanical coupling and high mechanical quality single crystal substrates with IDT electrodes and reflector gratings on top. The main excitation scheme of SAW resonators is LFE [76-78]. Both the BAW and SAW technologies have their own benefits and drawbacks. The SAW approach offers robust designs with higher tolerances to technical variation but it is incompatible with CMOS processes. The BAW technology is CMOS-compatible and has great performance in the lower GHz range but is susceptible to technical variation, which hinders the development of CMOS integration process.
The micromachined piezoelectric RF devices that employ plate-guided waves have been developed in order to fill the technological gap between BAW and SAW devices. Thin film plate acoustic resonators (FPAR) have been widely utilized in different fields since the advances in piezoelectric thin film deposition and MEMS microfabrication technologies [79-81]. They typically utilize the LFE excitation scheme and generate the Lamb wave mode propagating in the freestanding piezoelectric thin film and thus are named as Lamb wave resonator (LWR) [80, 82, 83]. Some authors have adopted the name of “contour-mode resonator (CMR)” [81, 84, 85].

Figure 3-3: LWRs with acoustic reflection achieved by (a) reflector grating and (b) suspended free edges of the piezoelectric thin film.

Similar to SAW resonators, acoustic waves in LWR are excited by IDT electrodes. Acoustic wave reflection can be achieved by either reflector gratings [79] or the suspended free edges of the piezoelectric thin film [81] (Figure 3-3). The latter structure is more commonly used due to its smaller size design. Additionally, LWR utilizes the BAW fabrication technological platform and thus is CMOS compatible while remains the robustness of SAW technology. This makes the system-on-chip integration between integrated circuits and frequency references possible for LWR. A number of wave modes can be induced depending on the electrode configuration.
and film thickness-to-wavelength ratio. Lamb wave can be classified as symmetric (S) or asymmetric (A) mode indicating the symmetry of particle displacement with respect to the median plane of the plate (Figure 3-4). A single LWR device may possess different order of resonances at different operating frequencies. The commonly observed resonances are the lowest order (A0 and S0) and first-order (A1 and S1) modes. The S0 wave mode is the most widely used in LWR devices due to its high acoustic phase velocity, low dispersion and moderate piezoelectric coupling [80].

![Figure 3-4: (a) Symmetric and (b) asymmetric Lamb wave modes.](a) Symmetric Lamb wave mode (b) Asymmetric Lamb wave mode

- Acoustic wave propagation direction
- Particle motion
- Original plate surface

Figure 3-4: (a) Symmetric and (b) asymmetric Lamb wave modes.
Figure 3-5: Different electrode configurations for Lamb wave devices. (a) Type-A: single-sided IDT. (b) Type-B: single-sided IDT with metallized backside. (c) Type-C: double-sided IDT.

Figure 3-5 shows the three fundamental electrode configurations for LWRs, whereas Figure 3-6 compares the phase velocity and electromechanical coupling of S0 and A0 with different electrode configurations for an AlN LWR [80]. In addition to the S0 mode with limited coupling of about 1.5%, the undesired A0 mode with similar coupling strength will exist as spurious noise for AlN LWR without metallized backside. The coupling increases when a plate electrode is added to the bottom of the piezoelectric thin film. At the same time, this metallized backside also suppresses the coupling strength of the A0 mode. With aligned top and bottom electrodes, the AlN LWR with double-sided IDT is able to generate the S0 and A0 mode with optimum coupling.
Figure 3-6: (a) The phase velocity dispersion of $S_0$ and $A_0$ modes for the different electrode configurations of AlN LWR, and (b) the corresponding electromechanical coupling coefficients [80].

Even though the AlN LWR with double-sided IDT (Type-C) possesses the most stable and largest coupling over a wide frequency span, this thesis employs the design with metallized backside single-sided IDT (Type-B). The main reason is that an IR absorbing blanket layer is required to be deposited on one side of the piezoelectric film for IR detection purpose. Since alignment is not needed for the top and bottom IDTs as in Type-B LWR, the fabrication process is more robust and simple. Although the overall coupling values are smaller and moderate frequency dependent, these are still much larger than that of quartz devices. Therefore, AlN LWR allows larger frequency tolerance and thus better yield.
3.2 Resonant Infrared Detectors based on Piezoelectric Devices

Despite the advantages of low noise and high resolution, non-CMOS compatibility and non-scalability have brought the development of resonant IR detectors to a standstill since its early discovery in 1985 using quartz BAW resonators [19]. With the advances of micromachining technology today, resonant IR detection technology has been revived [21-25, 86]. Resonant IR detectors belong to thermal detectors and they can potentially equal or surpass the performance of photon detectors.

3.2.1 Operating Principle

Figure 3-7 shows a general schematic of a resonant IR detector employing LWR technology. The detector has a similar structure as a conventional thermal detector as depicted in Figure 2-9 (a). The device consists of a piezoelectric thin film whereby excitation IDT electrodes located at the bottom surface and a thin IR absorbing metal layer on the top surface. There are at least one anchor for mechanical support and thermal isolation.
A resonant IR detector measures the change in resonant frequency upon IR exposure. The resonant frequency, $f$ of the resonator can be expressed by [87].

$$f = \frac{\nu}{\lambda} \quad \text{Equation 3-5}$$

$$\nu = \frac{C_{ij}}{\sqrt{\rho_{eq}}} \quad \text{Equation 3-6}$$

$$\lambda = 2p \quad \text{Equation 3-7}$$

where $\nu$ is the acoustic phase velocity within the piezoelectric film, $\lambda$ is the wavelength of the generated acoustic wave, $p$ is the IDT electrode pitch, $C_{ij}$ is the the piezoelectric film elastic constant, and $\rho_{eq}$ is the equivalent mass density of the detector. Upon IR irradiation, $p$, $C_{ij}$ and $\rho_{eq}$ change as temperature increases due to material softening, giving rise to a change in $f$. The dependence of $p$, $C_{ij}$ and $\rho_{eq}$ on temperature can be characterized using the equations below [80]:

$$p = p(T_0)(1 + \alpha_{11}\Delta T) \quad \text{Equation 3-8}$$

$$C_{ij} = C_{ij}(T_0)(1 + \alpha_{C_{ij}}\Delta T) \quad \text{Equation 3-9}$$

$$\rho_{eq} = \rho_{eq}(T_0)[1 - (\alpha_{11} + \alpha_{22} + \alpha_{33})\Delta T] \quad \text{Equation 3-10}$$

where $\alpha_{C_{ij}}$ and $\alpha_{ij}$ are temperature coefficient of stiffness constant and expansion of piezoelectric film in $ij$-direction, respectively; $T_0$ refers to the reference temperature and $\Delta T$ is the temperature change within the detector relative to $T_0$. The temperature dependent resonant frequency, $f$ is determined by:
where \( \alpha_f \) is temperature coefficient of frequency (TCF) of the detector. Noticeably, \( f \) is directly determined by \( \alpha_f \) and \( \Delta T \). Definition of \( \Delta T \) has been explained in Equation 2-19 while \( \alpha_f \) can be defined by a series of equations below [80].

\[
\alpha_f = \frac{1}{f} \frac{\delta f}{\delta T}
\]

Equation 3-12

By substituting Equation 3-5 to Equation 3-7 into the above equation, we have

\[
\alpha_f = \frac{1}{f} \frac{\delta f}{\delta T} = \frac{1}{v} \frac{\delta v}{\delta T} - \frac{1}{p} \frac{\delta p}{\delta T}
\]

Equation 3-13

where

\[
\frac{1}{v} \frac{\delta v}{\delta T} = \frac{1}{\sqrt{C_{ij}}} \frac{\delta \sqrt{C_{ij}}}{\delta T} - \frac{1}{\sqrt{\rho_{eq}}} \frac{\delta \sqrt{\rho_{eq}}}{\delta T} = \frac{1}{2} \left[ \frac{1}{C_{ij}} \frac{\delta C_{ij}}{\delta T} - \frac{1}{\rho_{eq}} \frac{\delta \rho_{eq}}{\delta T} \right]
\]

Equation 3-14

Finally, the TCF can be defined by

\[
\alpha_f = \frac{1}{2} \left[ \alpha_{C_{ij}} + (\alpha_{11} + \alpha_{22} + \alpha_{33}) \right] - \alpha_{11}
\]

Equation 3-15

### 3.2.2 Material Selection

#### 3.3.2.1 AlN as piezoelectric material

In this thesis, the piezoelectric material used is AlN. AlN thin films are widely exploited because they have excellent properties such as chemical stability, high thermal conductivity, electrical isolation, a wide band gap (6.2 eV), a thermal expansion coefficient (4.5 ppm/K) close to that of Si (2.6 ppm/K), and a high
acoustic velocity (> 10,000 m/s). Therefore, AlN thin films are applied not only for surface passivation of semiconductors and insulators [88-90], but also for optical devices in the ultraviolet spectral region, acousto-optic (AO) devices, and acoustic wave devices [91-93].

AlN has several advantages over ZnO, GaN and lead zironate titanate (PZT). First, it is compatible with standard MEMS processing techniques [27, 94, 95]. It is very selective to many wet chemical and dry plasma etching processes but can be readily etched in chlorine (Cl) based etchants [96, 97]. Its hardness and melting point prevent the AlN films from degradation during processing. Second, AlN films with excellent crystallinity and orientation can be reproducibly deposited or grown on many different substrates and films, including dielectrics, semiconductors, and metals [27, 98, 99]. AlN thin films with thickness down to 250 nm have been successfully deposited by CMOS-compatible technologies at low temperature (200 – 400 °C) [87], enabling post-CMOS integration.

Third, AlN exhibits moderate electromechanical coupling in conjunction with high acoustic velocities, thereby making it a useful material for resonant devices [100, 101]. Finally, although AlN does not have very high piezoelectric coefficients compared with other piezoelectric materials, it is adequate for many applications. Its crystal qualities allow for very sensitive devices with high quality (Q) factors. Because of its low dielectric losses and high breakdown field, the FOM (=$Q\cdot k_e^2$, where $k_e^2$ is the effective electromechanical coupling coefficient of piezoelectric material) for AlN transducers can be 24 times higher than comparable PZT transducers [102].
AlN FBARs operating in TE mode have been proven to have low motional resistance (~ 50 - 700 Ω), high $Q$-factor (up to 4000) in air, and multiple operating frequencies on a single substrate [91, 103, 104]. The resonant frequency of a TE resonator is governed by the thickness of the piezoelectric film (also equal to electrode distance). The piezoelectric film thickness has to be reduced in order to push a TE resonator to higher frequencies (> GHz). When the electrode layers constitute a larger portion of the whole resonator structure, the $Q$-factor is reduced due to mass loading.

Comparing to the TE mode, AlN LWRs that are operating in LFE mode are more appropriate for IR detection application due to its structure configuration. Recently, an AlN-based oscillator operated at 1.05 GHz has been demonstrated [105]. Both the $Q$-factor and the $k_t^2$ value have been optimized by having an AlN film with a thickness, $T_{AlN}$ of approximately 0.45 times the desired operation acoustic wavelength, $\lambda$, deposited directly on Si substrates [79, 80]. A bottom electrode is not necessary in LWRs, hence the major acoustic path encounters less damping effects. Furthermore, the longitudinal acoustic wave generated in TE-FBARs has higher acoustic attenuation than the shear acoustic waves generated in LFE-LWRs [80].

### 3.3.2.2 Mo as IDT electrodes

In this project, the AlN LWRs are designed up-side-down (Figure 3-7) unlike the conventional resonator design as depicted in Figure 3-3 (b) and Figure 3-5 (b). AlN films are preferentially grown on various metal electrodes including Pt, Al, and Au due to the lattice match [104, 106-108]. However, Pt and Au thin films are facing adhesion and etching issues while Al thin films are easily oxidized and exhibit low etching selectivity with AlN. Therefore, Mo becomes the material of choice for IDT
electrodes because of its low resistivity, high acoustic impedance, perfect adhesion with AlN and high etching selectivity with AlN [109, 110]. Furthermore, the microcrystalline structure of Mo can be altered to match the \( c \)-oriented polycrystalline AlN by depositing a thin layer of AlN seed layer prior to the deposition of Mo [111]. Mo with a thickness of about 200 nm is IR reflective and thus, a Fabry-Perot optical cavity can be formed within AlN film as described in Section 2.3.1 (Figure 2-10 (b)) by having an IR absorbing layer on another surface of AlN film.

### 3.3.2.3 TiN as IR absorber

Most semiconductor materials and metals have a highly reflective surface, thus a low optical absorptivity. The most common way to improve absorption is to use coatings of high absorptivity materials such as carbon blacks or metal blacks [43, 47]. However, deposition of such thick IR absorbing materials will impose additional mechanical load to the resonator, which then affects its resonant performance. Three-layer stack interferometric absorption structures are utilized in the AlN resonant IR detector. As explained in Section 2.3.1, a very thin film of metal (\( \sim 1 – 2 \) nm) is needed to achieve the desired \( R_s \) of 377 \( \Omega/\square \). Thickness measurement and deposition of such thin films with good uniformity is a challenge. Therefore, a metal ceramic thin film is proposed due to its higher resistivity and thus thicker film is allowed to achieve the desired \( R_s \).

Titanium nitride (TiN) has been reported as one of the promising IR absorbing materials [48]. It is a unique material having both covalent (Ti-N) and metallic (Ti-Ti) bonding characteristics. Because of the metallic properties, TiN has acceptable resistivity of about 200 \( \mu\Omega\cdot\text{cm} \) [112]. Due to its higher resistivity compared with
pure metals, TiN can be deposited thicker to have a value of $R_s (377 \, \Omega/\square)$ that matches with the free space impedance. Moreover, it has excellent thermal and chemical stability, a high melting point, extreme hardness and brittleness attributed to the existence of covalent bonds [113]. Thus, it is suitable for rugged (high temperature and high pressure) applications. Most importantly, TiN is CMOS compatible [114, 115] and its tuneable residual stresses [113] ensures the mechanical strength of the bolometric membrane. Using TiN to be the IR absorbing material, as well as the floating electrodes, a resonator can function as an IR detector without the concern of absorber-induced mechanical loading. Furthermore, TiN can be patterned together with AlN due to the ultra-thin thickness, which makes the device fabrication process simpler.

### 3.3 Device Design Consideration based on Simulation

A series of simulations were performed using ANSYS and COMSOL Multiphysics software to predict and optimize the structural design of the AlN resonant IR detector. Both resonant and thermal behaviour of the designed structures will be discussed in the following sections. For Lamb wave propagation, the wave mode is identical along $Y$-direction and thus 2D simulation is sufficient to study the resonant behaviour of AlN LWR devices. Nevertheless, 3D simulation is more appropriate for the investigation of anchor design and thermal behaviour, which accounts for acoustic reflections and heat transfer from all angles.

Because of the periodic nature of IDTs, a pair of IDT electrodes with opposite polarity is sufficient for 2D simulation of SAW device. This is valid only if there are an adequate number of the electrodes, $N$ and the aperture length, $L_{AL}$ is much longer...
than the generated acoustic wavelength, \( \lambda \). Since the AlN LWR design in this project has a much smaller area than a SAW device (thus small values of \( N \) and \( L_{AL} \)), complete structure in \( X \)-direction (the in-plane direction that perpendicular to \( L_{AL} \)) is required in 2D simulation.

Table 3-1: Domain settings for resonant and thermal behavior simulations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Resonant behavior study (Piezoelectric device module)</th>
<th>Thermal behavior study (Solid heat transfer module)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlN</td>
<td>Piezoelectric</td>
<td>Heat transfer in solid</td>
</tr>
<tr>
<td>Mo</td>
<td>Linear elastic</td>
<td></td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>Linear elastic and electrical</td>
<td></td>
</tr>
</tbody>
</table>

**Domain and boundary condition:** Both domain and boundary settings are very critical for any simulation study. Domain settings define the material functions while boundary settings include the atmospheric conditions and all the non-ideal factors. The domain settings are identical for both 2D and 3D simulations as listed in Table 3-1.

The boundary settings for 2D and 3D simulations are slightly different because anchor conditions of the AlN LWR are included in the 3D simulations. Figure 3-8 clearly illustrates the 2D and 3D simulated structures with the boundary conditions listed in Table 3-2. \( \Gamma \) and \( \Lambda \) refer to the edge and surface boundary, respectively with the subscripts \( A, S, \) and \( M \) indicate \( \text{AlN, SiO}_2 \), and \( \text{Mo} \). Combination of any two of the characters refers to the interface between the respective materials. TiN is not included in the simulation because the ultra-thin layer doubles the meshing nodes and thus the simulation time and memory space without any significant impact on the simulation results.
Figure 3-8: Schematic of the simulated (a) 2D and (b) 3D structure with labelled boundary conditions.

Table 3-2: Boundaries settings for the 2D and 3D simulations.

<table>
<thead>
<tr>
<th>Edges</th>
<th>Structural</th>
<th>Electrical</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_{A1}, \Gamma_{S1}, \Gamma_{S2}, \Gamma_{S3}, \Gamma_{S4} )</td>
<td>( \Gamma_{SM1} ) Free</td>
<td>Zero-charge</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{AS1} )</td>
<td></td>
<td>Floating potential</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{AM1} )</td>
<td></td>
<td>Terminal 1</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{AM2} )</td>
<td></td>
<td>Terminal 2</td>
<td></td>
</tr>
<tr>
<td>( \Lambda_{SA1} )</td>
<td>Zero-charge</td>
<td>Thermal contact</td>
<td></td>
</tr>
<tr>
<td>( \Lambda_{SM1} )</td>
<td></td>
<td>Thermal isolation</td>
<td></td>
</tr>
<tr>
<td>( \Lambda_{S1}, \Lambda_{S2}, \Lambda_{S3}, \Lambda_{S4} ) Free</td>
<td>Fixed constraint</td>
<td>Constant temperature</td>
<td></td>
</tr>
<tr>
<td>( \Lambda_{SA2} )</td>
<td>Floating potential</td>
<td>Boundary heat source</td>
<td></td>
</tr>
<tr>
<td>( \Lambda_{AM1} )</td>
<td>Terminal 1</td>
<td>thermal contact</td>
<td></td>
</tr>
<tr>
<td>( \Lambda_{AM2} )</td>
<td>Terminal 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At the initial state, the simulated structure has a temperature of 293.15 K, zero electric displacement, zero potential and zero displacement. As the fabricated devices will be tested under vacuum environment, atmosphere damping is negligible in the piezoelectric simulation while convection heat loss can be ignored in the heat
transfer simulation. Heat loss due to radiation is also neglected because of its relatively small effect at the temperature range up to 573 K [116].

Table 3-3: Material properties of AlN and Mo used in the simulation study [80, 117-126].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Material</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elastic constant, $C_{ij}$ or Young’s modulus, $E$ [10^9 N/m^2]</strong></td>
<td><strong>AlN</strong></td>
<td><strong>Mo</strong></td>
<td><strong>SiO$_2$</strong></td>
</tr>
<tr>
<td></td>
<td>$C_{11}$</td>
<td>345</td>
<td>312 (with Poisson’s ratio of 0.31)</td>
</tr>
<tr>
<td></td>
<td>$C_{12}$</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{13}$</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{33}$</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{44}$</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{66}$</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td><strong>Fist order temperature coefficient of elastic constant or Young’s modulus, $\alpha_{C_{ij}}$ [ppm/K]</strong></td>
<td></td>
<td>$\alpha_{C11}$</td>
<td>-134</td>
</tr>
<tr>
<td></td>
<td>$\alpha_{C12}$</td>
<td>-80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\alpha_{C13}$</td>
<td>-180</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\alpha_{C33}$</td>
<td>-160</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\alpha_{C44}$</td>
<td>-100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\alpha_{C66}$</td>
<td>-50</td>
<td></td>
</tr>
<tr>
<td><strong>Piezoelectric stress coefficient, $e_{ij}$ [C/m^2]</strong></td>
<td></td>
<td>$e_{15}$</td>
<td>-0.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e_{31}$</td>
<td>-0.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e_{33}$</td>
<td>1.55</td>
</tr>
<tr>
<td><strong>Relative permittivity, $\varepsilon_{ij}$</strong></td>
<td></td>
<td>$\varepsilon_{11}$</td>
<td>9.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\varepsilon_{33}$</td>
<td>10.73</td>
</tr>
<tr>
<td><strong>Thermal conductivity, $k$ [W/m·K]</strong></td>
<td>158</td>
<td>138</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Thermal expansion coefficient, $\alpha_{ij}$ [ppm/K]</strong></td>
<td></td>
<td>$\alpha_{11}$</td>
<td>5.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\alpha_{33}$</td>
<td>4.15</td>
</tr>
<tr>
<td><strong>Specific heat capacity, $C$ [J/kg·K]</strong></td>
<td>740</td>
<td>250</td>
<td>680</td>
</tr>
<tr>
<td><strong>Mass density, $\rho$ [kg/m$^3$]</strong></td>
<td>3260</td>
<td>10200</td>
<td>2200</td>
</tr>
</tbody>
</table>

The material properties of AlN, Mo and SiO$_2$ used in the simulation studies are summarized in Table 3-3. AlN is a piezoelectric material with a hexagonal crystal structure. The elastic constant, piezoelectric stress coefficient and relative permittivity of such a crystal can be expressed in a matrix form (Equation 3-16 to Equation 3-18).
\[ C_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{12} & C_{11} & C_{13} \\ C_{13} & C_{13} & C_{44} \\ \end{bmatrix} \]

Equation 3-16

\[ e_{ij} = \begin{bmatrix} e_{31} & e_{31} & e_{33} & e_{15} \end{bmatrix} \]

Equation 3-17

\[ \varepsilon_{ij} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{11} & \varepsilon_{33} \end{bmatrix} \]

Equation 3-18

For the ease of illustration, the parameters involved in this simulation study are summarized in Figure 3-9. The simulated structures are up-side-down with that of Figure 3-9.

Figure 3-9: The illustration of parameters involved in the simulation.

### 3.3.1 Effects of SiO\textsubscript{2} Passivation Layer

A silicon dioxide (SiO\textsubscript{2}) layer was added to the AlN LWRs at the earlier design stages to facilitate the fabrication process, which is utilizing xenon difluoride (XeF\textsubscript{2}) as the releasing etchant. The effect of the SiO\textsubscript{2} on the frequency response of the AlN
LWRs was first studied in a COMSOL 2D simulation with the device parameters listed in Table 3-4.

Table 3-4: The device structural parameters studied in COMSOL 2D simulation.

<table>
<thead>
<tr>
<th>AlN thickness, $T_{\text{AlN}}$ (µm)</th>
<th>1</th>
<th>Mo thickness, $T_{\text{Mo}}$ (nm)</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic wavelength, $\lambda = 2p$ (µm)</td>
<td>25</td>
<td>Metallization ratio ($l_{\text{IDT}} : p$)</td>
<td>0.75</td>
</tr>
<tr>
<td>Bottom SiO$<em>2$ thickness, $T</em>{\text{BotOx}}$ (nm)</td>
<td>300</td>
<td>Number of IDT fingers, $N$</td>
<td>12</td>
</tr>
<tr>
<td>Top SiO$<em>2$ thickness, $T</em>{\text{TopOx}}$ (nm)</td>
<td>100 – 700 (with 150 nm interval)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3-10 depicts the COMSOL 2D simulated frequency response of the SiO$_2$-passivated AlN LWRs. The resonant frequency reduces with SiO$_2$ thickness due to the increasing mechanical loading [127, 128]. The displacement profile of AlN LWRs is shown separately in Figure 3-11 with the same enlarged scale of 120. The device without SiO$_2$ passivation layer gives a resonant frequency of 371.5 MHz, which translate into the acoustic velocity of 9288 m/s. This value is slightly lower than the expected one of > 10000 m/s [80] because the metallization ratio is more than 0.5 and hence imposing additional mechanical loading to the AlN LWRs.

![Graph showing simulated frequency response of AlN LWRs with different SiO$_2$ passivation layer thicknesses.](image)

Figure 3-10: Simulated frequency response of AlN LWRs with different SiO$_2$ passivation layer thicknesses.
The value of $k_t^2$ is gradually degrading with increasing SiO$_2$ thickness because of energy absorption by the SiO$_2$ passivation layer [128]. It is well-known that SiO$_2$ has a positive TCF [80, 127-129] which is in opposite sign with that of AlN. Therefore, the effective TCF of AlN LWRs changes sign from negative to positive when the SiO$_2$ passivation layer thickness exceed a threshold value (Figure 3-12), depending on the value of $\lambda$ and $T_{AlN}$. In conclusion, SiO$_2$ shall be excluded from the AlN resonant IR detectors for optimum performance.

Figure 3-11: Simulated displacement profile of AlN LWRs with different SiO$_2$ passivation layer thicknesses.

Figure 3-12: Simulated resonant frequency shift of AlN LWRs with temperature at different SiO$_2$ passivation layer thicknesses.
3.3.2 Effects of Anchor Design

The anchor design is a critical parameter for a LWR performance as the acoustic energy can dissipate through the support anchors and thus, degrade the $Q$-factor. In this simulation study, the SiO$_2$ passivation layer is excluded from the AlN LWRs. Devices with identical structural geometry but with varied anchor designs (Table 3-5) were studied in 3D simulations.

![Diagram of AlN LWRs with AlN/Mo and Mo anchors](image)

Figure 3-13: The 3D simulation structure of AlN LWRs (a) with AlN/Mo and (b) Mo anchors. The structure bottom view is shown in (c).

<table>
<thead>
<tr>
<th>$T_{AlN}$ (µm)</th>
<th>1</th>
<th>$\lambda$ (µm)</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{Mo}$ (nm)</td>
<td>200</td>
<td>$W_{AlN} \times L_{AlN}$ (µm$^2$)</td>
<td>150 × 166</td>
</tr>
<tr>
<td>$N$</td>
<td>12</td>
<td>$W_{anc} \times L_{anc}$ (µm × µm)</td>
<td>12.5 × 31.25</td>
</tr>
<tr>
<td>$l_{IDT}$ : $p$</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-5: Geometry specifications of devices in 3D simulation with different anchor designs.

As depicted in Figure 3-13, AlN LWRs with AlN/Mo and Mo anchors were first investigated. The length, $L_{anc}$ and width, $W_{anc}$ of the AlN anchor is exactly the same as the Mo anchor. Figure 3-14 compares the resonant behaviours of the AlN LWRs with AlN/Mo and Mo anchors in both COMSOL and ANSYS 3D simulations. Both simulation results agree with each other, whereby there is no significant difference in resonant characteristic between devices with and without AlN at the support
anchors. However, it is manifest that the $Q$-factor at anti-resonance is enhanced for the device with Mo anchors.

Figure 3-14: Comparison of resonant behavior for AlN LWRs with AlN/Mo and Mo anchors in (a) COMSOL and (b) ANSYS 3D simulations with the insets enlarging the frequency response at resonance.

Figure 3-15: The effect of anchor design on the thermal behaviour of AlN LWRs. The inset shows the temperature profile of the devices.
In addition to resonant performance, the anchor design also plays an important role in the thermal behavior of the AlN LWRs as an IR detector. As explained in Section 2.3.2, the temperature rise, $\Delta T$ within the detector is governed by $C_{th}$ and $G_{th}$ as given in Equation 2-19 and Equation 2-20. The polycrystalline AlN is a high thermal conductive material and thus the device with AlN/Mo anchors is expected to have a much lower $\Delta T$ and longer $\tau_{th}$ compared with that of the device with Mo anchors. From the COMSOL 3D simulation results (Figure 3-15), $\Delta T_{Mo}$ is about 5.5 times higher than $\Delta T_{AlN/Mo}$ but $\tau_{th,Mo}$ is 5.7 times longer than $\tau_{th,AlN/Mo}$ when the IR power intensity is 300 W/m$^2$. Assuming an optimistic TCF of -30 ppm/K and $f$ of about 400 MHz, $\Delta T_{AlN/Mo}$ of 0.08 K translates to a $\Delta f$ of about 2 kHz. Detecting this small amount change of resonant frequency in a MHz-device is a great challenge due to the presence temperature fluctuation noise. Therefore, the optimized AlN resonant IR detectors are based on the up-side-down AlN resonator with two Mo support anchors.

The effect of the Mo anchor dimensions on frequency response of AlN LWRs was then investigated. The devices under test have the same geometry parameters as stated in Table 3-5 except that the metallization ratio is 0.96. $W_{anc}$ was first fixed at 10 µm and $L_{anc}$ was varied. The ANSYS 3D simulation results are delineated in Figure 3-16 (a). There is a slight improvement in $Q$-factor when $L_{anc}$ changes from 30 µm to 31.25 µm as the latter one is an odd multiple of a quarter-wavelength [130]. In addition, longer $L_{anc}$ (5*quarter-wavelength, 31.25 µm) shows a better performance than the shorter one (3*quarter-wavelength, 18.75 µm). However, $L_{anc}$ cannot be infinitely long owing to the constraints imposed by mechanical stability and electrical characteristic. The optimum $L_{anc}$ can only be decided by experimental
results where since the simulation does not take into account the process-induced film stress.

Figure 3-16: The effect of anchor design on frequency response of AlN LWRs. (a) \(W_{\text{anc}}\) is first fixed at 10 \(\mu\text{m}\) and \(L_{\text{anc}}\) is varied. The value of \(L_{\text{anc}}\) is then fixed at 31.25 \(\mu\text{m}\) and \(W_{\text{anc}}\) is varied in (b) arbitrary integers and (c) different multiples of quarter-wavelength. The insets enlarge the frequency response at resonance.

Figure 3-16 (b) and (c) depict the frequency response of the devices with fixed \(L_{\text{anc}}\) of 31.25 \(\mu\text{m}\) and varying \(W_{\text{anc}}\) from 5 \(\mu\text{m}\) to 14 \(\mu\text{m}\). It is known that narrowing \(W_{\text{anc}}\) and positioning the anchors on nodal points of the resonant mode can minimize the acoustic energy radiation [131]. However, there is no significant trend observed in the simulation results. A device with \(W_{\text{anc}}\) of 12.5 \(\mu\text{m}\) gives the best performance.
with the highest $Q$-factor and cleanest frequency response. This is because the anchor of the AlN resonator consists of only Mo, which has high acoustic impedance and hence diminishes the acoustic radiation to the substrate [109].

![Figure 3-17: The effect of anchor design on frequency response of AlN LWRs. The inset shows the temperature profile of the AlN LWR.](image)

The device thermal sensitivity and response speed can also be tuned by varying the Mo anchors dimension. From Figure 3-17, devices with longer and narrower anchors give the higher $\Delta T$ but also longer $\tau_{th}$. Therefore, there is a trade-off between sensitivity and speed depending on applications. For a resonator with anchor dimension of 12 $\mu$m wide and 31.25 $\mu$m long, $\Delta T$ and $\tau_{th}$ of about 262 mK and 4.70 ms, respectively were simulated with the IR power density of 363 W/m$^2$.

### 3.3.3 Effects of Edge Reflection, ER

An optimized resonator for sensing applications should have the least spurious modes to ensure the acoustic energy confinement and constructive interference of the acoustic waves, thus the high $Q$-factor of the desired resonant mode. AlN LWRs are excited by the IDT electrodes without reflectors array at both sides of the IDTs.
Indeed the acoustic wave reflection is realized by the AlN piezoelectric film edges. It has been reported that the AlN piezoelectric film edges has a significant effect on the overall frequency response of the LWR because of the interaction between resonant modes induced by the mechanical boundaries and electric field [132, 133].

![Figure 3-18: The COMSOL 2D simulated frequency response of AlN LWRs in (a) odd and (b) even number of IDT fingers with different values of $d_{ER}$. The displacement profiles of the devices are shown at the bottom of each graph.](image)

The effect of the edge reflector distance, $d_{ER}$ from the outer electrode center to the piezoelectric film edge, was investigated using COMSOL 2D simulation. The simulated structure was similar with the structure depicted in Table 3-4 except that the IDT metallization ratio is 0.5 and there is no SiO$_2$ passivation layer. Figure 3-18 shows the frequency response of AlN LWRs, having odd ($N = 11$) and even number ($N = 12$) of IDT fingers with different values of $d_{ER}$. Both devices give the desired single resonant mode within a frequency span of 200 MHz when $d_{ER}$ is equal to...
quarter-wavelength. When \( d_{ER} \) is equal to 1.5*quarter-wavelength or 2*quarter-wavelength, the next lower and higher order of \( S \) modes are generated but with lower \( Q \)-factor and \( k_t^2 \). Odd or even number of IDT fingers does not impose any effect on the device resonant performance but the exact number of IDT fingers does (see Sections 3.3.5 and 5.5.5).

### 3.3.4 Effects of IDT Metallization Ratio

![Figure 3-19](image)

Figure 3-19: (a) COMSOL 2D and (b) ANSYS 3D simulation results show the effect of metallization ratio on frequency response of AlN LWRs.

The effect of IDT metallization ratio on the frequency response of an AlN LWR is depicted in Figure 3-19. The \( Q \)-factor of the device is not significantly affected by the metallization ratio but the resonant frequency and \( k_t^2 \) of the device is decreasing with \( l_{IDT} \) mainly due to the increasing mechanical mass loading and excessive acoustic energy absorption by the Mo IDT electrodes.

Since the value of \( k_t^2 \) is not the primary consideration in the resonator design for sensing applications, wider IDT finger are favorable to maximize the reflection of IR radiation that is transmitted through the TiN-absorber and AlN film, enabling
multiple absorptions. The ANSYS 3D simulation gives a similar trend for the resonant frequency shift with that of COMSOL 2D simulation as the metallization ratio increases. However, some metallization ratios show very noisy and attenuated frequency response because acoustic reflections from all angles are taken into account. Thus, the 3D simulation is necessary to obtain a more realistic frequency response for the resonator designs. The optimum IDT metallization ratio (as high as possible) shall be determined by experimental verifications to ensure the acceptable resonant characteristic.

3.3.5 Effects of Bolometric Size

Scalability of IR detector is an important factor for thermal imaging applications that involve array of detectors. Large detector arrays are required to improve the IR camera resolution. Small pixel size of IR detectors reduces chip size, cost, power consumption, and response time but deteriorates the IR absorption due to reduce in absorption area. In other words, thermal sensitivity is the key factor to be considered in IR detectors scalability. For a resonant IR detector, $Q$-factor is the key parameter to ensure device detectivity. In this section, the effect of device dimension on the resonant performance of AlN LWR is investigated.

The COMSOL 2D simulation was employed to study the effect of $N$ on the frequency response of the AlN LWRs with different values of $d_{ER}$ as depicted in Figure 3-20. For $d_{ER}$ of quarter-wavelength, the resonant frequency does not shift for different $Ns$, which implies that the S0 mode is less sensitive to both mass loading and $N$. For $d_{ER}$ of 1.5*quarter-wavelength or 2*quarter-wavelength, the frequency spacing between the lower and higher resonance is decreasing with increasing $N$. 

68
This agrees well with the mode spacing of contour mode resonator as explained in Equation 3-19 [134],

\[ f_{\pm q} = a \cdot \left( \frac{N \pm q}{N} \right) f_0 \]  

Equation 3-19

where \( f_0 \) is the resonant frequency of Lamb wave S0 mode; \( q \) is an integer which refers to the order number of Lamb wave S-mode; \( a \) is the constant accounts for the material properties. Therefore, the AlN resonant IR detectors shall have the 1.5*quarter-wavelength \( d_{ER} \) to ensure both robustness and spurious peak suppression.

Figure 3-20: The effect of \( N \) on frequency response of AlN LWRs with \( d_{ER} \) of (a) quarter-wavelength (b) 1.5*quarter-wavelength, and (c) 2*quarter-wavelength where \( N \) varies from 2 to 12.
The frequency responses of AlN LWRs with different aperture lengths, $L_{AL}$ were then compared in ANSYS 3D simulation. For SAW resonators or delay lines, it has been proven that $L_{AL}$ of > 30 wavelengths is advisable to prevent acoustic wave diffraction [135]. There is no reported work that relates the effect of $L_{AL}$ on the performance of LWR. From Figure 3-21, there is no obvious trend observed in the frequency response of resonators with different values of $L_{AL}$. The device with $L_{AL}$ of 50 μm gives the worst resonant performance while the one with $L_{AL}$ of 100 μm gives the best. No significant resonant frequency shift is observed except for the device with $L_{AL}$ of 25 μm, where the resonant frequency is about 6 MHz higher than the other. Experimental results to verify the effect of different structural parameters on AlN LWR resonant and IR sensing performance are discussed in CHAPTER 5.

![Graph](image)

Figure 3-21: The effect of $L_{AL}$ on frequency response of AlN LWRs.
CHAPTER 4: Device Fabrication

4.1 Overall Process Flow

The fabrication of the AlN resonant IR detectors was performed at IME-A*STAR, Singapore. Throughout the project, different AlN resonant IR detectors have been designed and fabricated in three phases. Major efforts have been given in process and recipe development in the phase-one fabrication. In the phase-two fabrication, a different process flow was implemented using the same masks set as phase-one for the verification of another device structure design. Optimization was done on the process flow and device structural design in the phase-three fabrication. All the process steps performed to manufacture the devices are compatible with standard CMOS technology.

4.1.1 Phase-one Fabrication

The 3D schematic diagram and SEM image of the phase-one AlN resonant IR detector is shown in Figure 4-1. The Mo IDT electrodes were deposited on top of the AlN film and the whole resonator is passivated by a SiO$_2$ layer. A 100 nm thick layer of SiN was employed as IR absorber [44, 56] and located above the Mo IDT electrodes. Figure 4-2 delineates the overall fabrication process flow of the phase-one device.
The fabrication was started with the deposition of a 300 nm thick SiO$_2$ layer using high-density plasma chemical vapour deposition (HDP-CVD). Next, a 1 μm thick AlN film and a 200 nm thick Mo layer were deposited by sputtering. The Mo layer was first patterned to form the IDT electrodes, followed by patterning of the AlN to
define the pixel geometry. Then, a film stack of 400 nm SiO$_2$ (by HDP-CVD)/ 100 nm SiN/ 350 nm SiO$_2$ was deposited by plasma-enhanced chemical vapour deposition (PECVD). The SiO$_2$/SiN/SiO$_2$ film stack was subsequently patterned by inductively coupled plasma (ICP) reactive ion etching (RIE) to open the contacts for the Mo IDT electrodes. Afterwards, 600 nm Al was deposited by sputtering and patterned by RIE to form the contact pads. Finally, the SiO$_2$/SiN/SiO$_2$ film stack was again etched by ICP-RIE to create the XeF$_2$ release window.

4.1.2 Phase-two Fabrication

In phase-two, the same mask set as phase-one was employed. However, the SiN IR absorber was replaced with a three-layer (TiN/AlN/Mo) film stack interferometric absorption design. Therefore, the resonator was designed up-side-down (Figure 4-3) with the Mo IDT electrodes at the bottom surface of the AlN film which also functions as IR reflector. A 10 nm thick TiN film was deposited on the top surface of the AlN, serving as IR anti-reflection and facing towards the IR radiation. By eliminating the SiN layer, the mechanical loading and damping could be reduced thus, further enhancing the resonant performance of the AlN resonator. The overall process flow of phase-two fabrication is illustrated in Figure 4-4.

Figure 4-3: The phase-two AlN resonant IR detector.
After the deposition of 300 nm thick HDP-CVD SiO$_2$, 20 nm thick AlN seed layer and 200 nm thick Mo film were sputtered on the oxide wafer in the same chamber. Then, the Mo/AlN film stack was patterned into IDT electrodes by ICP-RIE. Another 500 nm HDP-CVD SiO$_2$ was deposited to cover and fill up the Mo IDT electrodes gaps. Chemical mechanical polishing (CMP) was employed to flatten the topology and expose the Mo IDT electrodes. Subsequently, a film stack of 1 μm AlN and 10 nm TiN was deposited by sputtering and atomic layer deposition (ALD), respectively, and patterned by ICP-RIE to form the pixel geometry. Again, 400 nm thick HDP-CVD SiO$_2$ was deposited and patterned by ICP-RIE for contact opening.
Similar with the phase-one devices, the fabrication of the phase-two devices ends with Al contact pads formation, release window opening and XeF$_2$ releasing.

### 4.1.3 Phase-three Fabrication

![Diagram of phase-three AlN resonant IR detector](image)

Figure 4-5: The phase-three AlN resonant IR detector.

The fabrication process flow and the structural design of the AlN resonant IR detector have been optimized in phase-three. Figure 4-5 shows the 3D schematic diagram and SEM image of the phase-three device. Very similar to phase-two devices, the phase-three devices also contained Mo IDT electrodes at the bottom surface of the AlN film and TiN as IR absorber. However, the thick AlN was eliminated from the anchors, which only consist of Mo, AlN seed layer and Al$_2$O$_3$, to improve thermal isolation of the devices. Noticeably, the thick SiO$_2$ passivation did not exist in phase-three devices, which eliminates the excessive mechanical loading and the counter-TCF factor. Additionally, a release isolation wall was added surrounding the pixel geometry to confine the release region. Hence the electrical interconnects were shortened and the series parasitic resistance was minimized.
As shown in Figure 4-6, 4 μm thick SiO₂ layer was first deposited using wet thermal oxidation and low pressure chemical vapour deposition (LPCVD), followed by ICP-RIE patterning to define the release isolation trenches. The 1 μm thick polycrystalline silicon (poly-Si) was deposited by LPCVD to fill up the trenches (2 μm wide and 4 μm deep). The CMP was then applied to flatten the device surface and expose the SiO₂.

![Diagram of fabrication process flow](image)

Figure 4-6: Overall fabrication process flow of the phase-three AlN resonant IR detectors.

Afterwards, a film stack of 50 nm Al₂O₃ (by ALD)/ 50 nm AlN seed layer (by sputtering)/ 200 nm Mo (by sputtering) was deposited. The Mo film was then patterned by ICP-RIE to form the IDT electrodes and the etching stopped on AlN seed layer. Al₂O₃ is highly resistance to etching in vapour hydrofluoric acid (VHF), which will be used for the structure release at the latter process step. The 50 nm thick Al₂O₃ below the Mo/AlN seed film stack ensures the protection of the SiO₂ during VHF release. Thanks to the high conformal deposition of ALD Al₂O₃, the dishing regions of the poly-Si channel after CMP can be fully covered to prevent the
VHF leakage into the substrate region. A serious leakage of VHF can attack and lift-off the Mo interconnects and contact pads, resulting in device failure. The additional $\text{Al}_2\text{O}_3$ layer also strengthens the device anchor, which consists of 200 nm thick Mo and 50 nm thick AlN seed layer.

Subsequently, another film stack of 1 $\mu$m AlN (by sputtering)/ 10 nm TiN (by ALD)/ 10 nm $\text{Al}_2\text{O}_3$ (by ALD) was deposited and patterned by ICP-RIE to define the pixel geometry. SiO$_2$ CMP can be optionally performed prior to AlN deposition for surface planarization. Again, the 10 nm thick $\text{Al}_2\text{O}_3$ film on top of the TiN functions as passivation layer to prevent extended exposure of TiN to VHF. Finally, the release window was first opened by RIE-patterning of the film stack of AlN seed layer/$\text{Al}_2\text{O}_3$/SiO$_2$ before the structure release by VHF.

### 4.2 Silicon (Si) Deposition and Etching

For all samples, P-type single crystal Si wafers with single side polished were used. Prior to any fabrication steps, the Si wafers were cleaned using a sulfuric peroxide mixture (SPM) solution to remove organic particles. Whenever furnace process is required, the cleaning steps involve additional standard RCA procedure to further remove metal and silicon particles. The Si wafers is the starting substrate, supports the device built on top of it.

#### 4.2.1 LPCVD Poly-Si Deposition

Si is extremely resistant towards etching in VHF. In phase-three, LPCVD poly-Si was deposited to fill up the release isolation trenches (aspect ratio of 2) attributed to its good step coverage and uniformity. This formed a Si isolation wall to confine the
VHF release region. The deposition was done in a Semco LPCVD furnace at a temperature of 610 °C and at a pressure of 300 mTorr. With the silane (SiH₄) gas flow of 400 sccm, the deposition rate is about 200 Å/min. Figure 4-7 compares the trench filling using PECVD and LPCVD deposition. In the worst case, small voids might be formed within the trench during LPCVD deposition. However, the void size is much smaller than that formed by PECVD. Also, the void is at a much lower position which will not affect the subsequent process steps after CMP. The undoped LPCVD poly-Si is not electrically conductive and so it does not affect the device functionality. The quality of the poly-Si layer is not critical as it is not the active part of the device. However, film stress control is important because the wafer warpage can severely affect subsequent process steps especially the lithography step which will invoke alignment issues.

![Figure 4-7: Step coverage of the deposited film by (a) PECVD and (b) LPCVD.](image)

**4.2.2 XeF₂ Isotropic Dry Etching**

Isotropic etching using XeF₂ is an ideal solution for many MEMS devices. It provides numerous unique advantages and capabilities compared to wet and plasma
etching. XeF$_2$ can be used to etch Si, Mo and Ge. In this project, Si was isotropically etched by XeF$_2$ at the last process step for device release in phase-one and –two device fabrications. Owing to the high selectivity over Si (> 2000:1) in XeF$_2$ etching, SiO$_2$ was utilized as the etch stop material in the device release process. Long undercuts (> 100 μm) can be easily achieved without much consume of the etch stop layers. The etching process was carried out in a Xetch® Xenon Difluoride Etching System. XeF$_2$ and N$_2$ were pumped into the expansion chamber at the pre-set pressure. The gas mixture was later allowed to enter the process chamber. The etch time is determined by the number of chips to be processed. XeF$_2$ etch rates are very dependent on the amount of exposed Si. By avoiding unnecessary exposed Si and optimizing the etch recipe, undercutting of 2 to 3 μm in a minute is readily attainable. Figure 4-8 shows the SEM image of a XeF$_2$-released structure of the phase-one device.

![SEM image of XeF$_2$-released structure of phase-one device.](image)

**Figure 4-8**: SEM image of XeF$_2$-released structure of phase-one device. The inset clearly shows the XeF$_2$ released pit.
4.2.3 Si CMP

In phase-three, Si CMP was employed to flatten the wafer surface after SiO$_2$ trenches etching and poly-Si filling for the formation of the release isolation wall (Figure 4-9). CMP combines the chemical reaction and mechanical polishing to remove excessive poly-Si on top of SiO$_2$. Because of the mechanical action, CMP easily gives uniformity issues. The etching rate is much faster at the wafer edge than that at wafer center.

The 1.5 µm thick poly-Si CMP was done in an Ebara CMP tool with the optimized recipe (Table 4-1), which has a good selectivity over SiO$_2$ of about 100:1. Therefore, the polishing rate drops dramatically once the SiO$_2$ surface is exposed. Further polishing results in the phenomenon of dishing wherein the poly-Si in the trenches is removed more than the surrounding SiO$_2$, giving rise to a concave surface at the poly-Si channel.

Figure 4-9: Formation of release isolation wall in phase-three devices.
Table 4-1: Recipe of the poly-Si CMP using the Ebara CMP tool.

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Step 1</th>
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<th>Step 3</th>
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<td>0</td>
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<td>Chuck rotation (rpm)</td>
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<td>5</td>
<td>5</td>
</tr>
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<td>Back pressure (psi)</td>
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<td>1</td>
<td>-2</td>
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<td>off</td>
<td>off</td>
<td>on</td>
</tr>
</tbody>
</table>

Depending on the conditions of the CMP pads, the poly-Si removal rate varies in the range of 150 nm/min to 200 nm/min. An optimized polishing time is critical to fully remove the Si but yet prevent the dishing effect due to over polishing as shown in Figure 4-7. Severe dishing results in several problems for the subsequent process steps, including inefficiency of the release isolation wall and stringers formation during metal etching. To reduce the dishing effect, a short SiO\textsubscript{2} CMP can be carried out right after Si CMP.

4.3 Silicon Dioxide (SiO\textsubscript{2}) and Silicon Nitride (SiN) Deposition and Etching

4.3.1 CVD SiO\textsubscript{2} Deposition and Thermal Oxidation

SiO\textsubscript{2} layers play an important role in MEMS devices. They can be either structural or sacrificial parts of MEMS devices depending on their deposition or growth methods. In the phase-one and –two fabrications, XeF\textsubscript{2} was used as the etching agent to release the AlN resonators. Since Mo was used for the IDT electrodes, which is highly susceptible to etching when exposed to XeF\textsubscript{2}, SiO\textsubscript{2} was required to
passivate the devices. In addition, the metal RIE etchings of Al, Mo and AlN were aggressive and hence SiO$_2$ was needed either as hardmask material or etch stop layer to protect the layers underneath in all three fabrication phases.

Two types of CVD SiO$_2$ (PECVD and HDP-CVD) were deposited in an AMAT Centura CVD tool at a temperature of 400 °C. PECVD SiO$_2$ was deposited at a pressure of 3 Torr and RF power of 270 W with the reacting gases of SiH$_4$ and N$_2$O. On the other hand, HDP-CVD SiO$_2$ was deposited at a pressure of 6 mTorr and RF power of 3000 W with the reacting gases of SiH$_4$ and O$_2$. Compared with PECVD SiO$_2$, HDP-CVD SiO$_2$ has higher film stress but is much denser and thus has better selectivity in metal RIE etching processes.

![Comparison of SiO$_2$ step coverage deposited using (a) PECVD, (b) HDP-CVD and (c) thermal oxidation.](image)

As illustrated in Figure 4-10, PECVD SiO$_2$ encounters overhang issue and has the sidewall of < 90 ° which makes the Al patterning a serious disaster. Whereas HDP-CVD SiO$_2$ has a better gap fill capability because of the sidewall of > 90 °. Owing to the high film stress, thick HDP-CVD SiO$_2$ can cause wafer warpage, which can induce problems in further lithography steps. In addition, the plasma power is too high in HDP-CVD processes which will easily oxidize the thin TiN layer in phase-
two and –three devices. Therefore, PECVD SiO$_2$ with lower film stress is employed when thicker SiO$_2$ (> 500 nm) is required or direct deposition on TiN is unavoidable.

In phase-three, SiO$_2$ was used as the sacrificial material in the VHF releasing process. A 4 µm thick SiO$_2$ layer was required to build up the release region. Compared with dry oxidation, SiO$_2$ grows much faster by wet oxidation but with poorer electrical and chemical properties. Since the SiO$_2$ layer functions as the sacrificial material, these properties are not critical in the AlN resonator. Therefore, 1 µm thick of SiO$_2$ was grown by wet oxidation at a temperature of 1050 °C under water vapour atmosphere. Another 3 µm thick SiO$_2$ layer was deposited by LPCVD using tetraethyl orthosilicate (TEOS) source at a temperature of 700 °C, which produces lower film quality but has higher deposition rates. Even though the film stress was high, there were no wafer warpage issues since both wafer surfaces were grown/deposited with SiO$_2$, thereby the stress from the front-side and back-side of the wafer was balanced.

4.3.2 PECVD SiN Deposition

A PECVD SiN IR absorber was employed in phase-one devices. The SiN was deposited in-situ before and after the PECVD SiO$_2$ in AMAT Centura CVD tool at a temperature of 400 °C, a pressure of 4.2 Torr and RF power of 410 W with the reacting gases of NH$_3$, SiH$_4$, and N$_2$.

4.3.3 SiO$_2$ and SiN ICP-RIE Anisotropic Etching

In addition to contacts and release windows opening, SiO$_2$ ICP-RIE anisotropic etching was also employed to pattern the SiO$_2$ hardmask prior to Mo and AlN structuring. Photoresist (PR) is the common masking layer in SiO$_2$ ICP-RIE and its
thickness varies with SiO$_2$ thickness that is to be etched. Both the SiO$_2$ and SiN ICP-RIE etching process were performed using an Omega FXP GTM System at a temperature of 10 °C and coil RF power of 1500 W. The main etching gas for SiO$_2$ and SiN ICP-RIE were C$_4$F$_8$ (process pressure of 10 mTorr) and CF$_4$ (process pressure of 4 mTorr), respectively. The platen RF power and process pressure were 400 W and 10 mTorr for SiO$_2$ ICP-RIE; 600 W and 4 mTorr for SiN ICP-RIE. Figure 4-11 depicts the SEM images of the SiO$_2$ and SiN etch profiles. More SEM images regarding SiO$_2$ hardmask etch profiles are shown in Sections 4.4.2 and 4.4.2.

![SEM images of SiO$_2$ and SiN etch profiles](image)

Figure 4-11: SiO$_2$ and SiN etching for (a) contact and (b) release window opening.

### 4.3.4 VHF Isotropic Dry Etching

As mentioned previously, the phase-three devices were released by VHF instead of XeF$_2$. Similar to XeF$_2$, VHF is able to provide stiction-free released structure by isotropically etching away the sacrificial SiO$_2$ layer underneath the active device (Figure 4-12). Since Si, AlN, Al$_2$O$_3$ and Mo have high selectivity over SiO$_2$ in VHF etching, the AlN resonator does not require an additional passivation layer for protection. By having the poly-Si release isolation wall, the VHF release region was confined within a desired range to minimize the device consumed area and interconnect length. The VHF releasing process was performed in a Primaxx$^\text{®}$ Etch.
System at a temperature of 45 °C and a pressure of 125 Torr. The gases involved in the etching process were HF vapour as the primary etching gas, ethanol used to desorb the H₂O reaction product from the surface of the device, and N₂ used to offset changes to vapour pressures of the active gases and prevents ethanol saturation in the vaporizer.

Figure 4-12: The SEM image of the VHF-released structure of phase-three device.

4.3.5 SiO₂ CMP

Figure 4-13: SiO₂ CMP on Mo IDT electrodes to flatten the surface topology prior to AlN deposition.

In phase-two and –three fabrications, SiO₂ was polished using CMP after Mo IDT electrodes structuring. This is to flatten the topology induced by the Mo IDT
electrodes before AlN deposition to minimize the microstructure disorder which will affect the quality of the AlN film and thus the resonant characteristics. Figure 4-13 shows the SEM image of the Mo IDT electrodes embedded in the SiO₂ layer after CMP. Because of the mechanical action, there will be erosion of the Mo IDT electrodes during the CMP process. Again, CMP process time has to be carefully optimized to minimize the erosion of Mo IDT electrodes. For the planarization of 700 nm thick SiO₂ layer, the optimized recipe as shown in Table 4-2 was employed.

Table 4-2: Recipe of the SiO₂ CMP process using an AMAT CMP tool.

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</tr>
<tr>
<td>Slurry flow rate (ml/min)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>0</td>
</tr>
<tr>
<td>Rinse (on/off)</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>on</td>
</tr>
</tbody>
</table>

4.4 Molybdenum (Mo)/ Aluminium Nitride (AlN) Deposition and Etching

4.4.1 Deposition of Mo and AlN

AlN is the key material in the resonant IR detectors. For acoustic wave generation with high electromechanical coupling coefficient, $k_e^2$ and $Q$-factor, a highly $c$-axis oriented AlN film is required [110, 136]. The RF reactive sputtering deposition of AlN on a SiO₂ surface has been well developed in phase-one fabrication. The AlN film was deposited using a SPTS Sigma FXP tool at a temperature of 200 °C and a
process pressure of 50 mTorr using a pure Al target in the reactive N$_2$/Ar gas mixture with a ratio of 5. The RF power and DC bias are 147 W and 100 V, respectively.

In phase-two and –three, the AlN film was deposited on the patterned Mo IDT electrodes. Mo has a microstructure in body-centered cubic (bcc) with low index planes, which is mismatched with the (0002) planes of AlN. Therefore, a thin AlN seed layer (> 20 nm) was prepared prior to the deposition of Mo. The Mo electrodes and the AlN layer were deposited using the same tool, at a temperature of 200 °C in 50 mTorr Ar gas with a RF power of 100 W.

Figure 4-14: XRD patterns for a 1 μm AlN film deposited on 200 nm thick Mo IDT electrodes (a) without and (b) with 20 nm thick AlN seed layer.
With the same deposition conditions for the AlN and Mo films, the one with AlN seed layer gives the XRD peak intensity of AlN and Mo 40 times higher than that without AlN seed layer (Figure 4-14). This proves that the crystallinity of the AlN film and Mo electrode were significantly improved by the AlN seed layer. The full-width at half-maximum (FWHM) of the rocking curves was evaluated for the AlN film and it decreases from 8.38 ° to 1.94 ° with the addition of AlN seed layer, implying that the crystal orientation of the AlN film is improved. This agrees well with data published in [111].

**4.4.2 AlN RIE Anisotropic Etching**

AlN is a hard material with bulk hardness similar to quartz, about 2.0 Kg/mm. Thus, structuring of AlN is normally accomplished with the assistance of a hardmask because PR is too soft to be the mask in the aggressive AlN RIE process. Depending on the etch-stop layer and device design, the hardmask material for patterning AlN layer could be e.g. a metal or an oxide.

![Diagram of AlN etching](image)

Figure 4-15: Illustration of AlN etching with PR as the masking layer in phase-one fabrication.
For the first approach (Figure 4-15), a single layer of 2.9 μm thick PR was used as the masking layer to etch the 500 nm AlN and stop on a 300 nm thick PECVD SiO$_2$ layer using a Centura Metal Etching tool with BCl$_3$ and Cl$_2$ as the etching gases. The process temperature, pressure, RF power and DC-bias are 25 °C, 15 mTorr, 130 W and 250 V, respectively. After an AlN partial etch, the wafer was inspected using DRSEM. A thick wall of metal polymer was observed along the AlN sidewall as shown in Figure 4-16 (a), which results from the reaction between the AlN etch byproducts and PR. The AlN film then continued being etched until endpoint detection. Some overetch time was added after endpoint detection as a severe etch uniformity was optically observed.

![Figure 4-16: AlN etching profile in the first approach with PR as masking layer.](image)

The PR was stripped using oxygen plasma with a small amount of CF$_4$ component in a Mattson tool, followed by polymer clean in Verteq Megasonic Cleaner. Figure 4-16 (b) shows that the metal polymer was still not fully removed. In addition, there were still AlN residues detected by EDX at the wafer center while it was cleared at the wafer edges. After a series of PR ashing and polymer clean steps, the metal polymer was finally removed as shown in Figure 4-16 (c). Due to the multiple ($O_2 +$
CF₄) plasma exposure and polymer clean, the surface of AlN was roughened. The critical dimension (CD) of AlN was enlarged by at least 0.5 μm because of the thick metal polymer formation during the etching process. On the other hand, SiO₂ selectivity was very poor when this AlN etch recipe was used. Roughly 120 nm and 80 nm of SiO₂ had been consumed at wafer edge and center, respectively, for a 500 nm AlN etch.

To solve the SiO₂ selectivity issues, the etch recipe was tuned to replace BCl₃ with HBr. The SiO₂ selectivity has been improved and the AlN residues are much lesser at endpoint detection (Figure 4-17 (a)). Additionally, the metal polymer wall is much thinner than that of the one using initial recipe and thus giving a better CD control. However, the metal polymer became more stubborn. The cycles number of PR ashing and polymer cleans is doubled in order to clean the metal polymer formed, resulting in a highly rough AlN surface.

Figure 4-17: AlN etch profile using modified recipe with only PR as masking layer.
Figure 4-18: AlN etching with SiO₂ as hardmask and stop on SiO₂ or Mo surface.

The problems of metal polymer formation and SiO₂ selectivity in AlN etching cannot be solved without using a hardmask. In the optimized AlN etching process, SiO₂ was employed as the hardmask material (Figure 4-18). PR was stripped away after SiO₂ hardmask patterning to avoid the exposure of AlN to PR and thus minimize the metal poly formation.

Furthermore, ICP-RIE was employed instead of RIE and the etching tool was switched to an Omega FXP GTM System. The optimized AlN etch recipe uses the etching gases of BCl₃, HBr and Cl₂ with the process temperature, pressure, coil RF power and platen RF power of 45 °C, 7 mTorr, 700 W and 300 W, respectively. This optimized recipe has a faster etch rate and good SiO₂ and Mo selectivity over AlN. From the SEM images shown in Figure 4-19, there is no polymer formation surrounding the etched AlN.
Figure 4-19: SEM images of the patterned AlN at different stages in (a) phase-one and (b) phase-two fabrications using optimized recipe.

### 4.4.3 Mo RIE Anisotropic Etching

Mo is deposited on either AlN film or seed layer. Thus the etch recipe of Mo was optimized such that the etch selectivity towards the AlN layer is high enough. The Mo ICP-RIE etching process (Figure 4-20) was also performed in an Omega FXP GTM System at a temperature of 45 °C, a pressure of 13 mTorr, a coil RF power of 700 W and a platen RF power of 100 W using Cl₂ and O₂ as the etching gases. A SiO₂ thin film is normally used as the hardmask material in Mo etching to prevent the CD deviation and edge erosion as observed in the PR-masked etching profile (Figure 4-21).
Figure 4-20: Illustration of Mo etching in the fabrication of AlN resonant IR detectors.

Figure 4-21: Mo etching profile with PR as the masking material.

4.5 Titanium Nitride (TiN) Deposition

TiN was employed as IR absorber in the phase-two and -three devices. A highly uniform and thin TiN film (10 nm) was deposited on the AlN film using ALD in a Picosun ALD System at a temperature of 200 °C and a plasma power of 300 W with the precursors tetrakis(dimethylamido)titanium (TDMAT) and NH₃. TDMAT and
NH₃ pulses were injected into the N₂ carrier gas in sequence at a pre-set pressure using computer controlled solenoid valves. Due to its ultra-thin thickness, TiN was etched together with the AlN using the same recipe in an Omega FXP GTM System. Sheet resistivity of the deposited 10 nm TiN film was measured by four-point probe measurement, which gave a value of about 300 Ω/□.

4.6 Aluminium (Al) Deposition and Etching

Table 4-3: Al etching recipes used by Centura Metal Etching tool.

<table>
<thead>
<tr>
<th>Parameter (Unit)</th>
<th>Al RIE (by Centura Metal Etching)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
</tr>
<tr>
<td>Pressure (mTorr)</td>
<td>12</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>25</td>
</tr>
<tr>
<td>BCl₃ flow rate (sccm)</td>
<td>60</td>
</tr>
<tr>
<td>Ar flow rate (sccm)</td>
<td>15</td>
</tr>
<tr>
<td>Cl₂ flow rate (sccm)</td>
<td>110</td>
</tr>
<tr>
<td>DC-Bias (V)</td>
<td>100</td>
</tr>
<tr>
<td>Power (W)</td>
<td>1300</td>
</tr>
</tbody>
</table>

Al was employed as contact pads in the phase-one and –two devices. After contact opening, the Al sputter deposition was performed in an AMAT Endura PVD tool at 5 mTorr Ar pressure and < 1×10⁻⁵ Torr base pressure with an Ar flow rate of 40 sccm and a power of 400 W.

The Al film was then structured into contact pads with a 2 μm thick PR masking layer using RIE in a Centura Metal Etching tool. The standard recipe shown in Table 4-3 was the first attempt to pattern the Al contact pads. However, stringers were found surrounding the AlN resonator due to the step height as depicted in Figure 4-22 (a). A modified recipe with more isotropic characteristics was developed to
solve the stringers issues. The standard recipe was first applied in the AlN etching process until the detection of endpoint, followed by overetch with the modified recipe. As seen in Figure 4-22 (b) and Figure 4-23, no Al stringers are observed surrounding the AlN resonator. The modified recipe consumes more SiO$_2$ than the standard recipe. The rough surface after the Al etch was due to the pattern transfer from Al residues left after endpoint detection during the standard recipe etching and also the poor SiO$_2$ selectivity.

Figure 4-22 : SEM images of Al etching results using (a) the standard etch recipe and (b) the combined standard and modified recipe in phase-one device.

Figure 4-23: SEM images of Al etching results using the combined standard and modified etch recipe in phase-three devices.
CHAPTER 5: Characterization of Resonant Behavior

5.1 Experiment Setup

The frequency response analysis of the AlN resonant IR detectors was performed under vacuum condition (~ 1x10^{-5} mbar) using the setup as depicted in Figure 5-1. The vacuum probe station from Cascade Microtech® is equipped with RF feedthroughs, enabling electrical connections between the device under test (DUT) and network analyzer.

Figure 5-1: Experiment setup for resonant characteristic and noise analysis of the AlN resonant IR detectors.

Network analyzer. A network analyzer is an instrument that measures the parameters of electrical networks. Generally, a network analyzer quantifies the
impedance mismatch between two RF components to optimize signal integrity and power efficiency. Each time a RF signal travels across a medium, it will partly get reflected and transmitted (with negligible heat loss) as depicted in Figure 5-2. The network analyzer generates a RF signal across a range of frequencies and the DUT responds with the incident RF signal. The amount of signal transmitted to and reflected from the DUT normally changes with frequencies. In this project, the AlN resonant IR detectors were characterized using an Agilent E5071B ENA RF Network Analyzer, which gives the scattering (S-) parameters of the devices.

Figure 5-2: Schematic of a two-port network with signals in and out.

**Scattering (S-) parameter.** S-parameters are complex vector quantities which indicate the ratio of two RF signals. They are described in $S_{ij}$ where $i$ and $j$ refer to the DUT output and input port of the RF signal, respectively. The S-parameter refers to the reflection coefficient when $i = j$, else it indicates the signal transmitted at port-$i$ with respect to the incident signal at port-$j$. The matrix algebraic representation of two-port S-parameters can be expressed by

$$
\begin{pmatrix}
  b_1 \\
  b_2
\end{pmatrix} =
\begin{pmatrix}
  S_{11} & S_{12} \\
  S_{21} & S_{22}
\end{pmatrix}
\cdot
\begin{pmatrix}
  a_1 \\
  a_2
\end{pmatrix}
$$

Equation 5-1

$S_{21}$ and $S_{12}$ characterize the DUT insertion loss, gain, and attenuation; while $S_{11}$ and $S_{22}$ give the return loss and voltage standing wave ratio (VSWR). S-parameters can be cascaded for multiple devices to produce a composite result. The incident power
does not need to be precisely set to an absolute value because the $S$-parameters are expressed in ratios. Any offset in the input reflected in the DUT will get cancelled out in the calculation of ratios of incident and response signals.

![Enlarged view of GSG probe tip footprints under microscope](image)

Figure 5-3: The GSG probe for high frequency measurements.

![Figure 5-4: Planarization of GSG probe tips](image)

Figure 5-4: Planarization of GSG probe tips. (a) Only two tips are in contact with the Contact Substrate. (b) All three tips are in contact with the Contact Substrate but one tip makes a deeper scratch than another. (c) Probe tips are in-plane: all three tips leave an even scratch on the Contact Substrate.

**Ground-signal-ground (GSG) probe.** For a two-port RF device characterization, two GSG probes are required. Before the frequency response measurements, calibration of the probes and network analyzer is necessary. The GSG probes used in the measurement are from Cascade Microtech with the footprints as shown in Figure 5-3. The probe tips need to be aligned in-plane before probing to DUT to ensure all three tips are in contact with the DUT contact pads during measurements. A dedicated “Contact Substrate” with a deposited soft Au film was used to calibrate
the probe tip alignment. Figure 5-4 demonstrates the steps of GSG probe tip planarization.

**Impedance calibration.** In order to obtain accurate results, impedance calibration of the network analyzer is essential upon every measurement. This can be performed with a set of calibration standards from the network analyzer calibration kits. A set of correction factors is created by comparing the known values that are stored in the network analyzer against the measured values using the calibration standards. During post-calibration, the correction factors are then applied to the measurement data for error compensation. There are a few of calibration options available, including Thru-Reflect-Reflect-Match (LRRM), Thru-Reflect-Match (LRM), Thru-Reflect-Line (TRL), Short-Open-Load-Reciprocal (SOLR) and Short-Open-Load-Thru (SOLT). In this work, the SOLT technique is employed to calibrate the network analyzer. Figure 5-5 shows the different configurations performed in SOLT calibration using the dedicated “Impedance Standard Substrate (ISS)”.

Figure 5-5: Different configurations of SOLT calibration on the dedicated ISS.
5.2 Equivalent Electrical Circuit Model

Nowadays the use of an electrical equivalent circuit model to analyse mechanical systems is pervasive, particularly with respect to the depiction of piezoelectric resonators and transducers. This is mainly because the measurement equipment is often itself completely electrical in nature. The mechanically vibrating system can be equivalent to a certain purely electrical network. A few equivalent circuit models have been developed and they are proved to well-fit the resonant behaviour of piezoelectric resonators [137-141]. Basically, an equivalent circuit model consists of both motional and static branches that give the overall electrical impedance of a resonator. The static branch mainly provides the information of electrical properties of the resonator and electrical parasitic components of the system. The motional branch gives the hint of electromechanical coupling and $Q$-factor of a resonator. Hence, continuous optimization of the piezoelectric resonator is possible by fitting the measurement data to the equivalent circuit model.

![Figure 5-6: The conventional BVD circuit model.](image)

Among all the equivalent circuits, the Butterworth van Dyke (BVD) equivalent model as shown in Figure 5-6 is the most popular because of its simplicity and yet sufficient to express the behaviour of the resonators. The motional branch consists of motional resistance, $R_M$, motional capacitance, $C_M$, and motional inductance, $L_M$. 
The static capacitance, \( C_O \), denoting the intrinsic capacitance of the piezoelectric film, makes up the static branch and is parallel to the motional branch.

![modified BVD circuit model](image)

Figure 5-7: The modified BVD circuit model.

The BVD model has been widely used to characterize BAW and SAW devices since its first invention in 1914 by Butterworth [142] and in 1925 by Van Dyke [143]. In 1999, a modified Butterworth van Dyke (MBVD) model as illustrated in Figure 5-7 was proposed to improve the fitting accuracy between measured data and fitting model [144]. Since then, the MBVD model is more commonly employed to describe the resonant characteristics of piezoelectric resonators. The additional resistance, \( R_O \) is added into the static branch to take account of the piezoelectric material dielectric loss. The component \( R_S \) is added in series with the BVD circuit to take into account the parasitic series resistance contributed by the electrical interconnects and contact pads.

The overall electrical impedance of the resonator at resonance, \( Z_{MBVD} \) can be predicted as

\[
Z_{MBVD}(f) = R_S + \frac{Z_{motional}(f) \cdot Z_{static}(f)}{Z_{motional}(f) + Z_{static}(f)} \quad \text{Equation 5-2}
\]

where
Chapter 5

\[ Z_{motion}(f) = R_M + j[2\pi f L_M + 1/2\pi f C_M] \]  
Equation 5-3

\[ Z_{static}(f) = R_O + j[1/2\pi f C_O] \]  
Equation 5-4

Each of the parameters in the MBVD model can be defined by the resonator physical geometry and material properties as illustrated in Equation 5-5 to Equation 5-8 [145]:

\[ C_O \approx N\varepsilon_{33}\varepsilon_0 \frac{W_{IDT}L_{IDT}}{T_d} \]  
Equation 5-5

\[ C_M = N \frac{8}{\pi^2} \frac{W_{IDT}L_{IDT}}{T_d} \frac{E_{eq}d_{31}^2}{E_{eq}d_{31}^2} \]  
Equation 5-6

\[ R_M = \frac{1}{N} \frac{\pi T_d}{8} \frac{\sqrt{\rho_{eq}}}{L_{IDT}E_{eq}^{3/2}d_{31}^2Q_s} \]  
Equation 5-7

\[ L_M = \frac{1}{N} \frac{\rho_{eq} W_{IDT}T_d}{8} \frac{1}{L_{IDT}E_{eq}d_{31}^2} \]  
Equation 5-8

where \( N, W_{IDT}, \) and \( L_{IDT} \) are the number, width and length of IDT fingers; \( \varepsilon_0 \) denotes the vacuum permittivity; \( \varepsilon_{33} \) and \( T_d \) refer to the dielectric constant and film thickness of the piezoelectric material along \( c \)-axis; \( E_{eq}, \rho_{eq}, d_{31} \) and \( Q_s \) are the equivalent elasticity, effective mass density, piezoelectric coefficient and \( Q \)-factor of the piezoelectric resonator at the resonant frequency, \( f_s \).

After obtaining the parameters by equivalent circuit fitting, the resonant frequency (or series frequency, \( f_s \)) and the anti-resonant frequency (or parallel frequency, \( f_p \)) can be estimated as shown in Equation 5-9 and Equation 5-10 [146]:

102
The effective coupling coefficient, $k_t^2$ and $Q$-factors, $Q_s$ (at $f_s$) and $Q_p$ (at $f_p$) can be determined by [146]:

$$k_t^2 = \left( \frac{\pi}{2} \right)^2 \left( \frac{f_s}{f_p} \right) \left( \frac{f_p - f_s}{f_p} \right)$$  \hspace{1cm} \text{Equation 5-11}

$$Q_s = \frac{1}{2\pi f_s C_M (R_M + R_S)}$$  \hspace{1cm} \text{Equation 5-12}

$$Q_p = \frac{1}{2\pi f_p C_M (R_M + R_O)}$$  \hspace{1cm} \text{Equation 5-13}

As shown in Equation 5-10 and Equation 5-11, the ratio of $C_M/C_O$ defines the frequency spacing between $f_s$ and $f_p$ and thus determines $k_t^2$. On the other hand, the value of $C_M$ plays an inerse role in giving high $Q$-factor resonator. The common FOMs used to characterize a piezoelectric resonator are $Q$, $f$ and $k_t^2$. The product of $Q \cdot k_t^2$ directly affects insertion loss and bandwidth of filters; power consumption and phase noise in oscillators. The product of $Q \cdot f$ is inversely proportional to the noise equivalent mass resolution in a resonator and it is therefore important in defining frequency stability and also phase noise, which is critical for sensing applications. Therefore, the equivalent circuit model is of particular importance for optimization to further enhance the FOMs of resonant-based sensors.
The MBVD model can be fitted to both the one-port and two-port piezoelectric resonator network as illustrated in Figure 5-8. In addition to the parasitic terms of \( R_P \), another additional capacitance, \( C_f \) has been included in the two-port circuit model to account for substrate and device feedthrough between the two ports.

![Diagram of one-port and two-port MBVD circuit models](image)

**Figure 5-8:** (a) The one-port and (b) two-port MBVD circuit models.

The parameters in two-port MBVD model are re-defined as follow:

\[
C_O = C_{O,in} + C_{O,out} \quad \text{Equation 5-14}
\]

\[
C_{O,in} \approx N_{in} \varepsilon_{33} \varepsilon_0 \frac{W_{IDT} L_{IDT}}{T_d} \quad \text{Equation 5-15}
\]

\[
C_{O,out} \approx N_{out} \varepsilon_{33} \varepsilon_0 \frac{W_{IDT} L_{IDT}}{T_d} \quad \text{Equation 5-16}
\]

\[
C_M = \frac{8}{\pi^2} \frac{W_{IDT} L_{IDT}}{T_d} E_{eq} d_{31}^2 \frac{N_{in}^2}{N_{in} + N_{out}} \quad \text{Equation 5-17}
\]
\[ R_M = \frac{\pi T_d}{8 L_{IDT}} \sqrt{\frac{\rho_{eq}}{E_{eq} d_{31}^2}} Q_s \frac{N_{in} + N_{out}}{N_{in}^2} \]  \hspace{1cm} \text{Equation 5-18}

\[ L_M = \frac{\rho_{eq} W_{IDT} T_d}{8 L_{IDT}} \frac{1}{E_{eq} d_{31}^2} \frac{N_{in} + N_{out}}{N_{in}^2} \]  \hspace{1cm} \text{Equation 5-19}

where the variables are the same as in Equation 5-5 to Equation 5-8 and the subscripts \( in \) and \( out \) refer to quantities associated with input and output ports of the resonator, respectively.

![Mason lumped circuit model for piezoelectric resonators.](image)

After the invention of the BVD model, Mason subsequently introduced another model in 1950s which includes acoustic transmission lines, mechanical ports, and piezoelectric transformers, thereby extending the circuit to encompass electromechanical conversion devices of wide generality [147]. Today, the Mason model is universally used for BAW and SAW device characterization. The Mason model is applicable to a wide frequency range while the BVD model is only valid in a small frequency region around a single resonance. As depicted in Figure 5-9, the Mason model consists of one electrical port and two mechanical ports. Force, \( F \) and velocity, \( v \) are mechanical variables while voltage, \( V \) and current, \( I \) are electrical variables. The detailed descriptions of the model can be found in [140]. The several parameters in the equivalent circuit are defined as:

105
\[ Z_1(f) = jZ_0 \tan \left( \frac{2\pi f \cdot l_c}{2v_c} \right) \quad \text{Equation 5-20} \]

\[ Z_2(f) = -jZ_0 \csc \left( \frac{2\pi f \cdot l_c}{v_c} \right) \quad \text{Equation 5-21} \]

\[ Z_0(f) = Z_c A_c \quad \text{Equation 5-22} \]

\[ \eta = h_{33} C_0 \quad \text{Equation 5-23} \]

where \( v_c \) is the wave propagation velocity in the piezoelectric medium; \( l_c \) is half of the thickness of the piezoelectric film; \( Z_c \) is the acoustic impedance of the piezoelectric material; \( A_c \) is the interface area between electrode and piezoelectric film; \( \eta \) is the conversion factor of the electromechanical transformer; \( C_0 \) is the intrinsic capacitance of the piezoelectric film when the strain is null; \( h_{33} \) is the piezoelectric stress coefficient. The Mason model also makes a distinction between the TE and LFE mode that are denoted by positive and negative \( C_0 \). The Mason model can be simplified as delineated in Figure 5-10. When only a particular resonant mode within a small frequency range is of interest, the Mason model can be further simplified to the BVD model as depicted in Figure 5-8.

\[ \begin{align*}
I & \quad \text{Input} \\
V & \quad \text{Output} \\
C_0 & \\
\end{align*} \]

\[ \begin{align*}
R_M & \\
C_M & \\
L_M & \\
\eta & \\
\end{align*} \]

Figure 5-10: The simplified Mason lumped circuit model.

Comparing with one-port resonators, two-port resonators have the advantage of transduction at higher frequencies due to the electrical isolation between input and
output terminals. The two-port design also simplifies the making of electrically coupled filters. The disadvantages are that, in a planar solution, the two-port topology increases the motional impedance by a factor of 4 for a given transduction area [145].

5.3 Root Mean Square Frequency Noise

![Diagram](a) RMS noise measurement of a two-port resonator.

Instantaneous root-mean-square (RMS) frequency noise gives the immediate hint of frequency instabilities of a resonator, which defines the sensing resolution or detectivity for IR detector. The RMS frequency noise can be determined from either the magnitude or phase measurement of the $S$-parameters. In this work, $S_{21}$ of the two-port resonators is used to characterize the noise performance. As seen in Figure
5-11 (a), the $S_{21}$ magnitude and phase are first obtained in a small frequency span of about 5 MHz around the resonant frequency, $f_0$.

**RMS frequency noise by $S_{21}$ phase noise.** The gradient of $S_{21}$ phase, $d\phi/df$ is calculated at $f_0$. Then, the RMS value of $S_{21}$ phase, $\sigma_{\phi,\text{RMS}}$ is acquired by setting the network analyzer to a single frequency (zero-frequency span) at $f_0$ as seen in Figure 5-11 (b). The RMS frequency noise, $f_{\text{RMS}}$ is thus obtained using the Equation 5-24:

$$f_{\text{RMS}} = \frac{\sigma_{\phi,\text{RMS}}}{d\phi/df}$$

**RMS frequency noise by $S_{21}$ magnitude noise.** Similarly, the gradient of $S_{21}$ magnitude, $d|S_{21}|/df$ is first obtained at $f_{\phi,\text{min}}$ (frequency where the $S_{21}$ phase is at minimum, which also corresponds to the maximum value of $d|S_{21}|/df$). Next, the RMS value of $S_{21}$ magnitude, $\sigma_{S_{21},\text{RMS}}$ is acquired from the network analyzer at $f_{\phi,\text{min}}$ (Figure 5-11 (c)). The value of $f_{\text{RMS}}$ is then estimated by:

$$f_{\text{RMS}} = \frac{\sigma_{S_{21},\text{RMS}}}{d|S_{21}|/df}$$

Dividing $f_{\text{RMS}}$ by the square root of intermediate frequency (IF) bandwidth, $f_{\text{IF}}$ of the network analyzer, the frequency noise spectral density, $f_{\text{NSD}}$ can be extracted.

$$f_{\text{NSD}} = \frac{f_{\text{RMS}}}{f_{\text{IF}}}$$

**5.4 Network Analyzer Parameter**

In order to obtain optimum results using the network analyzer, the measurement parameters has to be carefully chosen. The phase-three devices were tested in this
Section in order to obtain the most suitable measurement setting. The network analyzer does not operate in a continuous ramp sweep mode throughout the desired frequency span. Indeed, it makes stepped measurements at selected frequency points based upon the chosen number of points in that sweep. Depending on the frequency interval and selected intermediate frequency bandwidth (IF BW), information might be missed out when gaps are created in the sweep as illustrated in Figure 5-12. To ensure sufficient overlap, the frequency interval (= frequency span /number of measurement points) must be set smaller than the IF BW.

![Figure 5-12: Illustration of stepped frequency sweep.](image)

![Figure 5-13: (a) The measured frequency response and (b) RMS value of $S_{21}$ phase of the AlN resonant IR detector at different IF BWs.](image)
To investigate the resonant behaviour of the AlN resonant IR detector, a frequency span of 20 MHz and measurement points of 16000 were set, which defines the frequency interval of 1.25 kHz. As seen from Figure 5-13 (a), there is no significant difference in frequency response even when the frequency interval is larger than the IF BW. Nevertheless, the standard deviation value of $S_{21}$ phase, $\sigma_\phi$ increases with IF BW as more noise signals are unfiltered. Reducing IF BW diminishes the measurement noise floor, but also increases the measurement time. In this project, IF BW of 1 kHz was chosen for the frequency response measurement, which results in a measurement time of about 15 s.

The power handling capability of a resonator directly affects the phase noise. Therefore, the driving power of the resonator should be maximized to achieve an optimum noise performance. Before being fatal to device operation, high driving power causes a nonlinear response in the AlN resonator, which is associated with signal distortion, and originates intermodulation products as proved in Figure 5-14 (a).

![Figure 5-14](image)

Figure 5-14: (a) The measured frequency response and (b) standard deviation of $S_{21}$ phase of the AlN resonant IR detector at different driving powers.
Due to dielectric losses and parasitic resistance, the AC power dissipates in the resonator and transforms into heat, causing a temperature increase in the resonator [84]. The resonant frequency of the tested AlN resonator started to shift down at a driving power of -10 dBm at which the temperature rise becomes significant. A bending of the $S_{21}$ frequency response was observed at a driving power of 0 dBm. From Figure 5-14 (b), the value of $\sigma_\phi$ decreases with the driving power and rebounds after -15 dBm due to the increasing thermal noise which agrees well with the frequency response in Figure 5-14 (a). Therefore, the driving power for the following measurements will be set at -15 dBm.

### 5.5 Results and Discussion

Table 5-1: Geometry specification of phase-two devices.

<table>
<thead>
<tr>
<th>Device parameter</th>
<th>P2-1</th>
<th>P2-2</th>
<th>P2-3</th>
<th>P2-4</th>
<th>P2-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top SiO$<em>2$ thickness, $T</em>{\text{TopOx}}$ (nm)</td>
<td>100</td>
<td>250</td>
<td>400</td>
<td>550</td>
<td>700</td>
</tr>
<tr>
<td>Bottom SiO$<em>2$ thickness, $T</em>{\text{BotOx}}$ (nm)</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AlN thickness, $T_{\text{AlN}}$ (µm)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo thickness, $T_{\text{Mo}}$ (nm)</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiN IR absorber thickness, $T_{\text{TiN}}$ (nm)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustic wavelength, $\lambda = 2p$ (µm)</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of IDT fingers, $N$</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallization ratio ($l_{\text{IDT}} : p$)</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture length, $L_{\text{AL}}$ (µm)</td>
<td>150</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge reflector distance, $d_{\text{ER}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Quarter-wavelength</td>
</tr>
<tr>
<td>Bolometric area, $W_{\text{AlN}} \times L_{\text{AlN}}$ (µm$^2$)</td>
<td>150 × 166</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anchor dimension, $W_{\text{anc}} \times L_{\text{anc}}$ (µm × µm)</td>
<td>12.5 × 31.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The tested devices in the following sections are from phase-three fabrication, except for Section 5.5.1 where the devices are from phase-two fabrication. Unless specially specified, all the device parameters are listed in Table 5-1.

5.5.1 Effects of SiO₂ Passivation Layer

As described in Section 4.1, a SiO₂ passivation layer is required in phase-one and – two devices to prevent the Mo IDT electrodes from etching during XeF₂ releasing step. In this section, the effect of the SiO₂ passivation layer thickness on phase-two devices was investigated. The resonant characteristics of the five tested phase-two devices are plotted in Figure 5-15 with their resonant characteristics summarized in Table 5-2. Both $k_t^2$ and Q-factor of AlN LWRs degrade with increasing thickness of the SiO₂ passivation layer because of excessive energy absorption and energy leakage to substrate through SiO₂.

![Graph showing frequency response of AlN LWRs with different SiO₂ thicknesses.](image)

Figure 5-15: The measured frequency response of AlN LWRs with different SiO₂ thicknesses.
Table 5-2: Resonant characteristics of AlN LWRs with different SiO$_2$ thicknesses.

<table>
<thead>
<tr>
<th>Device parameter</th>
<th>P2-1</th>
<th>P2-2</th>
<th>P2-3</th>
<th>P2-4</th>
<th>P2-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{TopOx}}$ (nm)</td>
<td>100</td>
<td>250</td>
<td>400</td>
<td>550</td>
<td>700</td>
</tr>
<tr>
<td>$T_{\text{BotOx}}$ (nm)</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>$f_0$ (MHz)</td>
<td>381.01</td>
<td>374.07</td>
<td>367.49</td>
<td>361.54</td>
<td>356.81</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>632</td>
<td>624</td>
<td>615</td>
<td>609</td>
<td>612</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>1836</td>
<td>1794</td>
<td>1626</td>
<td>1543</td>
<td>1607</td>
</tr>
<tr>
<td>$\kappa t^2$ (%)</td>
<td>0.68</td>
<td>0.61</td>
<td>0.64</td>
<td>0.58</td>
<td>0.52</td>
</tr>
</tbody>
</table>

5.5.2 Effects of Anchor Design

In the previous section, it has been proven that the SiO$_2$ layer slightly degrades the resonant characteristic of AlN LWRs. In phase-three fabrication, the process flow has been revised to eliminate the SiO$_2$ passivation layer. Devices with various structural designs have been included to verify the simulation results. Firstly, the effect of the support anchor structural design on the device resonant characteristics was studied. The measured frequency responses are plotted in Figure 5-16 and fitted with the two-port MBVD circuit model (Figure 5-8 (b)).

Figure 5-16: The measured and fitted frequency response of the AlN LWRs with support anchors of (a) AlN/Mo and (b) Mo.
There is a slight improvement in $k^2$ and $Q$, for device with Mo anchors, which is most probably due to the process variation. The value of $Q_p$ is enhanced from 1487 to 3405 when the AlN is eliminated from the support anchors. Overall, the measurement results are in good agreement with the simulation results. Obviously, the resonant characteristic of the AlN LWRs is not deteriorated by removing the AlN from the support anchors. Indeed, a slight enhancement is observed. For IR sensing applications, AlN LWRs with Mo anchors are favorable to obtain thermal isolation from the substrate. The desired $G_{th}$ can be achieved by adjusting the Mo anchor dimension, and thus achieving the optimized pixel size and parasitic resistance.

Figure 5-17: The measured frequency response of AlN LWRs with $W_{anc}$ fixed at 12.5 μm and varying $L_{anc}$.

Since the anchor dimensions of the AlN LWRs are critical for IR sensing properties and mechanical robustness, devices with different anchor dimensions have been fabricated and tested. From the simulation results in Section 3.3.2, it is clear that devices with $W_{anc}$ of 12.5 μm and $L_{anc}$ of odd multiples of quarter-wavelength result in better resonant performance. Figure 5-17 compares the frequency response of the
AlN LWRs with different multiples of quarter-wavelength. However, there is no significant disparity between the devices with \( L_{\text{anc}} \) of odd and even multiples of quarter-wavelength. Increasing \( L_{\text{anc}} \) does not improve the resonant performance of the AlN LWRs. This can be attributed to the high acoustic impedance of Mo anchors which minimize the acoustic radiation loss [109]. The Mo anchors dimension effect is insignificant compared with AlN film quality and film deflection of the released structure. Therefore the Mo anchor dimensions can be freely designed to achieve the optimum IR responsivity and mechanical robustness without compromising the resonant characteristics of the AlN LWRs.

5.5.3 Effects of the Edge Reflector, ER

![Graph showing frequency response](image)

Figure 5-18: The measured frequency response of the AlN LWRs with (a) odd and (b) even numbers of IDT fingers with different values of \( d_{\text{ER}} \). The \( Q \)-factor and \( k_t^2 \) of the device with \( d_{\text{ER}} \) of quarter-wavelength are also included in the graphs.

AlN LWRs having odd \((N = 11)\) and even \((N = 12)\) numbers of IDT fingers with different values of \( d_{\text{ER}} \) are fabricated and tested with the results plotted in Figure 5-18. The measurement results are in good agreement with the simulation results in Section 3.3.3 where devices with \( d_{\text{ER}} \) of quarter-wavelength, having either odd or
even number of IDT fingers, give the clean and strong single resonant mode within a large frequency span of 600 MHz. More than one resonant mode is found in the devices with \( d_{ER} \) of 1.5*quarter-wavelength and 2*quarter-wavelength due to the interference effect among the reflected acoustic waves from the AlN film edges. These resonant peaks are very noisy and they have a poor \( Q \)-factor.

5.5.4 Effects of IDT Metallization Ratio

The period of IDT determines the resonant frequency of AlN LWRs. However, there is no reported work on the effects of IDT metallization ratio on the frequency response of AlN LWRs. In addition to the function as IDT electrodes, the 200 nm thick Mo also serves as IR mirror to reflect back any IR radiation that transmits through the TiN-absorber and AlN film and hence achieves multiple absorptions. Wider IDT line width is favorable for optimum IR reflection but resonant characteristics are degrading after a threshold value of IDT metallization ratio.

![Figure 5-19: The measured frequency response of AlN LWRs with different metallization ratios.](image)

Figure 5-19 compares the measured frequency response and fitted components, \( C_O \) and \( R_M \) of AlN LWRs with different IDT metallization ratios. The measurement
results align well with the simulation outcome in Section 3.3.4, whereby the resonant frequency of the AlN LWRs is reducing with the \( l_{\text{IDT}} \) because of the mechanical mass loading. The value of \( C_O \) and thus the \( S_{21} \) magnitude increases with \( l_{\text{IDT}} \). There is an indeterminate trench of \( Q \)-factor and \( k_t^2 \) with IDT metallization ratios as the most of the frequency response curves are noisy due to the non-planarized AlN film. Narrow \( l_{\text{IDT}} \) results in an inefficient electric field and low \( C_O \) value, hence deteriorates the resonant characteristic. Yet devices with wide \( l_{\text{IDT}} \) incur excessive mechanical mass loading and acoustic energy absorption by the IDT, worsening also the resonant performance of AlN LWRs. The device with a metallization ratio of 0.75 gives the best resonant performance with the lowest \( R_M \) of 53, while the one with metallization ratio of 0.5 gives the worst \( R_M \) of 183.

5.5.5 Effects of the Pixel Size

![Figure 5-20: The measured frequency response of AlN LWRs with different values of \( L_{\text{AL}} \).](image)

In this section, devices with different pixel sizes are studied. When the IR sensing area is scaled down, either the number of IDT fingers, \( N \) or the aperture length, \( L_{\text{AL}} \).
has to be shrank to obtain the targeted operating resonant frequency. AlN LWRs with varied $L_{AL}$ are first compared in Figure 5-20. For device of $N = 12$, resonant performance is guaranteed if the $L_{AL}$ is more than or equal to 100 μm. $L_{AL}$ of 200 μm does not improve the device resonant performance because of the AlN film deflection. The frequency responses of devices with $L_{AL}$ of 25 μm and 50 μm are badly damped owing to insufficient $C_O$ and a weak electric field across the AlN film. The 150 μm $L_{AL}$ device shows the best resonant performance with $k_t^2$ of 0.74, a $Q_S$ of 1353 and a $Q_P$ of 1908.

Table 5-3: The resonant characteristic of AlN LWRs with different IDT fingers number at $d_{ER}$ of quarter-wavelength.

<table>
<thead>
<tr>
<th>Device</th>
<th>$k_t^2$ (%)</th>
<th>$Q_S$</th>
<th>$Q_P$</th>
<th>$C_O$</th>
<th>$R_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N12_150 μm × 166 μm</td>
<td>0.74</td>
<td>1353</td>
<td>1908</td>
<td>1120</td>
<td>53</td>
</tr>
<tr>
<td>N11_137.5 μm × 166 μm</td>
<td>0.74</td>
<td>708</td>
<td>828</td>
<td>1080</td>
<td>127</td>
</tr>
<tr>
<td>N08_100 μm × 116 μm</td>
<td>0.79</td>
<td>553</td>
<td>585</td>
<td>1060</td>
<td>400</td>
</tr>
<tr>
<td>N07_87.5 μm × 116 μm</td>
<td>0.67</td>
<td>424</td>
<td>-</td>
<td>960</td>
<td>605</td>
</tr>
</tbody>
</table>

Figure 5-21 examines the effect of $N$ on the frequency response of AlN LWRs. The resonant frequency does not shift with $N$ when the $d_{ER}$ is equal to quarter-wavelength. However, the resonant characteristic is degrading with reducing $N$ due to the reducing $C_O$. (Table 5-3). The $Q$-factor and $k_t^2$ value are not available for the device with $N$ smaller than 4 due to the poor resonant performance. The bottom three plots in Figure 5-21 (a) represent the devices with $N=4$, $N=3$, and $N=2$ from the top. When the $d_{ER}$ is equal to 1.5*quarter-wavelength and 2*quarter-wavelength, the frequency spacing between the lower and higher resonant mode is decreasing with $N$ [134]. The measurement results are in good agreement with the simulation results in Section 3.3.5.
Figure 5-21: The effect of $N$ on the frequency response of the AlN LWRs with $d_{ER}$ of (a) quarter-wavelength, (b) 1.5*quarter-wavelength and (c) 2*quarter-wavelength. The insets magnify the frequency response at the resonances.

5.5.6 Effects of Pressure and Temperature

For any uncooled thermal IR detector, the temperature rise, $\Delta T$ in the sensing material after IR absorption is directly affected by the heat conduction mechanism. Therefore, the pressure level of the operating environment is of particular important because it gives significant impact to the effective thermal conductance, $G_{th}$ between
the IR detector and its surrounding by increasing $G_{\text{gas}}$ and $G_{\text{conv}}$ through gas conductance and convection, respectively.

Figure 5-22: (a) The measured frequency response, (b) resonant characteristic and (c) standard deviation of $S_{21}$ phase of AlN LWRs at different operating pressure levels.

In addition, increasing the operating pressure level deteriorates the frequency response ($Q$-factor and $k_t^2$) of AlN LWRs due to additional viscous damping effect from the ambient as shown in Figure 5-22 (b). When oscillating, the resonator has to overcome the resistance of air trapped in the actuation gaps (squeeze-film damping) and those generated by friction with air for the sides parallel to the vibration displacement (slide-film damping) [109, 148, 149]. The energy loss caused by squeeze-film damping dominates especially at low and medium frequencies. Figure 5-22 (c) depicts that the noise level of AlN LWRs is increased as the
operating pressure increases from vacuum to atmospheric. To ensure device sensitivity and minimize noise level, all the measurements are done under pressure level of $1 \times 10^{-5}$ mbar.

With advancements in the field of automotive, aerospace, geothermal, oil and gas exploration, there is an increasing demand on ruggedized sensors with capability of operating under harsh environment (extremes of temperature, pressure, chemical corrosion, etc.). Real-time sensing enables increased operation lifetimes, improved efficiency and reduced emissions. SiC and AlN are the most popular materials employed in ruggedized electronics owing to their mechanical robustness, chemical inertness, and electrical stability. SiC is widely used in integrated circuits (IC) while AlN is a strong candidate for making RF components for operation in harsh environment to realize wireless telemetry. In this session, the resonant characteristic of AlN resonant IR detector operating at elevated temperatures up to 300 °C has been studied.

Figure 5-23: (a) The stability of the resonant frequency and (b) standard deviation of $S_{21}$ phase of AlN LWRs at elevated temperatures before and after annealing.
Figure 5-23 shows the resonant frequency stability of AlN LWRs subjected to multiple temperature cycles, from 23 °C to 300 °C. The device resonant frequency was less stable with slight increase in every cycle before annealing. After the first four testing cycles, the device was annealed at temperature of 300 °C under vacuum for 15 hours and the resonant frequency became stable. As expected, the noise level of the device is increasing with temperature due the increasing thermal noise.

Table 5-4: The resonant characteristics of the AlN LWRs before and after annealing at elevated temperatures.

<table>
<thead>
<tr>
<th>Testing temperature</th>
<th>Before annealing</th>
<th>After annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_t^2$ (%)</td>
<td>$Q_s$</td>
</tr>
<tr>
<td>23 °C</td>
<td>0.71</td>
<td>1738</td>
</tr>
<tr>
<td>50 °C</td>
<td>0.70</td>
<td>1684</td>
</tr>
<tr>
<td>100 °C</td>
<td>0.71</td>
<td>1682</td>
</tr>
<tr>
<td>150 °C</td>
<td>0.70</td>
<td>1591</td>
</tr>
<tr>
<td>200 °C</td>
<td>0.70</td>
<td>1592</td>
</tr>
<tr>
<td>250 °C</td>
<td>0.70</td>
<td>1573</td>
</tr>
<tr>
<td>300 °C</td>
<td>0.69</td>
<td>1542</td>
</tr>
</tbody>
</table>

The frequency response was fitted with the Mason lumped circuit model and the resonant parameters are listed in Table 5-4. The value of $Q_s$ is slightly improved after device annealing because of the increase in piezoelectric response. On the other hand, $Q_p$ is degraded and $k_t^2$ remains unaffected by the device annealing. Both the $Q$-factors gradually decrease with temperature before and after device annealing. There is no significant oxidation of AlN annealed under vacuum is reported. However, the $Q$-factors are influenced by material softening, thermoelastic damping and thin film stress at elevated temperatures. In conclusion, the overall resonant
performance of AlN LWRs is stable at elevated temperatures of up to 300 °C after device annealing. It is believed that the devices can be operated steadily even up to 600 °C with proper pre-annealing steps [127].
CHAPTER 6: Infrared Sensing Characterization

6.1 Experiment Setup

Figure 6-1: Experiment setup for IR sensing and thermal characterization of the AlN resonant IR detectors.

For IR sensing properties and thermal characterization, a similar setup as described in Section 5.1 was employed with an additional temperature-controlled chuck and a blackbody source as depicted in Figure 6-1. The temperature chuck is capable of testing from -60 to 300 °C.
**Blackbody source.** The blackbody source from Oriel® Instruments of Newport Corporation provides a spectrum of IR with the spectral irradiance determined by Equation 6-1 and plotted in Figure 6-3 (a).

\[
H_\lambda = \frac{C_1}{\lambda^5 \left[ \exp\left(\frac{C_2}{\lambda T_B}\right) - 1 \right]} F \zeta \frac{a^2}{4d^2}
\]

Equation 6-1

where \( H_\lambda \) refers to spectral irradiance; \( \lambda \) is the emitted wavelength; \( T_B \) is the blackbody source temperature; \( C_1 \) and \( C_2 \) denote the first and second radiation constant, respectively; \( F \) and \( a \) are the RMS conversion factor and aperture diameter of the blackbody source; \( \zeta \) is the transmission of the optical path; \( d \) is the distance between the aperture plane and the sensing area plane.

![Figure 6-2: The wavelength dependent transmission of (a) ZnSe optical filter and (b) edge-pass optical filter.](image)

**Optical filter.** A 5 mm distance optical filter made of ZnSe from Korth Kristalle GmbH is used to filter the IR spectrum with transmission wavelengths between 0.5 and 20 \( \mu \)m as depicted in Figure 6-2 (a). The IR spectrum can be further confined to LWIR by stacking another edge-pass optical filter (Figure 6-2 (b)) on top of the
ZnSe optical filters. The effective transmission of the optical path is the product of the transmission of both filters. Figure 6-3 (b) gives the resulting IR radiant power density incidents on the AlN resonant IR detector at different blackbody source temperatures through different optical filter systems.

![Graph](a) The IR spectral irradiance and (b) radiant power density incidents on the AlN resonant IR detector at different blackbody source temperatures.

**6.2 Infrared Absorption Characterization**

**6.2.1 Three-layer Film Stack Interferometric Absorption**

In this project, the AlN resonant IR detectors utilize the three-layer film stack interferometric absorption design as explained in Section 2.3.1, whereby an ultra-thin TiN absorber on the top surface of the AlN dielectric film and Mo IDT electrodes function as IR reflecting film on the bottom surface. The wavelength dependent absorption, \( \eta_\lambda \), of the three-layer film stack system can be described by [55]:

\[
\text{Spectral irradiance (mW/cm}^2\mu\text{m)}
\]
\[
\eta_\lambda = \frac{4}{D n^2} \left\{ f_t (f_b + 1)^2 + f_b \right\} \sin^2 \theta + (f_b + f_t \cos^2 \theta \right\} \tag{6-2}
\]

where

\[
D = \left[ \frac{(f_b+1)(f_t+1)}{n^2} + 1 \right]^2 \sin^2 \theta + \left[ \frac{f_b+f_t+2}{n^2} \right] \cos^2 \theta; 
\]

\[
f_b = 120\pi/R_b ; f_t = 120\pi/R_t ; \theta = 2\pi n T_d/\lambda ;
\]

\(R_b\) is the sheet resistance of the back bottom surface metal film; \(R_t\) is the sheet resistance of the top surface metal film (facing IR radiation), \(T_d\) is the thickness of the dielectric film with a refractive index of \(n\). The dielectric layer is assumed to be non-absorbing, which is valid for many dielectric materials and low conductivity semiconductors including AlN. The bottom surface of the AlN resonant IR detectors is the 200 nm thick Mo IDT electrodes. Assuming it is a high conductivity metal layer of about zero sheet resistance and thus a perfect IR reflector, Equation 6-2 can be simplified to:

\[
\eta_\lambda = \frac{4f_t}{(f_t + 1)^2 + n^2 \cot^2 \theta} \tag{6-3}
\]

as \(R_b \to 0\) and \(f_b \to \infty\). The optimum absorption of unity can be attained when:

- \(T_d = (2m+1)\lambda/4n\) where \(m = 0, 1, 2, \ldots\)

- \(f_t = 1\) \((R_t = 377 \Omega/\square)\)

Figure 6-4 estimates the effect of the thickness of the TiN (lower \(R_t\) corresponds to thicker \(T_{TiN}\)) and AlN layers on the absorption spectral of the IR detector. IR absorption improves with increasing \(R_t\) up to the threshold value of 377 \(\Omega/\square\). A
A slight decline is observed when $R_t$ is further increased after 377 Ω/□. Nevertheless, peak absorption of greater than 90 % is achievable with $R_t$ in the range of 200 – 600 Ω/□, giving a considerable tolerance in the TiN thickness in order to obtain an acceptable IR absorption. On the other hand, the thickness of the AlN layer determines the number of peaks absorption and their bandwidth range.

Figure 6-4: Estimated absorption spectral for different values of (a) $R_t$ and (b) $T_d$. 

$R_t = 377 \, \Omega/□$

$n = 2.01$

$T_d = 1 \, \mu m$

$n = 2.01$

(a)

(b)
6.2.2 Fourier Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy is a technique to obtain an IR spectrum of transmission, absorption, reflection, photoconductivity or Raman scattering of an object which can be in any phase. FTIR employs an interferometer which produces a signal called interferogram that “encodes” all the IR frequencies from the IR source. The measured interferogram signal is then “decoded” by Fourier transformation, giving the final spectral information. Figure 6-5 illustrates the working mechanism of FTIR system.

![FTIR System Diagram](image)

Figure 6-5: Schematic illustration of FTIR system.

![Absorption Spectra Comparison](image)

Figure 6-6: Comparison of absorption spectral between theoretical and measurement for (a) $T_d = 985$ nm and (b) $T_d = 1.45$ μm.

$R_{TiN} = 280 \, \Omega/\square$

$T_{AlN} = 985$ nm

$n = 2.01$

$R_{TiN} = 260 \, \Omega/\square$

$T_{AlN} = 1.45$ μm

$n = 2.01$
Chapter 6

The absorption spectrum of the fabricated AlN resonant IR detectors was measured by the Agilent Cary 620 FTIR spectrochemical microscope, which is able to provide focal plane array (FPA) imaging, enabling the measurement on a small area (5 μm × 5μm). Figure 6-6 compares the theoretical and measured absorption spectral of the AlN resonant IR detectors. The measurement range was set from 2 μm to 8 μm due to the limitation of the FTIR spectroscopy system. The SWIR absorption band can be accurately predicted by theory while there is a deviation of the theoretical prediction in the MWIR band. Nevertheless, the absorption spectrum of the TiN-AlN-Mo film stack can be easily designed by tuning the thickness of AlN.

For temperature sensing and thermal imaging applications, a reference device is always needed to provide the absolute temperature reading and thus enhancing the image contrast. The reference device is identical to the sensing device except that the TiN thin film is eliminated from the reference device. There is about 90 % difference in absorption spectral between the sensing and reference device as delineated in Figure 6-6.

6.3 Infrared Sensing Characterization

6.3.1 Temperature Coefficient of Frequency

In addition to ΔT (Equation 3-11), TCF is another important parameter, which takes account for all the thermal effects on AlN resonant IR detectors, to determine the device sensitivity or responsivity. Ideally, Equation 3-15 can be used to estimate the effective TCF of the device. However, the individual temperature coefficients for each material can be hardly estimated accurately from literature due to process variation in fabrications, the interlayer-induced defects and the film residual stress of
the composite film stack. Therefore, experimental work was carried out to obtain the effective TCF of the detector. The resonant frequency was measured from 25 to 300 °C with interval of 50 °C. A total time of one hour was given for temperature ramping and stabilization in every temperature interval.

Figure 6-7: Relation between resonant frequency and temperature of the AlN resonant IR detector before and after annealing.

Figure 6-7 shows the relation between the resonant frequency and the temperature of an AlN resonant IR detector with an IR sensing area of 150 μm × 166 μm. The effective TCF of the device is slightly enhanced from –24 ppm/K to –26 ppm/K after annealing. Since annealing improves the device resonant stability (Section...
and the TCF, all the devices tested in the following sections were pre-annealed under vacuum at 300 °C for 15 hours.

6.3.2 Steady State Response

Resonant frequencies of AlN resonant IR detectors were measured before and after 60 s exposure to the IR source at steady-state, which were then being compared (Figure 6-8). The obtained frequency shift, \( \Delta f \), was divided by the incident IR power, \( P_{IR} \), in order to calculate the device responsivity, \( \mathcal{R} \), as defined by Equation 6-4 with the resonant frequency of the detector as the measurable electrical output signal.

\[
\mathcal{R} = \frac{\Delta f}{P_{IR}} = \frac{f(T_0)\alpha_f\Delta T}{P_{IR}}
\]

Equation 6-4

Figure 6-8: Frequency response of an AlN resonant IR detector upon IR illumination at steady state.
6.3.3 Transient Response

![Illustration of transient sensing response and estimation of response time of AlN resonant IR detectors.](image)

Figure 6-9: Illustration of transient sensing response and estimation of response time of AlN resonant IR detectors.

The thermal time constant of AlN resonant IR detectors determines the device speed, which can be estimated by COMSOL 3D simulation as described in Section 3.3. Experimentally, the response time of the AlN resonant IR detectors is characterized by the $S_{21}$ magnitude at single excitation frequency, $f_c$ with respect to modulated IR illumination over time. The value of $f_c$ was chosen to be in the inductive region of the $S_{21}$-f plot, between the resonant and anti-resonant frequencies, where the plot gradient, $d|S_{21}|/df$ is maximum as illustrated in Figure 6-9 (a). In this interval of frequencies, the resonant frequency shift, $\Delta f$ induced by the IR exposure is
associated with the greatest variation in the $S_{21}$ magnitude, $\Delta|S_{21}|$. Measurement data is captured within a narrow IF bandwidth, which allows the sampling at about 50 $\mu$s intervals. Figure 6-9 (b) shows the measured rise and fall response of an AlN resonant IR detector. Figure 6-9 (c) and (d) show magnified regions of the response to illustrate the device rise time and fall time that can be fitted by double exponential functions.

6.4 Results and Discussion

All the tested devices in the following sections are from phase-three fabrication (except for Section 6.4.1 in which the devices are from phase-one and -two fabrications) with the identical geometry specification as Section 5.5. Unless specified, otherwise the blackbody source was set at temperature of 1100 °C and the single ZnSe optical filter was employed.

6.4.1 Effects of SiO$_2$ Passivation Layer

The effect of the SiO$_2$ layer on the thermal behaviour and IR sensing properties of AlN resonant IR detectors was first studied. The unresolved frequency shift was observed in the steady-state frequency response for devices with SiO$_2$ thicknesses above 400 nm when they were exposed to IR radiation. This translates to the unresponsive behaviours in the transient response plot (Figure 6-10 (a)). One can attribute these insensitive devices to the small TCF and $\Delta T$ which give rise to the small $\Delta f$ as summarized in Figure 6-10 (b) and Table 6-1. Resolving the hundreds Hz of frequency shift at an operating frequency of MHz is challenging. In addition to damping effects, the SiO$_2$ layer severely deteriorates the responsivity of AlN resonant IR detectors.
Figure 6-10: (a) Transient response and (b) temperature-dependent resonant frequency shift of AlN resonant IR detectors with different SiO\textsubscript{2} thicknesses.

Table 6-1: The estimated IR response of AlN resonant IR detectors with different SiO\textsubscript{2} thicknesses.

<table>
<thead>
<tr>
<th>Device parameter</th>
<th>P2-1</th>
<th>P2-2</th>
<th>P2-3</th>
<th>P2-4</th>
<th>P2-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{TopOx}}$ (nm)</td>
<td>100</td>
<td>250</td>
<td>400</td>
<td>550</td>
<td>700</td>
</tr>
<tr>
<td>$T_{\text{BotOx}}$ (nm)</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>$f_0$ (MHz)</td>
<td>381.01</td>
<td>374.07</td>
<td>367.49</td>
<td>361.54</td>
<td>356.81</td>
</tr>
<tr>
<td>TCF (ppm/K)</td>
<td>-11.79</td>
<td>-8.01</td>
<td>-4.72</td>
<td>-1.98</td>
<td>+1.03</td>
</tr>
<tr>
<td>Simulated $\Delta T$ (mK)</td>
<td>75.5</td>
<td>68.2</td>
<td>60.9</td>
<td>53.4</td>
<td>45.6</td>
</tr>
<tr>
<td>Expected $\Delta f$ (Hz)</td>
<td>-340</td>
<td>-204</td>
<td>-106</td>
<td>-38.2</td>
<td>+16.8</td>
</tr>
</tbody>
</table>

It is interesting to note that a downshift of $S_{21}$ magnitude was observed for device with a designed acoustic wavelength, $\lambda$ of 4 μm (resonant frequency of about 2 GHz for device P2-5) under IR illumination as depicted in Figure 6-11. The $S_{21}$ magnitude shift, $\Delta S_{21}$ is increased with increasing absorbed IR power and reducing SiO\textsubscript{2} layer thickness (Figure 6-12). Similar effects were observed in the phase-one devices [26].
Figure 6-11: (a) Frequency response and (b) steady-state IR response of the AlN resonant IR detector with 1 μm thick SiO$_2$ passivation layer (device P2-5).

Figure 6-12: The $S_{21}$ magnitude shift at resonance in relation to absorbed IR power for AlN resonant IR detectors with different SiO$_2$ thicknesses.

Figure 6-13 shows that there is no significant difference in frequency response between the ambient and vacuum ($1\times10^{-5}$ mbar) measurement results. Only a small downshift of the resonant frequency was observed in ambient measurements because of the additional atmosphere damping under ambient. This verifies that the IR-induced $\Delta S_{21}$ does not contributed by thermal effect.
Figure 6-13: Comparison of IR response under ambient and vacuum conditions for AlN resonant IR detector with 1 μm thick SiO$_2$ passivation layer (device P2-5).

Figure 6-14: Capacitance variation of AlN resonant IR detector under ambient and vacuum condition for a device with a 1 μm thick SiO$_2$ passivation layer (device P2-5). The highlighted regions indicate the IR exposure period.

To investigate this phenomenon, capacitance of the device, $C_{\text{AlN}}$, was measured across the Mo IDT electrodes at a frequency of 100 kHz and plotted in Figure 6-14. There is about +8.0 fF of $\Delta C_{\text{AlN}}$ observed upon IR exposure under vacuum and ambient condition. From the Mason lumped circuit model, the -0.072 dB of $\Delta S_{21}$ results in a $\Delta C_O$ of +38 fF. There is an obvious discrepancy between $\Delta C_{\text{AlN}}$ and $\Delta C_O$ because $C_{\text{AlN}}$ is mainly contributed by the fringing field among the Mo IDTs while
$C_O$ takes account for the plate capacitance of AlN. Thus, $\Delta C_O$ is much larger than $\Delta C_{\text{AlN}}$. Also, the frequency-dependent capacitance and the dielectric loss contribute to the difference in $\Delta C_{\text{AlN}}$ and $\Delta C_O$. Nevertheless, both $C_{\text{AlN}}$ and $C_O$ increase with IR irradiation. Therefore, it proves that there are additional charges generated at the interface between Mo IDT and AlN during IR illumination. The IR-induced charges are believed to cause the $S_{21}$ magnitude downshift of AlN LWRs. The parasitic capacitance associated with the silicon substrate is mainly attributed to the large contact pads. However, the contact pads are made of 700 nm thick Al, which is very reflective to IR. Thus, it can be safely assumed that the parasitic capacitance is insensitive to IR illumination.

Undoped single crystal AlN is a semiconductor with a direct bandgap of 6.2 eV, corresponding to a photon wavelength of 200 nm. The photon energy of IR radiation with a wavelength longer than 1.1 µm ($< 1.12$ eV) is not sufficient to enable the band-to-band intrinsic transition. The detection of additional charges through the capacitance measurement can be explained by the free carrier absorption. These carriers can arise from lattice defects and impurities in the polycrystalline AlN films created during sputter deposition process. There are always impurities that exist in AlN films such as oxygen, carbon and silicon in addition to nitrogen and aluminum vacancies [150, 151]. Oxygen is a major residual impurity with a significant amount even in single crystal AlN [150-153], which can cause irregular crystallization and formation of lattice dislocations and defects. It is believed that the charge carriers get excited into the higher energy states from these defects localized energy states during IR irradiation, which then contributes to the photo-sensitive property of
polycrystalline AlN films. A similar observation has also been reported in the visible light wavelength range [154].

On the other hand, the increase in $C_{\text{AlN}}$ can also be attributed to the possible lattice absorptions in AlN [155-158]. As the electronegativities of Al (1.61) and N (3.04) are very different, there is a significant ionic characteristic in the chemical bonding of AlN. Thus single phonon Reststrahl absorption can occur where the incident IR radiation can couple with the oscillating electric field produced by the electrostatic motions of opposite charges. In principle, ionic compounds exhibit good transmission with a constant refractive index and a low absorption coefficient up to the lattice absorption band (typically > 10 µm wavelength for AlN [158, 159]) at which point the single phonon generates a heavily absorbing mode of vibration and a subsequent strong reflection coefficient. The refractive index and extinction coefficient rises rapidly at the resonant Reststrahl frequency. Since the dielectric constant is approximately proportional to the square of the refractive index, $C_{\text{AlN}}$ increases upon IR radiation due to the increase in the dielectric constant. More than one absorption band with a weaker peak can be present in AlN corresponding to the multi-phonon transitions due to inharmonic terms [156] or a defect-induced electric dipole moment [151].

This IR-induced $S_{21}$ shift phenomenon was only observed for devices operating at resonant frequency higher than 800 MHz. After verification with the MBVD circuit model, the small change in $C_{O}$ can only shift $S_{21}$ in a significant magnitude at high operating frequencies. An in depth study and investigation is needed for a quantitative explanation of the charge generation within the AlN film. Since this $S_{21}$ shift could induce undesired noise for AlN resonant IR detectors, all devices
discussed in this thesis are operated at a few hundred MHz frequency where there is no $S_{21}$ downshift observed.

### 6.4.2 Effects of Anchor Design

![Figure 6-15: Transient response with the steady-state responsivity and response time for devices having different anchor designs.](image)

In this section, the effect of anchor designs on the IR sensing properties of AlN resonant IR detectors was investigated. The tested devices have the identical geometry specification except the support anchor dimension and composite film stack. Figure 6-15 compares the transient response of the device with AlN/Mo and Mo support anchors. AlN increases the effective thermal conductivity, $G_{th}$ of the device and thus degenerates the device responsivity but shortens the device response time. In accordance to Equation 2-12 and Equation 2-14, the dimensions of the Mo anchors that determine the value of $G_{th}$ also significantly affect the device sensitivity and response time as demonstrated in Figure 6-16 and Figure 6-17.
6.4.3 Effects of IDT Metallization Ratio

The absorption spectrum of AlN resonant IR detectors worsens with decreasing metallization ratio of the IDT electrodes due to the increasing optical transmission loss (Figure 6-18). Therefore, the device sensitivity deteriorates as \( l_{IDT} \) is getting narrower. The device response time slightly increases with \( l_{IDT} \) because the wider \( l_{IDT} \) contributes to the increasing device heat capacity, \( C_{th} \). From the simulation results in Section 5.5.4, metallization ratio of 0.75 gives the optimum device resonant performance with acceptable device responsivity (\( \mathcal{R} \) of about 6.18 \( \text{W}^{-1} \)) and response time (\( \tau_{th} \) of about 3.15 s).
Figure 6-18: (a) Absorption spectrum; (b) transient response; (c) steady-state response and response time for AlN resonant IR detectors having different metallization ratios.

### 6.4.4 Effects of Pixel Size

Pixel size is of particular importance for thermal-type of IR detectors since it determines the amount of incident IR power to be absorbed. Minimizing pixel size is always an important focus in IR detection, particularly for thermal imaging applications whereby large array format detectors are desired to reduce cost, power consumption, device weight and size. Even though small pixel size is advantageous at system level, it degenerates both the resonant (Section 5.5.5) and IR sensing properties at device level for AlN resonant IR detectors. The device speed is improved with smaller pixel size due to the reduced effective heat capacity, $C_{th}$, but the IR detectivity drops as less IR power being absorbed (thus smaller $\Delta T$) decreases
with decreasing pixel size. Figure 6-19 compares the transient sensing response of AlN resonant IR detectors with different aperture length, $L_{AL}$. Having similar radiant responsivity, the longer $L_{AL}$ results in a larger shift in resonant frequency because the larger amount of IR power is being absorbed.

![Graph comparing transient response, steady-state responsivity and response time of AlN resonant IR detectors with different $L_{AL}$](image)

**Figure 6-19:** Transient response, steady-state responsivity and response time of AlN resonant IR detectors with different $L_{AL}$s.

![Graph comparing transient response, steady-state responsivity and response time of AlN resonant IR detectors with different IR absorbing areas ($W_{AlN} \times L_{AlN}$)](image)

**Figure 6-20:** Transient response, steady-state responsivity and response time of AlN resonant IR detectors with different IR absorbing areas ($W_{AlN} \times L_{AlN}$).

In addition to $L_{AL}$, device miniaturization of AlN resonant IR detectors can be achieved by reducing the number of IDT fingers, $N$. Surprisingly, device responsivity is enhanced when $N$ is reduced (and thus $W_{AlN}$ is reduced) in spite of the lower amount of absorbed IR power (Figure 6-20). This effect can be explained
by the increased TCF value when the ratio of $W_{\text{AlN}}$ to $L_{\text{AlN}}$ is decreased. For identical $L_{\text{AlN}}$, device effective TCF increases from -26 ppm/K for $N=12$ to -30 ppm/K for $N=11$; from -27 ppm/K for $N=8$ to -31 ppm/K for $N=7$. The theory behind the dependency of TCF on the dimensions of the LWR is still unknown and unreported elsewhere.

### 6.4.5 Effects of Ambient Temperature

![Absorption spectrum of AlN resonant IR detectors at elevated temperatures.](image)

**Figure 6-21**: Absorption spectrum of AlN resonant IR detectors at elevated temperatures.

Figure 6-21 depicts the absorption of the TiN-AlN-Mo three-layer film stack structure at different temperatures. The refractive index, $n$ and AlN film thickness, $T_d$ grow gradually with temperature, resulting in a right shift of the IR absorption spectrum as explained in Equation 6-3. In addition, the sheet resistance of TiN...
increases with temperature and thus enhance the IR absorption as the value of $R_t$ is closer to 377 $\Omega/\square$. Nonetheless, the temperature effect on the IR absorption spectrum is insignificant compared with the thermal noise effect (Figure 6-22). Therefore, it was assumed constant from room temperature up to 300 °C.

![Graph showing frequency fluctuation with operating temperature](image)

**Figure 6-22:** Frequency fluctuation with operating temperature.

After FTIR inspection of the IR absorption spectrum, the sensing performance of AlN resonant IR detectors was studied at elevated temperatures of up to 300 °C. The device responsivity and stability is improved after annealing as described in Figure 6-23 (c) with the response time at about 3.20 ms. These results align well with the discussion in Section 5.5.6. As expected, the device IR responsivity degrades with temperature due to the increasing thermal and background fluctuation noise as explained in Section 2.3.3.
Figure 6-23: Transient sensing response of AlN resonant IR detectors (a) before and (b) after annealing at elevated temperatures. (c) Steady-state responsivity and (d) response time of the devices during temperature cycling.

6.5 Noise-equivalent-temperature-difference (NETD)

Two IR detection ranges have been inspected with the transient and steady-state response in relation to absorbed IR power plotted in Figure 6-24 (a) and (b). From the MBVD equivalent circuit modelling, the shift of resonant frequency, $\Delta f$ can be attributed to the shift of motional inductance, $\Delta L_M$. Since $\Delta f/f_0$ is directly proportional to the absorbed IR power as shown in Figure 6-24 (c), $\Delta L_M/L_M$ is also linearly proportion to the absorbed IR power.
Figure 6-24: Transient response of AlN resonant IR detectors in the IR detection range of (a) 0.5 – 20 μm and (b) 5.5 – 20 μm. (c) The shift of resonant frequency in relation to the absorbed IR power.

After investigation of effects of the device structural design on the IR sensing properties of AlN LWRs, the NETD was estimated using Equation 2-26 for device with the most promising performances. For resonant thermal IR detectors, the noise signal, $\sigma_N$ is defined by the frequency instability of the detector that can be characterized by measuring the Allan variance of the $S_{21}$ phase, $\sigma_0$ [160, 161].
\[
\sigma_\phi(\tau) = \frac{1}{2(M-1)} \sum_{m=2}^{M} (\phi_m - \phi_{m-1})^2
\]

Equation 6-5

where \(\tau\) is the averaging interval time; \(\phi_m\) is the average phase measured over the \(m\)th time interval of \(\tau\); \(M\) is the number of phase measurements, set to be 16000. For the unpassivated device with specification as listed in Table 5-1, the lowest measured values of \(\sigma_\phi(\tau)\) are plotted in Figure 6-25. Based on the measured results, the NETD of AlN resonant IR detectors can be estimated in the LWIR regime with the assumption of unity for \(F\) and \(\zeta\). Taking the optimum \(\sigma_N\) of \(1.69 \times 10^{-9}\) (\(\sigma_\phi\) of \(7.90 \times 10^{-5}\) deg) and \(\mathcal{R}\) of 6.42 W\(^{-1}\), NETD of about 20 mK is achievable for the devices with IR absorbing area of 166 \(\mu\)m \(\times\) 150 \(\mu\)m at \(f_0\) of 377 MHz as calculated using Equation 2-26.

![Figure 6-25: Measured S\(_{21}\) phase Allan variance of an AlN resonant IR detector at \(f_0\) of 377 MHz and \(d\phi/df\) of \(1.24 \times 10^{-4}\) deg/Hz.](image-url)
Figure 6-26 relates the device NETD with anchors thermal conductance, IR absorbing area and operating temperature. As predicted, the NETD enhances with decreasing $G_{th}$ and increasing $A_D$ due to lower heat loss and higher absorbed IR power and thus the responsivity, $\mathcal{R}$. On the other hand, NETD increases with temperature owing to the increasing thermal noise.

![Graphs](image)

Figure 6-26: Relation of NETD of AlN resonant IR detectors with (a) device effective thermal conductance, $G_{th}$, (b) IR absorbing area, $A_D$, and (c) operating temperature.
CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

The design, fabrication and investigation of AlN resonant uncooled IR detectors have been reported in this thesis. Through resonant, thermal, noise and sensing characterization, the potential of using piezoelectric resonators for IR sensing applications has been demonstrated. With the advantages of low noise characteristics and the capability of high temperature operation, piezoelectric resonators could serve as a promising alternative for uncooled IR detection.

The thesis started with the structural design of AlN resonant IR detectors using COMSOL Multiphysic and ANSYS simulation tools. The effect of device geometry on resonant and thermal behaviour of the IR detectors was investigated. It was found that the IDT design includes metallization ratio, aperture length, thickness, and number of fingers brings significant impact to the overall resonant performance of AlN LWRs. Additionally, AlN film edge reflection distance can determine the resonant mode order of the LWR. Anchor length of quarter-wavelength is advisable to minimize acoustic energy radiation. On the other hand, temperature sensing properties can be enhanced by minimizing the anchor width and maximizing the anchor length at the expense of device response time.
With the basic understanding of AlN LWR resonant and thermal behaviours through simulations, a device fabrication process was developed. Three phases of devices have been fabricated. Feasibility of each process step and recipe development was mainly studied in first phase including the AlN and Al patterning. In phase-two, the device functionality was characterized for the AlN LWRs with up-side-down design to enable the integration of three-layer interferometric absorption structure. Devices with an optimized structural design were fabricated in phase three process. Instead of XeF\textsubscript{2}, VHF was used to release the AlN resonant IR detectors. Therefore, the SiO\textsubscript{2} passivation layer was removed. This enhances the device effective TCF magnitude and thus the temperature sensing properties. Poly-Si release isolation wall was added surrounding the device to confine the release region and thus minimize the parasitic resistance and capacitance by shorten the metal interconnects. The CMOS-compatible process flow in principle enables the post CMOS integration with readout circuits.

Upon successful fabrication of AlN resonant IR detectors, their IR sensing properties together with their resonant and thermal behaviour was evaluated to verify the simulation results. MBVD equivalent circuit model was employed to fit the resonant parameters of the AlN LWRs. The tested devices consist of 1 \( \mu \)m thick AlN, 200 nm thick Mo, and 10 nm thick TiN. The SiO\textsubscript{2} passivation layer of devices in the phase-one and –two damped the device resonant characteristic (lower \( k_t^2 \) and \( Q \)-factor). Devices with thicker SiO\textsubscript{2} layers have lower resonant frequencies for the same IDT pitch and metallization ratio due to mass loading. Most critically, the thick SiO\textsubscript{2} layers increase the device effective heat capacity and counteract the
negative TCF of AlN. As a result, the device response time increases while the device IR responsivity deteriorates.

Overall, the experimental results of phase three devices aligned well with the simulation results. When AlN was eliminated from the device anchors, it did not deteriorate the device resonant performance. The IR detectors with only Mo anchors achieved $Q_s$ of 1317, $Q_p$ of 3405 and $k_t^2$ of 1.32% at a resonant frequency of 388 MHz. It has been proven that the dimensions of the Mo anchors have no significant effect on the resonant characteristics of the IR detectors due to high acoustic impedance of Mo. However, the longer and narrower anchors result in longer response times and improved responsivity. IR detectors with Mo anchor dimension of 12.5 μm × 31.5 μm × 200 nm gave a response time of 3.15 ms and a responsivity of 5.56 W^-1.

A larger metallization ratio (wider IDT line width for a fixed IDT pitch) resulted in lower resonant frequencies and damped frequency response due to the increasing mass loading and energy absorption by the Mo IDT electrodes. However, wider IDT line width improved the IR absorption because of the more efficient interferometric absorption system. On the other hand, a too narrow IDT line width gave insufficient electric field and low $C_o$ values, hence degrading the resonant characteristics of the AlN LWRs. From experiments, the optimum IDT line width was found to be 9.38 μm and 10.16 μm for a IDT pitch of 12.5 μm. These devices had a peak absorption of at least 90% (responsivity of 6.0 W^-1) with $Q_s$ of > 1000, $Q_p$ of > 1200 and $k_t^2$ of 0.8%.
Even though small IR absorbing area is desired for faster speed and lower cost, it deteriorates the device sensitivity due to reduced amount of absorbed IR power. Furthermore, a small IR sensing area limits the number of IDT fingers and aperture length, which worsen the LWR resonant characteristics. It is worth noting that the devices with fewer IDT fingers (smaller ratio of $W_{\text{AlN}}$ to $L_{\text{AlN}}$) give better sensitivity due to improved TCF.

The device with the best performance (estimated NETD of 20 mK) was chosen for elevated temperature test. It has been shown that AlN resonant IR detectors worked well at high temperatures up to 300 °C. Thanks to the high temperature robustness of AlN, Mo, TiN and Al₂O₃, there was no significant deviation in IR absorption spectrum observed when the device was subject to elevated temperatures. Although the device $Q$-factor and IR sensitivity were degraded with temperatures due to material softening and increasing thermal noise, the NETD of about 36 mK was achievable with a response time of 3.20 ms at a temperature of 300 °C, which is superior to other thermal IR detectors. This capability of high temperature operation caters to more applications in rugged industries include automotive, aircraft engine, geothermal, oil and gas exploration.

7.2 Recommendations for Future Work

This thesis has demonstrated the fabrication and development of AlN resonant IR detectors. Potentially, there is still room for improvement which can be considered for future research.
a) **IR sensing characterization at higher temperature range.**

Due to the limit of experiment setup, the AlN resonant IR detectors were tested only up to 300 °C. There is a reported work on AlN LWR operating at 600 °C for harsh environment RF applications [127]. Theoretically, the AlN resonant IR detectors in this work are also able to work up to 600 °C or higher. AlN is an intrinsically-poled, non-ferroelectric material (no Curie point), which has been reported to retain its piezoelectric properties at temperature above 1000 °C [162-164].

Mo, TiN and Al₂O₃ are high temperature capable materials with melting points of 2623 °C, 2950 °C, and 2072 °C respectively. At room temperature, oxygen absorption saturates at about two monolayers on Mo under ambient atmospheric [165]. Weak oxidation of Mo starts at 300 °C in air. Significant amounts of MoO₂ and MoO₂ were observed from 600 °C in air. TiN oxidizes rapidly to form TiO₂ in air at temperature above 450 °C [166, 167]. However, it remains un-oxidized with proper passivation up to 600 °C [167]. In this project, the 10 nm thick ALD TiN was deposited on AlN and passivated by 10 nm ALD Al₂O₃. Since the devices will be operated under vacuum, it can be safely assumed that oxidation is insignificant up to 600 °C, which is suitable for aircraft engines and industrial gas turbine applications.

b) **Development of metamaterial-based IR absorption structure.**

IR absorption of nearly 100 % can be easily achieved by three-layer interferometric absorption structures as demonstrated in this thesis. However, the IR detection range is limited to a certain bandwidth, depending on the thickness of the dielectric layer. For LWIR detection, a thick dielectric layer is required which increases the device heat capacity and thus the response time. For NIR and SWIR detection, a very thin
dielectric layer is necessary. In this thesis, the dielectric layer is also the piezoelectric film which drives the device operation. The piezoelectric film cannot be too thin as it will lose its piezoelectric properties. The reported thinnest AlN piezoelectric film is 250 nm [25, 87], corresponding to 2 μm IR peak absorption.

During the past decade, there has been an increased interest in the understanding and applications of metamaterials [168-170]. Metamaterials are structured composites with subwavelength periodic metal patterns situated on top of a dielectric layer with a metal back plate as shown in Figure 7-1 (b). The metal structures are not limited to square pads [169, 171, 172]. The design of most of these metamaterial structures is based on simultaneous resonant excitation of an electric dipole and magnetic dipole. Through careful design of the unit cell, broadband IR absorption is achievable. Fabricating metamaterial structures on the IR detectors requires no additional processing cost or complexity. In addition to the feasibility of integration of metamaterials with the IR detectors, it is flexible to design for the wavelength of interest. This makes them excellent candidates for broadband absorption.

Figure 7-1: Schematic illustration of (a) three-layer film stack interferometric absorption structure and (b) metamaterial-structured absorption system.
enhancement. Multiple of IR detection bandwidths can be achieved on a single chip with a fixed thickness of AlN and thus enabling spectroscopic applications.

c) Improvement of device NETD by developing AlN LWR with multiple modes.

Dual or multiple-mode resonators are always of interest in sensing applications for self-referencing or multiple sensing purposes. This can be achieved because different resonance modes are sensitive to different measurands. Dual-mode AlN FBARs with longitudinal and shear resonance modes have been reported for mass and liquid sensing, respectively [173]. On the other hand, dual mode ZnO FBARs are also employed as self-reference sensors without the need of additional reference devices to eliminate environmental fluctuations, thereby simplifying the readout circuits and signal processing [174].

In this work, the AlN LWR can be engineered to have multiple resonance modes through tuning the AlN deposition parameters, IDT electrode configurations or AlN film geometry. Since the AlN resonant IR detectors operate in a vacuum environment where no contaminants could present to interrupt the IR sensing process, dual mode AlN LWRs can be employed to enhance the temperature sensitivity and thus the IR responsivity as described in [175]. In order to maximize the enhancement in device sensitivity, the resonant frequencies of the two resonance modes have to be as close as possible but a significant difference in TCFs is required.

d) Improvement of device NETD by enhancing device effective TCF.

It has been reported that the residual film stress can significantly influence the TCF of a resonator [176, 177]. In the deposition of highly stressed films, the mechanical stress itself is transmitted through the exciting-electrode of the quartz crystal and
tends to bend the crystal. It was shown that the existence of tensile stress in the film can cause the resonant frequency of an AT-cut quartz crystal to be higher than that of a stress-free film [176]. In addition to the difference in coefficient of thermal expansion (CTE) between films, residual film stress can also be attributed to the intrinsic stress related to nucleation and grain boundary effects during growth of film and temperature cycling.

Figure 7-2: AlN resonant IR detectors with the TCF enhancer (a) deposited on top of the device and (b) embedded within the upper portion of AlN.

Utilizing the film stress-induced resonant frequency shift concept, it is possible to enhance the device effective TCF of the AlN resonant IR detectors by depositing a layer of material in an open square shaped with a CTE that is higher than that of AlN. As illustrated in Figure 7-2, the open square-shaped TCF enhancer can be either deposited on top of the device or embedded within the upper portion of the AlN film. According to Equation 3-15, the device effective TCF is governed by $\alpha_{Cij}$ and $\alpha_{ij}$. For a constant $\alpha_{Cij}$, decrease in $\alpha_{22}$ and $\alpha_{33}$ or increase in $\alpha_{11}$ makes the effective TCF more negative and thus more sensitive to temperature changes.

COMSOL Multiphysics was employed to estimate the efficiency of the above structure in TCF enhancement. For simplicity, a 2D axisymmetric model was created as illustrated in Figure 7-3. In a 3D projection, the model is a circular
membrane of radius, \( r \) of 75 μm. The position where \( r = 0 \) in the model was set to axial symmetry and the other end of the structure was free to move. In addition to piezoelectric devices physics, thermal expansion physics was added to the simulation. Al was chosen as the TCF enhancer as its CTE of 23.6 ppm/K is much larger than that of AlN.

![Diagram showing the 2D axisymmetric model in the finite-element analysis for TCF simulation.](image)

Figure 7-3: The 2D axisymmetric model in the finite-element analysis for TCF simulation.

![Graph showing the stimulated TCF of AlN resonator with and without Al TCF enhancer.](image)

Figure 7-4: The stimulated TCF of AlN resonator with and without Al TCF enhancer.

The simulation was first implemented for the model without a Al TCF enhancer, followed by the models with 100 nm open square shaped Al situated at the top of the device. The resonant frequency of both models reduces with temperature and their TCF values are calculated and displayed in Figure 7-4. The model without Al shows
the least TCF of about -25 ppm/K while the one with Al gives a TCF of about -85 ppm/K. Despite that the model in this simulation has a different structure as compared to the actual device, the Al TCF enhancer is believed to be able to bring the similar enhancing effect to the actual device because both the devices consist of the membrane that is made of the identical material composite layers. Thus, the TCF of AlN resonant IR detectors can be tuned by adding a material with mismatched CTE to the AlN resonant IR detectors. More work has to be done to investigate the damping effect of Al TCF enhancer on device resonant characteristics, noise performance and IR absorption.
Author’s Publications

Patents


Journal Papers


International Conference


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