ALUMINUM NITRIDE PIEZOELECTRIC MICROELECTROMECHANICAL RESONANT PHYSICAL SENSORS

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Abstract

Miniaturized sensors are nowadays found in a wide variety of application, such as smart mobile devices, automotive, healthcare and environmental monitoring. The recent advancements of Micro/Nano-Electro-Mechanical Systems (MEMS/NEMS) technology have a tremendous impact on the sensor miniaturization, power consumption and cost reduction, which allow envisioning a new era of sensor fusion in which the data collected from multiple individual sensors are combined to get information about the environment that is more accurate and reliable than the individual sensory data. This trend towards sensor fusion has dramatically increased the demand of new technology platforms, capable of delivering multiple sensing and wireless communication functionalities in a small footprint. In this perspective, the unique capability of Aluminum Nitride (AlN) piezoelectric MEMS/NEMS resonant technology to deliver high performance resonant sensors (i.e. accelerometers and gyroscopes) and radio frequency (RF) components (i.e. filters and oscillators) makes it the best platform for the implementation of the next generation miniaturized, low power, multi-functional and reconfigurable wireless sensing and communication systems.

In this dissertation, a stepping stone towards the development of compact, power efficient and high resolution physical sensors: infrared (IR) detectors and magnetic field sensors, is set by taking the unique advantage of the AlN MEMS/NEMS resonant technology, which is the combination of extremely high sensitivity to external perturbations (due to their very reduced dimensions) and ultra-low noise performance (due to the intrinsically high quality factor, $Q$, of such resonant devices). For the first time, a spectrally selective uncooled NEMS resonant IR detector based on a plasmonic
piezoelectric material is demonstrated, showing high resolution (noise equivalent power of 2.1 nW/Hz$^{1/2}$) and ultra-fast response (thermal time constant of 440 μs), marking a milestone towards the implementation of a new class of high performance, miniaturized and low power IR spectroscopy and multi-spectral imaging systems. On the other hand, the proposed magnetic field sensor based on a piezoelectric and magnetostrictive bilayer of AlN/FeGaB showed a detection limit of 16 nT/Hz$^{1/2}$ and angular resolution of 0.34°, proofing its potential for the application of extremely small magnetic field detection and miniaturized electronic compasses for mobile devices.
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1. INTRODUCTION

1.1 AlN Resonant Sensing Platform

Sensors are nowadays found in a wide variety of applications, such as smart mobile devices, automotive, healthcare and environmental monitoring. The recent advancements in terms of sensor miniaturization, low power consumption and low cost allow envisioning a new era for sensing in which the data collected from multiple individual smart sensor systems are combined to get information about the environment that is more accurate and reliable than the individual sensor data. By leveraging such sensor fusion (fused sensor information from multiple sensors) it will be possible to acquire complete and accurate information about the context in which human beings live, which has huge potential for the development of the Internet of Things (IoT) in which physical and virtual objects are linked through the exploitation of sensing and communication capabilities with the intent of making life simpler and more efficient for human beings [1].

This trend towards sensor fusion has dramatically increased the demand of new technology platforms, capable of delivering multiple sensing and wireless communication functionalities in a small foot print. In this context, Micro- and Nanoelectromechanical systems (MEMS/NEMS) technologies can have a tremendous impact since they can be used for the implementation of high performance sensors [2-5] and wireless communication devices [6-10] with reduced form factor and Integrated Circuit (IC)
integration capability. In particular MEMS/NEMS resonators [11-14] have been used successfully as ultra-sensitive detectors for sensing mass, fluids flow and chemical or biological agents [15-17]. The fundamental advantages of MEMS/NEMS resonant sensors over other existing sensor technologies is related to the unique combination of extremely high sensitivity to external perturbations (due to their very reduced dimensions) and ultra-low noise performance (due to the high quality factor, $Q$, of such resonant devices) [18].

More recently, the Aluminum Nitride (AlN) piezoelectric MEMS resonator technology has emerged as a promising approach for the implementation of the next generation high performance wireless sensing and communication systems. The advantages of AlN MEMS resonant technology lie in not only the high sensitivity (overall reduced volume) and low noise performance (intrinsically high quality factor), but also the unique scaling capability (high quality, ultrathin ~10s nm thick AlN film can be directly deposited on Silicon substrates by low temperature sputtering process, differently from other MEMS resonant technology, such as Quartz [19] and Gallium Nitride [20]), high power handling capability [21] and CMOS process compatibility [22]. To date, miniaturized and high performance resonant sensors and RF components based on the same AlN piezoelectric MEMS resonant technology have been demonstrated individually, including accelerometers [23, 24], gyroscopes [25], microphones [26], filters [27, 28] and oscillators [29, 30]. It is believed that these high performance and miniaturized sensors and RF components could be potentially fabricated and integrated within a same chip for the implementation of high performance and compact wireless sensing and communication systems on a chip (SOC).
To further expand the application range of the AlN piezoelectric MEMS resonator technology, in this dissertation, two fundamental physical sensors: Infrared (IR) detectors and magnetometers, based on the same AlN nano-plate resonant sensing platform, have been designed and experimentally demonstrated for the first time. The most important parameters that out to be considered for the design and optimization of physical sensors are the device sensitivity to the measurands, i.e. IR radiation for IR detectors and magnetic field for magnetometers, the noise performance and ease of readout. All these fundamental challenges associated with the development of compact, power efficient and high resolution physical sensors (IR detectors and magnetometers) are addressed in this work by proposing an AlN micromechanical resonant structure that, by taking advantage of advanced material properties and innovative device engineering, is characterized by a unique set of application enabling features, such as (a) high sensitivity, enable by using AlN piezoelectric nano-plates working at high order of lateral-extensional mode of vibration with innovative design solutions; (b) ultra-low noise performance, due to the intrinsic high Q of the resonant device enabled by the effective confinement of acoustic energy in the resonant body of the device; (c) ease of readout, due to the excellent piezoelectric transduction properties of AlN at micro and nano scale which enables the use of low power and self-sustained CMOS oscillators as direct frequency readout.

In this dissertation, the fundamental operation of AlN nano-plate resonators (NPRs) is introduced first. Then, the design, fabrication and characterization of the IR detectors and magnetometers based on the AlN piezoelectric nano plate resonant technology is discussed, respectively. Finally, the future work, emphasizing on the
system level implementation of high performance IR/THz imaging and spectroscopy is proposed.

1.2 IR Detectors

Infrared (IR) detectors are devices that convert IR radiation power into an electrical output. IR radiation lies in the electromagnetic wave range from 780 nm to 1 mm [31]. The IR spectrum can be divided into near infrared (NIR), short wavelength infrared (SWIR), medium wavelength infrared (MWIR), long wavelength infrared (LWIR), and far infrared (FIR), whose spectral ranges are listed in Table I. Among the IR radiation spectrum, the two atmospheric windows of 3-5 μm (MIR) and 8-14 μm (LWIR) are with the most interest, and more recently, the electromagnetic radiation in Terahertz (THz) range has received increasing interest, as many materials of interest have unique spectral fingerprints in the THz range, resulting in a hot research topic of THz spectroscopy and THz imaging [32, 33].

<table>
<thead>
<tr>
<th></th>
<th>Wavelength (μm)</th>
<th>Frequency (THz)</th>
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<tbody>
<tr>
<td><strong>NIR</strong></td>
<td>0.78 - 1</td>
<td>385 - 300</td>
</tr>
<tr>
<td><strong>SWIR</strong></td>
<td>1 - 3</td>
<td>300 - 100</td>
</tr>
<tr>
<td><strong>MIR</strong></td>
<td>3 - 8</td>
<td>100 – 37.5</td>
</tr>
<tr>
<td><strong>LWIR</strong></td>
<td>8 - 15</td>
<td>37.5 - 20</td>
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<tr>
<td><strong>FIR/THz</strong></td>
<td>15 - 1000</td>
<td>20 – 0.3</td>
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IR detectors were developed to fulfill military needs in the early years, such as night vision, missile tracking, target recognition and surveillance. More recently, the trend of IR technology for civilian applications has been steadily growing. Nowadays, IR detectors can be found in a wide variety of peaceful applications, including medical diagnostics, biological and chemical threat detecting, electrical power system inspection, IR spectroscopy and IR imaging. The increasing demands for the development of high performance, power efficient and compact IR detectors to meet both military and civilian needs have driven great research efforts both in academic laboratories and industrial research and development departments.

IR detectors can be divided in two categories: photonic detectors and thermal detectors. Photonic detectors are built by semiconductor materials [34, 35], and their electrical output signal results from the interaction between photons and electrons. They have the advantages of high signal to noise performance and fast response. However, in order to achieve such high performance, they typically need cryogenic cooling to prevent thermally generated carriers [36, 37], making them bulky, expensive and power inefficient. Thermal detectors, on the other hand, rely on the physical properties change of the materials through the temperature variation induced by IR radiation. They have been implemented by bolometers [38], thermoelectric [39] and pyroelectric materials [40], and they are generally less expensive, compact and more power efficient than semiconductor photon detectors because they are usually operated at room temperature, but they exhibit relatively worse resolution and slower response.

With the recent advances in Micro/Nano-Electro-Mechanical Systems (MEMS/NEMS), miniaturized IR thermal detectors based on MEMS/NEMS technology
have attracted a great deal of attention thanks to their potentially ultra-high resolution and unique advantages in terms of size and cost, compared to conventional cryogenically cooled semiconductor photon detectors [18]. Among different MEMS IR sensing technologies, i.e. microbolometers, pyroelectric detectors, and thermoelectric detectors, uncooled IR detectors based on MEMS resonators have emerged as one of the most promising technologies due to their unique advantages in terms of high sensitivity to external perturbation (extremely reduced overall volume) and low noise performance (intrinsically high quality factor Q). MEMS resonant IR detectors implemented by gallium nitride [3] and quartz [19] piezoelectric resonators have been demonstrated recently and show promising performance. However, complex, bulky, power inefficient and expensive electronic readouts, based on open-loop measurements involving the use of network analyzers, are necessary so far to characterize the device performance, which has prevented these technologies to meet the stringent miniaturization, cost and power requirements of civilian and military IR imaging and sensing applications. Furthermore, the mass production of these piezoelectric materials is incompatible with CMOS process, making it potentially difficult to integrate the detectors with CMOS circuitry on a single chip.

In this work, a stepping stone towards the development of MEMS resonant IR thermal detectors with high sensitivity, high resolution, fast response and compact readout was set by introducing a novel AlN micromechanical resonant structure that, by taking advantage of advanced material properties and innovative device engineering, enables the implementation of uncooled IR detectors with unprecedented performance. For the first time, ultra-thin (250nm - 500 nm thick) AlN piezoelectric plasmonic
resonant metamaterial (PPRM) using fully metallic anchors with minimized cross-sectional areas to support the freestanding piezoelectric resonant body and provide the electrical connection to it were implemented as the core of the resonant IR detector. Such innovative device concept results in a unique set of application enabling features: (a) high sensitivity, due to excellent thermal isolation from the heat sink (enabled by the large thermal resistance associated with the fully metallic anchors); (b) spectrally selective IR absorption, due to the properly tailored optical properties of the plasmonic resonant structure (enabled by the ultrathin piezoelectric plasmonic metasurface); (c) ultra-low noise performance, due to the intrinsic high $Q$ of the resonant device (enabled by the effective confinement of acoustic energy in the resonant body of the device by using fully metallic anchors with minimized cross sectional areas); (d) ease of readout, due to the excellent piezoelectric transduction properties of AlN at micro and nano scale which enables the use of a low power and self-sustained CMOS oscillator as direct frequency readout (differently from gallium nitride and quartz, ultra-thin and high quality AlN film can be deposited directly on Silicon substrates by low-temperature sputtering deposition and processed by post-CMOS compatible process [22]). Totally three different kinds of prototypes were characterized and showed high responsivity, high resolution, fast response and spectrally selective IR detection capability, making it the best candidates for the implementation of the next generation high performance, power efficient and compact IR sensing and imaging systems.
1.3 Magnetic Field Sensors

Magnetic field sensors, or magnetometers, are devices measure the strength and direction of the magnetic field in space of interest. Low power and high resolution integrated magnetometers are crucial elements to be included in the next generation multi-functional and reconfigurable wireless sensing and communication systems. For example, a wireless inertial measurement unit (WIMU), which is the main component of inertial navigation systems used in aircraft, spacecraft and guided missiles, exploits sensor fusion from a combination of accelerometers, gyroscopes and magnetometers to measure the craft’s velocity, orientation and gravitational forces. Furthermore, an electronic compass, in which the combination of an accelerometer and a magnetometer provides compass functionalities, is embedded in almost every modern smartphone. Such systems would greatly benefit from the development of new technology platforms, capable of delivering high performance accelerometers, gyroscopes and magnetometers as well as Radio Frequency (RF) components, such as resonators, filters and oscillators, integrated in a single chip.

Such increasing demand for compact, low cost, ultra-sensitive and power efficient integrated magnetometers has driven great research efforts towards the implementation of high performance MEMS based solutions for magnetic field sensing. In particular MEMS magnetic field sensors based on Lorentz force [41, 42], and magnetostrictive composites [43-48], have been recently demonstrated. However, such MEMS resonant magnetometers are typically operated in an open-loop mode with an external frequency source used to excite vibration in the micromechanical structure (typically a cantilever).
Therefore, complex and power inefficient sensor readouts (involving the use of lock-in and charge amplifiers) are necessary to acquire the sensor response, which has prevented the use of these technologies for the implementation of highly integrated, low power and multi-functional wireless sensing platforms. More recently, a Lorentz force magnetometer, fabricated in a standard silicon MEMS process, and connected to a self-sustained loop with amplitude modulated (AM) readout was demonstrated [49], showing a magnetic field resolution of 128 nT/Hz\(^{1/2}\). Nevertheless, the power consumption of resonant Lorentz force magnetometers is intrinsically limited by the bias current (typically > 1 mA) required for the functionality of the device (the sensitivity to magnetic field is proportional to the bias current amplitude [41]), which poses challenges to the employment of these devices in low-power wireless platforms.

In this perspective, magnetometers based on magnetostrictive/piezoelectric magnetoelectric heterostructures have great potential since they are characterized by high resolution and do not require a bias current. MEMS magnetic sensors based on direct magnetoelectric coupling have been demonstrated showing high resolution (~ pT/Hz\(^{1/2}\)) detection of the AC magnetic field matching the electromechanical resonance frequency (typically several kilo Hertz) of the heterostructure (limited bandwidth due to the high magnetoelectric coupling occurring only at the electromechanical resonance) [48]. On the other hand, high resolution detection (~ 100 pT) of low frequency and DC magnetic fields has been demonstrated by exploiting the Young’s modulus sensitivity to magnetic field (delta-E effect) of magnetoelectric MEMS resonators [43, 50, 51]. Nevertheless, the capability to interface an intrinsically high sensitivity magnetoelectric MEMS resonant sensor technology with frequency modulated (FM) output to a compact and low-power...
self-sustained oscillator as direct frequency readout has not been demonstrated to date due to the lack of MEMS magnetoelectric resonators with sufficiently high electromechanical performance.

In this work, a stepping stone towards the development of a compact, power efficient and high resolution magnetic field sensor is set by demonstrating a high frequency MEMS-CMOS oscillator based on a self-biased magnetoelectric nano-plate resonator (NPR). For the first time, an ultra-thin (FeGaB/Al$_2$O$_3$)$\times$10 (FeGaB for short) multilayer [50, 51] with high magnetostrictive coefficient [52] is integrated within an AlN nano-plate resonant body, forming an AlN/FeGaB nano-plate resonator working at a higher order contour-extensional mode of vibration [53]. The efficient on-chip piezoelectric actuation and sensing of a high frequency bulk acoustic mode of vibration in a nano-plate structure, instead of a beam, enables the fabrication of a high frequency and high power handling resonator with power efficient transduction [21]. At the same time the strong magnetostrictive coupling [54] between the FeGaB magnetic film and the AlN piezoelectric nano-plate resonator guarantees ultra-high sensitivity of the device resonance frequency to magnetic field (due to the magnetic field induced variation of the device Young’s modulus, delta-E effect [50, 51, 55]). Furthermore, the electrically conductive magnetostrictive FeGaB thin film is also employed as top floating electrode in the lateral field scheme [53] used to excite vibration in the piezoelectric nano-plate, which enables the achievement of high values of electromechanical coupling coefficient, $k_r^2$, comparable to the ones of conventional AlN NPRs [53]. Such high electromechanical performance of the AlN/FeGaB nano-plate resonator enables the use of a compact, low power and self-sustained CMOS oscillator as direct frequency readout, resulting in the
first complete prototype of a high performance magnetoelectric MEMS-CMOS magnetometer with detection limit pushed in ~10s nT/Hz$^{1/2}$ range.
2. AlN NANO-PLATE RESONATORS

2.1 AlN Nano-Plate Resonators

The core technology for the proposed physical detectors is based on AlN nano-plate resonators (NPRs) working at a higher order of lateral-extensional mode of vibration [53]. Figure 2-1 illustrates a 3-dimensional (3D) representation of the AlN NPR employed in this work. A thin AlN film (250 nm ~ 500 nm thick) is sandwiched between a bottom inter-digital transducer (IDT) and top electrically floating metal plate. The bottom IDT is used to excite the contour-mode of vibration of the piezoelectric film and the top floating metal plate is used to confine the electrical field within the thickness direction of the AlN film. When an alternating current (ac) signal is applied within the thickness direction of the AlN film, shown in Figure 2-2, a lateral-extensional mode of vibration can be excited through the $d_{31}$ piezoelectric coefficient [9].
Figure 2-1. 3D representation of an AlN NPR with bottom inter-digital transducers and top floating metal plate. The 2D FEM simulated lateral-extensional mode of vibration (total displacement) is superimposed to the AlN film.

Figure 2-2. Schematic illustration of the Lateral Field Excitation (LFE) scheme of the AlN NPR: black dash lines represent the electric field and blue arrows represent the strain induced by the $d_{31}$ piezoelectric coefficient.

The resonance frequency of such AlN NPR is defined by the pitch of the IDT, $W_0$ (Figure 2-1), and the equivalent Young’s modulus, $E_{eq}$, and density, $\rho_{eq}$ of the resonant material stack, given by (2-1).

$$f = \frac{1}{2W_0} \sqrt{\frac{E_{eq}}{\rho_{eq}}} \quad (2-1)$$
The performance of an AlN NPR in electrical domain can be modeled by the modified Butterworth Van Dyke (MBVD) equivalent circuit [56], shown in Figure 2-3 (a). The MBVD circuit consists of two branches in parallel: an acoustic branch, composed by the series combination of the motional resistance, $R_m$ (quantifying dissipative losses), motional capacitance, $C_m$ (inversely proportional to the stiffness), and motional inductance, $L_m$ (proportional to the mass), and an electrical branch composed by the series combination of the capacitance, $C_0$ (capacitance between the device terminals), and resistance, $R_0$ (representing the dielectric loss). A series resistance, $R_s$ is also included in the circuit to represent the electrical loss associated with the metal electrodes and routing. The series resonance occurs at frequency $f_s$, when the impedance of the motional capacitance and motional inductance cancel with each other, resulting in a minimum impedance (maximum admittance), while the parallel resonance occurs at frequency $f_p$, when the impedance of the circuit is maximum (minimum admittance), shown in Figure 2-3 (c). The equations to calculate the series and parallel resonance frequency are given by (2-2) and (2-3). The measured electrical performance of a typical AlN NPR is shown in Figure 2-3.
Figure 2-3. (a) Modified Butterworth Van Dyke (MBVD) equivalent circuit of the AlN NPR; (b) SEM image of a fabricated 500 nm thick AlN NPR. The dimensions of the resonator are: $L = 200 \mu m$, $W = 75 \mu m$, $W_0 = 25 \mu m$; (c) Measured admittance amplitude versus frequency and MBVD model fitting of the fabricated AlN NPR; (d) Measured Phase and MBVD fitting of the admittance of the fabricated AlN NPR.

\[
f_s = \frac{1}{2\pi} \sqrt{\frac{1}{L_m C_m^*}} \quad (2-2)
\]

\[
f_p = \frac{1}{2\pi} \sqrt{\frac{1}{L_m C_m} + \frac{1}{L_m C_0}} \quad (2-3)
\]
The two most important parameters to evaluate the performance of an AlN NPR are the quality factor, $Q$, and electromechanical coupling coefficient, $k_t^2$. The quality factor is a dimensionless parameter representing the ratio of the energy stored in the vibrating resonant structure to the energy dissipated per cycle by the damping processes (the higher is the $Q$, the lower is the energy loss), while the electromechanical coupling coefficient is a numerical measure of the conversion efficiency between the electrical and mechanical energy in the electromechanical resonator. The typical values of $Q$ and $k_t^2$ for ultrathin ($\lesssim 500$ nm thick) AlN NPRs employing LFE scheme (Figure 2-2) are around 1000 ~ 2000 and 1% ~ 2%, respectively. For a given geometrical capacitance, $C_0$, and operating frequency, $f_0$, the motional resistance ($R_m$), capacitance ($C_m$) and inductance ($L_m$) of the resonator are determined by the values of $Q$ and $k_t^2$, given by (2-4) to (2-6).

$$R_m = \frac{1}{\omega_0 C_0 k_t^2 Q} \quad (2-4)$$

$$C_m = \frac{8}{\pi^2} k_t^2 C_0 \quad (2-5)$$

$$L_m = \frac{1}{\omega_0^2 C_m} \quad (2-6)$$

In particular the device equivalent motional resistance, $R_m$, is inversely proportional to the $k_t^2 \cdot Q$ product (2-4). The achievement of a low value of motional resistance, in a radio frequency electromechanical resonator, is of crucial importance for the direct interface of the device with compact and low-power 50Ω electronics [9].
Therefore, the figure of merit (FOM) of an electromechanical resonator is defined as the $k^2 \cdot Q$ product.
3. AlN RESONANT IR DETECTORS

3.1 Working Principle

A MEMS/NEMS resonant infrared (IR) sensor is a particular class of thermal detectors that relies on a transduction scheme based on the change in vibration frequency of a microelectromechanical resonator with a temperature dependent mechanical resonance frequency. The incident IR radiation heats the MEMS resonator changing its resonance frequency. By monitoring such resonance frequency shift the incident IR power is detected. Unlike other IR sensors, MEMS resonant IR sensors do not require cooling and are suitable for the implementation of high performance, miniaturized and power efficient thermal imagers and spectrometers.

The core of the proposed uncooled resonant IR detector is an AlN nano-plate resonator (NPR) working at a high order of contour-extensional mode of vibration [53]. It can be connected to the feedback loop of a CMOS amplifier forming a MEMS-CMOS oscillator (Figure 3-1), whose output frequent is set by the resonance frequency of the AlN NPR [57].
Figure 3-1. Schematic illustration of the working principle of the proposed uncooled resonant IR detector based on an AlN NPR MEMS-CMOS oscillator.

When an IR radiation is absorbed by the resonant structure, the temperature of the resonator rises in several microseconds to milliseconds because of the large thermal resistance but extremely small thermal mass of the freestanding resonant structure completely released from the substrate. Due to the temperature dependence of the equivalent Young’s modulus, $E_{eq}$, AlN contour mode resonators with the thickness of AlN films below 1 µm show a typical temperature coefficient of frequency (TCF) around -30 ppm/K [58], resulting in a shift in the resonance frequency (Figure 3-1). As the output frequency of the MEMS-CMOS oscillator is set by the MEMS resonator, the IR radiation can be readily detected by monitoring the output frequency of the MEMS-CMOS oscillator.
3.2 Theoretical Analysis

The core of a MEMS resonant IR detector is a microelectromechanical resonator whose resonance frequency is highly sensitive to temperature. An IR absorbing material is typically integrated on the surface of the resonator. The freestanding micromechanical resonant structure can be simply modeled as a thermal mass (with thermal capacitance $C_{th}$) coupled to the heat sink at a constant temperature, $T_0$, via a thermal conductance, $G_{th}$ (thermal resistance, $R_{th}=1/G_{th}$). Upon exposure to IR radiation, the absorbed power causes a large and fast increase of the device temperature, $\Delta T$, due to the excellent thermal isolation and extremely low thermal mass of the freestanding micromechanical structure (released from the substrate):

$$\Delta T = \frac{\eta Q_p}{\sqrt{G_{th}^2 + \omega^2 C_{th}^2}} \quad (3-1)$$

where $Q_p$ is the incident IR power, $\eta$ is the absorption coefficient of the material stack forming the resonator (typically set by the IR absorbing material), $\omega$ is the modulation frequency of the incident IR radiation, respectively. Such IR induced temperature rise results in a shift in the mechanical resonance frequency of the micromechanical resonator due to the large temperature dependence of the structure equivalent Young's modulus. Absolute values of temperature coefficient of frequency, $|TCF|$, in the 10 - 100 ppm/K range are typically achieved in MEMS resonators [18-20, 58]. Therefore, for IR radiation slowly varying over time ($\omega \approx 0$), the overall responsivity of the MEMS resonant detector to IR radiation can be expressed according to eq. (3-2):
Taking advantage of the high quality factor, $Q$, resonant system (unique feature compared to conventional micro-bolometers), extremely small IR-radiation-induced frequency variations can be detected by a compact and low power electronic readout (i.e. a single transistor oscillator circuit). In fact, higher resolution and stability, compared to static measurements, is typically achieved in the MEMS domain by exploiting the high $Q$ resonant behavior of a micromechanical structure. Such MEMS resonant sensors use frequency as the output variable, which is one of the physical quantities that can be monitored with the highest accuracy and converted to digital form by measuring zero-crossings without the need of an analog-to-digital-converter to digitize the voltage or current readout.

A crucial parameter that ought to be considered for the design and optimization of a MEMS resonant IR sensor is the noise equivalent power, NEP, which represents the IR power that gives a signal-to-noise ratio equal to 1 in a 1 Hz measurement bandwidth (minimum detectable IR power) and it is defined as the noise-induced frequency fluctuation, $f_n$, divided by the responsivity of the detector, given by:

$$NEP = \frac{f_n}{R_s} = \frac{f_n}{\eta \cdot R_{th} \cdot TCF \cdot f_0}$$

(3-3)

Among different noise sources, the fundamental limit to the frequency stability of a MEMS resonant IR sensor is set by [59]: (1) the thermal fluctuation noise associated with the spontaneous temperature fluctuations of the detector element due to the finite heat conductance $G_{th}$ to the surroundings, (2) the background fluctuation noise due to radiative
heat exchange with the environment, and (3) the thermomechanical noise originated from thermally driven random motion of the mechanical structure. Therefore, the minimization of the NEP values associated with each of these three fundamental noise contributions (respectively $NEP_{th}$, $NEP_{rad}$, and $NEP_{mec}$) is typically used to drive the design of MEMS resonant IR sensors:

$$NEP_{th} = \frac{2T_0}{\eta} \sqrt{\frac{K_B}{R_{th}}}$$  \hspace{1cm} (3-4)

$$NEP_{rad} = \frac{1}{\eta} \sqrt{16A\varepsilon\sigma k_B T_0^3}$$  \hspace{1cm} (3-5)

$$NEP_{mec} = \sqrt{\frac{K_B T_0^2}{4P_c \eta \cdot R_{th} \cdot TCF \cdot Q}}$$  \hspace{1cm} (3-6)

where $K_B$ is the Boltzmann constant, $T_0$ is the temperature of the resonator, $A$ is the area of the device, $\varepsilon$ is the emissivity, $\sigma$ is the Stefan-Boltzmann constant, $P_c$ is the power used to drive the mechanical resonance in the structure, $Q$ is the resonator’s quality factor. The total NEP can be expressed as:

$$NEP_{tot} = \sqrt{NEP_{th}^2 + NEP_{rad}^2 + NEP_{mec}^2}$$  \hspace{1cm} (3-7)

Equation (3-4)-(3-6) indicates that minimum NEP, thus a high resolution resonant IR detector, can be achieved by maximizing the device thermal resistance $R_{th}$, absorption coefficient $\eta$, temperature coefficient of frequency, TCF, quality factor $Q$, and power handling $P_c$. The minimization of detector NEP also minimizes its noise equivalent temperature difference (NETD) which is a widely used figure of merit for IR detector arrays, especially IR imaging systems based on focal plane arrays (FPA), representing the
minimum temperature change of the scene that induces a detector output signal equal to
the noise level [31]:

\[
NETD = \text{NEP} \left( \frac{4F^2 + 1}{\eta A \gamma} \right) \left[ \int \frac{\partial M(\lambda)}{\partial T} d\lambda \right]^{-1}
\]

where \( F \) is the focal ratio of the optics, \( B \) is the measurement bandwidth and \( \gamma \) is the
transmission of the optical path between the IR source to the IR detector, and the last
term on the right-end side of the equation is the radiant exitance integrated over the
wavelength range of interest [31]. It is worth noting that, beyond the minimization of the
NEP, a small focal ratio of the optics and a large absorption coefficient are generally
desirable for the implementation of high resolution infrared imagers.

Another crucial parameter to be considered for the design of a high performance
MEMS IR resonant sensor is its response time which is characterized by the thermal time
constant, \( \tau \), of the device, defined as the product between its thermal resistance, \( R_{th} \), and
capacitance, \( C_{th} \):

\[
\tau = R_{th} \cdot C_{th}
\]

Equation (3-9) indicates that by improving the thermal isolation of the sensing element
from the heat sink (hence increasing \( R_{th} \)) the NEP of the device is reduced but its
response time is increased. Therefore, a trade-off between these two important
performance metrics needs to be generally considered for the design of the detector.
Nevertheless, for a given thermal resistance (guaranteeing a satisfactory NEP) the
response time of the sensor can be reduced by minimizing its thermal capacitance which
directly translates into reducing the volume of the micromechanical resonant structure.
3.3 Device Fabrication

The proposed AlN nano-plate resonant IR detector was fabricated using a 5-mask post-CMOS compatible microfabrication process (Figure 3-2). The fabrication started with a high resistivity (resistivity >20,000 Ω•cm) Silicon wafer. First, 100 nm thick Pt was sputter-deposited and patterned by lift-off process to define the bottom inter-digital transducer (IDT). Then, 250 ~ 500 nm thick high quality c-axis orientated AlN film was sputter-deposited on top of the Pt IDT. Next, the AlN film was wet-etched by H$_3$PO$_4$ to open vias to the bottom electrodes and dry-etched by inductively coupled plasma (ICP) in Cl$_2$ based chemistry to define the shape of the AlN resonator. After that, 100 nm thick Au was deposited by E-beam deposition and patterned by lift-off process to define the probing pad and top electrical floating plate. Then, 100 ~ 200 nm Si$_3$N$_4$ was deposited by plasma enhanced chemical vapor deposition (PECVD) and patterned by ICP as the IR absorber. Finally, the Si substrate underneath the AlN resonator was etched by Xenon Difluoride (XeF$_2$) to completely release the device.
3.4 Device Characterization

3.4.1 Proof of Concept of thermal power detection using AlN NPRs

In order to experimentally examine the thermal power detecting capability of AlN NPRs, a thermal detector based on an AlN piezoelectric microelectromechanical resonator with an integrated suspended heat source was designed and fabricated. Figure 3-3 shows the 3D schematic representation of the proposed AlN micromechanical resonant thermal detector: a typical AlN NPR working at a high order lateral-extensional...
mode of vibration was overlapped by a suspended heat absorber. When the incident thermal power is absorbed by the absorber, the generated heat transfers to the AlN resonant body through the air gap between the heat absorber and the AlN resonator by conductive heat transfer, increasing the temperature of the AlN resonator, and a corresponding frequency shift is recorded.

Figure 3-3. (a) 3-D schematic representation of the proposed micromechanical resonant thermal detector and its equivalent thermal circuit; (b) Scanning electron microscope (SEM) image of the fabricated micromechanical resonant thermal detector.
An equivalent thermal circuit for the proposed micromechanical resonant thermal detector was considered (Figure 3-3 (a)) to optimize the device design. In the thermal circuit, $P_{in}$ is the absorbed thermal power; $T_0$, $T_A$ and $T_R$ are the temperatures of the heat sink, heat absorber and resonator, respectively; $R_{A1}$ is the thermal resistance between the heat source and the heat sink through the length of the micromachined suspended absorbing element; $R_{A2}$ is the thermal resistance associated to the thickness of the absorbing element; $R_{air}$ is the thermal resistance between the heat source and the resonator through the air gap; $R_R$ is the thermal resistance associated to the length of the resonator. To optimize the device performance, it is required that $T_A \approx T_R$, hence $R_R >> R_{A2} + R_{air}$. This translates in reducing the thickness of the heat absorber (to reduce $R_{A2}$), the air gap (to reduce $R_{air}$), and the thickness of the resonator plate (to increase $R_R$). A large value of $R_{A1}$ (hence thin heat absorber) is also desired so that a small power $P_{in}$ absorbed could cause a large temperature rise.

To verify the theoretical analysis and further optimize the device performance, 3-dimensional Finite Element Method (FEM) simulation using COMSOL Multiphysics was performed. To optimize the air gap between the heat absorber and resonator, heat transfer efficiency, defined by the temperature ratio between the resonator ($T_R$) and the heat absorber ($T_A$), was introduced. Figure 3-4 (a) shows that efficient heat transfer from the heat absorber to the resonator can be achieved by scaling the air gap to nano-scale (air gap smaller than 1 µm guarantees $T_R > 0.6 T_A$). To simulate the sensitivity of the device, different levels of input power (from 1 nW to 1 mW) were applied to the heat absorbing element and the corresponding temperature of the resonator was recorded. A temperature sensitivity of the resonator to the input thermal power of 13.3 mK/µW was recorded. To
simulate the response time of the device, 1 µW power was applied to the heat absorbing element and the time domain temperature rises of the AlN resonator, air gap and heat absorber were recorded and shown in Figure 3-4 (b). A thermal time constant, \( \tau \), as low as 80 µs was achieved thanks to the overall small volume of the device (to reduce the thermal mass).

The proposed micromechanical resonant thermal detector was implemented with a 500nm thick AlN nano-plate resonator integrated with a nano-scale heat absorbing element separated by a 250nm air gap. To test the performance of the device, the heat absorbing element was implemented with a nano-hot plate (600nm thick SiO\(_2\) with 50nm thick Pt resistive heater) as the heat source. The micromechanical resonant thermal detector was fabricated using a microfabrication process based on what was previously demonstrated. The fabricated device is shown in Figure 3-3 (b).

The electrical response of the fabricated micromechanical resonant thermal detector was tested by an Agilent E5071C network analyzer after performing an open-short-load calibration. The measured admittance response versus frequency and the Butterworth-van Dyke (BVD) fitting are shown in Figure 3-5. The resonance frequency of the device was found to be 966.625 MHz. High device figure of merit \( (FOM = Q^*k_t^2 > 20) \) was achieved indicating that the implementation of the suspended nano-hot plate has no effect on the electromechanical performance of the AlN resonator, compared with conventional AlN contour-mode resonators. It is also worth noting that the motional resistance of the resonator is very close to 50 Ω, which enables the device to be easily interfaced with low power electronics [9].
Figure 3-4. FEM simulation of the thermal properties of the thermal detector: (a) Heat transfer efficiency between the heat absorber and resonator for different sizes of the air gap; (b) Temperature variation and thermal time constant for 1 μW input power for a 250 nm air gap device.
The Temperature Coefficient of Frequency (TCF) of the fabricated micromechanical resonant thermal detector was measured using a temperature controlled RF probe station, and found to be -32.5 ppm/K. To test the sensitivity of the device, different levels of input power were applied to the nano-hot plate and the corresponding resonance frequency of the device was recorded. The temperature rise of the AlN resonator was extracted from the frequency shift and measured temperature coefficient of frequency, shown in Figure 3-6. The sensitivity of frequency shift with respect to input power was calculated to be 0.3 ppm/µW (290 Hz/µW) and the temperature rise factor was extracted to be 9.2 mK/µW, which is close to the simulated value, 13.3 mK/µW, despite the slightly simplified 3D model of the device was built for the FEM simulation in COMSOL.
To examine the detection limit of the fabricated micromechanical resonant thermal detector, extremely low levels of square wave input power at low frequency (3 Hz) were applied to the heater. The transient response of the device was measured by exciting the thermal sensor at a single frequency, $f_c = 966.8$ MHz, for which the slope of admittance amplitude curve versus frequency is maximum, and monitoring the variation over time of the device admittance amplitude [60]. Figure 3-7 (a) shows that thermal power higher than 150 nW can be readily detected experimentally. To evaluate the Noise Equivalent Power (NEP) of the device, a root mean square (RMS) noise in 100 Hz bandwidth was experimentally measured to be 303 µdB (corresponding to a noise spectral density of 30.3 µdB/Hz$^{1/2}$) and a responsivity of 4633 dB/W was extracted from the measured TCF (-32.5 ppm/K), temperature rise factor (9.2 mK/µW) and the slope of the admittance curve at 966.8 MHz (0.01604 dB/KHz). A NEP of 6.5 nW/Hz$^{1/2}$ was extracted by dividing the measured noise spectral density by the responsivity.

Figure 3-6. Measured resonance frequency shift of the device to different levels of input power applied to the nano-hot plate and extracted temperature rise of the AlN resonator.
Figure 3-7. (a) Device admittance response (at 966.8 MHz) to different levels of square wave input power at 3 Hz to the heater; (b) Dynamic response of the device admittance amplitude (at 966.9 MHz) to an applied square wave power (14.5 µW) at 100 Hz to the heater. The inset shows the zoom-in device response from 15.5 ms to 17.5 ms, indicating a time constant of 350 µs.
The dynamic response of the fabricated micromechanical resonant thermal detector was tested by applying a 100 Hz square wave thermal power (amplitude 14.5 µW) to the heater. The device admittance amplitude (at 966.9 MHz) response to the square wave input power is shown in Figure 3-7 (b). The results indicate that a thermal time constant (63.2 % admittance change from power off to power on) of 350 µs was achieved (the inset in Figure 3-7 (b)). Despite the measured thermal time constant is higher than the simulated value (80 µs), due to the larger dimension of the fabricated air gap resulting from residual stress in the SiO₂ layer (Figure 3-3 (b)), it can be considered the smallest ever reported for MEMS resonant thermal detectors.

In summary, the demonstrated ultra-fast and high resolution thermal detector based on the AlN piezoelectric microelectromechanical resonator with an integrated suspended heat source verifies the concept of using AlN NPRs for thermal power detection and proves the potential capability for the implementation high performance uncooled IR thermal detectors based on the AlN NPRs technology.

3.4.2 1st Generation IR detector based on an AlN NPR

The first generation IR detector was proposed based on a 250 nm thick AlN NPR working at a high order lateral-extensional mode of vibration and coated directly with thin (100 nm thick) Silicon Nitride (Si₃N₄) IR absorber on top. The reason to choose thin Si₃N₄ film as IR absorber is that it can be easily deposited by chemical vapor deposition (CVD) process and it has been demonstrated as a broadband IR absorber with modest absorption [61, 62].
Figure 3-8 shows the 3D representation of the proposed AlN NPR based IR detector. The thermal properties: thermal time constant and temperature rise factor (thermal resistance) of the proposed AlN NPR IR detector were simulated by COMSOL Multiphysics. In the 3D Finite Element Method (FEM) simulation by COMSOL, the thermal conductivity and heat capacity of AlN were set to be 80 W/(m·K) and 740 J/(Kg·K), respectively, and other materials properties were set by default by COMSOL [57]. The 3D FEM simulated results are shown in Figure 3-9. A thermal time constant as fast as 1.3 ms was achieved, thanks to the overall reduced volume of the resonant structure (to reduce the thermal mass). The temperature rise factor (thermal resistance) of the AlN NPR was found to be 72.5 mK/µW, which guarantees the high sensitivity of the device.
Figure 3-9. 3D FEM simulation of the AlN NPR: (a) thermal time constant and (b) temperature rise factor. The inset in (b) shows the uniform temperature distribution across the AlN NPR.

The AlN nano-plate resonator was fabricated using a five-mask microfabrication process, as detailed in the previous section. The electrical performance of the fabricated AlN NPR integrated with thin Si$_3$N$_4$ IR absorber was tested by an Agilent E 5071C network analyzer after a short-open-load calibration on a standard substrate. The measured admittance amplitude and phase versus frequency and Butterworth-Van Dyke (BVD) model fitting are shown in Figure 3-10. The extracted mechanical quality factor $Q$
and electromechanical coupling coefficient $k_t^2$ are 1283 and 1.56%, respectively, which are comparable to the conventional 250 nm thick AlN contour-mode resonators [53]. Such high electromechanical performance of the device (FOM = $Q \cdot k_t^2 = 20$) guarantees the capability of the MEMS resonator to be connected to a CMOS oscillator as direct frequency readout.

![Figure 3-10](image)

Figure 3-10. Measured admittance and phase versus frequency of the fabricated AlN NPR and Butterworth-Van Dyke (BVD) model fitting.

The temperature coefficient of frequency (TCF) of the fabricated AlN NPRs was measured by a temperature controlled RF probe-station. The measured TCF of the fabricated AlN NPR with Si$_3$N$_4$ thin film absorber is shown in Figure 3-11. The TCF of the AlN NPR with Si$_3$N$_4$ absorber was found to be -35 ppm/K, which is the typical value for AlN contour-mode resonators [58]. Based on the measured TCF (-35 ppm/K) and simulated thermal resistance (72.5 mK/µW), the responsivity of the IR detector was calculated to be 310 Hz/µW.
Figure 3-11. Measured temperature coefficient of frequency (TCF) of the fabricated AlN NPR with 100 nm thick Si$_3$N$_4$ film.

The fabricated AlN NPR was directly wire bonded to the feedback loop of a CMOS inverting amplifier integrated circuit (IC) using a K&S 4523 wedge bonder. The fabricated and wire-bonded MEMS and CMOS dies are shown in Figure 3-12. The CMOS readout circuit consists of a Pierce oscillator implemented by means of a CMOS inverter biased in its active region. Transistors $M_1$ and $M_2$ form the CMOS inverting amplifier while transistor $M_3$ acts as a large resistor to provide biasing of $M_1$ and $M_2$ in the active region.
Figure 3-12. (a) The fabricated AlN NPR MEMS chip was wire bonded to the CMOS die; (b) Scanning Electron Microscope (SEM) image of the fabricated AlN NPR; (c) Schematic of the CMOS oscillator as the frequency readout.

The noise performance of the fabricated AlN NPR MEMS-CMOS oscillator was evaluated by measuring the Allan Deviation using an Agilent 53230A frequency counter. The measured allan deviation versus measurement time is shown in Figure 3-13. Allan deviation is a measurement of the noise-induced frequency fluctuation of an oscillator [63]. A minimum Allan Deviation of 3.5 Hz was measured at a measurement time of 100 ms (measurement bandwidth of 10 Hz), indicating a noise spectral density of 1.1 Hz/Hz$^{1/2}$ at 10 Hz bandwidth. The Noise Equivalent Power (NEP) of the IR detector was estimated to be $\sim$3.5 nW/Hz$^{1/2}$ by dividing the measured noise spectral density by the responsivity of the device (310 Hz/μW).
Figure 3-13. Measured Allan Deviation of the AlN NPRs based MEMS-CMOS oscillator.

The IR response of the fabricated AlN NPR MEMS-CMOS oscillator based IR detector was characterized by a Cool Red Infrared light source from Ocean Optics [64], with a radiation spectrum from 0.5 µm to 12 µm and an Agilent 53230A frequency counter. The device was placed 10 cm away from the IR source in air and the output of the source was modulated at 0.5 Hz by an MC 2000 optical chopper with an MC1F2 blade [65]. The measured IR response of the device (output frequency of the oscillator versus time) is shown in Figure 3-14. It shows that the resonance frequency decreases by ~ 300 Hz when the IR radiation is on, which corresponds to an absorbed IR radiation power of ~ 1 µW (given the extracted device responsivity of 310 Hz/µW).
The much miniaturized sensor size makes the proposed IR detector a perfect candidate for the implementation of high performance FPA based IR imaging systems. One of the most important metrics for focal plane arrays is the noise equivalent temperature difference (NETD). It is the temperature difference of the scene required to produce a unity single to noise ratio. According to (3-8), assuming $F = 1$ (by using a focusing lens with equal focal length and entrance pupil), $\eta = 1$ (by using blackbody absorber such as carbon nanotube forest [66]), $\varepsilon = 1$, and the radiant exitance of 2.62 W/K·m² for the wavelength from 8 to 14 µm [67], the calculated NETD is 1.44 K.

Finally, the geometric parameters and performance metrics of the 1st generation uncooled resonant IR detector based on the AlN NPR MEMS-CMOS oscillator are summarized in Table II.
Table II. Summary of the geometry and performance parameters of the 1\textsuperscript{st} generation uncooled resonant IR detector based on the AlN NPR MEMS-CMOS oscillator.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area</td>
<td>200 × 75 × 0.25</td>
<td>μm × μm × μm</td>
</tr>
<tr>
<td>Anchor size</td>
<td>25 × 10 × 0.35</td>
<td>μm × μm × μm</td>
</tr>
<tr>
<td>frequency</td>
<td>122.6</td>
<td>MHz</td>
</tr>
<tr>
<td>Quality factor</td>
<td>1283</td>
<td>-</td>
</tr>
<tr>
<td>Minimum noise</td>
<td>3.5</td>
<td>Hz</td>
</tr>
<tr>
<td>Thermal resistance</td>
<td>7.25 × 10\textsuperscript{4}</td>
<td>K/W</td>
</tr>
<tr>
<td>TCF</td>
<td>-35</td>
<td>ppm/K</td>
</tr>
<tr>
<td>Responsivity</td>
<td>310</td>
<td>Hz/μW</td>
</tr>
<tr>
<td>Time constant</td>
<td>1.3</td>
<td>ms</td>
</tr>
<tr>
<td>NEP</td>
<td>3.5</td>
<td>nW/Hz\textsuperscript{1/2}</td>
</tr>
<tr>
<td>NETD</td>
<td>1.44</td>
<td>K</td>
</tr>
<tr>
<td>Power consumption</td>
<td>2.3</td>
<td>mW</td>
</tr>
</tbody>
</table>

3.4.3 2\textsuperscript{nd} Generation IR detectors based on AlN NPRs with Pt anchors

The 1\textsuperscript{st} generation ulcooled IR detectors based on the AlN NPRs MEMS-CMOS oscillators shows promising performance and IR detecting capability. To further improve
the device performance, in terms of reducing both the NEP and NETD, thus improving the resolution, a second generation device prototype is introduced in this section.

![Diagram of AlN nano-plate resonator with fully metallic (Pt) anchors](image)

Figure 3-15. 3-dimensional representation of the AlN nano-plate resonator with fully metallic (Pt) anchors to support the freestanding resonant body.

Equation (3-6) shows that the noise equivalent power is inversely proportional to the device thermal resistance. Low NEP, thus high resolution, of the IR detector can be achieved by maximizing the thermal resistance, $R_{th}$. By equation (3-2) it shows that the thermal resistance of the resonant detector is determined by the tethers used to support the freestanding resonant body. Therefore, the thermal resistance of the device can be maximized by engineering the anchors of the AlN resonator. According to this consideration, a new device concept, based on the use of fully metallic tethers to support a nano-plate piezoelectric resonator (Figure 3-15), is introduced in this section as an innovative design solution to maximize the thermal resistance and minimize the thermal mass, in order to achieve high resolution and fast response of the uncooled resonant IR detector. Such innovative device concept results in a unique set of application enabling features: (a) high sensitivity, due to excellent thermal isolation from the heat sink (enabled by the large thermal resistance associated with the fully metallic anchors); (b) ultra-low noise performance, due to the intrinsic high $Q$ of the resonant device (enabled
by the effective confinement of acoustic energy in the resonant body of the device by using fully metallic anchors); (c) ease of readout, due to the excellent piezoelectric transduction properties of AlN at micro and nano scale which enables the use of a low power and self-sustained CMOS oscillator as direct frequency readout (differently from gallium nitride and quartz, ultra-thin and high quality AlN film can be deposited directly on Silicon substrates by low-temperature sputtering deposition and processed by post-CMOS compatible process [22]).

The core of the proposed resonant uncooled thermal detector is an AlN piezoelectric resonant nano-plate working at a higher order contour-extensional mode of vibration employing a lateral field excitation scheme [53], completely released from the substrate and supported by two Platinum (Pt) anchors. Figure 3-15 shows the 3-dimensional representation of the proposed AlN nano-plate resonator with fully metallic anchors: the freestanding vibrating body consists of a 500 nm thick AlN piezoelectric layer sandwiched between a 50 nm thick gold (Au) film as a top electrically floating electrode and a 100 nm thick Pt bottom inter-digital transducer (IDT); two Pt tethers (100 nm thick, 3.5 µm wide and 20 µm long) are employed to support the piezoelectric resonant body and provide electrical connection to it.
Figure 3-16. Measured admittance curve versus frequency and modified Butterworth-Van Dyke (MBVD) model fitting of the fabricated AlN resonator with Pt anchors.

The proposed AlN nano-plate resonant IR detector with Pt anchors was fabricated using a 4-mask post-CMOS compatible microfabrication process, as detailed in the previous section. The electrical performance of the fabricated AlN nano-plate resonator with Pt anchors was measured by an Agilent E5071C network analyzer after performing an open-short-load calibration on a standard substrate. The measured resonance frequency of the device was 273.6 MHz (Figure 3-16). The mechanical quality factor $Q$, electromechanical coupling coefficient $k_t^2$, and motional resistance $R_m$ were extracted by modified Butterworth-Van Dyke (MBVD) model fitting. High mechanical quality factor, $Q$ of 2119, was achieved, which is comparable to the best recorded $Q$ of conventional AlN contour mode resonators [68], indicating the effective confinement of acoustic energy within the resonant body by using Pt anchors. The achieved high electromechanical performance ($Q_m = 2119$ and $k_t^2 = 1.55\%$) of the resonator is crucial
for the implementation of low noise thus high resolution and low power uncooled resonant IR detector.

![Graph showing temperature coefficient of frequency (TCF)](image)

Figure 3-17. Measured temperature coefficient of frequency (TCF) of the fabricated AlN resonator with Pt anchors.

The resonance frequency sensitivity of the resonator to temperature was characterized by measuring the resonator’s temperature coefficient of frequency (TCF) using a temperature controlled RF probe station (Figure 3-17). The measured TCF was found to be -8.21 KHz/K (-30 ppm/K), which is comparable with typical TCF values for 500 nm thick AlN contour-mode resonators [18].
Figure 3-18. Finite element method (FEM) simulation of the temperature of the AlN resonator in time domain, showing a thermal time constant of 6 ms.

The thermal properties of the AlN nano-plate resonator with Pt anchors were estimated by 3D finite element method (FEM) simulation using COMSOL Multiphysics. The thermal resistance of the device was evaluated by applying different levels of power from 100 nW to 500 nW, simulating the absorbed IR radiation power, to the resonator and monitoring the corresponding temperature rise of the AlN nano-plate. The thermal resistance of the IR detector was extracted to be $4.2 \times 10^5$ K/W, which is about one order of magnitude higher than previously demonstrated resonant IR detectors based on conventional AlN nano-plate resonators [57, 69], thanks to the employing of fully metallic anchors to maximize thermal isolation of the resonant body from the heat sink. The thermal time constant of the device was estimated by simulating the transient temperature response of the AlN nano-plate to different levels of absorbed IR power. The simulation result in Figure 3-18 gives a thermal time constant of 6 ms. The temperature
distribution across the AlN resonant body was also simulated by applying an input power of 100 nW to the resonator. A maximum temperature rise of ~41.84 mK at the center of the resonant nano-plate and a maximum temperature difference of ~1.35 mK across the length of the resonator were recorded, translating into a relative temperature variation of only ~3.2% (Figure 3-19). The achievement of such uniform temperature distribution across the AlN resonant body was enabled by the large thermal resistance of the anchors and the relatively low thermal resistance of the AlN nano-plate. The responsivity of the device can be calculated by multiplying the measured TCF (8.21 KHz/K) and simulated thermal resistance ($4.2 \times 10^5$ K/W), and found to be ~3.4 Hz/nW, which is two orders of magnitude higher than quartz (11.4 Hz/µW) [19], and three orders of magnitude higher than gallium nitride (1.7 Hz/µW) [20] based piezoelectric resonant IR detectors.

Figure 3-19. Simulated temperature profile across the AlN nano-plate resonator. A thermal power of 100 nW was applied to the resonator.
The fabricated AlN nano-plate resonator with Pt anchors was shown in the scanning electron microscope (SEM) images in Figure 3-20. The active sensing area is defined by the width, \( W \), and length, \( L \), of the resonator: \( 70 \ \mu\text{m} \times 144 \ \mu\text{m} \). The CMOS IC chip, which consists of an inverting amplifier and a 50 Ω buffer stage, was fabricated using the ON Semiconductor 0.5 µm CMOS process. The fabricated AlN MEMS resonator and CMOS IC chip were mounted on a custom designed printed circuit board (PCB) and electrically connected by wire-bonding (Figure 3-20).

Figure 3-20. Fabricated uncooled resonant IR detector: (a) the AlN MEMS resonator was directly wire-bonded to the CMOS chip; (b) schematic of the CMOS inverting amplifier circuit; (c)-(d) the dimension of the AlN resonator: \( L = 144 \ \mu\text{m}, \ W = 70 \ \mu\text{m}, \ W_0 = 14 \ \mu\text{m}, \)
$L_A = 20 \, \mu m$ and $W_A = 3.5 \, \mu m$. The thickness of the AlN plate and Pt anchor is 500 nm and 100 nm, respectively.

Figure 3-21. Measured (a) output spectrum and (b) allan deviation of the AlN MEMS-CMOS oscillator.

The bias voltage applied to the CMOS inverter was 1.8 V and the corresponding current was 0.6 mA, translating to a power consumption of 1 mW. The output spectrum of the oscillator was measured by an Agilent N9010A signal analyzer and shown in
Figure 3-21. The output frequency was found to be 273.9 MHz, and the corresponding output power was -5.64 dBm. The noise performance of the oscillator was characterized by measuring the Allan deviation [63], which is a measure of noise-induced frequency fluctuation, using an Agilent 53230A frequency counter. A minimum Allan deviation of 7.5 Hz was recorded at a measurement time of 30 ms (measurement bandwidth of 33 Hz), translating to a noise-induced frequency fluctuation of 31.5 ppb and noise spectral density of 1.3 Hz/Hz$^{1/2}$. The NEP of the IR detector can be calculated by dividing the measured noise spectral density (1.3 Hz/Hz$^{1/2}$) by the responsivity (3.4 Hz/nW), and found to be 382 pW/Hz$^{1/2}$ in a 33 Hz measurement bandwidth, which is a 9× improvement from the 1st generation device.

Figure 3-22. Measured frequency response of the oscillator to the IR radiation from the QCL mid IR source. The modulation frequency of the IR radiation set by the optical chopper was 1.3 Hz. The gate time of the frequency counter was set to 30 ms, at which
the allan deviation of the oscillator is minimum. The inset shows the measured thermal time constant of the IR detector, when the gate time was set to 1 ms.

The frequency response of the oscillator to IR radiation was characterized by a quantum cascaded laser (QCL) from EOS photonics. The QCL is a mid IR source with maximum IR power centered at ~ 5 µm. A Zinc Selenide (ZnSe) focusing lens (diameter of 25.4 mm and focal length of 100 mm) with transmission of ~ 70% from 0.8 µm to 12 µm was used to focus the IR light from the QCL to the IR detector. An optical chopper was placed between the QCL and focusing lens to modulate the IR light. The output frequency of the AlN MEMS-CMOS oscillator was recorded by an Agilent 53230A frequency counter. The incident IR spot size and power density were characterized by a S302C thermal power sensor (the sensing area of the thermal sensor is Ø12mm with a Ø9.3 mm aperture) and PM100D optical power and energy meter from Thorlabs. The IR radiation from the QCL was focused by the ZnSe lens and detected by the thermal power sensor, which was placed 100 mm away from the lens (at the focal point of the lens). The spot size of the IR radiation at the focusing point of the IR lens was found to be ~ 3 mm. Considering the sensing area of the fabricated AlN nano-plate resonant IR detector ($L \times W = 144 \, \mu m \times 70 \, \mu m$), the actual amount of power at the IR detector when it is placed at the focal point of the ZnSe IR lens was extracted to be ~ 140 µW.

To measure the frequency response of the fabricated AlN MEMS-CMOS oscillator, it was placed at the focal point of the focusing lens, and the QCL was placed also 150 mm away from the lens. The measured frequency response of the oscillator to the incident IR radiation from the QCL is shown in Figure 3-22. A frequency down shift of 9.5 KHz was recorded when the IR radiation was switched on, translating to the
absorbed IR power of 2.8 µW (considering the responsivity of 3.4 Hz/nW). Based on the estimated delivered power at the sensing area of the detector (~140 µW), the IR absorption of the resonant structure can be calculated to be ~2%. Considering the measured TCF of the resonator, the temperature rise of the device can be extracted from the frequency shift, and found to be 1.16 °C. The low absorption (~98% of the incident IR radiation was reflected by the 50 nm Au plate and the rest ~2% was dissipated by the resonant structure due to material loss), is not ideal for the implementation of high performance thermal detectors. However, it is worth noting that broadband IR absorbing materials with near unity absorption have been demonstrated [70, 71], and can be potentially integrated with the proposed IR detector to further improve the device performance. More recently, frequency selective IR/THz absorber based on plasmonic metamaterial structures [72-75] have been demonstrated, which can be integrated with the proposed IR detecting platform based on the AlN resonant technology for the implementation of high performance, miniaturized and low cost IR/THz spectrometers.

The response time of the IR detector was experimentally measured by reducing the measurement time from 30 ms to 1 ms (increasing the measurement bandwidth from 33 Hz to 1 KHz). The measurement result shown in the inset of Figure 3-22 gives a response time of ~5 ms, which matches the simulated value of ~6 ms. Such fast response of the device allows the frame rate of 50 Hz operation in FPA based IR imaging systems.
Figure 3-23. Calculated NETD of the IR detector as a function of the thermal resistance ($R_{th}$ values higher than $10^7$ K/W are theoretically prohibited by the radiation limit).

The normalized detectivity, $D^*$, of the fabricated IR detector was extracted according to (3-7), and found to be $2.6 \times 10^7$ cm·Hz$^{1/2}$/W. The high resolution ($\sim 382$ pW/Hz$^{1/2}$) and low thermal time constant ($\sim 5$ ms) make the proposed IR detector a perfect candidate for the implementation of high performance FPA based IR imaging systems. One of the most important metrics for focal plane arrays is the noise equivalent temperature difference (NETD). It is the temperature difference of the scene required to produce a unity single to noise ratio. According to (3-8), assuming $F = 1$ (by using a focusing lens with equal focal length and entrance pupil), $\eta = 1$ (by using blackbody absorber such as carbon nanotube forest [66]), $\varepsilon = 1$, and the radiant exitance of 2.62 W/K·m$^2$ for the wavelength from 8 to 14 µm [67], the calculated NETD is 411 mK, which is a 3.5× improvement from the 1st generation device. To reduce the NETD, the thermal resistance of the AlN resonator needs to be further increased by scaling the
metallic anchors. Figure 3-23 illustrates the NETD dependence on thermal resistance of the device. It indicates that with the current device prototype, NETD values below 100 mK (benchmark of the nowadays commercial IR cameras) can be achieved by further increasing the thermal resistance of the device by 4 times (from $\sim 4.2 \times 10^5$ to $1.7 \times 10^6$ K/W). However, increasing the thermal resistance by further scaling the metal anchors sacrifices the response time of the thermal detector. To maintain the thermal time constant of the device while engineering the metal anchors, the thermal mass of the detector needs to be scaled at the same time. This can be achieved to take the advantage of the unique scaling capabilities of AlN technology (ultra-thin, 10s nm thick high quality AlN film can be deposited by sputtering process [76]) to scale the AlN resonator, making it possible to achieve low NETD while maintaining the fast response of the IR detector.

Finally, the geometric parameters and performance metrics of the 2nd uncooled resonant IR detector based on the AlN NPR with Pt anchors MEMS-CMOS oscillator are summarized in Table III.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area</td>
<td>$144 \times 70 \times 0.5$</td>
<td>$\mu m \times \mu m \times \mu m$</td>
</tr>
<tr>
<td>Anchor size</td>
<td>$20 \times 3.5 \times 0.1$</td>
<td>$\mu m \times \mu m \times \mu m$</td>
</tr>
<tr>
<td>frequency</td>
<td>273.9</td>
<td>MHz</td>
</tr>
<tr>
<td>Quality factor</td>
<td>2119</td>
<td>-</td>
</tr>
<tr>
<td>Minimum noise</td>
<td>7.5</td>
<td>Hz</td>
</tr>
<tr>
<td>Thermal resistance</td>
<td>$4.2 \times 10^5$</td>
<td>K/W</td>
</tr>
</tbody>
</table>
### 3.4.4 3rd Generation spectrally selective IR detectors based on plasmonic piezoelectric metamaterial

Despite the demonstrated potential of the AlN nano-plate resonator technology for the development of uncooled broadband IR detectors, high performance and spectrally selective MEMS resonant IR detectors have not been demonstrated so far, due to the lack of naturally occurring materials with strong absorption coefficients over ultra-thin thicknesses that are also compatible with conventional transduction and microfabrication techniques.

In this section, a stepping stone towards the development of high performance and spectrally selective MEMS resonant IR detectors is set by demonstrating an ultra-thin (650 nm) Piezoelectric Resonant Metamaterial (PRM). Sensing and actuation of a high frequency (161.4 MHz) bulk acoustic mode of vibration in a free-standing ultra-thin piezoelectric metamaterial is demonstrated for the first time and exploited for the implementation of a novel MEMS resonator with a unique combination of optical and
electromechanical properties. The use of an ultra-thin piezoelectric metamaterial to form the resonant body of the device eliminates the electromechanical loading effect associated with the integration of an IR absorber (guaranteeing high electromechanical performance: quality factor, $Q \approx 1116$ and electromechanical coupling coefficient, $k_t^2 \approx 1.0\%$) and enables strong and spectrally selective absorption of LWIR radiation in an ultra-low volume device (due to the properly engineered IR absorption properties of the piezoelectric metamaterial forming the resonant body of the device); resulting in a fast (thermal time constant $\approx 440 \, \mu$s) and high resolution (measured noise equivalent power $\approx 2.1 \, \text{nW/Hz}^{1/2}$ at 100 Hz bandwidth) LWIR detector prototype with a $\approx 80\%$ absorption for an optimized spectral wavelength of 8.8 $\mu$m with Full Width at Half Maximum (FWHM) of 1.5 $\mu$m. The demonstrated PRM detector technology marks a milestone towards the implementation of a new class of high performance, miniaturized and low power IR spectroscopy and multi-spectral imaging systems.

Figure 3-24. Overview of the plasmonic piezoelectric nanomechanical resonant infrared detector. (a) Mock-up view: an AlN nano-plate is sandwiched between a bottom metallic
interdigital electrode and a top nanoplasmonic metasurface. The incident IR radiation is selectively absorbed by the plasmonic metasurface and heats up the resonator, shifting its resonance frequency from $f_0$ to $f'$ due to the temperature dependence of its resonance frequency. (b) SEM images of the fabricated resonator, metallic anchors, and nanoplasmonic metasurface. The dimensions of the resonator are: $L = 200$ μm, $W = 75$ μm, $W_0 = 25$ μm (19 μm + 6 μm), $L_A = 20$ μm, $W_A = 6.5$ μm. The dimensions of the unit cell of the plasmonic metasurface are: $a = 1635$ nm, $b = 310$ nm.

The proposed plasmonic NEMS piezoelectric resonator, illustrated in Figure 3-24a, is composed of an AlN piezoelectric nano-plate (500 nm thick) sandwiched between two metal layers. The bottom layer (100 nm thick platinum) is patterned to form an interdigital transducer (IDT) used to actuate and sense a high order lateral-extensional mode of vibration in the nano-plate [53]; the top electrically floating layer (50 nm thick gold) is patterned with the goal of confining the electric field induced by the bottom IDT across the piezoelectric nano-plate, while simultaneously enabling absorption of IR radiation in the ultrathin piezoelectric nano-plate thanks to suitably tailored plasmonic resonances. The nano-plate is released from the silicon substrate to freely vibrate, and is mechanically supported by two ultrathin metallic tethers (100 nm thick, 6.5 μm wide and 20 μm long) which also provide electrical contact.

As we show in the following, the proposed plasmonic nanomechanical resonant structure provides all the fundamental features necessary for the implementation of uncooled IR detectors with unprecedented performance. First, we need to maximize its absorption within the spectrum of interest: to this end, an array of subwavelength patches (Figure 3-24b) is patterned within the top metal electrode of the device. Proper patterning
of such plasmonic nanostructures in the top metal layer allows the whole device to behave as a spectrally selective IR ultrathin absorber [77], significantly enhancing the electromagnetic field concentration within the AlN dielectric. While a single array of subwavelength patches is fundamentally bound to absorb no more than half of the impinging radiation for symmetry constraints [78], the presence of the piezoelectric nano-plate allows us to go beyond this limit, and absorb a large portion of IR energy at resonance. At the same time, we need to achieve maximum thermal isolation of the resonant body from the heat sink, which is ensured by minimizing the thickness of the tethers used to support the nano-plate. The anchors of piezoelectric MEMS/NEMS resonators are conventionally composed of a thick and thermally conductive piezoelectric layer, directly patterned on the same layer forming the vibrating body of the resonator [53], and a thin metal layer employed to route the electrical signal to the actuation electrode integrated in the body of the resonator. On the contrary, here the relatively thick piezoelectric material is completely removed from the anchors, minimizing their thicknesses (ultimately limited by the need of a thin metal layer for electrical routing), resulting in a resonant thermal detector with dramatically enhanced responsivity (0.68 Hz/nW). Third, we need to achieve also a low thermal time constant (440 μs), obtained by exploiting the unique properties of high-quality ultrathin AlN films on a Si substrate deposited with a low temperature sputtering process, enabling low-volume piezoelectric nano-plate resonant structures with a significantly reduced thermal mass. Despite the resonator volume scaling, we are also able to obtain low-noise performance, thanks to the piezoelectric transduction properties of AlN ultrathin films, which enable efficient on-chip piezoelectric actuation and sensing of a high Q>1000, and high-frequency bulk
vibration modes in a freestanding nano-plate, leading to resonators with very low noise spectral density (~1.46 Hz/Hz$^{1/2}$ at 100 Hz measurement bandwidth).

Figure 3-25. (a) SEM image of nanoplasmonic piezoelectric resonators (supported by conventional AlN/Pt anchors) with different plasmonic nanostructures and metal planes coverage; (b) 3D finite element method (FEM) simulation and experimental verification of the electromechanical coupling coefficient ($k_r^2$) dependence on the metal plane coverage; (c) Electrical performance of the resonators with different metal plane coverage; (d) FTIR measured absorption of the resonators with different metal plane coverage.
The spectrally selective plasmonic resonant NEMS structure consists of two functional parts defined by the geometry of the top metal layer: a central section in which a solid top metal plane is employed to effectively confine the electric field induced by the bottom IDT across the piezoelectric nano-plate to achieve efficient piezoelectric transduction of the lateral-extensional mode of vibration in the nano-plate, and two sections in which plasmonic nanostructures are properly patterned in the top metal layer of the structure enabling resonant absorption of IR radiation in the ultrathin piezoelectric vibrating nano-plate. A trade-off between the relative sizes of the two functional parts (i.e. percentages of the nano-plate surface area covered by the plasmonic nanostructures and the solid metal plane) needs to be considered in order to maximize absorption while maintaining sufficiently high electromechanical transduction efficiency ($k_t^2 \sim 1\%$). According to this consideration, the design of the nanoplasmonic resonator was optimized by 3D FEM simulations and verified experimentally. The electromechanical coupling coefficient values of nano-plate resonators with different coverages of the top solid metal plate were simulated using 3D COMSOL multiphysics, and compared with the experimentally extracted $k_t^2$ values of three fabricated nanoplasmonic piezoelectric nano-plate resonators with different partial coverages of the solid metal plate (Figure 3-25a and b). The three nanoplasmonic resonators were tested in a RF probe station and their electrical admittances versus frequency were measured using a vector network analyzer. The $k_t^2$ values, for all the different configurations, were extracted by MBVD model fitting of the measured admittance amplitude versus frequency curves.

Despite the difference in absolute values due to imperfections in the model and material coefficients used in the simulation, the experimentally recorded variations of $k_t^2$,
for different coverages of the top metal plate, follow the same trend achieved by FEM simulations. The results of this combined FEM analysis and experimental characterization indicate that a coverage of the solid metal plate as low as ~20% (~80% of the nano-plate surface covered by plasmonic nanostructures) is sufficient to maintain a $k_r^2 \sim 1\%$. The IR absorption spectra of the three fabricated nanoplasmonic resonators were also characterized. The FTIR measurements indicate that high IR absorption (> 80%) can be achieved if the plasmonic nanostructures cover ~ 80% of the nano-plate top surface (Figure 3-25c and d). Following these results, the coverage of the plasmonic nanostructures on the top metal layer of the plasmonic piezoelectric NEMS resonator prototype discussed in the main text was set to 80% given the demonstrated capability of achieving high absorption coefficient while maintaining high electromechanical transduction efficiency when this configuration is employed.

Figure 3-26. Transmission line model of the piezoelectric resonator: a normally incident TEM wave impinges on the structure shown in Figure 3-24. The outer transmission line sections represent the free-space, $Z_{MTS}$ is the surface impedance of the array of gold patches (metasurface), and the inner transmission line section takes into account the AlN dielectric and the ground platinum layer, respectively. Each section is characterized by its characteristic impedance $Z$ and propagation constant $\beta$.
Thanks to the structure symmetry and assuming a continuous platinum layer beneath the AlN, the analysis of a single unit-cell of the metasurface suffices to investigate the electromagnetic behavior of the whole device. This analysis is carried out using the equivalent transmission line of Figure 3-26. This circuit is totally rigorous [79, 80], i.e. exactly equivalent to solving Maxwell’s equations, assuming that i) a TEM wave is normally impinging on the resonator and ii) the operation frequency is well below the cut-off frequency of the higher order modes excited in the metasurface. Note that these two conditions are indeed fulfilled in this case.

The characteristic impedance and propagation constant of the different transmission line sections involved in the model are

\[
Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \quad Z_{AlN} = \sqrt{\frac{\mu_0}{\epsilon_{\epsilon_{AlN}}}} \quad Z_{Pt} = \sqrt{\frac{\mu_0}{\epsilon_{\epsilon_{Pt}}}} \quad \beta_0 = \frac{\omega}{c} \quad \beta_{AlN} = \frac{\omega}{c} \sqrt{\epsilon_{AlN}} \quad \beta_{Pt} = \frac{\omega}{c} \sqrt{\epsilon_{Pt}}
\]  

(3-10)

where the subscripts “0”, “AlN” and “Pt” denote free-space, aluminum nitrate dielectric, and platinum, respectively, ‘c’ is the speed of light, \( \omega \) is the radial frequency and \( \epsilon \) is permittivity, respectively. In addition, the platinum layer is modelled following a simple Drude model

\[
\epsilon_{\mu} = 1 - \frac{\omega_p^2}{\omega^2 + j\omega \tau^{-1}}
\]  

(3-11)

with plasma frequency \( \omega_p = 7.88 \cdot 10^{15} \text{rad/s} \) and relaxation time \( \tau = 7.8 f_s \) [81].

The electromagnetic model of the array of gold patches is very challenging and there are no closed-form expressions available for a general case. However, in case of electrically small unit-cells (i.e. \( a + b \ll \lambda_0 \), being \( \lambda_0 \) the operating wavelength) and
densely packed planar patches \((b \ll a)\), the surface impedance of the array of gold patches can be approximated by [79]

\[
Z_{MTS} = \frac{a + b}{a \sigma_{Au}} - j \frac{\pi}{2 \omega \varepsilon_{eff} (a + b) \log \left( \csc \left( \frac{\pi b}{2a + b} \right) \right)}
\]

(3-12)

where \(\sigma_{Au}\) is the gold conductivity and \(\varepsilon_{eff} = (1 + \varepsilon_{AlN})/2\) is the effective permittivity surrounding the metasurface. We have numerically verified that eq. 3-12 provides accurate results in the specific metasurfaces under consideration. However, note that the near field created by the actual thickness of the gold patches \((\approx 50 \text{ nm})\) slightly decreases the effective distance between patches. This phenomenon, common in microwave and optics [82], is easily taken into account by using an effective separation distance \(b\) slightly lower than the physical one.

The proposed circuit is analyzed using an analytical transfer-matrix approach [82], thus providing the absorption coefficient of the resonator versus frequency. The metasurface employed to cover the AlN resonator is designed in two steps: i) the input impedance and absorption of the AlN slab grounded by the platinum layer are computed using the equivalent circuit of Figure 3-26 in the absence of the metasurface (i.e. \(Z_{MTS} \approx \infty\)), and ii) the dimensions of the unit-cell and patches of the metasurfaces are chosen with the help of eq. 3-11 and 3-12 aiming to match the input impedance of the structure to the free-space impedance at the operation frequency, therefore maximizing the absorption coefficient. Finally, the electromagnetic behavior of the designed structure is confirmed using the full-wave commercial software CST.
It is important to point out the good agreement between theory and measurement (Figure 3-27), especially taking into account that the fabricated device does not have a continuous Pt layer, but a patterned one (patterned IDT with a partial coverage of ~70%, which is needed to excite a 160 MHz contour-extensional mode of vibration in the plasmonic piezoelectric nano-plate). However, the influence of this pattern is limited because i) most of the unit cells – around 70% – are grounded by a continuous Pt layer, and ii) it basically introduces a small capacitance to the ultrathin platinum layer electromagnetic response. We have further verified with CST full-wave simulations that the influence of this pattern is negligible.

The patch and unit cell dimensions were chosen to provide a Fabry-Perot like resonance around 8.8μm. While a conventional longitudinal resonance would lead to a significant thickness, severely affecting the mechanical and thermal response of the resonator, in our design we tailored the plasmonic metasurface patterned on top of the grounded AlN nano-plate to have a large capacitive surface reactance \( x_r = \frac{1}{\omega C_r} \), under an \( e^{-\omega t} \) time convention. Stacked on top of a grounded slab, the dominant resonance is achieved when \( x_r = -Z_0 \tan(\beta d) \), where \( Z_0 \) and \( \beta \) are the characteristic impedance and propagation constant of the AlN substrate. It confirms that, by tailoring the surface reactance of the plasmonic metasurface to be largely capacitive, it is possible to induce an ultrathin Fabry-Perot resonance in the substrate.

In our device, the plasmonic nanostructures cover 80% of the top metal layer, as a trade-off between large absorption, achieved by coating the entire layer, and high electromechanical transduction efficiency, achieved by removing a portion of the
metasurface and replacing it with continuous metal. We achieved an electromechanical coupling coefficient, $k_t^2 \sim 1\%$. Figure 3-27 presents the predicted absorption with and without top subwavelength patches, highlighting how the metasurface can largely increase the absorption at resonance, despite the deeply subwavelength thickness of the device. Our measurements match significantly well the simulations.

![Figure 3-27](image)

Figure 3-27. Absorption properties of the proposed plasmonic nanomechanical resonator. (a) Simulated and measured (Fourier transform infrared, FTIR) absorption spectra of a 500 nm thick AlN slab grounded by a Pt layer (without plasmonic nanostructures). It shows two intrinsic absorption peaks, associated to AlN at 11.3 µm (888 cm$^{-1}$) and 15.5 µm (647 cm$^{-1}$) [83], and one at 4 µm associated to the resonant structure. (b) Simulated and measured (FTIR) absorption spectra of the fabricated plasmonic nanomechanical resonator. The dimensions of the Au patches which compose the metasurface are $a=1635$ nm and $b=310$ nm, and the thickness of the Au, AlN and Pt layers are 50nm, 500nm, and 100nm, respectively.
Figure 3-28. Measured temperature coefficient of frequency of the fabricated plasmonic piezoelectric NEMS resonator.

Based on this design, the proposed IR detector (Figure 3-24) was fabricated using a post-CMOS compatible microfabrication process involving a combination of photolithography (4 masks) and electron-beam lithography (1 step). The Fourier transform infrared (FTIR) absorption spectrum of the device was first measured showing that ~ 80% of the impinging optical power is absorbed at the desired spectral wavelength (Figure 3-27b), which validates the performance of the designed piezoelectric metasurface. By removing the plasmonic pattern from the device top electrode would lead to negligible absorption, confirming the uniqueness of the proposed design (Figure 3-27a). The resonator frequency sensitivity to temperature was characterized using a temperature controlled radio frequency (RF) probe station, obtaining TCF~23 ppm/K (Figure 3-28), which matches the typical TCF values recorded for 500 nm thick AlN contour-mode resonators [18]. The electromechanical performance of the resonator was characterized by measuring its admittance versus frequency (Figure 3-32a). A high Q =
1116 and electromechanical coupling coefficient $k_t^2 = 0.86\%$ were extracted by equivalent model fitting, demonstrating the unique advantages of the proposed design in terms of high electromechanical transduction efficiency and low loss.

The device thermal resistance, in air and at room temperature, was directly extracted from the measurement of the admittance amplitude-frequency (A-f) nonlinearity induced by self-heating [84]. The source of admittance A-f nonlinearities in AlN contour-mode MEMS resonators is attributed to the softening of the equivalent Young’s modulus due to self-heating effects. Therefore, the thermal resistance of the device can be experimentally extracted by measuring the A-f response of the resonator for different input IR powers, according to

$$R_{th} = \frac{\Delta f}{\Delta P_e \cdot (1 - \Gamma^2) \cdot k_{IF} \cdot TCF \cdot f_0}$$  \hspace{1cm} (3-13)$$

where $\Delta f$ is resonance frequency shift, $\Delta P_e$ is the input RF power to the resonator, $\Gamma = (Z - Z_0)/(Z + Z_0)$ is the reflection coefficient ($Z_0 = 50$ $\Omega$), $k_{IF}$ is a constant introduced to take into account the effect of the sampling speed of the network analyzer ($k_{IF} = 1$ for IF bandwidth of 100 Hz used in the measurement), TCF is the temperature coefficient of frequency, $f_0$ is the resonance frequency of the resonator. The thermal resistances of two devices, with same geometries but different anchors (Detector1 is with Pt anchors and Detector2 is with conventional AlN/Pt anchors) were extracted based on this method. The measured A-f response and extracted thermal resistance are shown in Figure 3-29 and listed in Table IV, respectively.

<p>| Table IV. Measured parameter values used for the extraction of thermal resistance. |</p>
<table>
<thead>
<tr>
<th></th>
<th>$\Delta P_c$ (mW)</th>
<th>$\Delta f$ (kHz)</th>
<th>$Z$ (Ω)</th>
<th>$\Gamma$</th>
<th>TCF (ppm/K)</th>
<th>$f_0$ (MHz)</th>
<th>$R_{th}$ (K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector1</td>
<td>0.1</td>
<td>3.6</td>
<td>785</td>
<td>0.880</td>
<td>23</td>
<td>161.4</td>
<td>4.3×10⁴</td>
</tr>
<tr>
<td>Detector2</td>
<td>0.1</td>
<td>1.9</td>
<td>745</td>
<td>0.875</td>
<td>23</td>
<td>169.9</td>
<td>2.1×10⁴</td>
</tr>
</tbody>
</table>

The mismatch between the FEM simulated results and the experimentally measured results is attributed to the heat conduction through air, as the experiment was conducted in air and FEM simulation did not include the contribution of heat transfer from air conduction (simulating the case of vacuum). Basically, the measured $R_{th}$ is a parallel combination of the thermal resistance related to the anchors of the resonator and the thermal resistance associated with the air between the resonator and the Silicon substrate, as illustrated in Figure 3-30. Based on the measured and simulated $R_{th}$, the $R_{Air}$ of the two devices can be extracted and found to be $5.3 \times 10^4$ K/W and $5.0 \times 10^4$ K/W, respectively. Considering the thermal conductivity of air at 1 atm, and the geometries of the resonator, the average air gap between the resonator and Si substrate can be extracted to be ~20 μm, which is reasonable for a typical XeF$_2$ isotropic etching of Si to completely release the resonator.
Figure 3-29. Measured frequency response of (a) the IR detector with Pt anchors and (b) a reference resonator with conventional AlN/Pt anchors for different input RF powers.

Figure 3-30. Equivalent thermal circuit of the IR detector with Pt anchors: $P_{in}$ is the input IR power, $T_{AlN}$ and $T_0$ are the temperature of the AlN resonator and heat sink (Si substrate), respectively. $R_{th\_anc}$ and $R_{th\_air}$ are the thermal resistance of the Pt anchors and air, respectively.

Figure 3-31. Thermal resistance associated to the anchors ($R_{th\_anchor}$) and the air gap ($R_{th\_air}$) and total thermal resistance ($R_{th\_tot}$, parallel combination of $R_{th\_anchor}$ and $R_{th\_air}$) for different thicknesses of the device anchors in air (a) and vacuum (1 mTorr) (b). The measured thermal resistances of Detector1 (with Pt anchors) and Detector2 (with
conventional AlN/Pt anchors) in air (a) and FEM simulated in vacuum (b) are marked in the respective graphs.

The thermal resistance of the IR detector is limited by the finite thermal resistance of the air gap between the resonator and Si substrate when it is tested in air. Figure 3-31 shows that the maximum thermal resistance of the IR detector in air at 1 atm (air thermal conductivity of 0.024 Wm\(^{-1}\)K\(^{-1}\)) is 5.4×10\(^4\) K/W for a Pt anchor thickness of 10 nm. However, the thermal resistance of the IR detector can be improved significantly by reducing the pressure of air, thus increasing its thermal resistance. Figure 3-31 shows the calculated thermal resistance in vacuum at 10 mTorr (air thermal conductivity reduced to ~1×10\(^{-4}\) Wm\(^{-1}\)K\(^{-1}\)). It indicates that the total thermal resistance of the IR detector is completely determined by the dimension of the anchor, eliminating the influence of the air conduction. The FEM simulated thermal resistance of 2.3×10\(^5\) K/W matches well with the calculated value (Figure 3-31). A maximum thermal resistance of the IR detector is predicted to be 1.7×10\(^6\) K/W for a Pt anchor thickness of 10 nm, which could potentially reduce the NEP to the order of ~pW/Hz\(^{1/2}\).

The response of the fabricated IR detector in the LWIR band was characterized using a 1500 K globar (2-16 μm emission) as an IR source. For the sake of comparison, the incoming IR radiation was also detected using a conventional AlN MEMS resonator with same frequency sensitivity to absorbed heat but without plasmonic pattern (hence non-enhanced IR absorptance). Thanks to its properly engineered optical properties, the piezoelectric plasmonic resonator showed four-fold enhanced responsivity (Figure 3-32b), despite its absorption band (full width at half maximum of 1.5 μm) being much narrower than the source. With a narrowband source at the frequency of interest, the responsivity
would be much larger. The smallest impinging optical power that can be detected was experimentally estimated by measuring the device responsivity, $R_s$, and noise spectral density, demonstrating a measured low noise equivalent power, NEP $\approx 2.1 \text{ nW/Hz}^{1/2}$ at the designed spectral wavelength (for which IR absorptance $\approx 80\%$). The NEP is arguably considered the most important performance metric for an infrared detector and the value measured for the realized proof of concept detector proposed here is already comparable to the best commercially available uncooled broad-band thermal detectors, while providing unique spectral selectivity in the LWIR band. The response time of the detector was also evaluated by measuring the attenuation of the device response when exposed to IR radiation modulated at increasingly faster rates, showing a low thermal time constant, $\tau \approx 440 \mu\text{s}$.

Importantly, even though the proposed resonator possesses a unique combination of efficient electromechanical transduction, strong and spectrally selective IR absorption capability and very low NEP, there is still plenty of room to improve the performance of these piezoelectric plasmonic NEMS devices. First, novel designs could be employed to improve the absorption of the piezoelectric metasurface to near unity [75]. Second, in order to reach the thermal fluctuation noise limit (Figure 3-32d), all the noise sources contributing to the generation of frequency fluctuations, such as the resonator flicker noise, random walk and drifts [85], need to be carefully investigated and mitigated. Moreover, the volume of the plasmonic piezoelectric resonator can be further reduced (for instance, by scaling the thickness of the piezoelectric nano-plate) and its design can be optimized -investigating optimal materials and innovative geometries for the device anchors in order to increase the thermal resistance up to $\approx 10^7 \text{ K/W}$, which is typical of
conventional microbolometers. As a result, we expect this technology to achieve NEP in the order of $\sim 1\text{pW/Hz}^{1/2}$ (Figure 3-32d), thus enabling the implementation of multi-spectral thermal imagers with noise equivalent temperature difference as low as $\sim 1\text{ mK}$.

Figure 3-32. (a) Measured admittance curve versus frequency and MBVD model fitting of the resonator for $Q_{IR} = 0$. (b) Measured response of the plasmonic piezoelectric resonator and a conventional AlN MEMS resonator to a modulated IR radiation emitted by a 1500 K globar (2 -16 $\mu$m broadband spectral range). (c) Measured frequency response of the detector. The 3db cut-off frequency, $f_{3db}$, was found to be 360 Hz, resulting in a time constant $\tau = 1/(2\pi f_{3db})$ of 440 $\mu$s. (d) NEP for different values of thermal resistance ($R_{th}$). The solid lines indicate the calculated NEP values associated
with each of the three fundamental noise contributions (as expressed in Eq. 3-4, 3-5, and 3-6), assuming: resonator area=200 μm × 75 μm, ε = 1, T₀ = 300 K, P₀ = 0 dBm, |TCF| = 30 ppm/K, Q = 2000. The individual data points indicate the measured NEP values of 4 fabricated AlN resonant plasmonic IR detectors using 4 different anchor designs (hence 4 different R₉ values) and the ones of other MEMS/NEMS IR detector technologies based on GaN (broadband) [20] and Quartz microresonators (broadband) [19], and a Si₃N₄ nanobeam (spectrally selective, static measurement using off-chip optical readout) [59].

Finally, the geometric parameters and performance metrics of the 3rd spectrally selective uncooled resonant IR detector based on the AlN plasmonic resonant metamaterial are summarized in Table V.

| Table V. Summary of the geometry and performance parameters of the 3rd generation spectrally selective uncooled resonant IR detector based on the AlN PRM. |
|-------------|-------------------|-------------------|
| Parameters  | Values            | Units             |
| Active area | 200 × 75 × 0.5    | μm × μm× μm       |
| Anchor size | 20 × 6.5 × 0.1    | μm × μm× μm       |
| frequency   | 161.4             | MHz               |
| Quality factor | 1116           | -                 |
| Minimum noise | 1.46             | Hz/Hz¹/²          |
| Thermal resistance | 2.3 × 10⁵  | K/W               |
| TCF         | -23               | ppm/K             |
| Responsivity | 0.68             | Hz/nW             |
| Time constant | 440              | μs                |
| NEP         | 2.1               | nW/Hz¹/²          |
3.4.5 Scaling of AlN nano plate resonant IR detectors

The demonstrated high performance AlN nano-plate resonant IR detectors are very suitable for the implementation of high performance and miniaturized IR imaging systems. Such IR imaging system is based on the combination of IR detector arrays for IR radiation sensing and electronic readouts for image generation and processing. A Focal Plane Array (FPA) refers to an assemblage of individual detector pixels located at the focal plane of an imaging system [30]. A schematic illustration of a typical IR FPA imaging system is shown in Figure 3-33. The thermal radiation from the object is focused by the optical system on to the FPA, where the IR detector array is located at the focal plane of the optics, the physical property change of the IR detecting pixels is converted to electrical signal by the CMOS readout and the corresponding thermal image is generated.

Figure 3-33. A schematic illustration of a typical IR FPA imaging system.

For high resolution FPA imaging systems based on MEMS thermal detectors, i.e. microbolometers, the typical pixel pitch is ranging from 25 µm to 50 µm, and the array format is between 80 × 60 to 1024 × 768. The characteristic size of the IR detectors based on the AlN NPRs in this work is now 200 × 75 µm², which is relatively larger compared
with the commercial ones and is not suitable for the implementation of large but compact IR detector arrays. Therefore, the scaling of AlN NPRs is crucial for the implementation of high resolution FPA imaging systems.

The criteria for scaling the AlN CMRs into super high frequency (SHF) range was previously proposed and experimentally demonstrated by Dr. Matteo Rinaldi [79]. The similar scaling rules can be applied for scaling the AlN NPRs into a small form factor. Specifically, as the lateral dimension of the AlN NPRs is reduced, the device static capacitance, $C_0$, can be decreased significantly. When $C_0$ decreases to the point that it is smaller than the parasitic capacitance of the Silicon substrate, the device output signal can be completely masked. Therefore, scaling of the AlN NPRs into a small form factor is constrained by the need of keeping $C_0$ higher than the parasitic capacitance. This can be potentially overcome by reducing the thickness of the AlN thin film, thanks to the unique scaling capabilities of AlN piezoelectric resonant technology (ultra-thin and high quality AlN can be directly deposited on Si substrate, and 50 nm think AlN nano-plate resonators were successfully demonstrated before [59]).

In this section, the preliminary study of AlN NPRs scaling (in both lateral and vertical dimensions) was conducted by continuously shrinking the areas of the AlN NPRs based on three different thicknesses of AlN thin films (100 nm, 250 nm, and 500 nm). The device scaling starts with an AlN NPR with the area of 68 $\mu$m $\times$ 60 $\mu$m, and totally 6 resonators with different areas were fabricated and tested (Figure 3-34). The measured data (Figure 3-35) show that for relatively large resonators, the $Q$ is higher for thicker AlN than that of thinner ones. The reason is related to the better quality of thicker AlN films. However, for extremely small resonators, the $Q$ is higher for the thinnest AlN. This
is due to the much enhanced capacitance of the resonator, while for thicker AlN resonators with smaller capacitance, the resonance is masked by the parasitic capacitance (~40 fF).

Figure 3-34. SEM images of the fabricated 6 AlN NPRs (the AlN thickness is 100 nm) with different areas (device # 3-15 was not functional due to failed lift-off).
Figure 3-35. Measured admittance of AlN resonators with three thicknesses (a-500 nm, b-250 nm, and c-100 nm) and different areas (reducing area from 3-11 to 3-16). The corresponding electromechanical performances are listed in the tables.

The device scaling is also studied with lower frequency devices (< 600 MHz) with narrower anchors, which are more desirable for the implementation of high responsivity (due to the high thermal resistance which is mainly determined by the size of the anchors) IR detectors. Three AlN resonators with the same area (30 μm × 30 μm) but different AlN thicknesses were fabricated and tested, shown in Figure 3-36. It clearly shows that with the much enhanced device static capacitance, the Q is significantly improved for thinner resonators. The scaled AlN resonator based on a 100 nm thick AlN thin film demonstrated here (Figure 3-36) is suitable for the implementation of high performance FPAs.

Figure 3-36. Measured electromechanical performance of three resonators with same area but different AlN thicknesses.
4. AlN RESONANT MAGNETOMETERS

4.1 Working Principle

The core of the proposed magnetic field sensor is a piezoelectric (AlN) / magnetostrictive (FeGaB) bilayer nano-plate resonator. Figure 4-1 shows the 3-dimensional representation of such magnetoelectric resonant heterostructure. The AlN piezoelectric layer is sandwiched between the top FeGaB magnetostrictive layer and bottom Pt inter-digital transducer (IDT). When an AC signal is applied to the bottom IDT the top FeGaB electrode acts to confine the electric field across the thickness of the device and a high order contour-extensional mode of vibration is excited through the equivalent $d_{31}$ piezoelectric coefficient of AlN [53]. The resonance frequency of the resonator is determined by both the material properties (Young’s Modulus and density) and device geometry. When the AlN/FeGaB resonant nano-plate is exposed to an external magnetic field, $H$, the equivalent Young’s modulus [58] of the structure changes due to the magnetostrictive contribution to strain in a magnetic field associated with the FeGaB layer (delta-E effect [55]). Such magnetic field induced variation in Young’s modulus translates in a shift in the device resonance frequency (4-1).
Figure 4-1. 3D schematic of the AlN/FeGaB nano-plate resonator: \( W_0 \) is the pitch of the bottom inter-digital transducer; \( T_A \) and \( T_M \) are the thickness of the AlN and FeGaB films, respectively; \( W \) and \( L \) are the width and length of the resonant nano-plate, respectively. The 2D simulated lateral-extensional mode of vibration (total displacement) is superimposed to the AlN film.

The AlN/FeGaB nano-plate resonator is directly connected in the feedback loop of a sustaining CMOS amplifier, forming a magnetoelectric MEMS-CMOS frequency source whose output frequency is highly sensitive to external magnetic field (Figure 4-2). As the output frequency, \( f_0 \), of the AlN/FeGaB MEMS-CMOS oscillator is set by the resonance frequency of the AlN/FeGaB nano-plate resonator, a resonance frequency shift, \( \Delta f \), of the resonator due to external magnetic field results in an oscillator output frequency variation, \( f_0 - \Delta f \). By monitoring the output frequency of the AlN/FeGaB MEMS-CMOS oscillator, the external magnetic field can be readily detected.
4.2 Design Considerations

The resonance frequency of the AlN/FeGaB nano-plate resonator is defined by the equivalent Young’s modulus, $E_{eq}$, and density, $\rho_{eq}$, of the material stack forming the vibrating body of the device, and the pitch, $W_0$, of the bottom IDT, given by (4-1).

$$f = \frac{1}{2W_0} \sqrt{\frac{E_{eq}}{\rho_{eq}}}$$ (4-1)
The sensitivity of the proposed resonant magnetometer is defined as the output frequency shift with respect to the applied magnetic field magnitude, given by (4-2),

\[
S = \frac{\Delta f}{\Delta H} = \frac{\Delta f}{\Delta E} \cdot \frac{\Delta E}{\Delta H} = \frac{\Delta E}{\Delta H} \cdot \frac{f_0}{2E_{eq}}
\]  

(4-2)

where \(\Delta E/\Delta H\) is the equivalent Young’s modulus change caused by magnetostriction in the magnetic material (delta-E effect), and \(f_0\) is the output frequency of the oscillator. The limit of detection (LOD) of the proposed magnetic field sensor represents the minimum detectable magnetic field, when the signal-to-noise ratio is equal to 1 in a certain measurement bandwidth and it is defined as the noise-induced frequency fluctuation, \(f_n\), divided by the sensitivity of the sensor, given by (4-3).

\[
LOD = \frac{f_n}{S}
\]  

(4-3)

The noise-induced frequency fluctuation directly imposes an ultimate limit to magnetic field sensing. Among different noise mechanisms (thermomechanical noise, flicker noise, white noise, temperature fluctuation), thermomechanical noise sets the fundamental limit to the frequency stability of a resonant sensor [86]. Therefore, the minimization of thermomechanical LOD can be used to drive the design of the magnetometer. The frequency fluctuation originated from thermally driven random motion of the mechanical device is given by (4-4),

\[
f_n = \sqrt{\frac{K_B T_0 (1+\text{F})}{4P_c} \cdot \frac{f_0}{Q}}
\]  

(4-4)
where $K_B$ is the Boltzmann constant, $T_0$ is the temperature of the resonator, $F$ is the noise figure of the CMOS circuit, $B$ is the measurement bandwidth, $P_c$ is the resonator driving power. Combining equations (4-2)-(4-4), the thermomechanical LOD can be expressed as

$$\text{LOD} = \sqrt{\frac{K_B T_0 (1+F) B}{P_c}} \cdot \frac{1}{Q} \cdot \left( \frac{\Delta E/E_{eq}}{\Delta H} \right)^{-1}$$  \hspace{1cm} (4-5)

Equation (4-5) implies that optimal sensor performance can be achieved by maximizing the device quality factor, $Q$, power handling, $P_c$ and equivalent Young's modulus sensitivity to magnetic field, $(\Delta E/E_{eq})/\Delta H$.

Deposition of high quality ultra-thin AlN films on a Si substrate by low temperature sputtering process has been demonstrated resulting in resonant nano-plates with $Q>1000$, despite the total volume reduction [53, 57, 86]. Furthermore, the efficient on-chip piezoelectric actuation and sensing of a high frequency bulk acoustic mode of vibration in a nano-plate structure, instead of a beam, enables the fabrication of high frequency and high power handling, $P_c$, resonators with power efficient transduction [21, 53]. Magnetic field induced percentage change in Young’s modulus $(\Delta E/E_{eq})$ up to 20%-30% has been demonstrated in magnetostrictive soft magnetic films [55] and strong magnetostrictive coupling between the magnetic (FeGaB) and the piezoelectric (AlN) films can be achieved by setting their thicknesses to the same value (250 nm in this work), which guarantees ultra-high sensitivity of the equivalent device Young's modulus to magnetic field without reducing significantly the device piezoelectric transduction efficiency (high values of electromechanical coupling coefficient, $k_t^2$, are maintained).
4.3 Device Fabrication

The AlN/FeGaB nano-plate resonator was fabricated using a five-mask microfabrication process, shown in Figure 4-3. The fabrication started with a high resistivity Si substrate (resistivity > 10,000 Ω·cm). 5 nm/45 nm Titanium/Platinum (Ti/Pt) film was sputter-deposited on the Si substrate and patterned by lift off process to define the bottom IDTs and electrodes. Next, high quality c-axis oriented AlN thin film (250 nm thick) was sputter-deposited on top of the Pt IDTs. Hot H₃PO₄ (150 °C) was used to wet etch the AlN and open vias to the bottom Pt electrodes. Then, the AlN film was etched by Inductively Coupled Plasma (ICP) in Cl₂ based chemistry to define the dimension of the nano-plate resonator. After that, a 250 nm thick FeGaB film was sputter-deposited on top of the AlN film and patterned by lift off process. An in-situ magnetic field of 30 Oe was applied along the length, \( L \), of the resonator during the deposition to induce a uniaxial magnetic anisotropy in the device (easy axis of magnetization aligned to the length, \( L \), of the device). Then, a 100 nm thick Gold (Au) film was deposited by e-beam evaporation and patterned by lift-off process to define the top probing pad. Finally, Xenon Difluoride (XeF₂) isotropic etching was used to etch the Si substrate underneath the AlN/FeGaB nano-plate resonator to completely release the resonant structure.
Figure 4-3. 5-mask microfabrication process of the AlN/FeGaB nano-plate resonator: (a) 50 nm thick Pt was sputter-deposited on a high resistivity Si substrate and patterned by lift off process to define the bottom electrode; (b) 250 nm thick AlN was sputter-deposited; (c) Vias to the Pt bottom electrode were wet etched in H₃PO₄ and the shape of the resonator was defined by dry etching of AlN film in Cl₂ based chemistry; (d) 250 nm thick FeGaB was sputter-deposited and patterned by lift off process; (e) 100 nm Au was deposited by e-beam evaporation and patterned by lift off process to define the top probing pad; (f) The Si substrate underneath the AlN/FeGaB resonator was released by XeF₂ isotropic etching.

The fabricated AlN/FeGaB nano-plate resonator is shown in the Scanning Electron Microscope (SEM) image in Figure 4-4 (c) and (d). The sensing area of the magnetic field sensor is defined by the lateral dimensions of the resonant nano-plate
(L×W). The CMOS integrated circuit (IC) chip, consisting of an inverting amplifier and a 50 Ω buffer stage [29] (Figure 4-4 (b)), was fabricated in the ON Semiconductor 0.5 µm CMOS process. Both the MEMS and CMOS chips were mounted on a custom designed printed circuit board (PCB) and electrically connected by wire-bonding (Figure 4-4 (a)).

Figure 4-4. (a) The fabricated AlN/FeGaB MEMS-CMOS oscillator; (b) Schematic illustration of the CMOS integrated circuit amplifier: \(C_1 = C_2 = 1.5 \text{ pF}, (W/L)M_1 = 300, (W/L)M_2 = 675, (W/L)M_3 = 0.03\); (c) SEM image of the fabricated AlN/FeGaB nano-plate resonator: device width, \(W=60 \mu\text{m}\); device length, \(L=200 \mu\text{m}\); pitch of the bottom Pt IDT, \(W_0=25 \mu\text{m}\); (d) Cross sectional view of the AlN/FeGaB nano-plate.
4.4 Device Characterization

4.4.1 AlN/FeGaB Nano-Plate Resonator

The electrical response of the fabricated AlN/FeGaB nano-plate resonator was measured by an Agilent E5071C network analyzer after an open-short-load calibration on a standard substrate. The measured admittance amplitude and phase versus frequency and modified Butterworth-Van Dyke (MBVD) model fitting are shown in Figure 4-5. A resonance frequency of 167.8 MHz was recorded. The mechanical quality factor $Q_m$ and electromechanical coupling coefficient $k_t^2$ of the AlN/FeGaB nano-plate resonator were extracted and found to be 1084 and 1.18 %, respectively. Such high device figure of merit ($FOM = k_t^2 \cdot Q \approx 13$), comparable with the one of conventional 250 nm thick AlN nano-plate resonators [53], enabled the direct connection of the resonant device to a compact and low power self-sustained CMOS amplifier as a direct frequency readout.

The resonance frequency sensitivity of the fabricated AlN/FeGaB nano-plate resonator to external magnetic field was characterized by applying a DC magnetic field along the width, $W$ and length, $L$ of the resonator, respectively, and monitoring its resonance frequency shift (Figure 4-6). A Helmholtz coil was used with a Kepco Bipolar Operational Power Supply to generate DC magnetic field from -180 Oe to 180 Oe. As expected, the resonance frequency of the AlN/FeGaB resonator followed the typical trend of Young’s modulus change induced by magnetic field in anisotropic soft magnetic materials (delta-E effect) [55]. When an increasing magnetic field was applied along the width, $W$, of the resonator, which is the magnetic hard axis (since a bias field was applied...
along the length, $L$, of the device during the magnetic film deposition), the equivalent Young’s modulus of the nano-plate decreased due to the magnetostrictive stress caused by the rotation of the magnetic domains, and reached its minimum value for a magnetic field of $\sim 100$ Oe, which canceled the device intrinsic anisotropy field. By further increasing the amplitude of the magnetic field, the Young’s modulus increased and reached its maximum at the saturation of magnetization, with no reorientation of the magnetic domains.
Figure 4-5. (a) Measured admittance amplitude versus frequency and MBVD model fitting of the fabricated AlN/FeGaB nano-plate resonator; (b) Measured phase versus frequency and MBVD model fitting. The inset shows the MBVD circuit and the extracted parameters.
Figure 4-6. Measured resonance frequency response of the fabricated AlN/FeGaB nano-plate resonator to DC magnetic field applied along the width, W (black and red) and length L (blue and pink) of the resonator. The magnetic field was swept from -180 Oe to 180 Oe then back from 180 Oe to -180 Oe.

When an increasing magnetic field was instead applied along the length, L, of the device, which is the magnetic easy axis, the saturation of magnetization was readily reached for a relatively small value of magnetic field (~50 Oe) being the magnetic domains previously pre-oriented along the easy axis of the device [55] (a bias field was applied along $L$ during the magnetic film deposition).

The measurement results (Figure 4-6) clearly indicate an anisotropic sensitivity of the device resonance frequency to magnetic field arising from the intrinsic magnetic anisotropy of the FeGaB thin film, which can be exploited for the implementation of high performance electronic compasses as discussed in the following section.
The temperature sensitivity of the fabricated magnetoelectric MEMS resonator was also characterized in a temperature controlled RF probe station, and the measurement result is shown in Figure 4-7. A nonlinear temperature coefficient of frequency ranging between -67 and -156 ppm/K was recorded. Such large TCF is due to the temperature coefficient of Young's Modulus of the FeGaB film (conventional AlN contour-mode resonators, without magnetic film, typically show a TCF in the order of -30 ppm/K [18, 57, 58]). Such temperature sensitivity requires a temperature sensor with zero sensitivity to magnetic field (such as a conventional AlN contour-mode resonator [18]) to be ultimately integrated with the magnetometers for temperature calibration.

Figure 4-7. Measured temperature dependence of the resonance frequency of the AlN/FeGaB nano-plate resonator.
4.4.2 AlN/FeGaB MEMS-CMOS Oscillator

The fabricated AlN/FeGaB nano-plate resonator was directly wire-bonded to the CMOS IC chip (Figure 4-4(a)), forming a self-sustained magnetoelectric MEMS-CMOS oscillator. The oscillator design is described in [29, 30]. Briefly, the circuit consists of a Pierce oscillator implemented by means of a CMOS inverter biased in its active region. Transistors $M_1$ and $M_2$ form the CMOS inverting amplifier while transistor $M_3$ acts as a large resistor to provide biasing of $M_1$ and $M_2$ in the active region.

The output spectrum and phase noise of the AlN/FeGaB MEMS-CMOS oscillator were characterized by an Agilent N9010A spectral analyzer (Figure 4-8). The bias voltage ($V_{DD}$ in Fig 4-4 (b)) of the oscillator was 2.2 V and the current was 1.4 mA, resulting in a power consumption of ~3 mW (limited by the 0.5 μm CMOS technology employed). A maximum output power of -7.34 dBm was recorded, and a corresponding output frequency of 168.1 MHz. The phase noise values of -81.73 dBc/Hz at 1 KHz offset frequency and -130 dBc/Hz noise floor were measured. Such phase noise values are comparable to the one typically achieved with MEMS-CMOS oscillators based on conventional ultra-thin AlN contour-mode resonators [53].
Figure 4-8. Measured (a) output spectrum and (b) phase noise of the AlN/FeGaB MEMS-CMOS oscillator.

The Allan Deviation, which is a measurement of noise induced frequency fluctuation that directly determines the limit of detection of the sensor, was characterized by an Agilent 53230A frequency counter (Figure 4-9). A minimum Allan Deviation of 8.5 Hz was recorded for a bias voltage of 2.2 V at a measurement time of 100 ms,
translating into a noise induced frequency fluctuation of ~51 ppb at a 10 Hz measurement bandwidth, and a noise spectral density of 2.7 Hz/Hz^{1/2}.

Figure 4-9. Measured Allan Deviation of the AlN/FeGaB MEMS-CMOS oscillator shows a minimum value of 8.5 Hz at 100 ms measurement time.
Figure 4-10. (a) Frequency response of the AlN/FeGaB MEMS-CMOS oscillator to external magnetic field from -180 Oe to 180 Oe applied along the width, W of the resonator; (b) Measured frequency response of the AlN/FeGaB MEMS-CMOS oscillator for magnetic field sweeping back and forth from -90 Oe to 90 Oe.
The frequency sensitivity of the AlN/FeGaB MEMS-CMOS oscillator to magnetic field was characterized by applying a DC magnetic field parallel to the sensor and recording the output frequency of the oscillator. A Helmholtz coil with a Kepco Bipolar Operational Power Supply was employed to generate the DC magnetic field and the oscillator output frequency was monitored by an Agilent 53230A frequency counter. The measured frequency responses of the oscillator to external magnetic field applied along the easy (length, \( L \)) and hard (width, \( W \)) axis of the resonator (Figure 4-10 (a) and Figure 4-11 (a)) are similar to the ones recorded for the AlN/FeGaB resonator measured in open loop (Figure 4-6). The slight differences between the frequency responses of the sensor in closed and open loop configurations are attributed to the effect of the resonator admittance amplitude variation, under different magnetic field bias [51], on the oscillator loop gain.
Figure 4-11. (a) Frequency response of the AlN/FeGaB MEMS-CMOS oscillator to external magnetic field from -180 Oe to 180 Oe applied along the length, $L$ of the resonator; (b) Measured frequency response of the AlN/FeGaB MEMS-CMOS oscillator for magnetic field sweeping back and forth from -50 Oe to 50 Oe.
The hysteresis of the AlN/FeGaB MEMS-CMOS oscillator was also studied by sweeping the magnetic field from negative to positive values back and forth along the hard (Figure 4-10 (b)) and the easy axis (Figure 4-11 (b)). Hysteresis values of ~ 20 Oe and ~ 5 Oe were recorded for a magnetic field applied along the hard and easy axis, respectively, which match the typical values of coercive field, \( H_c \), measured in FeGaB thin film [52]. The remanent magnetization associated with such magnetic hysteresis was employed as internal magnetic biasing of the magnetostrictive component within the magnetoelectric composite to implement a self-biased magnetoelectric magnetometer with non-zero sensitivity to small values of external magnetic field (around 0 Oe) [87]. By applying the anisotropy field, \( H_k \sim 100 \) Oe, along the easy axis of the device, the saturation magnetization is reached and a non-zero slope of the frequency versus external magnetic field curve (non-zero sensitivity) is achieved. Once the bias is removed a non-zero sensitivity is maintained, due to the remanent magnetization, as long as the device is exposed to magnetic field values smaller than the anisotropy field, \( H_k \). (Figure 4-11 (b)). The elimination of the external magnetic field bias need is crucial for the implementation of miniaturized and low power magnetoelectric MEMS-CMOS magnetometers [88].

A maximum linear sensitivity of ~169 Hz/µT was extracted for magnetic field values in the 0 to 4 Oe range applied along the length of the resonator (Figure 4-12). A limit of detection (LOD) of 16 nT/Hz\(^{1/2}\) in the 0 to 4 Oe range was extracted for the device by dividing the measured noise spectral density (2.7 Hz/Hz\(^{1/2}\)) by the equivalent linear sensitivity (169 Hz/µT). Such low LOD indicates the device can be used as a self-biased magnetometer with ultra-high resolution in the 0 to 4 Oe range.
Figure 4-12. Sensitivity of the AlN/FeGaB MEMS-CMOS oscillator to magnetic field in the 0 to 4 Oe range applied along the length of the resonator. The device was pre-magnetized by applying a -100 Oe field along its length. Zero magnetic field bias was applied during the sensitivity measurement.

In order to investigate the capability of the magnetoelectric MEMS-CMOS magnetometer prototype to detect magnetic field magnitudes in the range of the Earth's magnetic field, the device was exposed to a 50 µT magnetic field (simulating the Earth's magnetic field). Figure 4-13 shows the measured frequency response of the magnetoelectric oscillator to a square wave magnetic field with amplitude of 50 µT at frequency of 0.33 Hz applied along the length, $L$ of the resonator with zero magnetic field bias. An output frequency shift of 7.1 KHz was recorded, which is slightly lower than the 8.45 KHz value estimated by the linear fitting in the 0 to 4 Oe range, due to the non-
perfect linearity of the frequency response to small magnetic field values around 0 Oe (inset in Figure 4-14 (a)).

Figure 4-13. Frequency response of the self-biased AlN/FeGaB MEMS-CMOS oscillator to a 50 µT magnetic field square wave (0.33 Hz) applied along the length of the resonator.

The angular sensitivity of the self-biased magnetoelectric MEMS-CMOS oscillator was also investigated by applying a 50 µT magnetic field step at different rotational angles from the resonator hard axis (width, W) and recording the corresponding induced resonance frequency shift for each angle (Figure 4-14). A magnetic field step and a relative frequency measurement (instead of a constant value of magnetic field and an absolute measurement of the oscillator output frequency) were employed in order to cancel any frequency drift not induced by the externally applied magnetic field and extract the actual angular sensitivity of the device. A quasi-sinusoidal response (Figure 4-
14) was recorded with a maximum positive frequency shift of 7.1 KHz when the 50 µT field was applied along the length of the resonator (90°), and maximum negative frequency shift of -4.9 KHz when the field was applied to the opposite direction (270°). When the 50 µT filed was applied along the width of the resonator (0°, 180° and 360°), no frequency shift was recorded.
Figure 4-14. (a) Measured and calculated output frequency shift of the self-based AlN/FeGaB MEMS-CMOS oscillator as a function of a 50 µT magnetic field applied at different rotational angles from the resonator hard axis (width, W). The inset shows the measured frequency response of the self-biased magnetometer to magnetic field ranging from -1 Oe to 1 Oe applied along the width and length of the resonator. (b) Polar plot of the self-biased magnetometer angular response to 50 µT magnetic field applied at different rotational angles from the resonator hard axis (width, W).

Such quasi-sinusoidal angular response of the magnetometer is due to the strongly anisotropic sensitivity of the self-biased AlN/FeGaB magnetolectric resonator to small magnetic field values around 0 Oe. The measured frequency response of the magnetometer to magnetic field values in the -1 to 1 Oe range applied along the length, L, and the width, W, of the resonator is shown in the inset in Figure 4-14 (a). A large sensitivity was measured when the magnetic field was applied along L (~145 Hz/µT from 0 Oe to 1 Oe, and ~ -90 Hz/µT from 0 Oe to -1 Oe, respectively) whereas an almost zero sensitivity was recorded when the magnetic field was applied along W. The angular response of the device to a 50 µT magnetic field was calculated based on the measured sensitivity values along L and W and it was found to be in good agreement with the experimental data (Figure 4-14).

$$\theta = \arcsin\left(\frac{f_n}{H_E S}\right)$$  \hspace{1cm} (4-6)

The angular resolution of the magnetometer for electronic compass application was extracted according to equation (4-6), where $f_n$ is the measured noise induced frequency fluctuation (Allan deviation), $H_E$ is the Earth’s magnetic field, and $S$ is the...
sensitivity. Considering a conservative estimate of the Earth’s magnetic field magnitude of 10 µT and magnetic field resolution values of ~59 nT in the 0° to 180° range and ~94 nT in the 180° to 360° range (measured minimum Allan deviation of 8.5 Hz divided by the sensitivity of 145 Hz/µT and 90 Hz/µT respectively), angular resolution values of 0.34° in the 0° to 180° range and 0.54° in the 180° to 360° range were extracted.

Finally, the geometric parameters and performance metrics of the AlN/FeGaB magnetoelectric MEMS-CMOS oscillator based resonant magnetometer are listed in Table IV.

Table IV. Summary of the geometry and performance parameters of the AlN/FeGaB magnetoelectric MEMS-CMOS oscillator based resonant magnetometer.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area</td>
<td>200 × 60 × 0.5</td>
<td>µm × µm × µm</td>
</tr>
<tr>
<td>frequency</td>
<td>168.1</td>
<td>MHz</td>
</tr>
<tr>
<td>Quality factor</td>
<td>1084</td>
<td>-</td>
</tr>
<tr>
<td>Minimum noise</td>
<td>8.5</td>
<td>Hz</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>169</td>
<td>Hz/µT</td>
</tr>
<tr>
<td>Limit of detection</td>
<td>16</td>
<td>nT/Hz(^{1/2})</td>
</tr>
<tr>
<td>Angular resolution</td>
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<td>°</td>
</tr>
<tr>
<td>Power consumption</td>
<td>3</td>
<td>mW</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

5.1 Summary

This dissertation has described the design and experimental verification of a MEMS/NEMS based piezoelectric resonant sensing technology suitable for the implementation of high performance, miniaturized, low power and CMOS integrable physical sensors. Two fundamental physical sensors: infrared detectors and magnetic field sensors, have been demonstrated based on AlN nano-pate resonators.

The potential of employing AlN NPRs for ultra-fast and high resolution thermal power detection was theoretically modeled and experimentally verified. Fundamental challenges associated to the implementation of mechanically resonant thermal detectors are overcome with the introduction of a MEMS technology platform in which a temperature sensitive AlN nano-plate resonator and a monolithically integrated micromachined suspended heat absorbing element are perfectly overlapped but separated by a sub-micron air gap. By placing the absorbing element outside the body of the resonator (but suspended over it) the electromechanical performance of the resonant device is not affected by the absorbing element and the material employed to implement it \((Q=2305 \text{ and } k_r^2=0.9\%)\). At the same time, efficient and quick heat transfer from the absorbing element to the micromechanical resonant device is achieved by minimizing the air gap between them. The detection capabilities of this first prototype were tested using
an integrated resistive heat source. A low NEP of 6.5 nW/Hz\(^{1/2}\) and a small thermal time constant of 350 \(\mu\)s were experimentally measured.

An innovative device concept, based on the use of fully metallic nanoscale tethers to support the resonant body of a piezoelectric MEMS resonator, which enables the implementation of piezoelectric MEMS resonators with maximum thermal resistance and quality factor was introduced for the first time. Such innovative design, with minimum anchor cross section, enabled the implementation of an uncooled resonant thermal detector with unprecedented performance: (1) the thermal resistance of the device was maximized \((R_{\text{th}} \sim 4.2 \times 10^5 \text{ K/W, more than 10X improvement compared to conventional piezoelectric resonators})\) resulting in a very high frequency sensitivity to absorbed power \((\sim 3.4 \text{ Hz/nW})\). (2) The acoustic energy was effectively confined in the freestanding resonant body of the device resulting in excellent electromechanical performance (mechanical quality factor \(Q_M \sim 2119\) and electromechanical coupling coefficient \(k_r^2 \sim 1.55\%\)) and ultra-low frequency noise \((\sim 1.3 \text{ Hz/Hz}^{1/2})\). Thanks to such unique combination of high sensitivity and low noise performance, an ultra-low detection limit of \(\sim 382 \text{ pW/Hz}^{1/2}\) was achieved \((2\sim 4\times\text{better than commercially available pyroelectric detectors})\). Furthermore, by taking advantage of the high resonator figure of merit \((\text{FOM}=k_r^2\cdot Q=33)\) a low power \((\sim 1 \text{ mW})\) self-sustained CMOS oscillator was employed as direct frequency readout resulting in the first complete and compelling prototype of a high performance MEMS-CMOS resonant thermal detector with detection limit pushed in \(\sim 100\text{s pW/Hz}^{1/2}\) range.

An uncooled NEMS resonant IR detector with unique spectrally selective IR detection capability was demonstrated. Sensing and actuation of a high frequency (162
(161.8 MHz) bulk acoustic mode of vibration in a free-standing ultra-thin piezoelectric plasmonic metasurface has been demonstrated and exploited for the implementation of a novel NEMS resonator with unique combined optical and electromechanical properties. By exploiting the piezoelectric properties of AlN thin-films, efficient on-chip transduction of the NEMS plasmonic resonant structure has been achieved, eliminating the need for the cumbersome and complex off-chip optical readouts employed in previous devices. Thanks to properly tailored absorption properties, strong (80%) and spectrally selective detection of IR radiation for an optimized spectral range around 8.8 μm has been experimentally verified. This work sets a milestone towards the development of a new technology platform based on the combination of nanoplasmonics and piezoelectric nano electro mechanical systems, which can potentially deliver fast (100s μs), high resolution (NEP as low as ~1pW/Hz^{1/2}), and spectrally selective uncooled IR detectors suitable for the implementation of high-performance, miniaturized and power efficient IR/THz spectrometer and multi-spectral imaging systems.

Finally, a high resolution magnetometer (16 nT/Hz^{1/2}) based on a high frequency (161.8 MHz) magnetoelectric MEMS-CMOS oscillator was demonstrated for the first time. A high electromechanical performance (FOM = k_t^2 Q ≈ 13) magnetoelectric MEMS resonator based on an AlN/FeGaB bilayer nano-plate (250 nm / 250 nm) was fabricated and connected in the feedback loop of a CMOS inverting amplifier (fabricated in the ON Semiconductor 0.5 μm CMOS process) to synthesize the first low noise (2.7 Hz/Hz^{1/2}) MEMS-CMOS magnetoelectric frequency source. The fabricated magnetoelectric MEMS-CMOS magnetometer showed a maximum sensitivity of 169 Hz/μT and a detection limit as low as 16 nW/Hz^{1/2} at zero magnetic field bias (self-biased
device). Due to the strongly anisotropic sensitivity of the self-biased AlN/FeGaB magnetoelastic resonator, the angular sensitivity of the magnetometer for electronic compass application was also investigated showing an ultra-high angular resolution of 0.34° for a 10 μT conservative estimate of the Earth’s magnetic field. The unique magnetic field sensing capabilities of the AlN/FeGaB magnetoelastic MEMS-CMOS oscillator demonstrated in this work further extend the application range of the core AlN nano-plate resonator technology making it the best candidate for the realization of the next generation miniaturized, low power, multi-functional and reconfigurable wireless sensing platforms that can fully leverage sensor fusion to acquire more accurate and reliable information about the context in which human beings live.

5.2 Recommendations for Future Work

5.2.1 AlN Resonant IR Detector Array

The demonstrated high performance IR thermal detector based on the AlN NPRs with Pt anchors is very suitable for the implementation of high performance and miniaturized IR imaging systems. Such IR imaging system is based on the combination of IR detector arrays for IR radiation sensing and electronic readouts for image generation and processing. The scaled AlN nano plate resonators (30 μm × 30 μm) can be used to build such IR detector arrays. To implement a high resolution IR camera with 1024×768 pixels using the 30 μm × 30 μm AlN resonators (considering a spacing of 10
μm), the chip size is about 40 mm × 30 mm. The MEMS chip can be bonded to CMOS die to form electrical connections with CMOS circuitry [89].

One fundamental challenge associated with the implementation of high performance MEMS resonant IR detector arrays is the realization of high IR absorption within the ultrathin MEMS resonant body. The author has recently demonstrated a high performance AlN piezoelectric fishnet like metasurface (PFM), addressing this fundamental challenge [90]. The proposed PFM IR detector is shown in Figure 5-1. The proper patterning of plasmonic nanostructures in the top metal layer of the device significantly enhances field concentration which provide a Fabry-Perot like resonance at ~4 μm, enabling strong absorption of short wavelength infrared (SWIR) radiation over the ultrathin structure (inset in Figure 5-2). The resonant body of the device is supported by two metallic anchors (with minimum cross-section) to maximize the thermal isolation of the device from the substrate (heat sink), thus maximizing the thermal resistance of the IR detector (Figure 5-1).

The responses of the fabricated AlN PFM IR detector and a reference device (a conventional AlN nano plate resonator with same TCF and $R_{th}$) to IR radiation were characterized using a 5 μm quantum cascaded laser (QCL) as an illumination source. The measured frequency responses in Figure 5-2 show that a ~7× enhanced responsivity was recorded for the PFM IR detector, thanks to its properly engineered absorption properties. Based on the measured noise spectral density of ~1Hz/Hz$^{1/2}$, the NEP of the detector was calculated by dividing the noise spectral density by the responsivity, and found to be ~1.9 nW/Hz$^{1/2}$. 
Figure 5-1. (a) 3D mock up view of the NEMS resonant piezoelectric fishnet-like metasurface. (b) SEM image of the fabricated device: the inset shows the dimensions of the fishnet-like metasurface.
Figure 5-2. Measured responses of the fabricated IR detector and a reference device (conventional AlN MEMS resonator) upon exposure to a 5 μm quantum cascaded laser (QCL) IR source, showing a 7× enhancement in the device responsivity. The inset shows the measured absorption of the fishnet-like metasurface.

The author believes that the combination of the scaled AlN resonators (30 μm × 30 μm) and the PFM technology has the great potential for the implementation of high resolution IR imaging systems, and recommends for future study.

5.2.2 IR/THz Spectroscopy

IR/THz spectroscopy, or IR/THz imaging, is accomplished by the combination of IR/THz sources and IR/THz detectors, shown in Figure 5-3. In this frequency-domain spectroscopy system, a multi-frequency continuous wave radiation propagates through the sample of interest and then focused onto a multi-color IR/THz detectors array capable of direct measurement of the frequency-dependent transmission through the sample of interest.

In recent years, there has been a lot of research effort and substantial progress in the development of high performance IR/THz sources, including photoconductive emitter [91], and Quantum Cascade Lasers (QCL) [92]. On the contrary, the development of high performance, power efficient and compact IR/THz spectrometers has been so far retarded by the lack of high resolution, fast, miniaturized, uncooled and multi-color IR/THz detectors. In this perspective, the proposed and demonstrated uncooled spectrally
selective IR detectors based on the AlN nano-plate resonant technology can be considered as one of the best candidates for the implementation of ultra-sensitive, fast, multi-color and highly miniaturized THz detectors.

![Diagram of frequency resolved IR/THz spectroscopy](image)

**Figure 5-3.** A schematic illustration of a frequency resolved IR/THz spectroscopy.

The author recommends using the demonstrated spectrally selective AlN piezoelectric plasmonic resonant metamaterial (PPRM) IR detectors to implement such frequency resolved IR/THz spectroscopy. A small IR/THz detectors array (e.g. 4×4) can be implemented by 16 AlN PPM IR detectors with properly tailored IR absorbing bandwidth [93]. The IR/THz source can by implemented using a tunable QCL (e.g. a 32 laser array integrated on a same chip) [94].
REFERENCES


