Novel uncooled detector based on gallium nitride micromechanical resonators

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ABSTRACT

This work presents measured results demonstrating an uncooled infrared (IR) detector based on gallium nitride (GaN) micromechanical resonators. GaN-based photonic detectors are typically designed to operate in the ultraviolet (UV) regime as the absorption spectrum of wide-band gap GaN peaks at a wavelength of ~360 nm. In contrast, the transduction mechanism of the device presented in this work is the pyroelectric perturbation of a GaN micromechanical resonator, allowing the detection of radiation in the IR regime. IR radiation within the absorption spectrum of the resonating stack material (mainly the IR absorber) is converted into heat causing pyroelectric charge release, which in turn shifts the resonant frequency via changes in the acoustic velocity of GaN. A thin-film IR absorber based on carbon-nanotube nanocomposite is proposed, which offers IR absorptivity of more than 95%. As a proof of concept, we demonstrate a GaN resonant detector operated at 119 MHz, which exhibits an IR sensitivity of ~4 Hz/10nW.

Keywords: Uncooled IR detector, gallium nitride, resonant IR sensor, pyroelectric effect, electrostriction

1. INTRODUCTION

Uncooled Infrared detectors are smaller, lighter, and consume significantly less power compared to cooled photonic detectors and thus are better alternatives for micro-autonomous systems. However, the sensitivity and detection speed of uncooled (or thermal) detectors are inferior to their cooled counterparts. Therefore, there is a critical need for high-performance uncooled detectors. Most commercially popular uncooled devices rely on the bolometric principle, in which the IR radiation results in a change in the resistivity of a thin-film detector layer. Alternatively, IR radiation could be detected by monitoring the shift in the resonant frequency of a micromechanical element. This principle is used in resonant IR detectors, which also belong to the class of thermal detectors and have demonstrated promising results[1, 2].

This work presents a micromechanical resonator fabricated from single crystal gallium nitride as the primary sensing platform. The IR power is extracted from the change in the resonant characteristics of the device in response to incident IR radiation. Most resonant thermal detectors rely on the temperature coefficient of frequency (TCF) of the resonator to detect the thermally induced frequency shift. In this work, a new principle is used to achieve orders of magnitude higher sensitivity compared to conventional frequency shifting thermal detectors. GaN is a strong pyroelectric material[3] and incident IR radiation on the GaN surface results in the spontaneous generation of electric charge, and hence generates a voltage across the GaN film. This voltage causes an additional change in the resonant frequency that exceeds the TCF-induced change by orders of magnitude. The sensitivity of the detector is further enhanced using an additional thin film that could efficiency absorb the infrared power.

2. THEORY OF OPERATION

2.1 Thermal absorption of IR radiation

The sensitivity of the GaN resonator used as the IR detector is a function of the material properties of GaN, structural dimensions of the device, and IR properties of the absorber layer. The conversion of incident IR radiation into temperature change is given by[4],

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

where G_{th} is the effective thermal conductance of the device (dominated by the thermal conductance of the tethers), C_{th}

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is the thermal capacity of the device, ω is the rate of change of the incident signal and η is the absorption efficiency of the irradiated surface (Fig. 1(a)). The thermal resistance of the tethers and the heat capacity of the resonator are calculated based on established relations[4, 5].

The use of specially fabricated thin films and coatings on the surface of thermal IR detectors to improve the absorption efficiency (η) is an established practice. In many instances, highly absorptive materials such as carbon black, amorphous silicon nitride and metal blacks are used[6,7]. This method can be used on the GaN resonators as well, with the added constraint of having a coating that is thin and light enough so to not appreciably degrade the performance of the resonator via mass-loading. The fabricated GaN resonator prototypes presented in this work have 50 nm thick layers of amorphous SiN_x deposited on their top surface to act as IR absorbers. SiN_x has an absorption coefficient of between 10% and 20% in the near- and mid- IR range ($\eta_{SiNx} = 0.1$ to 0.2) (Fig. 1(c)). η can be increased to nearly 0.95 by the use of a special nanocomposite made from carbon nanotubes (CNTs) and poly-(methylmethacrylate) (PMMA), developed by the authors[8].

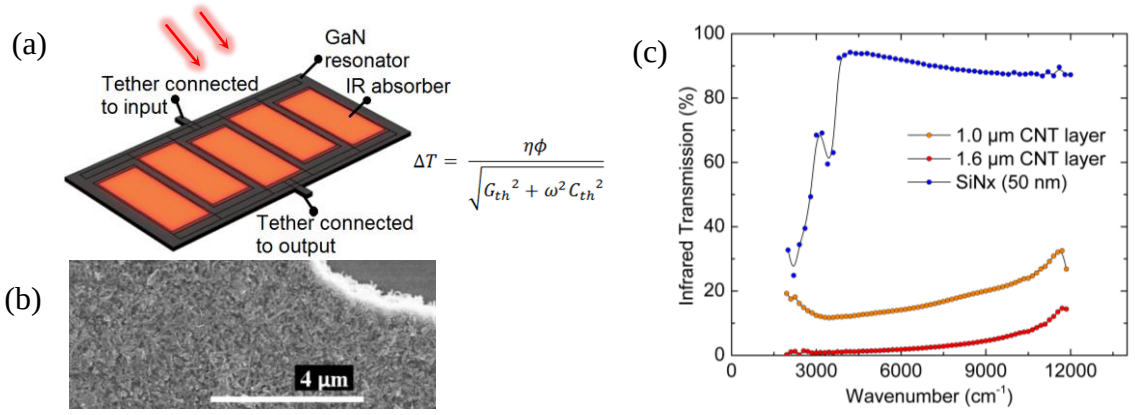

Figure 1: (a) Schematic showing the structure of a length-extensional GaN resonator, coated with silicon nitride absorber. (b) Scanning electron microscope image of a wafer coated with CNT-polymer nanocomposites that have near ideal broadband IR absorption, and shall replace the silicon nitride absorber. (c) 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[8].

2.2 GaN resonators as thermal detectors

GaN mechanical resonators and filters are promising components for high-power RF modules. GaN resonators based on piezoelectric actuation have been recently demonstrated by the authors[14-16] and other researchers[17, 18]. The mechanical resonance frequency for a length-extensional GaN resonator anchored at the midpoint by two tethers is given by,

$$f = \frac{n}{2L}\sqrt{\frac{C_{eff}}{\rho}} = \frac{nv}{2L}, \tag{2}$$

where C_{eff} is the effective stiffness, ρ is the mass density, n is the integer value for extensional mode number, and v is the effective acoustic velocity in GaN. When temperature changes due to absorbed IR radiation, the mechanical resonant frequency shifts due to the change in the elastic modulus of the resonating material. This material property is quantified as the temperature coefficient of frequency (TCF) and is measured to be -17.7 ppm/K for single crystal wurtzite GaN[14]. Other relevant electromechanical properties of GaN are given in Table 1.

Table 1: Thermal, elastic, piezoelectric, pyroelectric and electrostrictive properties of GaN.

Parameter	Value	REF.	Parameter	Value	REF.
Thermal conductivity	130 W m^{-1} K^{-1}	9	C_{11}	390 ±15 GPa	13
Specific heat capacity	490 J kg^{-1}K^{-1}	10	C_{12}	145 ± 20 GPa	13
Relative permittivity	9.28	11	C_{13}	106 ± 20 GPa	13
e_{31}	-0.33 C m^{-2}	12	C_{33}	398 ± 20 GPa	13
e_{33}	0.65 C m^{-2}	12	C_{44}	105 ± 10 GPa	13
P_V	7×10^5 V m^{-1} K^{-1}	3	M_{33}	1.2×10^{-18} m^2 V^{-2}	11

2.3 Pyroelectric perturbation

A temperature differential across a GaN film results in the spontaneous generation of electric surface charge (Q_c) due to the pyroelectric properties of GaN. Since only one face of the GaN resonator is irradiated, the thermal difference between the top and bottom of the resonator will result in a voltage across the device ($V_3 = Q_c/C$) . The pyroelectric voltage coefficient of GaN (P_V) is 7×10^5 $Vm^{-1}K^{-1}$ based on theoretical calculations[3]. The voltage difference across the thickness (t) of GaN is given by $V_3 = P_V t \Delta T$. This voltage V_3 and the corresponding electric field E_3 interact with the mechanical structure of the resonator due to the pyroelectric, piezoelectric, and electrostrictive properties of GaN. The piezoelectric strain along the length of the resonator is given by

$$\varepsilon_1 = \frac{e_{31} V_3}{c_{11} t}, \tag{3}$$

The strain in the length of the GaN resonator due to the linear piezoelectric interaction causes a corresponding change in the frequency of the resonator, which is given by

$$\frac{1}{f}\frac{\Delta f}{V_3} = -\frac{1}{L}\frac{\Delta L}{V_3} = -\frac{e_{31}}{c_{11} t}, \tag{4}$$

Numerically, this is a very small change, on the order of 0.5 ppm/V for the GaN film used here, and is not high enough to cause a perceptible shift in the resonant frequency. However, higher order strain-electric field effects play a significant part in GaN (in high field situations)[11]. As shown in the next section, electrostrictive effect in GaN plays a more significant role in shifting the resonant frequency upon IR radiation.

2.4 Electrostrictive dependence of GaN resonator frequency

Electrostriction is defined as the second order relation between mechanical strain and an applied electric field (where the first-order linear relation is the well-known piezoelectric effect). Under constant mechanical stress, the field dependent strain can be written as[11],

$$\varepsilon_{11} = d_{kij} E_k + M_{klij} E_k E_l, \tag{5}$$

Electrostriction in GaN has been considered by a number of researchers[11, 19] using *ab inito* principles and empirical data. The conclusion that is drawn from these studies is that GaN possesses a significant quadratic component in its electromechanical response. Willatzen and Lew Yan Voon[11] considered the case of a GaN thin film with AC and DC fields superimposed and derive the effect of the electrostriction on the acoustic velocity v of GaN. Following their analysis for the acoustic velocity along the resonator length, we get,

$$v = \sqrt{\frac{\epsilon'_{31} c_{11} + e_{31} e'_{31}}{\rho(\epsilon'_{31} + 2M_{31} E_3 e'_{31})}}, \tag{6}$$

where, $\epsilon'_{31} = (\epsilon_{31} - M_{31} E_3 e_{31})$, $e'_{31} = (e_{31} + M_{31} E_3 c_{31})$, and the coefficients ϵ, e and their corresponding primed counterparts represent permittivity and piezoelectric strain tensors, respectively. Based on the values for material properties of GaN, given in Table 1, the change in acoustic velocity in GaN per unit volt can be estimated (Fig. 2).

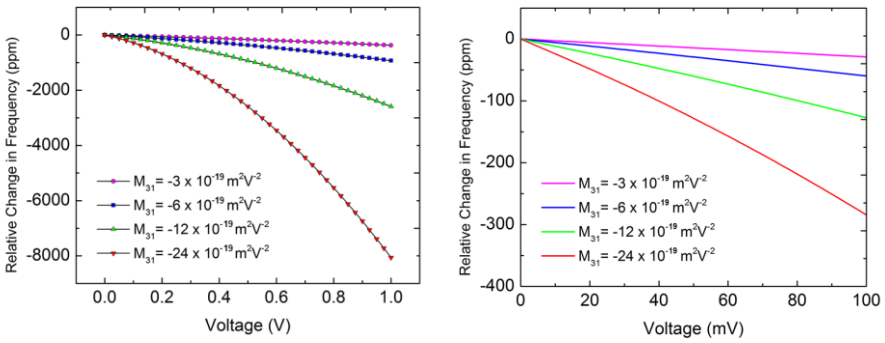

Figure 2: (a) The relative change in the resonant frequency of a length-extensional GaN resonator using the electrostrictive model for large voltages. The curve shows a marked quadratic nature. (b) For smaller voltages, the curve can be considered linear. Since the exact value for the electrostrictive coefficient M_{31} for GaN is unknown, we consider a range of values.

The values for M_{33} have been measured experimentally and estimated theoretically, but the values for M_{31} are unknown at this time. For the purposes of this model, we assume that M_{31} is half of M_{33}. Even using this conservative value, we get a relative change of -1000 ppm/V. Based on the pyroelectric perturbation equation, this translates to a change of -700 ppm/µm·K. For a 2.15 µm thick GaN resonator, the electrostrictive frequency shift becomes -1505 ppm/K, which is significantly larger than the combination of direct thermal effects (TCF, and piezoelectric strain) acting on the GaN resonator. This is a feature unique to GaN.

3. EXPERIMENTAL RESULTS

The experimental setup for measuring the frequency response of the GaN resonators is shown in Fig. 3(a). The fabrication details for the GaN resonators are provided elsewhere[16, 20]. A scanning electron micrograph (SEM) of the final device is shown in Fig. 3(b). The GaN sensor is placed in a temperature controlled probe station. IR energy is provided by a Tungsten-Halogen lamp and is coupled into the probe station using optical fibers. The RF performance of the GaN resonators is measured using an Agilent Vector Network Analyzer.

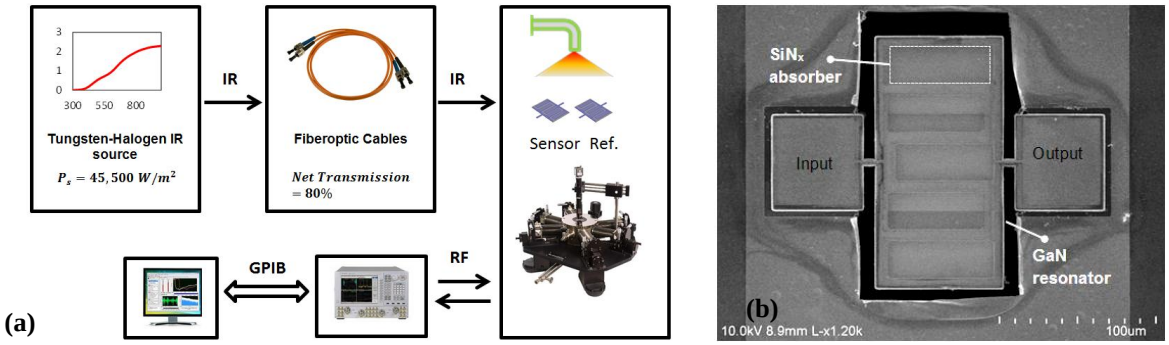

Figure 3: (a) Schematic showing the IR measurement setup of the GaN resonators. Both sensor and reference resonators are measured using an identical procedure. (b) A SEM image of a fabricated GaN resonator with SiN_x absorber.

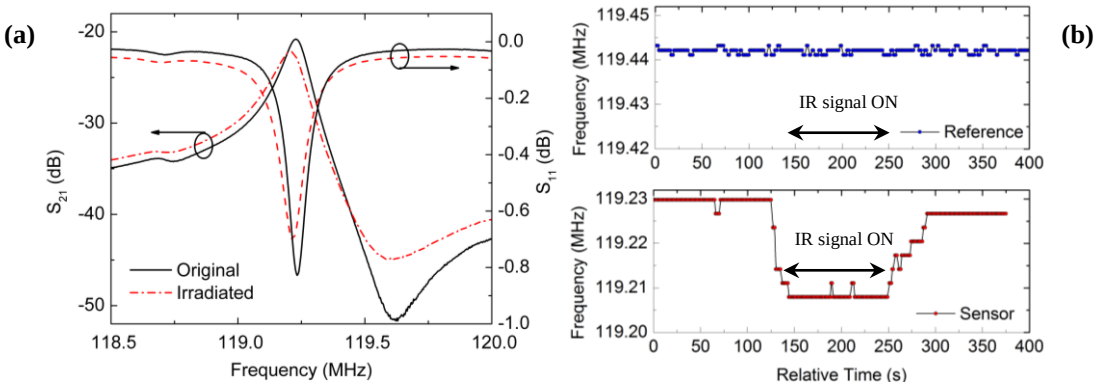

Figure 4: (a) The change in the frequency response of a 160 µm × 80 µm × 2.15 µm GaN resonator operated at its 5th length-extensional mode upon radiation with ~56 µW IR power (b) The change in frequency of sensor and a reference resonator on application of the IR signal. The reference resonator is identical to the sensor, except it does not have the SiNx coating. Note that the reference resonator remains invariant while the sensor exhibits a large change of -21.8 kHz (-183 ppm). The change in frequency upon IR radiation is 10% of the beat frequency ($f_{reference}$-f_{sensor}), which can be readily detected using a mixer.

The nominal RF response of the resonator and the subsequent change when it is subject to IR radiation is given in Fig. 4(a). Fig. 4 (b) shows the difference in the response of a sensor (with the SiN_x absorber) and a reference resonator (without the coating). The frequency change of the resonator can be accurately detected using the resonators in an oscillator loop and a mixer circuit. The oscillator needs an amplifier, which can be built using high electron mobility transistors (HEMTs) monolithically integrated with the GaN resonators on the same die.

Apart from the change in frequency, the resonator undergoes various other changes in its frequency response. The quality factor (Q) and the insertion loss (IL) both degrade, and bandwidth increases due to the addition of the thermal

energy to the resonant system. Fig.5 details the change in these parameters. The effective coupling coefficient, which is a parameter intrinsic to the GaN film, remains invariant as expected. These measurements are acquired concurrently with the frequency change of the sensor. Changes in these parameters can be used in different types of sensing schemes. Therefore, other interface circuitry measuring various resonator parameters can be used to detect the incident IR power.

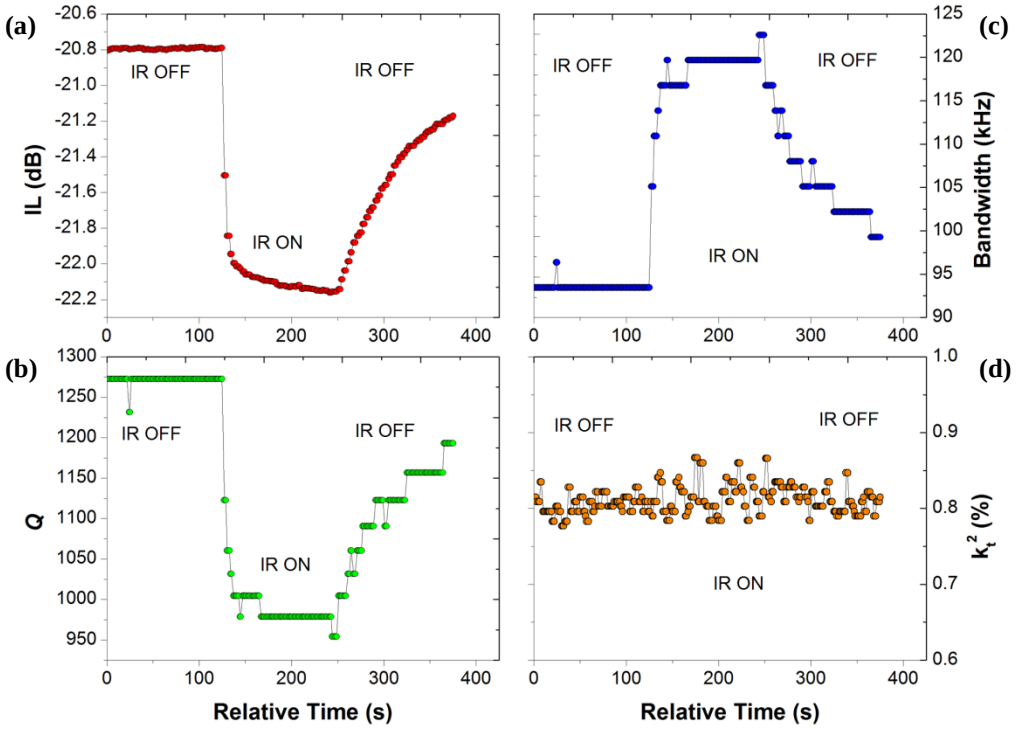

Figure 5: (a) Insertion loss, (b) *Q*, (c) bandwidth, and (d) effective coupling coefficient (k_t^2) of the resonator as functions of time when the IR signal is switched ON and OFF. These quantities can be used in alternate measurement schemes.

Based on the power output spectrum of the IR source, and taking into consideration fiber losses, we can calculate the power density incident on the resonator, subsequent thermal changes (Table 2) and the changes in the frequency response based on all the mechanisms mentioned above (Table 3).

Table 2. Heating of the GaN resonator.

Quantity	**Value**
Power density of lamp	45500 W m^{-2}
Power density after fiber losses, incident on resonator	36400 W m^{-2}
Power incident on resonator face (160 µm ×80 µm area with a fill factor of 0.61)	283.92 µW
Power absorbed by SiN_x, $\eta = 0.2$ (by CNT nanocomposite, $\eta = 0.9$)	56.8 (255.5) µW
Temperature change using SiN_x absorber (using CNT nanocomposite absorber)	192 (864) mK
Ideal time constant ($\tau = R_{th}C_{th}$)	291 µs

Table 3. Contribution of different effects in shifting the resonant frequency of the GaN resonant IR detector.

Mechanism	**Sensitivity (ppm/K)**	**Frequency change (SiN_x) (ppm)**	**Predicted frequency change (CNT nanocomposite) (ppm)**
TCF induced	-17.7	-3.3984	-15.2928
Piezoelectric (linear) strain	0.5	0.096	0.432
Pyroelectric – electrostrictive (quadratic)	-1505	-288.96	-1300.32
Measured frequency change (Sensor)	-	-183	-
Measured frequency change (Reference)	-	-13	-

4. CONCLUSIONS

In this work, we have presented a highly sensitive GaN resonant IR sensor with a silicon nitride thin film absorber. The various mechanisms of frequency change of the GaN resonator were explained. It was found that the combination of pyroelectric perturbation and electrostriction causes the largest change in frequency. As the coefficients used for the electrostriction have not been fully verified experimentally by researchers, we use conservative values in the expected range. To increase the IR sensitivity, a new absorber made from carbon nanotubes dispersed in a polymer can be used instead of silicon nitride. The CNT-based absorber has broadband, near-ideal absorption, and can increase the sensitivity by a factor of five. Fabrication of GaN devices coated with CNT-based IR absorber is currently underway.

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