Gallium nitride micromechanical resonators for IR detection

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ABSTRACT

This paper reports on a novel technology for low-noise un-cooled detection of infrared (IR) radiation using a combination of piezoelectric, pyroelectric, electrostrictive, and resonant effects. The architecture consists of a parallel array of high-*Q* gallium nitride (GaN) micro-mechanical resonators coated with an IR absorbing nanocomposite. The nanocomposite absorber converts the IR energy into heat with high efficiency. The generated heat causes a shift in frequency characteristics of the GaN resonators because of pyroelectric effect. IR detection is achieved by sensing the shift in the resonance frequency and amplitude of the exposed GaN resonator as compared to a reference resonator that is included in the array. This architecture offers improved signal to noise ratio compared with conventional pyroelectric detectors as the resonant effect reduces the background noise and improves sensitivity, enabling IR detection with NEDTs below 5 mK at room temperature. GaN is chosen as the resonant material as it possesses high pyroelectric, electrostrictive, and piezoelectric coefficients and can be grown on silicon substrates for low-cost batch fabrication. Measured results of a GaN IR detector prototype and a thin-film nanocomposite IR absorber are presented in this paper.

Keywords: Electrostriction, gallium nitride, pyroelectric effect, resonant IR sensor, uncooled IR detector,

1. INTRODUCTION

In the last two decades, infrared detectors have been extensively used as sensing solutions for a broad range of military, defense, security, industrial, and civilian applications. IR detectors enable real-time sensing with high frame rates, and can be used for target identification and discrimination. Unlike radar or laser systems, IR detectors are passive in nature, and thus can be operated at lower powers. Continuing improvements in fabrication techniques have resulted in small form factor (pixel pitch of ~17 μm) IR detectors that are light, portable, and durable. Two major categories of IR-detectors exist: photonic detectors and thermal detectors. Photonic detectors depend on the absorption of specific wavelengths of the electromagnetic spectrum while thermal detectors depend on the heating effect of the IR radiation to change a specific attribute of the device (e.g., resistivity). While significant advances have been made in developing high-performance photonic detectors, most such available systems require the use of cooling elements, as the detectivity and noise floor of these detectors get significantly degraded at room temperature and above. Cryogenic cooling systems add to the power consumption, mass, and cost. On the other hand, the development of uncooled detectors has lagged behind due to their lower theoretically achievable values for detectivity, and slower detection speed. As IR detectors transition from purely military applications on board aircraft or fixed platforms to smaller, portable systems with civilian, industrial and security applications, thermal detectors will gain a higher market share. The most commercially successful thermal detectors have been based on the bolometric principle, while other transduction mechanisms such as Golay cells and pyroelectric polarization have been used with varying success[1]. A relatively unexplored transduction scheme depends on the change in frequency of a mechanical microresonator[2-4]. This paper describes the principle of operation of GaN micromechanical resonators as IR detectors, provides theoretical values for their detection limit, and demonstrates the results of a proof-of-concept GaN IR detector operated at room temperature.

2. THEORY OF GAN-BASED RESONANT IR DETECTORS

2.1 General theory of resonant IR detectors

Micromechanical resonators are extremely popular as RF communication components but have also been used successfully as ultra-sensitive detectors for sensing mass, fluids flow, and specific chemical or biological agents. The use of microresonators for IR detection is a natural extension of their application to temperature sensing. Fig. 1 shows a

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general schematic of the resonant IR detector. The fundamental method of sensing infrared radiation using resonators is the change in their resonant frequency upon irradiation. The frequency of a resonator is given by $\omega = \sqrt{(k/m)}$, where k is the effective elastic stiffness and m is the effective mass of the resonator. In resonant IR detectors, the frequency shift is mainly due to the change in stiffness as a result of temperature change. In a non-pyroelectric resonator, the dominant mechanism that causes the change in stiffness is the temperature induced change in elasticity. The relative shift in the resonant frequency because of this effect is called the temperature coefficient of frequency (TCF) and can be as large as -30 ppm/K for silicon, and +20 to +80 ppm/K for quartz[4]. Therefore, any resonator with a non-zero TCF can be theoretically used as an IR sensor. However, the reliance on frequency shift because of the finite TCF imposes a relatively low limit on the IR sensitivity of the device. Other mechanisms of frequency change are explored in this work to demonstrate that resonators can become feasible solutions for uncooled IR sensing applications.

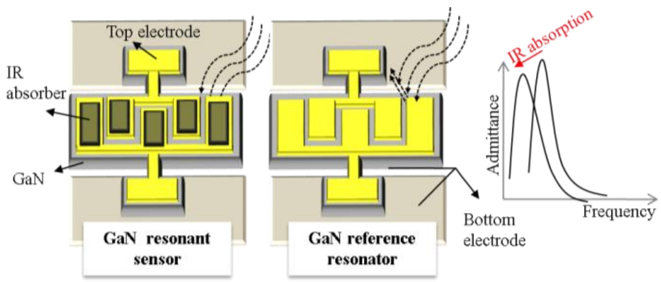

Figure 1. A schematic view showing the GaN IR sensor architecture. A reference resonator is used to reduce noise and cancel the frequency shift because of other changes such as increase in the ambient temperature. The detector response time is governed by the thermal time constant ($\tau_{th} = R_{th}C_{th}$), where R_{th} and C_{th} are the thermal resistance of the tethers and the thermal capacity of the resonator, respectively.

2.2 GaN resonators as IR detectors

Gallium nitride is a single crystal, wide band gap semiconductor, which in its wurtzite form is both piezoelectric and pyroelectric. Furthermore, GaN has been shown to exhibit significant second-order piezoelectric effects, also known as electrostriction. A temperature differential between the irradiated surface and the bottom surface of the GaN film will result in the spontaneous generation of electric surface charge (Q_c) due to the pyroelectric properties of GaN, and subsequently a voltage across the thickness (t) of the device ($V = Q_c/C_{el}$) . The pyroelectric voltage coefficient (P_v) of GaN has been theoretically estimated to be 7×10^5 $Vm^{-1}K^{-1}$, and values up to 10^4 $Vm^{-1}K^{-1}$ have been measured[5]. The relation between the temperature difference and spontaneous voltage is given by,

$$\Delta V = P_v t \Delta T \,. \tag{1}$$

Given that GaN films with thicknesses up to 5 µm can be grown epitaxially, voltages of up to 3.5 V/K can be generated. This voltage changes the acoustic velocity of the material by a significant margin, due to the piezoelectric and electrostrictive effect in GaN[6, 7]. Under constant mechanical applied stress, the field dependent strain can be written as,

$$\varepsilon_{ij} = d_{kij}E_k + M_{klij}E_kE_l, \tag{2}$$

where ε, d, E and M are the strain, piezoelectric coefficient, electric field and electrostrictive coefficient, respectively. Electrostriction in GaN is not widely researched; hence, the M_{ij} coefficients are not well characterized. The value of M_{33} has been estimated to be 1.2×10^{-18} m^2V^{-2} based on analytical estimates and empirical evidences [6,7]. Assuming conservative values for the M_{ij}coefficients, it is possible to get up to -1000 ppm/V for the length extensional mode, and -4000 ppm/V for thickness extension[8]. This translates to a shift of up to -14,000 ppm/K. While this value is a best case estimate, even a fraction of this is orders of magnitude larger than the TCF-induced frequency shift. In a practical realization of the IR detector array, a reference resonator is used (see Fig. 1) to measure the IR-induced frequency shift (Δf_{IR}) as a function of the beat frequency ($f_{sensor} - f_{reference}$). The beat frequency is much smaller than f_{sensor}, making the relative change in frequency shift per unit beat frequency a much higher number. The use of a reference resonator also cancels the common effect of ambient temperature fluctuations, mechanical shock, and acceleration.

2.3 IR absorbers

The conversion of IR radiation power ϕ to a temperature change is governed by[2]

$$\Delta T = \frac{\eta(\lambda)\,\phi}{\sqrt{{G_{th}}^2 + \omega^2 {C_{th}}^2}}, \quad (3)$$

where $\eta(\lambda)$ is the thermal absorption efficiency of the irradiated surface. Most semiconductor materials and metals have a highly reflecting surface, and consequently a low η. A common solution to increase ΔT is to use coatings of high absorptivity materials such as carbon black and metal blacks. Prototype GaN resonators developed in this work use a 50 nm thick silicon nitride (SiN_x) layer ($\eta = 0.1$ to 0.2). The thickness of this layer has to be small to prevent it from mechanically loading the resonator. We have recently demonstrated the use of a special nanocomposite made using carbon nanotubes (CNTs) dispersed in poly-(methylmethacrylate) (PMMA) which has η values as high as 0.95 at a thickness of 1.6 µm[9]. As shown in Fig. 2, the spectral characteristics of these CNT-based absorbers are relatively flat. This is in contrast to other materials or structures such as absorbing cavities, and similar to vertically aligned CNT forests (460 µm thick) used as IR absorbers[10]. In addition, the CNT-based nanocomposites are stable at high temperatures (Fig. 2(b)). Integrating the CNT-based nanocomposite with the GaN resonators is part of ongoing work.

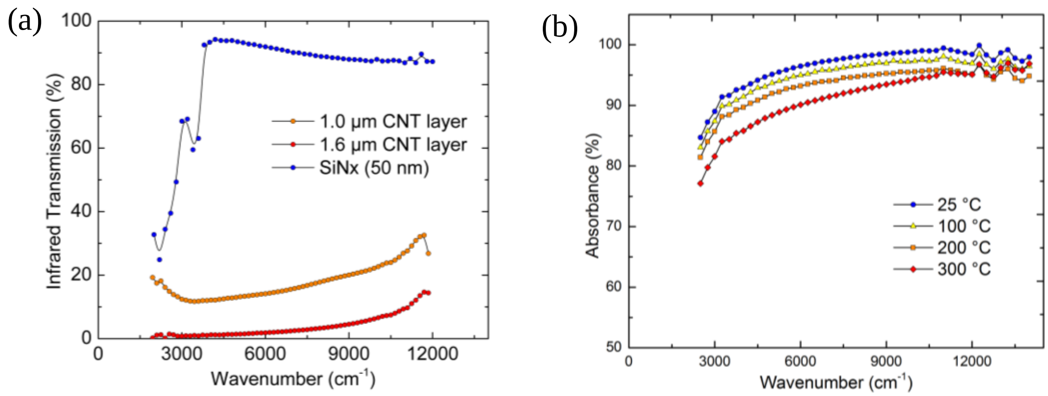

Figure 2. (a) Infrared transmission of a 50 nm thick amorphous silicon nitride layer compared to 1 µm and 1.6 µm thick CNT-based IR absorbers developed by authors[9]. (b) Effect of temperature on the absorption spectrum of the 1.6 µm thick CNT-based film. The average deviation from nominal value even at 300˚C is less than 10%. Thermal cycling does not change the IR response, or damage the film.

3. DESIGN AND FABRICATION

3.1 Fabrication

The GaN thin film can be epitaxially grown on 100 mm silicon <111> substrates, using a metal-organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE). Film thicknesses ranging from 500 nm to 3 µm are commercially feasible with current fabrication techniques, while thicker films can be custom grown. The GaN film is grown on top of an AlN/AlGaN transition layer to gradually reduce the film stress caused because of the lattice mismatch between the silicon substrate and the GaN epitaxial layer.

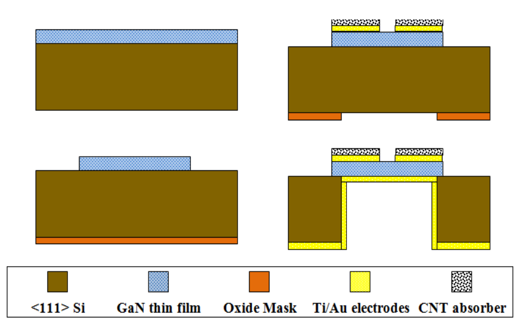

Figure 3. Process flow schematic for making resonant IR detectors augmented by thin film IR absorbers.

The GaN film is patterned and plasma etched using Cl_2/BCl_3 chemistry to define the resonator structure. Top electrodes of Au, with Ti as the adhesion layer are deposited and patterned using the lift-off process. In the current prototype, 50 nm thick layer of SiN_x is deposited on top of the electrodes. As mentioned previously, this layer will be replaced by the CNT-PMMA nanocomposite, which can be sprayed or spun onto the wafer. Devices are mechanically released using selective DRIE etching of silicon from the backside. Finally, the bottom electrode (Ti/Au stack complementary to the top electrode) is sputter deposited from the backside. The fabrication process flow is shown schematically in Fig. 3. This process or its variations has been successfully used to fabricate many different types of GaN resonators and filters[11-13].

3.2 Design

The frequency shift per temperature rise (ppm/K) of the presented resonant detectors is independent of area. However, as the absorbed power is area dependent, the device sensitivity (ppm/W) scales linearly with area. On the other hand, it is necessary to reduce the size of each resonator in order to improve the spatial resolution of the proposed FPA. Smaller sensors also offer a faster response time due to the smaller thermal mass. An optimum solution for the area exists that will balance these conflicting requirements. Another major goal of the design process is to improve the quality factor *(Q)* of the resonator (see Sec. 4.2). This can be done by optimizing the mechanical design of the tethers in order to reduce the amount of energy loss. Figure 4 (c) shows the measured response of a GaN resonator operated at its third-order length-extensional mode. This device exhibits the best $f \times Q$ figure of merit experimentally measured for GaN thus far, but further improvements in the design can improve this metric even further.

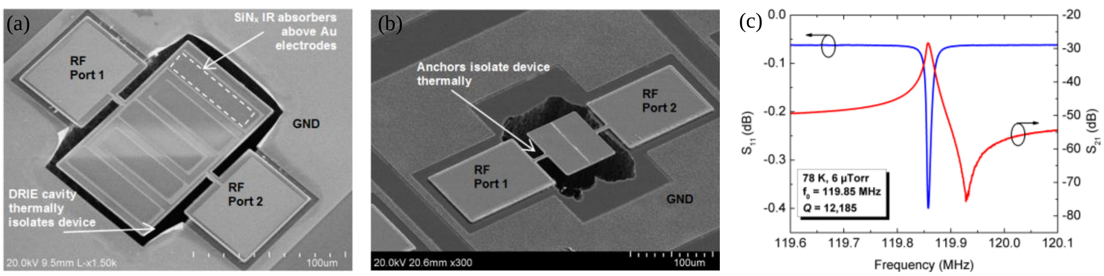

Figure 4. Scanning micrograph images of fabricated GaN resonators with dimensions (a) 120μm × 80μm and (b) 80μm × 60μm. Reducing area will improve the resolution of the proposed IR focal plane array. (c) RF performance of a 40μm × 80μm resonator with a Q of 12,185 (Q =8,000 at 300 K). This device demonstrated the highest $f \times Q$ for GaN so far.

4. PERFORMANCE

4.1 Measured performance

The IR performance of a fabricated device is given in Fig. 5. Comprehensive measurements and details of the test setup are provided elsewhere[8]. As shown in Fig. 5, perceptible shift in frequency is seen when the device is subjected to radiation in the near IR spectrum. While the preceding discussion has focused on measuring frequency shifts, it is also possible to design alternate sensing schemes that measure the shift in the insertion loss or bandwidth[8].

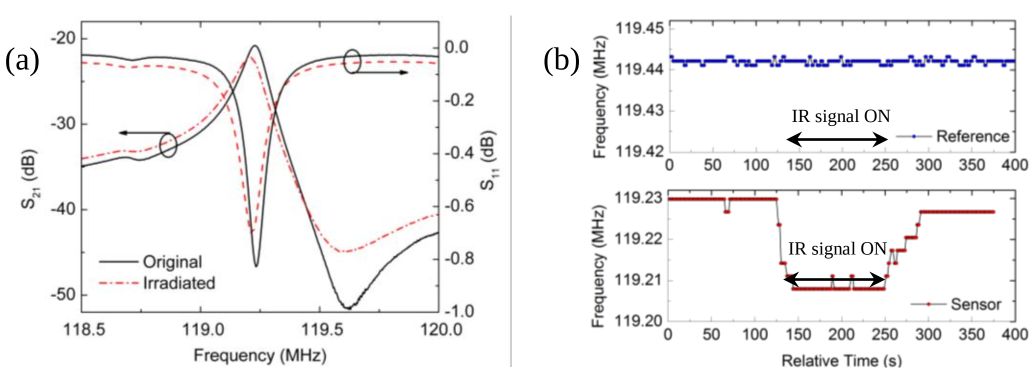

Figure 5: (a) The change in the frequency response of a 160 μm × 80 μm × 2.15 μm GaN resonator upon irradiation with ~56 μW of IR power (b) The change in the frequency of the sensor and a reference resonator with IR signal. Note that the reference resonator remains invariant while the sensor exhibits a large change of -21.8 kHz (-183 ppm). The two traces are shown with the same scale, but are at slightly different initial resonant frequencies due to fabrication variation.

4.2 Noise and limits of performance

The limiting factors on the performance of the resonant IR detectors are the minimum measurable frequency shift, below which interface circuitry would not be able to detect signals, and the noise floor. The frequency resolution can be improved by improving the Q of the resonator[14]. Improving Q is a subject that has been handled in depth from the perspective of design[15], material properties[16,17], and in specific circumstances involving GaN, using dynamic acoustoelectric interaction[11]. The dominant noise mechanism in thin-film mechanical resonators is the thermal fluctuation noise given by[4],

$$\Delta T = \sqrt{\frac{k_B T^2}{C_{th}}}, \tag{4}$$

The important metrics for comparison of thermal detectors are the detectivity (D^*_{th}) and the temperature fluctuation limited noise equivalent differential temperature (NEDT). For a proposed focal plane array of such detectors, these metrics are given by[18],

$$D^*_{th} = \left(\frac{\eta^2 A R_{th}}{4 k_B T_D^2}\right)^{1/2}, \tag{5}$$

$$NEDT = \frac{8F^2 T_D (k_B G_{th} B)^{1/2}}{\tau_{opt} \eta \beta A^{1/2}} \left[\left(\frac{\Delta P}{\Delta T}\right)_{\lambda_1 - \lambda_2}\right]^{-1}, \tag{6}$$

where, $F, \tau_{opt}, \eta, \beta, G_{th},$ and B are the focal number of the optical system, transmission of the optical window, detector surface absorption, fill factor, thermal conductance and frame rate. The term $\left(\frac{\Delta P}{\Delta T}\right)_{\lambda_1 - \lambda_2}$ is the derivative of the thermal power with respect to the source temperature in the range $[\lambda_1 - \lambda_2]$. Given a material system such as GaN, these parameters are largely dependent on the area of the resonator, and the details of the design. For the GaN resonators presented here, and assuming *f/1* optics with $\tau_{opt} = 0.7$ for the mid-IR range, and a 30 Hz frame rate, the theoretical estimates for these parameters at 300 K can be calculated. An NEDT of 1.12 mK with a noise floor of 4.8 μK is predicted. The detectivity of 3 $\times 10^8$ cm.Hz$^{0.5}$W^{-1} is estimated, which is still two orders of magnitude lower than the theoretical limit, leaving an opportunity for further development. An optimal design solution can be found for improving detectivity and NEDT, while ensuring that the spatial resolution of the FPA is high.

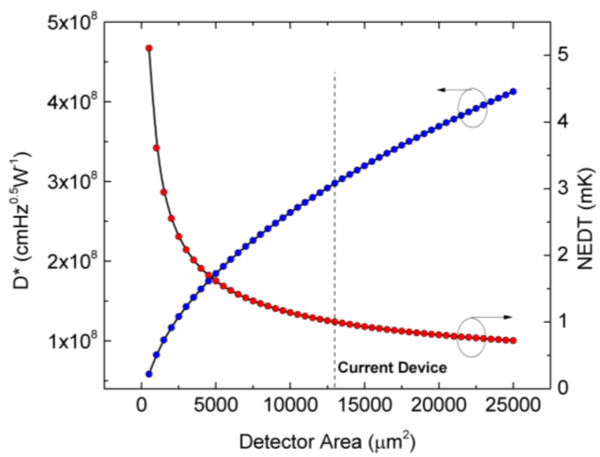

Figure 6. The analytically calculated values for D* and NEDT. The GaN resonator described in this work is modeled, with variation in area. The anchor dimensions are kept constant at 8 μm long and 4 μm wide.

5. CONCLUSIONS

The use of the resonant detectors presented in this work is the first step to realizing IR FPAs based on resonant sensors. While the detectivity of these devices will not be as high as photonic detectors, the broad band response, low noise, and uncooled operation provide an attractive alternative. The NEDT of this class of detectors is lower than some of the contemporary bolometric solutions, and will continue to improve with further development in micro and nanofabrication processes. The interface circuitry required to measure frequency shifts includes a high speed GaN transistor in a feedback loop with the resonator, forming an oscillator. However, different interfacial circuitry is possible, based on alternate methods of transduction, which allows a large amount of design flexibility based on the same resonator design.

Development of the CNT-polymer nanocomposite is a parallel task that has tremendous applications. Apart from its use as an integral part of the resonant IR detector, its low profile, low mass and density, near ideal absorptivity, and the ability to spray, spin or cast it onto a surface would make it an ideal paint for energy scavenging, thermal insulating, and IR radiation shielding applications.

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