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Harsh Environmental Surface Acoustic Wave Temperature Sensor Based on Pure and Scandium doped Aluminum Nitride on Sapphire †

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Abstract: This paper investigates the performance of surface acoustic wave (SAW) devices as low power MEMS temperature sensors using reactive sputter deposited aluminum nitride (AlN) and scandium doped aluminum nitride (AlScN) as piezoelectric layers on sapphire substrates. In detail, devices with a wavelength of 16 µm are fabricated with both AlN and AlScN films having a resonance frequency at room temperature of ~354 MHz and ~349 MHz, respectively. The samples are placed in a furnace and measured in argon atmosphere up to 800 °C. The temperature dependency on the frequency shows for both materials a linear decrease up to the maximum measured temperature level resulting in constant temperature coefficients of −27.62 kHz/°C and −27.81 kHz/°C, respectively.

Keywords: AlN; AlScN; SAW; harsh environmental; high temperature

1. Introduction

Surface acoustic wave (SAW) devices have been key components in telecommunication systems for the last decades [1]. The optimal choice of piezoelectric material is one of the main challenges to realize such sensors. Currently, commercially available SAW devices are based on langasite ($La_3Ga_5SiO_{14}$, LGS), langatate ($La_3Ga_{5.5}Ta_{0.5}O_{14}$, LGT) or langanite ($La_3Ga_{5.5}Nb_{0.5}O_{14}$, LGN), whose major disadvantage is the low phase velocity (e.g., 2700 m/s in LGS) and high acoustic propagation loses during high temperature load [2–4]. Aluminum nitride (AlN) or scandium doped aluminum nitride (AlScN) on sapphire is regarded as a promising alternative to LGS, LGT and LGN, given much higher phase velocities $\mathbf{v_p}$ above 5600 m/s [5,6]. With these higher phase velocities, higher frequencies $\mathbf{f_0}$ can be achieved with the same device dimensions (at fixed wavelength $\boldsymbol{\lambda}$), due to the relation $\mathbf{f_0 = \lambda / v_p}$. AlN promises operation up to 700°C even in pure oxygen atmosphere for two hours without measureable film degeneration [7]. Whereas, AlScN has a higher d_{33} and therefore the electro-mechanical coupling factor is increased by a factor of ~3, compared to pure AlN [8–10].

2. Experimental Details

The sapphire substrate is cleaned in pure argon plasma by an inverse sputter etch step, with a power of 500 W and a back pressure of 6 µbar for 5 min, before depositing the piezoelectric thin film. A target cleaning step prior deposition is performed at closed shutter position. Afterwards, AlN is sputtered from an aluminum target (Ø 150 mm, purity 5N) with a plasma power of 800 W at a back pressure of 2 µbar in pure nitrogen gas (purity 6N) with a constant gas flow of 50 sccm. AlScN is sputtered from a scandium/aluminum alloy target (27_{at}%/73_{at}%, Ø 100 mm) with a power of 400 W and a pressure of 4 µbar in an argon/nitrogen gas atmosphere (30/20 sccm). The distance between target and substrate is fixed at 65 mm. The parameters were chosen based on pre-investigations for good c-axis orientation [7,11]. The total film thickness *h* is 2 µm. Next, inter-digital transducers (IDTs) using a bilayer of 5 nm tantalum and 40 nm platinum as robust electrode material are patterned using a

standard lift-off process. The IDTs are aligned to ensure wave propagation parallel to the crystallographic *a*-direction (<$\mathbf{11\bar{2}0}$>) of the sapphire substrate. The IDTs have 40 finger pairs with an aperture of 1400 µm and a wavelength $\boldsymbol{\lambda}$ of 16 µm, what results in a normalized thickness $\boldsymbol{kh} = \boldsymbol{2\pi h/\lambda = 0.78}$. The distance between transmitter and receiver is 4350 µm. After fabrication, the devices are placed in a furnace and connected to a network vector analyzer from Rhode and Schwarz (ZVL6). S_{21}-parameters are measured starting at room temperature and in steps of about 200 °C up to 812 °C. At each temperature step, each device is measured 10 times by consecutively connecting and disconnecting the NVA to the samples. The sensitivity of the SAW devices is determined by measuring the shift of the resonance frequency during temperature load.

3. Results

Figure 1 shows a typical raw S_{21} characteristics of an AlN/sapphire delay line device with kh = 0.78 and a transmitter receiver distance of 4350 µm. Delay line devices are basically band-bass filters, which show a minimum damping at the resonance frequency f_0.

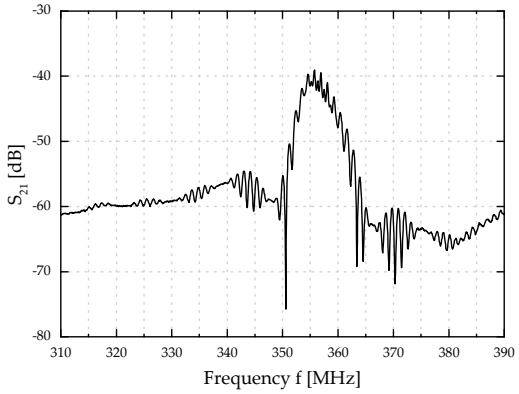

Figure 1. Raw S_{21} measurement for kh = 0.78 and a distance d = 4350 µm between transmitter and receiver.

The corresponding impulse response from Figure 1 is shown in Figure 2. The two arrows define the gating window of the first impulse starting at 0.87 µs for filtering the SAW signal to eliminate parasitic crosstalk between transmitter and receiver. The impulse response also shows the triple-transit as well the quintuple transit signal at 2.53 µs and 4.19 µs, respectively. The damping increases by around 20 dB for subsequent higher order signals, which is attributed to both the wave damping in transit and the transducer loses.

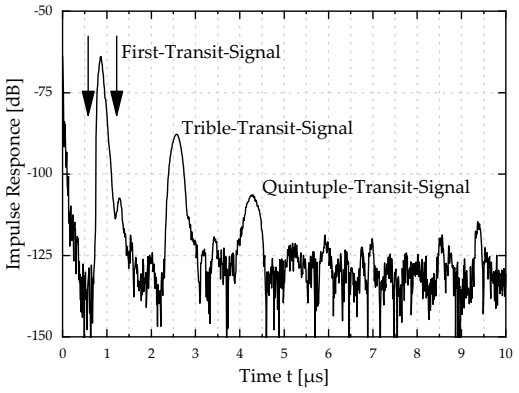

Figure 2. Impulse response for kh = 0.78; arrows indicate the gating window at the first peak.

Figure 3a shows selected gated S_{21} measurements for an AlN-based device between 25 °C and 812 °C. The resonance frequency f_0 shifts to lower values at higher temperatures due to the thermally

induced expansion of the materials involved. The different peak height at f_0 for each temperature is attributed to the varying contact resistance when manually re-contacting the SAW devices between each measurement step. A similar behavior is observed for the AlScN device, as illustrated in Figure 3b.

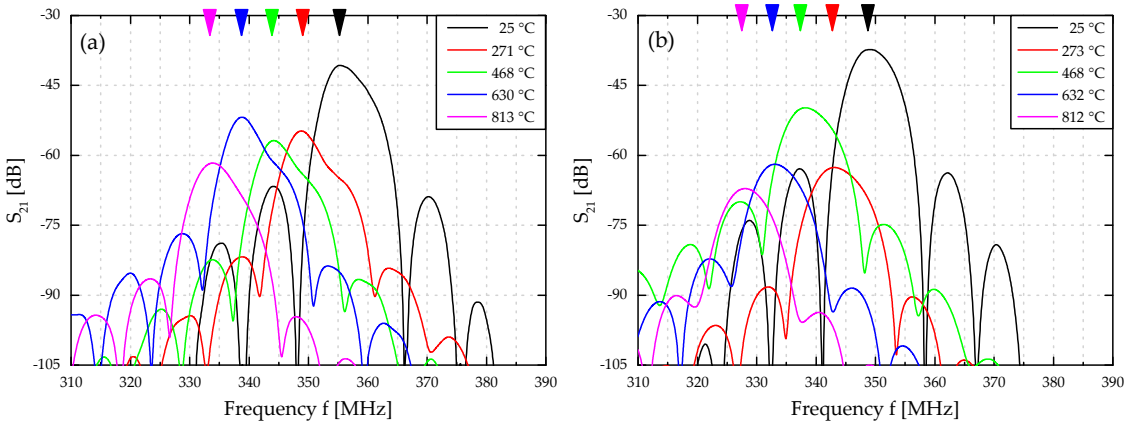

Figure 3. (**a**) Selected gated first impulse pure AlN (**a**) and AlScN (**b**) for operating temperatures up to 812 °C.

The temperature coefficient of frequency (TCF) is determined by plotting the evaluated resonance frequency f_0 versus the measurement temperature. At room temperature, the devices feature resonance frequencies f_0 = 354.78 MHz for AlN and f_0 = 349.22 MHz for AlScN. The lower sound velocities for AlScN is due to a lower Young's modulus of the piezoelectric layer. For pure AlN, a TCF of -27.62 kHz/°C and for AlScN a TCF of -27.81 kHz/°C are evaluated, as shown in Figure 4.

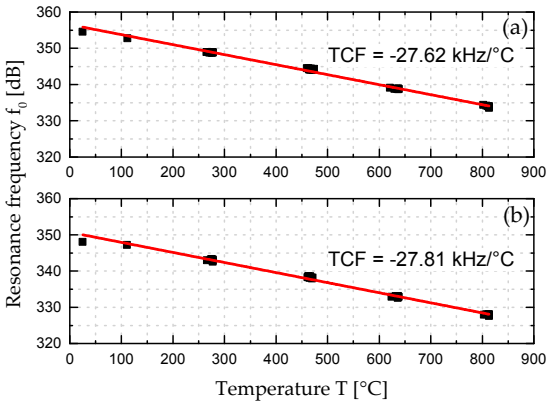

Figure 4. Temperature coefficient of frequency for AlN (**a**) and scandium doped AlN (**b**) on c-plane sapphire (10 measurement points at each temperature level).

4. Conclusions

Compared to LGS devices with a TCF requesting the quadratic term to represent the temperature dependence [12], SAW devices based on AlN or AlScN on top of a sapphire substrate show a linear behavior giving the opportunity to realize a MEMS temperature sensor up to 812 °C with a constant TCF. Due to the different sound velocities, a slightly different resonance frequency for the same structure size is observed. Combined with an additional antenna element, key components are available to pave the way for robust wireless and battery less linear temperature sensor modules for harsh environmental applications.

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Conflicts of Interest: The authors declare no conflict of interest.

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