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Ulrich Youbi, Sami Hage-Ali, Qiaozhen Zhang, Yang Yang, Demba Ba, et al.. High-Q Wireless SAW Sensors Based on AlN/Sapphire Bilayer Structure, Operating at 2.45 GHz Range for High-Temperature Applications. IEEE Sensors Letters, 2024, 10.1109/LSENS.2024.3419213 . hal-04628257

HAL Id: hal-04628257

<https://hal.univ-lorraine.fr/hal-04628257>

Submitted on 28 Jun 2024

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High-Q Wireless SAW Sensors Based on AlN/Sapphire Bilayer Structure, Operating at 2.45 GHz Range for High-Temperature Applications

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Received
published

Abstract—This work deals with the potential of the Al/AlN/Sapphire surface acoustic wave (SAW) structure as wireless sensor operating in the 2.45 GHz ISM band for high-temperature applications up to 500 °C. A first design was used to make SAW resonators by e-beam lithography and characterize them between room temperature and 500 °C in a wired configuration. Frequency variation with temperature showed good stability, repeatability, linearity, and sensitivity with a measured temperature coefficient of frequency (TCF) of -47 ppm/°C. The figure of merit, defined by the product of the electromechanical coupling coefficient and the quality factor, value varies between 0.8 and 2 throughout the whole temperature range, proving the potential of the structure for wireless interrogation at high temperature. Consequently, the SAW resonator was successfully wirelessly interrogated up to 500 °C at a distance of 1 m. Moreover, wireless interrogation of the sensor was possible up to 3 m at room temperature, with additional path losses of 19 dB, which could prove troublesome for operating temperatures above 400 °C. An optimization of the SAW resonator design was then subsequently carried out by simulation means in order to improve the figure of merit and allow wireless interrogation at higher temperatures and greater distances.

Index Terms—Sensors, Wireless, Batteryless, Surface acoustic waves, AlN, Sapphire, High temperature, FEM/COM simulation

I. INTRODUCTION

Surface acoustic wave (SAW) sensors, initially used as filters and resonators in communications systems, have undergone significant expansion in the sensor field over the last two decades [1]. Their high sensitivity to the variations of physical parameters, such as the temperature, has made them valuable tools for in situ measurements in a variety of physical and chemical processes requiring high temperatures. Unlike traditional measurement techniques, such as thermocouples, resistance temperature detectors (RTDs) and pyrometers, which involve cables or a direct optical path, SAW sensors offer the advantage of passive measurement, with no need for batteries or embedded electronics for their wireless interrogation. However, designing SAW sensors for high-temperature applications presents challenges, particularly regarding the choice of the sensor constitutive materials, including the piezoelectric substrate and electrode thin film [2]. Currently, langasite is recognized as the reference substrate for high temperature SAW applications [3-5]. Wireless SAW sensors based on langasite can operate up to 600 °C [6]. Unfortunately, this material also has significant drawbacks, including a drastic increase in propagation losses with frequency and temperature, thereby limiting its use at high temperatures to frequencies around 1 GHz [3]. In this context, the AlN/Sapphire combination has proved to be a promising alternative to langasite, offering outstanding high-temperature properties [7-11]. AlN/Sapphire structure exhibits very low acoustic propagation losses even at high frequencies [12], enabling the design of devices

operating in ISM frequency bands over 2 GHz. Moreover, AlN does not oxidize up to 600 °C, and oxidation remains very limited at 700 °C thanks to a thin protective layer of Al₂O₃ [7]. In this paper, we present high quality factor AlN/Sapphire SAW sensors operating in the 2.45 GHz ISM band, and demonstrate their wireless interrogation up to 500 °C. The paper is organized as follows: in Section II, we present the design and fabrication of the resonators. Results including impedance measurements and the wireless interrogation of SAW temperature sensors are described in Section III. To improve interrogation distance and enhance sensor performances, optimisation of the SAW resonator design is conducted and described in section IV. Section V summarizes and concludes this work.

II. INITIAL DESIGN AND FABRICATION

In order to explore the potential of the AlN/Sapphire structure at high temperatures, a first, slightly asynchronous, SAW resonator operating at 2.45 GHz was manufactured. The resonator consists of an interdigital transducer (IDT) made up of 100 pairs of fingers and of 300 reflectors on each side of the IDT, forming an acoustic Bragg mirror. The spatial period of the IDT (λ) was 2.3 μm , while the spatial period of the reflector was 2.29 μm . The metallization ratio of the reflectors and IDT was 70% and 60% respectively. The device aperture was set at 41.5 λ and the value of the gap between the IDT and the reflector was 0.478 μm .

AlN/Sapphire was purchased from MTI corporation (Richmond, CA) and consists of 1 μm -thick epitaxial (002) AlN thin film deposited by MOCVD on (0001) sapphire crystal. The fabrication process

began with the spin-coating of a positive PMMA resist bi-layer on the AlN/Sapphire substrate, followed by electron-beam lithography (Raith 150-II, Raith GmbH, Dortmund, Germany) and MIBK developing. An 80 nm thick aluminum layer was then deposited by electron beam evaporation and patterned by a lift-off. The low density and perfect electrical conductivity of aluminum make it suitable for SAW applications at 2.45 GHz at intermediate high temperatures.

III. IMPEDANCE MEASUREMENTS AND WIRELESS INTERROGATION

Impedance measurements were carried out using a vector network analyzer (VNA Agilent E5061B) and an RF probe station equipped with Signatone Thermal probing system S-1060 Series. The RF probes (Z Probe Süss Microtech, Garching, Germany) were custom adapted by adding a water-cooling system so that it can withstand temperatures up to 600 °C. However, we have restricted our characterization to 500 °C due to the use of aluminum electrodes.

Wireless measurements, with a general principle depicted in Figure 1, were carried out using a wireless interrogator from SAW Components Company (Dresden, Germany).

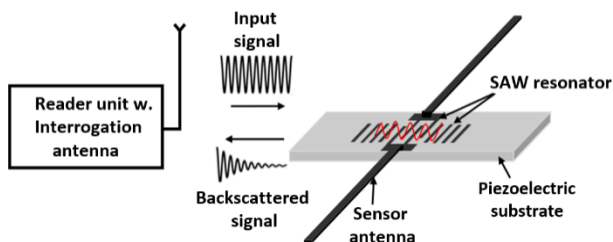


Fig. 1. General setup of wireless SAW resonator.

Electromechanical coupling coefficient (K^2) and quality factor (Q) were extracted as a function of temperature from experimental measurement of the SAW resonator admittance Y_{11} . Q is calculated thanks to formula (1), where f_0 is the frequency at the maximum of the conductance and Δf_{FWHM} the full width at half maximum [13].

$$Q = \frac{f_0}{\Delta f_{FWHM}} \quad (1)$$

The electromechanical coupling coefficient (K^2) is calculated from the following formula:

$$K^2 = 2 \frac{f_a - f_r}{f_r} \quad (2)$$

Where f_a and f_r are respectively, the resonance and anti-resonance frequencies extracted from the admittance-frequency characteristic.

The frequency response (S_{11}) was measured in wired configuration (RF probe) at various temperatures ranging from room temperature (RT) to 500 °C. The admittance magnitude Y_{11} is shown in Figure 2. At RT the center frequency was measured at 2.463 GHz, corresponding to a phase velocity of 5665 m/s. We mainly observe a decrease in frequency with increasing temperature, indicating a negative value of the temperature coefficient of frequency (TCF) [14]. Tests carried out in this temperature range also revealed a linear frequency response as a function of temperature, as well as an excellent reproducibility, in both wired and wireless configurations

(Fig. 3). The TCF is measured at a value of -47 ppm/°C. The quality factor remains high throughout the entire investigated temperature range (3500 at RT, and >1500 up to 400 °C), while the K^2 coefficient increases with temperature (0.048% at RT and 0.103% at 500 °C) as shown in Fig. 4. The figure of merit (FoM), defined as the product $Q \cdot K^2$ [15], varies between 0.8 and 2 over the investigated temperature range, demonstrating the potential of the device for wireless interrogation.

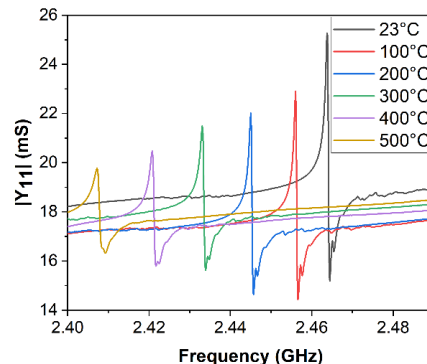


Fig. 2. Admittance magnitude of the SAW resonator for various temperatures, measured using water-cooled probes.

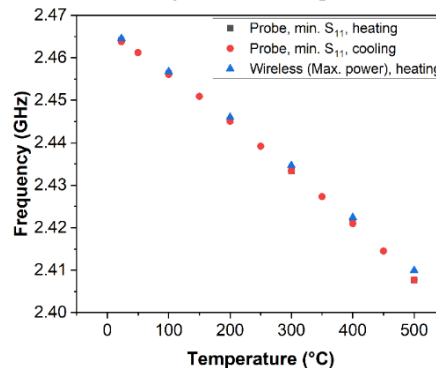


Fig. 3. Temperature dependence of the resonance frequency of the SAW resonator measured between RT and 500 °C in wired and wireless configuration.

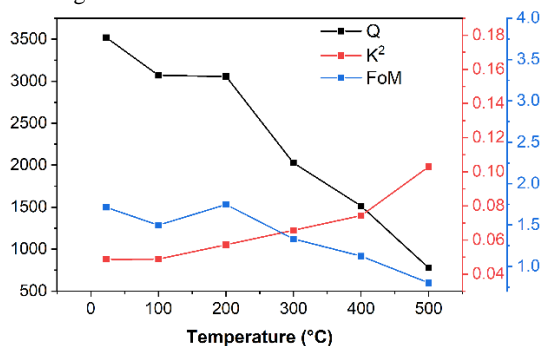


Fig. 4. Evolution of quality factor (Q), electromechanical coupling coefficient (K^2), figure of merit (FoM) with the temperature.

This potential was practically evaluated, using the Fig. 1 setup, by measuring the backscattered power as function of temperature using the SAW Components wireless interrogator coupled with a patch antenna array, and with the SAW sensor connected with a 14 elements, 60 cm long, aluminum Yagi-Uda antenna. As shown in

Figure 5, it was possible to track the center frequency of the backscattered signal with a signal-to-noise ratio (SNR) above 20 dB at 1 m over the entire temperature range up to 500 °C.

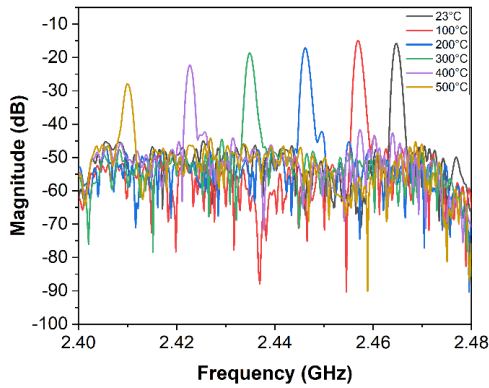


Fig. 5. Backscattered power of Al/AlN/Sapphire SAW resonator wirelessly interrogated at a distance of 1 m as a function of temperature.

In order to evaluate the potential of interrogating the sensor at greater distances, we increased the remoteness to 3 m. At this new distance, the sensor signal is 19 dB weaker but remains easily identifiable at room temperature, as shown in Figure 6.

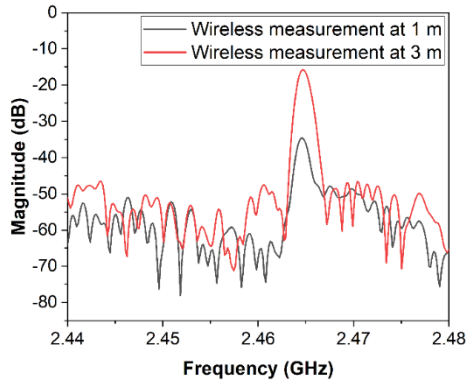


Fig. 6. Backscattered power of Al/AlN/Sapphire SAW resonator at 1 m and 3 m at room temperature.

This measured attenuation of 19 dB between 1 m and 3 m was compared with the theoretical one, considering the free space losses predicted by the De Friis equation [16].

The link budget between two antennas separated by a distance D in free space is given by (3):

$$(3) \quad \left(\frac{P_r}{P_e}\right)_{dB} = G_{r,dB} + G_{e,dB} - 20 \cdot \log\left(\frac{4\pi D}{\lambda}\right)$$

with P_r and P_e are the emission and reception power, G_e and G_r the gain of the emission and reception antennas, D the distance and λ the electromagnetic wavelength in free space. Should the distance increase 3-fold in a one-way transmission, the difference in dB in the link budget is $20 \cdot \log(3)$ dB. Considering a two-way, back and forth, backscattering scheme, the theoretical difference in the budget link between 1m and 3m is $2 \cdot 20 \cdot \log(3) = 19.08$ dB, in near-perfect agreement with the experiment.

By tracking the temperature at this distance over the investigated

temperature range, the signal would merge with the noise level above roughly 400 °C. This observation underlines the need to optimize the performance of SAW sensors, particularly regarding the quality factor and the figure of merit, to ensure reliability under high temperature conditions.

IV. DESIGN OPTIMISATION

The preliminary design allows the achievement of Al/AlN/Sapphire based SAW sensors with an operating frequency of 2.45 GHz that can be interrogated remotely up to at least 1 m at 500 °C. Increasing the interrogation distance or the operating temperature requires optimization of the resonator design (as shown in Figure 7) to increase its performance and in particular its FoM. In the following part, we undertake a simulation study for this purpose.

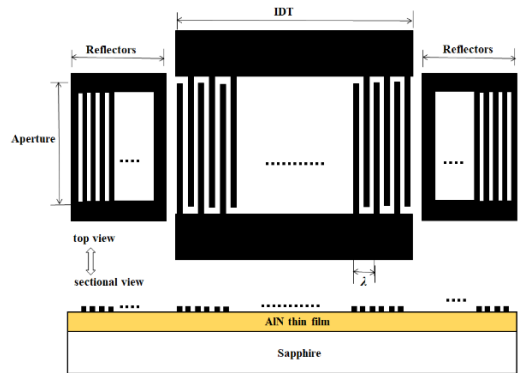


Fig. 7. The schematic for configuration of the one-port SAW resonator on Al/AlN/Sapphire structure with short circuited design.

To do this, modelling of the SAW resonator on Al/AlN/Sapphire structure was carried out using a method which combines the coupling-of-modes theory (COM) and the finite element method (FEM). The frequencies of the upper and lower edges of the band gap are determined from the admittance calculated by the FEM model. Q factor, static capacitance, and excitation coefficient are calculated from the measured admittances in experiments. Then, the frequencies of the upper and lower edges of the band gap, Q factor, static capacitance, and excitation coefficient are imported into the COM model. The calculated conductances of finite IDTs and reflectors are simulated by the COM model. We calculate the conductances by the COM model with varying the different pairs of IDTs, reflectors, aperture length and metallization ratios to optimize the device structure. Further details on this method can be found in our previous works [17, 18].

Simulation of the conductance allowed the calculation of the evolution of Q , K^2 and FoM as functions of the number of finger pairs in the IDT, reflectors number, aperture, IDT metallization ratio, electrodes thickness, etc. Those configuration parameters are optimized for the purpose of actual design.

As an example, Fig. 8 shows the calculated resonator conductance for several numbers of finger pairs in reflectors. In this case, the IDT wavelength is fixed at 2.303 μm and the Al electrodes thickness is 80 nm. Meanwhile, the mechanical and dielectric losses are considered in the calculation. Using formula (1), the quality factor is extracted from the conductance curve and plotted versus the

number of reflectors (inset figure 8).

As shown in inset Figure 8, we observe that the coupling K^2 monotonically decrease while the quality factor increases linearly with the number of reflectors, going from around 3000 with 100 reflectors to 8500 with 250 reflectors. In contrast, the FoM reaches its maximum of around 2.3 with 150 reflectors (Fig. 8). By analysing the results obtained after varying the different parameters of the design, an optimized structure has been defined with 400 pairs of fingers, 150 reflectors, an aperture of 95.5 μm and a metallization ratio of 60%. Its experimental implementation is ongoing to validate the study and above all to demonstrate the improvement of the signal collected remotely, the increase in SNR and the distance of high temperature interrogation.

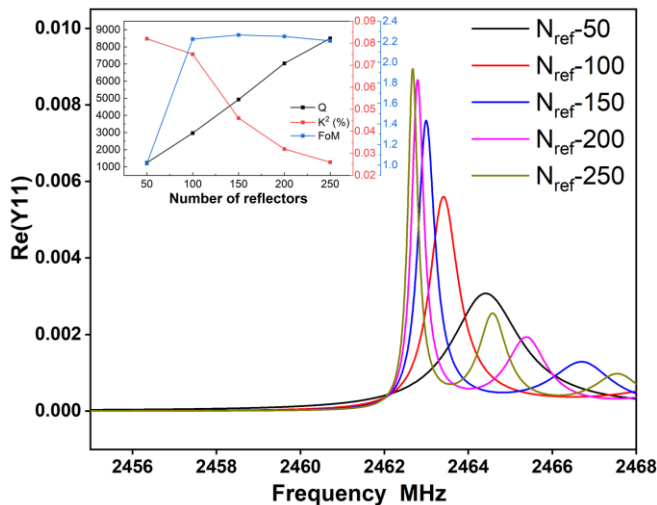


Fig. 8. Resonator conductance obtained by calculation for various number (N_{ref}) of reflectors. The pairs number (N_{IDT}) of electrode in IDT remains constant ($N_{\text{IDT}} = 150$).

V. CONCLUSION

The potential of wireless 2.45 GHz SAW sensors based on a AlN/Sapphire bilayer structure for high-temperature applications is presented. The obtained results demonstrate remarkable stability of the structure along with a temperature sensitivity (TCF) measured at -47 ppm/ $^{\circ}\text{C}$ over the entire temperature range. It was possible to successfully interrogate the wireless SAW sensors up to 500 $^{\circ}\text{C}$ at 1 m. With unavoidable additional path losses at greater distances, the optimization of the resonator design through simulations paves the way for improvements in FoM, allowing the wireless interrogation distance to be extended at high temperatures. The limitation of the study at 500°C results from the degradation of the aluminum electrodes, not the AlN/Sapphire substrate. Ongoing research is focusing on experimental implementation of the new design and the development of thin film electrodes suitable for the 2.45 GHz ISM band and higher temperatures [19].

ACKNOWLEDGMENT

This research was supported the CASSIOPEE Project funded by Institut Carnot ICEEL, and Campus France Gabon (U. Youbi PhD grant).

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