HIGH-QUALITY FACTOR, HIGH TCF SCANDIUM ALUMINUM NITRIDE MEMS RESONATOR FOR LOW-NOISE INFRARED SENSING

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ABSTRACT

This paper reports on the demonstration of a groundbreaking, high-sensitivity gas sensor based on a Scandium Aluminum Nitride (ScAlN) MEMS resonator integrated with plasmonic absorbers for spectrally selective IR sensing. The device achieved ≈ 75% absorptance at 4.5 µm, a mechanical quality factor (Q_m) approaching 2000, and an electromechanical coupling (k_t^2) of 2.7%. To the best of our knowledge, such a high Q had never been demonstrated before for ScAlN MEMS resonators with bottom interdigitated electrodes (allowing absorber integration on the top). Moreover, we showcased a notable advancement by adopting a novel material stack: AlN as the dielectric material for the Metal-Insulator-Metal (MIM) plasmonic absorbers, coupled with 30%-doped ScAlN for the resonant cavity. This strategic choice significantly improved the sensor's sensitivity, doubling it compared to previous implementations, by boosting both the device's Temperature Coefficient of Frequency (TCF) and its thermal resistance, leveraging ScAlN's superior thermal properties over AlN.

KEYWORDS

Chemical Sensing, Infrared Detector, Plasmonic Absorbers, Resonant Sensor, Scandium Aluminum Nitride, MEMS

INTRODUCTION

The growing demand for highly accurate and miniaturized infrared (IR) sensors is of critical importance to a variety of applications. These compact yet sophisticated sensors are finding multiple applications across various sectors, including consumer electronics, healthcare, and industrial automation [1]. Their ability to deliver precise data in small packages not only enhances the functionality of existing devices but also unlocks new possibilities for innovation in fields such as remote sensing, security systems, and environmental monitoring.

Recently, an innovative strategy combining piezoelectric Aluminum nitride (AlN) Contour-Mode Resonators (CMRs) with plasmonic metamaterials (Fig.1) has been proposed for the implementation of extremely sensitive and miniaturized IR sensors [2]. These sensors come with notable benefits such as minimal power consumption, CMOS-compatibility and remarkably high detection accuracy. Their operational concept generally relies on a closed-loop oscillator circuit that incorporates a MEMS resonator sensitized to IR radiation. As the impinging IR radiation gets absorbed by the resonator surface and converted into thermal energy, the consequent temperature increase induces a shift in the resonator's center frequency hence the output frequency of the oscillator. In this case, metal-insulator-metal (MIM) plasmonic absorbers are preferred over other IR absorbers owing to their lithographic tunability and high absorptance [2].

To excite the high-order contour mode of vibration within the piezoelectric layer, a commonly adopted configuration involves employing an interdigitated transducer (IDT) as the top electrode and utilizing an unpatterned floating plate as the bottom electrode [3]. This choice promotes the growth of a superior-quality, c-axis oriented piezoelectric film, ultimately leading to a high-quality factor. However, in our proposed sensor the floating plate serves a dual role, functioning both as the top electrode for the resonator and as the ground plate within the stack of MIM absorbers. Consequently, the IDTs are positioned at the bottom of the piezoelectric layer. This complicates the fabrication process, especially when aiming for high-quality factors.

Moreover, recent advancements have demonstrated the effectiveness of doping AlN with high concentrations of Scandium (Sc) as a viable method for enhancing the temperature coefficient frequency [4]. While a substantial Temperature Coefficient of Frequency (TCF) is typically seen as undesirable in most of applications and is usually compensated for, it proves advantageous in resonant thermal IR-sensing, where large acoustic property variations due to temperature fluctuations enhance system sensitivity and accuracy. Additionally, other studies have demonstrated that ScAlN achieves a thermal resistance two orders of magnitude higher than that of AlN, making it an ideal candidate for our detector, as the device's thermal resistance directly correlates with the sensor's sensitivity [5][6]. However, in previous implementations this enhancement comes at the cost of a reduced quality factor, particularly evident when Scandium concentrations exceed 20%, primarily due to constraints in material quality [7].

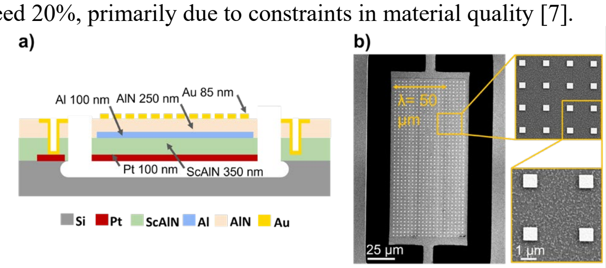

Figure 1: (a) Schematic cross-sectional view of the ScAlN resonator with plasmonic absorbers. (b) Top view SEM image of the fabricated resonator with plasmonic MIM absorbers.

EXPERIMENTAL RESULTS

In pursuit of optimal design, diverse geometries were meticulously explored to maximize the thermal resistance, quality factor, and electromechanical coupling of the devices. Additionally, a comprehensive characterization and optimization procedure was undertaken to maximize the quality of both piezoelectric materials and metals. Since, we believe that the quality of the ScAlN and, consequently, the Q of the resonator are closely linked to the quality of the underlying surface, we developed and optimized an LOR process aimed at refining the edges of the bottom electrode and eliminating the fencing, resulting a high quality c-axis oriented scandium film, with a rocking curve (RC) of 2.5°, as depicted in Fig.2.

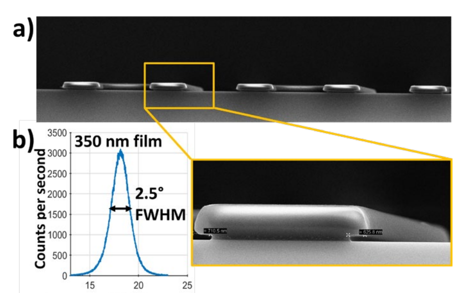

Figure 2: (a) Cross section SEM image of the bottom electrodes using the LOR process. (b) FWHM of the 350nm ScAlN film.

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The devices were fabricated successfully using a meticulous six-mask process, followed by measurement using a vector network analyzer (VNA) to assess their electromechanical performance. A remarkably high Q (Q_m~2000) and the electromechanical coupling (k_t^2~2.7%) were extracted, illustrated in Fig.3. The temperature coefficient of frequency (TCF) was also determined by conducting repeated admittance measurements across a range of temperatures using a heated stage, resulting in an estimated value of approximately -40 ppm/C. This represents a notable enhancement over previous implementations that relied on SiO_2 as the dielectric and AlN as the piezoelectric layer, which exhibited a TCF ≈-29 ppm/C [8]. This notable enhancement directly boosts the effectiveness of our sensor, as it aligns with increased sensitivity.

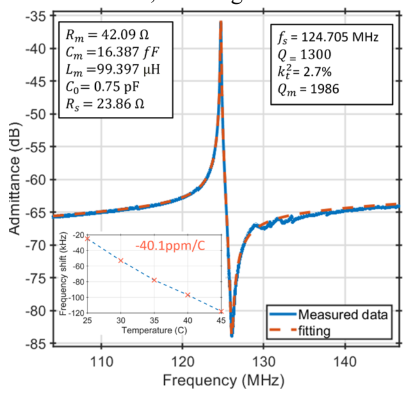

Figure 3: Admittance response of the measured resonant IR sensor and the corresponding mBVD fitting.

An FTIR measurement was also conducted to extract the IR absorption efficiency of the devices. The metamaterial IR spectral absorption (η_{peak}~75%) was extracted near the targeted wavelength (4.5µm). This wavelength aligns with the absorption spectrum of CO_2 and N_2O.

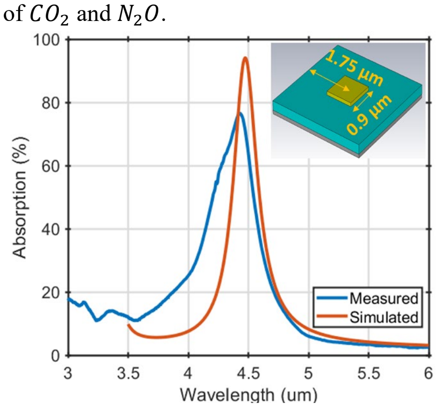

Figure 4: CST simulation of the absorption efficiency of the absorbers and the FTIR measurement of the fabricated device

To test the sensor responsivity to IR light, the device was placed under a quantum cascade laser center around 4.53μm (as shown in Fig.5). The total optical power delivered to the resonator was estimated to be 3.8 μW and resulted in a shift (Δf) of 4.25 kHz. This observed shift corresponds to a remarkable responsivity of 1.118 Hz/nW, doubling the performance of the previously showcased AlN/SiO_2 thermal detector, which had a reported responsivity of approximately ~0.6 Hz/nW [2].

Additionally, the thermal resistance and thermal time constant (τ) of the devices were found to be 8.33x10^4 K/W and 2.1ms, respectively.

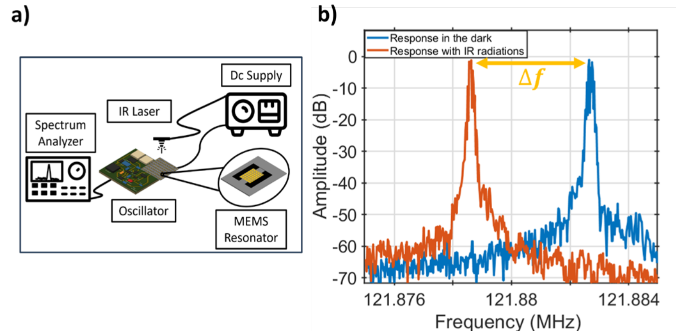

Figure 5: IR-induced frequency shift in the device and experimental set-up with IR source.

These remarkable high *Q devices* enabled the implementation of a low-noise Pierce oscillator, exhibiting a phase noise of -86 dBc/Hz @ 1kHz offset and a noise equivalent power (NEP) of 628 pW/Hz$^{1/2}$. In comparison, using a 600 Q resonator in the same circuit resulted in a phase noise of -77 dBc/Hz and an NEP of 1.838 nW/Hz$^{1/2}$.

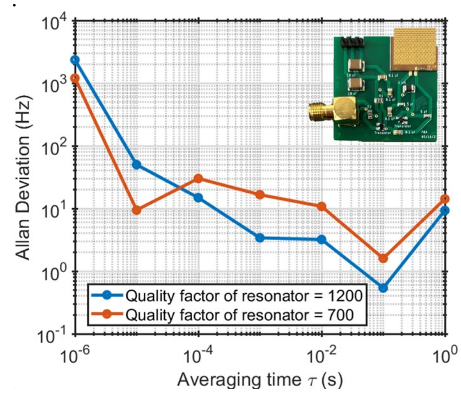

Figure 6: Measured Allan Deviation of the oscillators.

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