SENSITIVE UNCOOLED IR DETECTORS USING GALLIUM NITRIDE RESONATORS AND SILICON NITRIDE ABSORBERS

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ABSTRACT

This paper presents the theory and measured results of a low-noise un-cooled infrared (IR) detector, which uses a combination of piezoelectric, pyroelectric, electrostrictive, and resonant effects to achieve high sensitivity. The sensor consists of a high-Q gallium nitride (GaN) micro-mechanical resonator coated with an IR absorber layer. The IR absorber converts the IR energy into heat. The generated heat causes a shift in the frequency characteristics of the GaN resonators. IR detection is achieved by sensing the shift in the resonance frequency of the exposed GaN resonator as compared to a reference resonator. A prototype GaN-based IR sensor is implemented, showing a frequency shift of 400 Hz per µW of absorbed power. The change in the beat frequency upon IR radiation is 1830 ppm/µW, making it possible to sense IR radiation in nano watts range.

INTRODUCTION

The detection of infrared radiation is generally accomplished using either photonic or thermal detectors, both of which have generated a large amount of research over the last two decades [1]. The relative disadvantages of thermal detectors in terms of detectivity and response time are balanced by the fact that they do not require cooling systems, reducing the system weight, power consumption, and form factor. Furthermore, thermal detectors are better suited for radiation extending into the far wavelength IR, which is extremely useful for optical astronomy. While bolometric devices have been the most popular thermal sensors commercially, there is an increasing interest in resonant IR detectors [2]-[4]. This work presents a GaN-based resonant IR sensor that utilizes the unique material properties of GaN to achieve high sensitivity. A reference resonator is included in the system for self-calibration (Fig. 1). Fig. 2 shows a representative scanning electron micrograph (SEM) of a GaN detector.
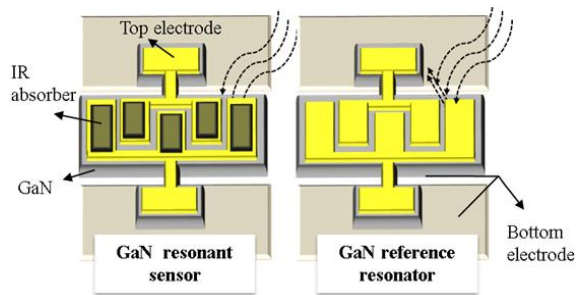

Figure 1: Schematic of a resonant sensor and a reference pair with interdigitated finger electrodes. The sensor is coated with an absorber layer. The reference resonator is either not coated with the absorber or the absorber layer on the reference resonator is blocked using the top electrode.

THEORY OF OPERATION
General Resonant IR detectors

In thermal IR detectors, radiation incident on the surface of the device increases its temperature. The conversion of incident IR
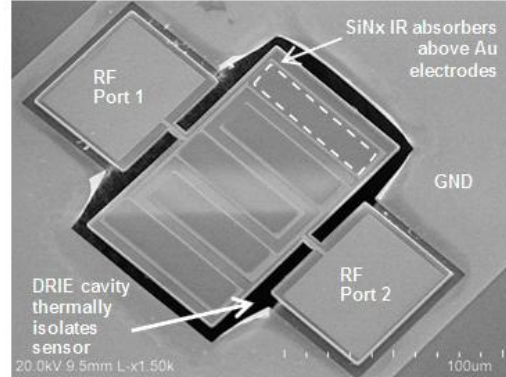

Figure 2: A SEM image of a fabricated GaN resonator with silicon nitride absorber. The dimensions of the device are 120 µm × 80 µm × 2.15 µm. The tethers are 4 µm ×10 µm.

radiation power $\phi(\lambda)$ into temperature change is given by [3]

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

where G_{th} is the effective thermal conductance of the device (dominated by the thermal conductance of the tethers), C_{th} is the thermal capacity of the device, ω is the rate of change of the incident signal, and $\eta(\lambda)$ is the absorption efficiency of the IR absorber layer. In resonant IR sensors, the resultant change in the resonator physical dimensions due to thermal expansion and the change in the elasticity of the resonator material are the main factors in changing the resonant frequency of the device [3]. The temperature-induced change in frequency is quantified by the well-known temperature coefficient of frequency (TCF). Broadly speaking, the temperature dependence of the material elasticity is the dominant factor in setting the TCF and puts an upper bound on the thermal sensitivity of the resonator. By designing the device in a dually-clamped configuration and allowing it to buckle with a change in temperature, it is possible to increase the temperature sensitivity beyond TCF. However, the non-linear nature of this buckling and the fabrication challenges involved in ensuring reliable and repeatable fabrication of devices near the buckling point make this a prohibitive exercise. A second way to increase the temperature sensitivity is to use a material that has an inherently large response to heat. Pyroelectric materials are suitable candidates for this application: a pyroelectric thin film generates a spontaneous surface charge and thus a potential difference across the thickness of the open-circuit film when the temperature of the film changes (e.g., upon IR radiation). The relationship between the pyroelectric voltage and the change in temperature of a film with thickness of *t* is given by,

$$V = P_V t \Delta T \qquad (2)$$

Most pyroelectric materials are also piezoelectric. In a resonator made from a pyro/ piezoelectric material, this voltage V can change the elastic properties of the resonator through linear

and second-order (electrostrictive) piezoelectric interactions. In this work, we use a combination of piezo and pyroelectric effects to achieve large temperature sensitivities in resonant IR sensors.

GaN Resonant IR detectors

GaN is an excellent choice of material for the proposed resonant IR sensor. GaN is a single crystal wurtzite material that can be grown as a high quality thin film using metallo-organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE). The piezoelectric nature of GaN has been used to make mechanical resonators in the past by the authors [5], [6] and other researchers [7], [8]. Along with this, GaN is known to be a pyroelectric, with a theoretical pyroelectric voltage coefficient (P_v) of 7×10^5 V/m-K, and measured P_v as high as 1×10^4 V/m-K [9]. GaN is also electrostrictive [10], [11]. In GaN, it has been found that a significant quadratic (electrostrictive) dependence of strain on electric field exists. Willatzen and Lew Yan Voon considered the case of a GaN thin film with AC and DC fields superimposed and derived the effect of the electrostriction on the acoustic velocity v of the material [11]. Following their analysis for the acoustic velocity along the resonator length, we get,

$$v = \sqrt{\frac{\epsilon'_{31}c_{11} + e_{31}e'_{31}}{\rho(\epsilon'_{31} + 2M_{31}E_3 e'_{31})}}, \qquad (3)$$

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. M_{31} is the electrostrictive transverse coefficient and E_3 is the electric field across the thickness of the film. The change in the acoustic velocity is directly related to the resonant frequency. For a length-extensional resonator we have

$$f = \frac{n}{2L}\sqrt{\frac{C_{eff}}{\rho}} = \frac{nv}{2L}, \qquad (4)$$

where C_{eff} is the effective stiffness, ρ is the mass density, and n is the mode of operation. Based on published values for the material properties of GaN and a M_{31} value of -6×10^{-19} m^2 V^{-2}, we get the relative frequency sensitivity to voltage as large as -1000 ppm/V (Fig. 3).

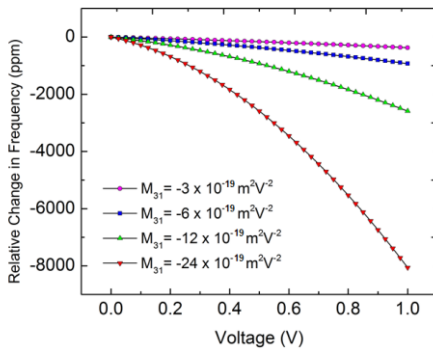*Figure 3: Predicted values of resonant frequency change due to electrostriction. For M_{31}= -6×10^{-19} m^2/V^2 (half of M_{33}) the relative frequency change is -1000 ppm/V (The accurate value of M_{31} is not known). The plot is derived based on the theoretical model for electrostriction in GaN [11].*

The pyroelectric-electrostrictive interaction of GaN can be utilized as the detection mechanism for implementing resonant IR detectors. For GaN resonators presented in this work, with a

thickness of 2.15 μm, and assuming a conservative value of 1×10^5 V/m-K for P_v, a temperature induced frequency shift of -215 ppm/K can be achieved, which is an order of magnitude greater than the measured TCF for GaN resonators (i.e., -17.7 ppm/K [5]). Thus, along with the TCF, the electrostrictive perturbation in GaN can be explored to enhance the sensitivity of thermal detectors.

Sensor Scheme

The IR sensors must be designed to work reliably at conditions that are sub-optimal for performance, in the presence of interfering signals due to shock, acceleration, and changes in ambient temperature. The best way to cancel out these interfering effects is to use a reference resonator that is similar to the sensor in all ways except one: the surface of the reference resonator does not have the absorber layer exposed. The small amount of density difference caused by the absorber and the expected variations in fabrication offset the frequency of the reference by a small amount, as compared to the sensor. This difference is enough to cause a small beat frequency which can be used as a reference to compare the frequency shift of the sensor with. In order to reduce this beat frequency, further design iterations of the reference can have the absorber layer, but coated with half the thickness of the top electrode. The frequencies of the two resonators can be described as functions of temperature by [12]

$$f_s(T_s) = f_s(T_0) + A_s\Delta T_s + B_s\Delta T_s^2 + \cdots \qquad (5)$$

$$f_r(T_r) = f_r(T_0) + A_r\Delta T_r + B_r\Delta T_r^2 + \cdots \qquad (6)$$

Neglecting non-linear temperature dependence, we can write the beat frequency as

$$f_B(T) = f_s(T_s) - f_r(T_r) = [A_s\Delta T_s - A_r\Delta T_r] + f_B(T_0) \qquad (7)$$

The subscripts *s, r,* and *B* indicate the sensor, reference, and beat frequencies, respectively. T_0 is the initial temperature. The coefficients A_i are the net coefficients of frequency change with respect to temperature, inclusive of all contributing mechanisms. Thus, the relative change in the beat frequency is a function of the incident IR radiation (Eq. 8). The beat frequency and the change thereof are easily measured using a mixer [12].

$$\text{IR sensitivity} = \frac{\Delta f_B/f_B(T_0)}{\phi(\lambda)} = \frac{[A_s\Delta T_s - A_r\Delta T_r]/f_B(T_0)}{\phi(\lambda)} \approx \frac{A_s\eta(\lambda)}{G_{th}f_B(T_0)} \quad (8)$$

EXPERIMENTAL RESULTS
Measurement setup

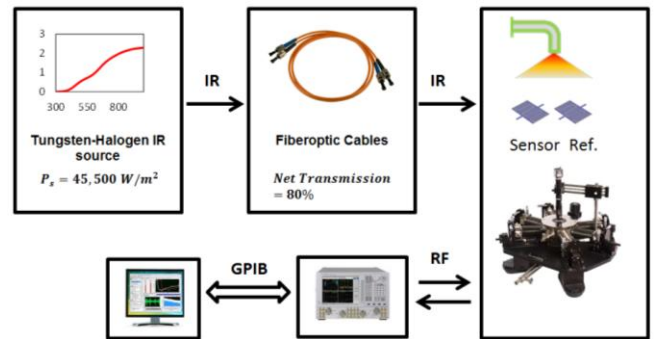The experimental setup for measuring the frequency response of the GaN resonators is shown in Fig. 4.

Figure 4: Schematic showing the IR measurement setup of the GaN resonators. Both sensor and reference resonators are measured using an identical procedure.

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.

Absorber Efficiency

As seen in Equation (8), a significant factor in setting the sensitivity is the absorptivity $\eta(\lambda)$ of the IR absorber layer. GaN is only selectively absorbing at UV wavelengths. Furthermore, the metal electrodes needed for piezoelectric actuation would have highly reflecting surfaces. For example gold is almost perfectly reflecting at any thickness above 17 nm [13]. One solution is to coat the electrodes with a material with higher absorptivity. In this work, the GaN resonators are coated with low temperature PECVD silicon nitride (SiN_x). Silicon nitride has an absorption efficiency of about 0.1 to 0.2 in the near IR spectrum (Fig. 5). To improve sensitivity, the absorber layer can be made out of carbon nanotube-based nanocomposites with an absorption coefficient of more than 0.9 over a broad spectrum [14].
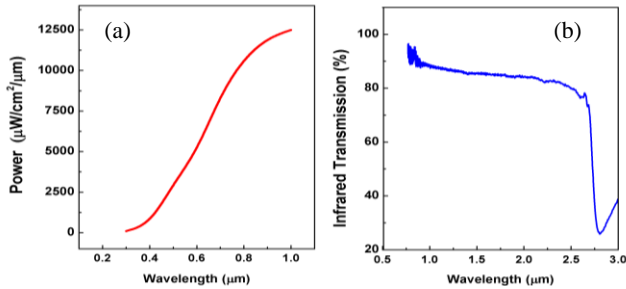

Figure 5: (a) Spectral distribution of the power supplied by the IR source. (b) Transmission spectrum for a 50 nm thick SiN_x film. In the relevant spectral range, < 1 μm, the film absorbs 10 to 20% of incident IR power. More efficient broadband absorbers can further improve the device sensitivity.

The nominal RF response of the resonator and the subsequent change when it is subject to IR radiation is given in Fig. 6. Based on the power output spectrum of the IR source, and taking into consideration fiber losses, we can calculate the power absorbed by the sensor to be 56 μW. Fig 7 shows the difference in the frequency response of this sensor and a reference resonator (without the coating). From Fig. 7, the relative shift in beat frequency is 22 kHz, which gives a sensitivity of ~1830 ppm/μW. The change in the reference frequency is only ~2 kHz, uncorrelated to the IR signal, and due to random fluctuations. This gives us a minimum detectable power of ~9 nW.
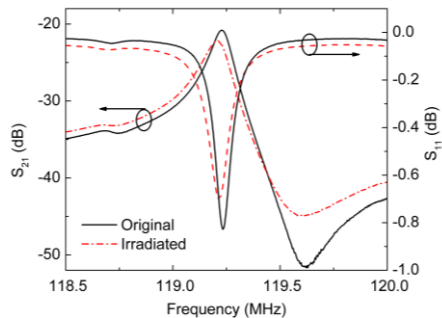

Figure 6: The change in the frequency response of a 160 μm × 80 μm × 2.15 μm GaN resonator operated at its 5th length-extensional mode upon radiation with ~56 μW IR power.
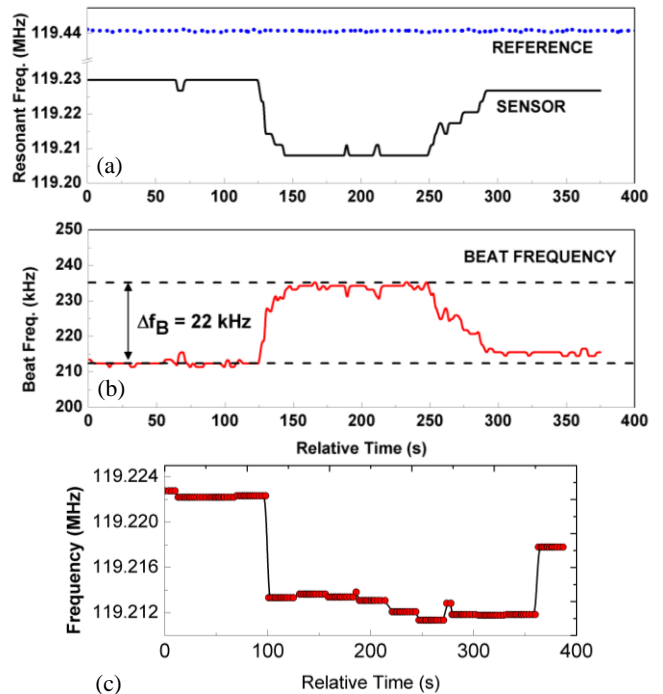

Figure 7: (a) The change in frequency of the sensor and a reference resonator on application of the IR signal. The reference resonator is identical to the sensor, except it does not have the SiNx coating. Beat frequency between the two exhibits a large change of -21.8 kHz (-183 ppm). The change in the beat frequency upon IR radiation is 10% of the original value. This can be readily detected using a mixer. (c) Faster scans reduce the overhead time due to the measurement system, but do not reduce parasitics.

The slow response seen in Fig. 7 is not the characteristic of the device, but rather of the thermal parasitics due to the probes, measurement speed, and delays inherent in the data acquisition system. We can verify this by acquiring faster (but less sensitive) scans (Fig. 7 (c)).
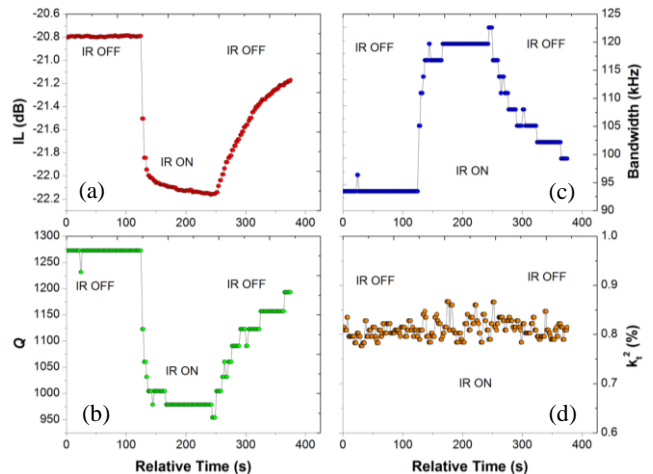

Figure 8: Figure 2: (a) Insertion loss, (b) Q, (c) bandwidth and (d) effective coupling coefficient (k_t^2) of the resonator as functions of the incident IR signal. These quantities can be used in alternate measurement schemes instead of frequency sensing.

Apart from the frequency, the resonator undergoes various other changes in its performance (Fig. 8) [15], [16]. The Q and the

loss both degrade, and the bandwidth increases due to the addition of the thermal energy to the resonant system. Changes in these parameters can be used in different types of sensing schemes. Table 1 shows relevant shifts in resonator parameters for three measured sensors. The measurement conditions are the same for all devices. The important metrics for comparison of thermal detectors are the detectivity ($\mathbf{D_{th}^*}$), response time, and thermal fluctuation noise floor (the dominant noise mechanism for mechanical resonators [3], [17]). For the range of resonator sizes in this work, the thermal noise floor is in the range of 1 µK to 10 µK at room temperature. Using this design, it is possible to achieve detectivity on the order of 1×10^9 cm.Hz$^{0.5}$.W^{-1}, with response time on the order of 1 ms (Fig. 9 (a)) [15]. Using better absorber layers, it is also possible to improve the sensitivity of the system (Fig. 9 (b)).

Table 1: Measured results for three different GaN IR sensors.

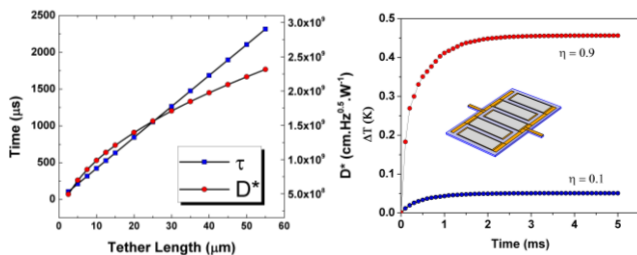|	Sensor 1 (Fig. 6)	Sensor 2	Sensor 3
Dimensions	160 µm × 80 µm	160 µm × 80 µm	120 µm × 80 µm
Original f$_0$ (MHz)	119.2267	119.4547	191.6475
Δf (kHz)	-21.861	-15.615	-10
Original Q	1272.566	813.83	2323
ΔQ	-318.33	-216.289	-406.63
Original IL (dB)	-20.804	-24.023	-16.522
ΔIL (dB)	-1.375	-1.309	-1.487

Figure 9: (a) D* and time constant as a function of the tether length. For the current resonator design, with an area of 160 µm × 80 µm, tether length of 20 µm gives an optimal value for these parameters. (b) The response time of 1 ms is verified using COMSOL simulations for this model (inset). Improving the absorber efficiency from 0.1 to 0.9 will improve the thermal sensitivity.

CONCLUSION

Resonant IR sensors made from GaN with a sensitivity of 1830 ppm/µW has been demonstrated using a sensor-reference pair. Utilizing a reference resonator enables large, perceptible changes in beat frequency due to irradiation, while cancelling out the effects of shock, acceleration, and ambient thermal change. A practical system would need further design optimization to get the best NEDT, D* and response time. The use of a broadband absorber with improved efficiency will improve the sensitivity of the detector by at least five times. Integration of the absorber and complete integration of the sensor-reference pair is ongoing work.

The interface circuitry required to measure frequency shifts can be co-fabricated on the same substrate, as GaN is a good material for high speed transistors. Alternate measurements schemes are also possible, using the same device. The use of the resonant detectors presented in this work is the first step to realizing IR focal plane arrays based on resonant sensors.

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