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Uncooled resonant infrared detector based on aluminum nitride piezoelectric film through charge generations and lattice absorptions

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This Letter demonstrates an aluminum nitride (AlN) based uncooled resonant infrared (IR) detector utilizing the photo-sensitive and piezoelectric properties of polycrystalline AlN. The AlN Lamb wave mode resonator is found responsive to IR illuminations by showing a decrease in the S_{21} magnitude instead of a resonant frequency shift. A -0.08 dB shift of S_{21} magnitude was observed for an IR incident power of 647 nW, which translates to a responsivity of 124 kdB/W. Photoresponse is proposed for the IR sensing mechanism through additional charge carriers generation rather than thermal effects. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4879024>]

Infrared (IR) radiation has many exciting and useful applications in different fields such as astronomy, military, and surveillance. IR detection is commonly accomplished by cooled photonic detection or uncooled thermal detection. Photon detectors measure the photocurrent that is converted from IR photons while thermal detectors absorb and convert the IR radiation energy into heat energy, resulting in a temperature rise, which then changes certain material properties that are measurable. Compared with photon detectors, thermal detectors have slower response times and lower overall performance. Nonetheless, without the need for cooling, they have the advantages of low weight, low power consumption, long term operation, low operation, and manufacturing cost.^{1–3} With the advances in silicon micromachining technologies, micro-electro-mechanical-systems (MEMS) types of thermal detectors have gained mounting attention due to improved thermal isolation structure and thus the device performance, especially in miniaturized and portable IR detection applications.

Among different types of thermal detectors, semiconductor-based resistive uncooled microbolometers are most favorable because they are relatively easy to fabricate compared with pyroelectric detectors⁴ and have a better responsivity than thermoelectric detectors.⁵ However, they are tardily facing bottleneck in performance optimization. In addition to background and thermal fluctuation noise, semiconductor-based microbolometers are susceptible to flicker ($1/f$) and Johnson noise, which inhibits their sensitivity enhancement.⁶ Therefore, there is an imminent need for novel technologies that could beat the sensing performance of photon detectors and yet retain the advantages of thermal detectors.

Resonant uncooled detector is gaining increasing interest in IR detection owing to the highest accuracy in frequency readout. The device $1/f$ noise can be neglected, thanks to high frequency (100 MHz–2.5 GHz range)

operation. Moreover, a resonator draws much less power than a resistor because no direct current (DC) is flowing through the sensing materials. By controlling the radio frequency (RF) power level, self-heating effect of the resonator can be minimized.⁷ The basic mechanism of a resonant IR detector is the detection of resonant frequency shift resulted from the thermal expansion induced strain and temperature dependent elastic constant upon the IR absorption.⁸ In recent years, quartz film bulk acoustic resonator (FBAR) IR detectors have been reported to possess a very good noise-equivalent-temperature-difference (NETD) of less than 5 mK.⁹ However, it is a great challenge to mass produce quartz detectors since they are non-scalable and incompatible with CMOS technology. To overcome this issue, different piezoelectric materials have been explored including GaN,¹⁰ ZnO,¹¹ and AlN¹² for IR sensing. Among these materials, thin AlN piezoelectric films with high quality and uniformity can be deposited at low temperature (~ 200 – 400 °C) by sputtering process on silicon substrates enabling post-CMOS integration processes.¹³ In this work, AlN resonator was proven to exhibit another photo-sensitive property when exposed to IR in addition to the thermal effects.

The SEM image of the fabricated IR detector is shown in Figure 1(a) with the A-A' schematic cross-sectional view depicted in Figure 1(b). The device consists of a conventional AlN MEMS resonator with only one-sided Mo (200 nm thick) standard interdigitated transducer (IDT) electrodes at the top surface of AlN film ($48\text{ }\mu\text{m} \times 48.8\text{ }\mu\text{m} \times 1.25\text{ }\mu\text{m}$). The Mo IDT electrode pitch is $2\text{ }\mu\text{m}$ with the metallization ratio of 1. The AlN resonator was passivated by SiO₂ (300 nm thick at bottom and 450 nm at top of AlN) to prevent the Mo electrodes from corrosion by XeF₂ during release process. A layer of 100 nm thick SiN was deposited on top of the device for IR absorption or anti-reflection.^{14,15} Resonant frequency, f_o of the AlN resonator can be determined by (1) and (2), where v is the acoustic velocity, c_{ij} is the elastic constant, and ρ is the mass density of AlN. Resonance occurs when IDT electrode pitch, p is an integer multiple of half acoustic wavelength, λ ³

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FIG. 1. (a) SEM image of the fabricated AlN-based IR detector and (b) its schematic cross-sectional view.

$$f_o = v/\lambda, \quad (1)$$

$$v = \sqrt{c_{ij}/\rho}. \quad (2)$$

Figure 2(a) plots the measured S_{21} -frequency curve of the AlN resonator. Two resonant modes were observed, lateral-extensional mode and thickness-extensional mode. In this work, the IR sensing operation was based on lateral-extensional mode because it is less sensitive to mass loading and piezoelectric film thickness uniformity.⁸ The measured S_{21} of the lateral-extensional mode was fitted

FIG. 2. (a) The measured resonant behavior of the AlN-based IR detector with the (b) fitted S_{21} magnitude and phase of the lateral-extensional resonant mode in two-port configuration.

with modified Mason lumped circuit model as depicted in Figure 2(b)^{16,17} where R_f , R_p , and C_f are the parasitic components, C_o is the static capacitance of the device, R_m , C_m , and L_m are the motional components. The discrepancy between fitting model and experimental data near the parallel resonance is attributable to a small spurious signal. The AlN resonator has a resonant frequency, f_o , of 2.026 GHz, quality factor, Q_s , of 1197 and effective coupling coefficient, k_t^2 , of 0.09%. An effective temperature coefficient of frequency (TCF) of about -3.3 ppm/K was obtained for the IR detector as delineated in Figure 3(a). This is a rather low value compared with the reported value because of the positive TCF of SiO_2 which counteracts the negative TCF of AlN.⁸ Regardless the low TCF, the improved Q_s and k_t^2 values at 120°C (see Figure 3(b)) manifest that the AlN resonant detector is advantageous for high temperature sensing applications.

To characterize the IR sensing properties of AlN resonator, blackbody source (BS) was used to provide a spectrum of IR irradiation on the resonator. A ZnSe optical filter from Korth Kristalle GmbH with transmitted wavelength of 0.5 to $20\ \mu\text{m}$ and a $725\ \mu\text{m}$ thick single crystal Si wafer (bandwidth of 1.12 eV), acting as an IR filter, were used to permit only IR with wavelength longer than $1.1\ \mu\text{m}$. Figure 4(a) illustrates the frequency response of the AlN resonator around the resonant point at different BS temperatures. There is no significant shift in resonant frequency but only a downshift of S_{21} magnitude across the frequency span observed under IR illumination. This phenomenon is different from other reported piezoelectric resonant IR detectors.^{10–12} COMSOL

FIG. 3. (a) The temperature dependent resonant frequency of the AlN-based IR detector; (b) fitted S_{21} magnitude and phase of the device at 120°C .

FIG. 4. (a) The measured S_{21} magnitude of the AlN-based IR detector under different blackbody source temperatures (BSxxx = blackbody source with xxx °C temperature; Si = Si wafer filter). (b) The shift of S_{21} magnitude with increasing IR incident power.

Multiphysics tool was then employed to estimate the temperature profile of the AlN resonator as shown in Figure 5. An IR incident power, P_{IR} , of 647 nW, corresponding to BS temperature of 1000 °C, causes almost no change in the AlN resonator temperature even assuming a full absorption because of the inefficient thermal isolation of the AlN film with anchors of $5 \mu\text{m}$ wide $\times$ $12 \mu\text{m}$ length.

However, it is worth noting that the downshift of S_{21} magnitude increases with BS temperature and P_{IR} (see Figures 4(a) and 4(b), respectively). A smaller shift of S_{21} magnitude was observed with additional Si wafer filter which proves that the IR detector is responsive to IR wavelength longer than $1.1 \mu\text{m}$. At BS temperature of 1000 °C (P_{IR} of 647 nW), about -0.08 dB shift of S_{21} magnitude was obtained corresponding to a responsivity of 124 kdB/W. With the intermediate frequency (IF) bandwidth of 1 kHz and standard

FIG. 5. The temperature profile of the AlN-based IR detector simulated at P_{IR} of 647 nW.

FIG. 6. Comparison of IR sensing performance of the AlN-based IR detector under ambient (Amb) and vacuum (Vac) condition at BS temperature of 1000 °C (BS1000) with and without Si wafer filter (Si).

stepped sweep mode (sweep time of 178 ms), a root mean square (RMS) noise of about 1148 μdB was obtained by an Agilent E5071B network analyzer. The device detectivity and noise-equivalent-power (NEP) were estimated to be $1.65 \times 10^7 \text{ cm}^2/\text{Hz}/\text{W}$ and $2.93 \times 10^{-10} \text{ W}/\sqrt{\text{Hz}}$, respectively, with the measured noise spectral density of 36.3 $\mu\text{dB}/\sqrt{\text{Hz}}$. The IR performance of the device was then compared under ambient and vacuum conditions. Figure 6 delineates no significant difference between the ambient and vacuum measurement results. Only a small downshift of resonant frequency was observed in ambient measurements because of the additional atmosphere damping under ambient. This observation strongly proves that there is no thermal effect involved in the S_{21} magnitude downshift upon IR illumination.

To investigate the aforementioned phenomenon, capacitance of the device, C_{AlN} , was measured across the Mo IDT electrodes at frequency of 100 kHz and plotted in Figure 7. The value of C_{AlN} rises by about 2.3 fF and 8.1 fF upon IR illumination with and without Si wafer filter, respectively, under both vacuum and ambient conditions. Table I compares the change of capacitance values obtained by measurement (ΔC_{AlN}) and extraction from modeling (ΔC_o) upon IR exposure. There is an obvious discrepancy between ΔC_{AlN} and ΔC_o because C_{AlN} is mainly contributed by the fringing field between the Mo IDT while C_o includes the plate capacitance of AlN. Thus, ΔC_o is much larger than ΔC_{AlN} . Also, the frequency-dependent capacitance and dielectric loss play

FIG. 7. Capacitance measurement of the AlN-based IR detector under ambient (Amb) and vacuum (Vac) condition at BS temperature of 1000 °C (BS1000) with and without Si wafer filter (Si). The yellow highlighted area indicates the IR illumination from BS.

TABLE I. The change of capacitance of AlN resonant IR detector under IR illumination.

Measurement condition	ΔS_{21} (dB) by measurement	ΔC_o (fF) by modeling	ΔC_{AlN} (fF) @ 100 kHz
BS1000 ^a	-0.08	+40	+8.3
BS1000 + Si ^b	-0.02	+30	+2.1

^aMeasurement was done under BS temperature of 1000 °C.^bMeasurement was done with silicon IR filter under BS temperature of 1000 °C.

the role to a certain extent in the difference in ΔC_{AlN} and ΔC_o . Nevertheless, both C_{AlN} and C_o increases under IR irradiation. Therefore, it proves that there are additional charges generated at Mo IDT interface during IR illumination which is believed to contribute to the S_{21} magnitude downshift of the AlN resonator. The parasitic capacitance associated with silicon substrate is mainly attributed to the large contact pads. However, the contact pads are made of 700 nm Al, which is very reflective to IR. Thus, it can be safely assumed that the parasitic capacitance is insensitive to IR illumination.

An undoped single crystal AlN is a semiconductor with a direct bandgap of 6.2 eV, corresponding to photon wavelength of 200 nm. The photon energy of IR wavelength longer than 1.1 μm (<1.12 eV) is not sufficient to enable the band-to-band intrinsic transition. The detection of additional charges through the capacitance measurement can be explained by the free carrier absorption. These carriers can arise from lattice defects and impurities in the polycrystalline AlN film created during sputtering deposition process. There are always impurities exist in AlN film such as oxygen, carbon and silicon in addition to nitrogen and aluminum vacancies.^{18,19} Oxygen is a major residual impurity with a significant amount in even the single crystal AlN,^{18–21} which can cause irregular crystallization and formation of lattice dislocations and defects. It is believed that the charge carriers get excited into a higher energy state from these defects localized energy states during IR irradiation, which then contributes to the photo-sensitive property of polycrystalline AlN film. The similar observation has also been reported in the visible light wavelength range.²²

On the other hand, the increase in C_{AlN} can also be attributed to the possible lattice absorptions in AlN.^{19,23–25} As the electronegativities of Al (1.61) and N (3.04) are very different, there is a significant ionic characteristic in the chemical bonding of AlN. Thus, single phonon Reststrahl absorption can occur where the incident IR radiation can couple with the oscillating electric field produced by the electrostatic motions of opposite charges. In principle, ionic compound exhibit good transmission with constant refractive index and low absorption coefficient up to the lattice absorption band (typically >10 μm wavelength for AlN^{25–27}) at which point the single phonon generates a heavily absorbing mode of vibration and subsequent strong reflection coefficient. The refractive index and extinction coefficient rises rapidly at the resonant Reststrahl frequency. Since dielectric constant is approximately proportional to the square of refractive index, C_{AlN} increases upon IR radiation due to the

increase in dielectric constant. More than one absorption band with weaker peak can present in AlN corresponding to the multi-phonon transitions due to inharmonic terms²³ or defect-induced electric dipole moment.¹⁹

In summary, the polycrystalline AlN piezoelectric resonator has been experimentally demonstrated to be responsive to IR radiation with a responsivity of 124 kdB/W , detectivity of $1.65 \times 10^7 \text{ cm}\sqrt{\text{Hz/W}}$ and NEP of $2.93 \times 10^{-10} \text{ W}/\sqrt{\text{Hz}}$. Since there is no difference between vacuum and ambient measurements, it is concluded that thermal effect is not involved in the IR sensing mechanism. Additional charges generation resulted from defect-induced carrier transitions within the localized energy states within the AlN film is proposed. Furthermore, Reststrahl absorptions can alter the dielectric constant of AlN due to the change of refractive index. In any event, the capacitance of AlN will rise upon IR radiation, and it was experimentally proven. An in depth study and investigation is needed for a quantitative explanation of the charge generation within the AlN film.

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