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# Surface acoustic wave devices based on AlN/Sapphire structure for high temperature applications

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## **Abstract**

AlN/Sapphire layered structure has been investigated as a potential substrate for surface acoustic wave (SAW) devices operating at high temperatures up to 950°C under air atmosphere. Frequency characterizations of the SAW delay lines based on this structure indicate a slight increase of 2 dB in the insertion losses after annealing for 30 minutes at 900°C. Scanning electron and atomic force microscopy as well as X-ray diffraction measurements suggest that these losses are due to the deterioration of the Pt/Ta electrodes and to a slight oxidation of the AlN film.

Surface acoustic wave (SAW) devices are key components for communication systems and have been widely used as filters, resonators or delay lines during the last three decades. Far from being confined to this single use, SAW devices offer very promising solutions in a wide range of applications including physical [1-3] and chemical [4] sensors. In addition to being small, simple and robust, these devices have the advantage of being passive (batteryless), remotely requestable (wireless) [5,6] and inexpensive if fabricated on a large scale. The use of SAW devices as passive and wireless sensors allows them to operate in extreme conditions such as those with high levels of radiation, high temperatures up to 1000°C, or electromagnetic interference, in which no other wireless sensor can operate. This is obviously conditioned by the fact that the materials constituting the device can withstand these harsh conditions [7].

Knowing that the conventional piezoelectric substrates such as quartz or lithium niobate cannot be used at high temperature [8], the groups working on this topic are focused on new generation of piezoelectric materials stable in these conditions. Now, there is a large consensus on the use of langasite ( $\text{La}_3\text{Ga}_5\text{SiO}_{14}$  or LGS) for such aim. Indeed, this material has been extensively studied at high temperature showing a very high stability up to its melting temperature at 1473°C and a great resistance to thermal shock treatment [9,10]. However, it is also characterized by relatively high acoustic propagation losses (4 mdB/ $\lambda$  at 1GHz) which dramatically increase with frequency and temperature, prohibiting operating frequencies over 1 GHz for applications at high temperature [11]. This limitation is quite embarrassing in the view of reducing the antenna size of the wireless devices. Moreover, it also decreases the sensors sensitivity, as it is directly proportional to the operating frequency. At last, if the high stability of LGS has been demonstrated under air atmosphere, its behavior under other gas environments is unknown. For these two reasons (limitation in frequency and unknown chemical stability), the existence of alternative solutions to LGS would be of great interest.

In this paper the suitability of the AlN/Sapphire bilayer structure for SAW devices operating at high temperatures was investigated. Indeed, aluminium nitride (AlN) has been identified as a very interesting candidate for a long time [12,13]. This material is chemically stable up to 1040°C in vacuum [14]. In the air, AlN thin films are expected to oxidize at temperatures close to 900°C, but withstand N<sub>2</sub>/H<sub>2</sub> atmosphere up to 1200°C [15]. However, it has never been investigated experimentally as piezoelectric material for SAW applications at very high temperature. Sapphire was chosen as a substrate for AlN thin films due to its stability at high temperatures, and low lattice mismatch with AlN, which is necessary for the growth of epitaxial films with good piezoelectric response [16]. Moreover, its acoustic wave velocity is very close to that of AlN, which limits the acoustic velocity dispersion [17].

The AlN/Sapphire structure has been already studied in order to develop SAW devices with zero Temperature Coefficient of Frequency (TCF) at room temperature, operating at high frequencies. Indeed, it presents many advantages that are still full of interest for applications at high temperature:

- Low propagation losses: 0.7 mdB/λ at 1 GHz [18].
- High acoustic SAW velocity, close to 5700 m.s<sup>-1</sup> [19], allowing the fabrication of high frequency devices (up to 5 GHz) by conventional photolithography.
- Relatively high electromechanical coupling coefficient (up to 0.65% in the case of AlN/IDT/Sapphire structure), compared to that of LGS (K<sub>2</sub>=0.44%) [17].
- TCF adjustable by the AlN thickness.

The AlN/Sapphire structure investigated in this letter, commercially available, consists in 3 μm thick epitaxial piezoelectric (002) AlN thin film grown on a (001) sapphire substrate. To perform interdigital transducers (IDT) withstanding high temperatures, 10 nm thick tantalum as adhesion layer and 100 nm thick platinum films as electrodes, were deposited by magnetron sputtering onto the AlN film [20]. SAW delay lines were then fabricated by conventional

photolithography and ion beam etching. The devices were constituted by two identical IDTs, with 50 pairs of fingers and a wavelength  $\lambda$  fixed to  $14\mu\text{m}$ . The IDT center spacing, acoustic aperture, and finger width to space ratio were  $85\lambda$ ,  $70\lambda$ , and 1:2, respectively. The frequency characterization of the resultant delay lines was accomplished by measuring the S-parameters using a network analyzer (Agilent N5230A) before and after annealing at temperatures ranging from 800 to 950°C, for 30 minutes under air atmosphere. A furnace with a quartz open tube was used to perform these heating processes, the devices lying on an alumina plate placed in the center of the quartz tube. It is important to note that all the samples were placed in (and removed from) the furnace as fast as possible, resulting in thermal shocks. The morphology of the AlN films as well as that of the Pt electrode was observed by scanning electron microscopy (SEM) (Jeol 6500F) and atomic force microscopy (AFM) (Veeco III-A dimension 3100), while their microstructure was obtained by X-ray diffraction (XRD) (PANalytical X'Pert PRO MRD).

Table I summarizes the main results. It appears an increase of the insertion losses with the temperature of annealing, which is very limited up to 900°C. As an example, the effect of annealing for 30 min. at 900°C on the  $S_{21}$  frequency response is illustrated in the Figure 1. This indicates that the AlN/Sapphire structure can be used for very high temperature SAW applications in air atmosphere, including thermal shocks, at least for short-time exposure. In fact, apart from a slight increase of 2 dB in the insertion losses, the profile of the response is unchanged after annealing. Two main hypotheses can be formulated to explain that enhancement of the insertion losses. The first one is the decrease of the electrode conductivity. In fact, the SEM images show an advanced degradation of the electrode fingers of the IDTs consisting of a strong recrystallization and agglomeration phenomena of platinum [20], which lead to the formation of big crystallites and voids (Fig. 2b). XRD measurements, carried out in the  $\theta$ -2 $\theta$  scan, evidence this recrystallization as the Pt (111) peak becomes narrower and more intense after annealing (Fig. 3). It is known that the

voids tend to decrease the conductivity of platinum thin films. However, the increase in the grain size and thus the reduction of the number of grain boundaries can balance it and enhance the conductivity [21], so there is no definitive conclusion. Anyway, the agglomeration phenomena are so advanced after the annealing at 950°C that some finger electrodes are almost broken (Fig.2c). This advanced deterioration could explain that the increase in the insertion losses becomes important at this temperature (Tab.I). The second mechanism proposed to explain the evolution of the  $S_{21}$  frequency response is the formation of a very thin aluminium oxide film (a few nanometers) on the surface of the AlN film. Moreover, the latter could also be responsible of the slight shift of the operating frequency observed with the enhancement of the heating temperature (Tab. I). XRD measurements confirm that this hypothetical oxide layer must be very thin as the intensity of the (002) AlN peak is not changed after annealing at 950°C for 30 minutes (Fig. 3). It must also be noted that the full width at half maximum (FWHM) of the (002) AlN rocking curve (RC) has not been modified by the annealing treatments, confirming the great stability of the AlN crystal under these harsh conditions (Tab. I). AFM measurements reveal a modification of the AlN surface after annealing. This change is quite weak in terms of surface roughness (Tab. I). The latter, initially quite high, is slightly decreased by a few nanometers after the high temperature treatment. The main result brought by AFM measurements appears on Figure 4 which highlights a clear modification of the surface topography, consisting in the smoothing of the AlN crystallites (Fig. 4). This phenomenon could be a result of the formation of an amorphous aluminium oxide layer on the AlN surface.

In summary, AlN/Sapphire is an attractive structure for SAW devices operating at very high temperature, giving an alternative to the wide-used langasite family, especially for high frequency applications. Moreover, it offers an outstanding natural advantage for harsh conditions. Indeed, it is possible to sandwich the IDTs between the AlN thin film and the substrate, which would provide

natural protection against external aggression and increases the electromechanical coupling coefficient from 0.3% to 0.65% [17]. Besides, this alternative configuration could help increase the lifetime of simple platinum electrodes by slowing down the agglomeration phenomena appearing at very high temperatures [20], since platinum grains would be mechanically fixed. Nonetheless, the commercial monocrystalline AlN/Sapphire plate used in this letter prohibits the realization of such structures, as it is necessary to have the opportunity to deposit the AlN film after realizing the electrodes on the sapphire substrate. In this aim, another study concerning the home-made growth of heteroepitaxial AlN films on 3-inch sapphire wafers by magnetron sputtering has been achieved [22].

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### **Figure captions.**

**Figure 1:** Insertion losses vs. frequency of a delay line based on AlN/Sapphire structure. Measurements were performed before and after annealing at 900°C

**Figure 2:** SEM images of the Pt/Ta electrodes placed on AlN/Sapphire structure before annealing (a), after 30 min. at 900°C (b), after 30 min. at 950°C (c). IDT finger width is 3,5 µm.

**Figure 3:** XRD diagram of 3 µm-thick monocrystalline AlN film on sapphire substrate performed before (line) and after annealing at 950 °C (scatter)

**Figure 4:** 3D AFM images of the AlN surface before annealing (a), after 30 min. at 900°C (b), after 30 min. at 950°C (c).

Figure 1

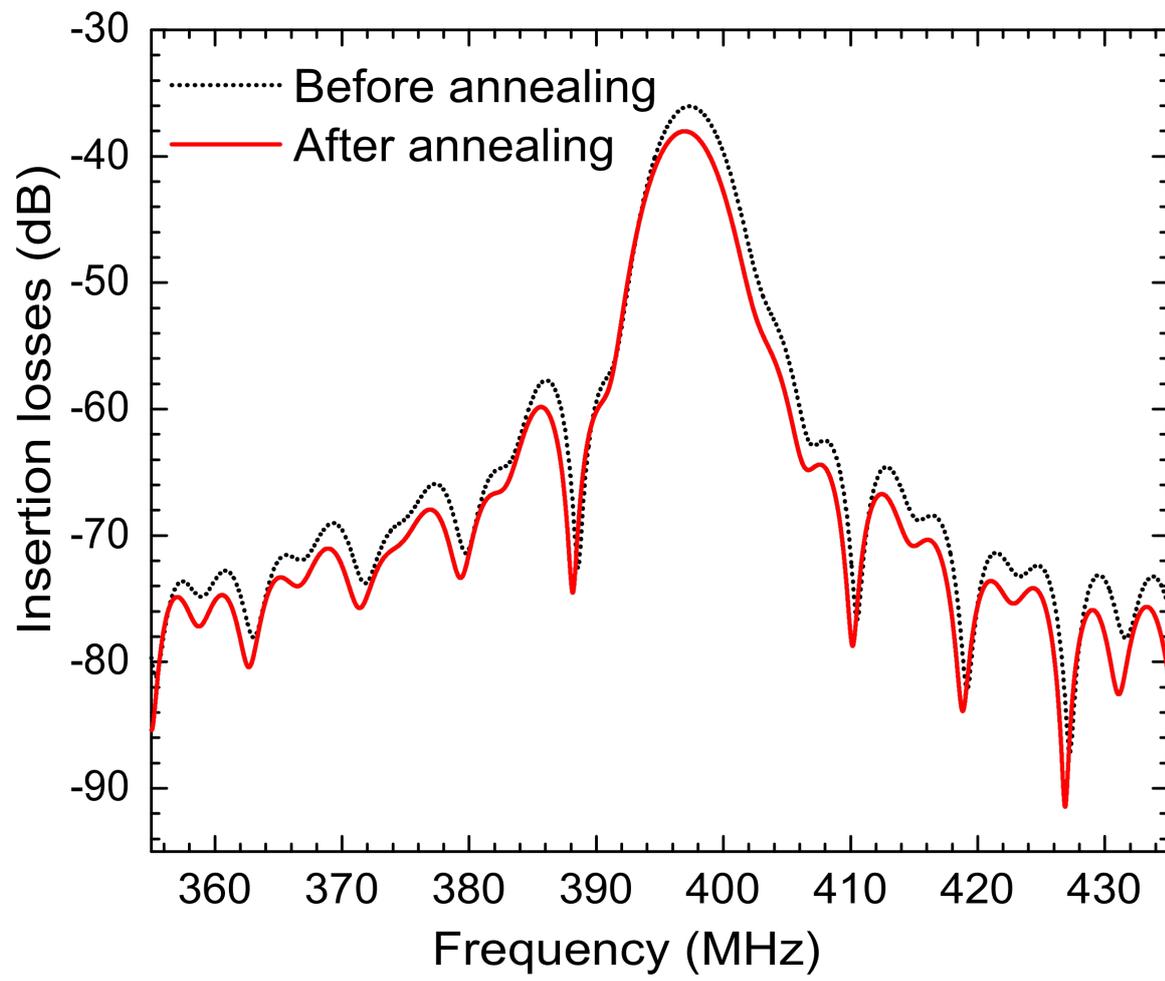


Figure 2

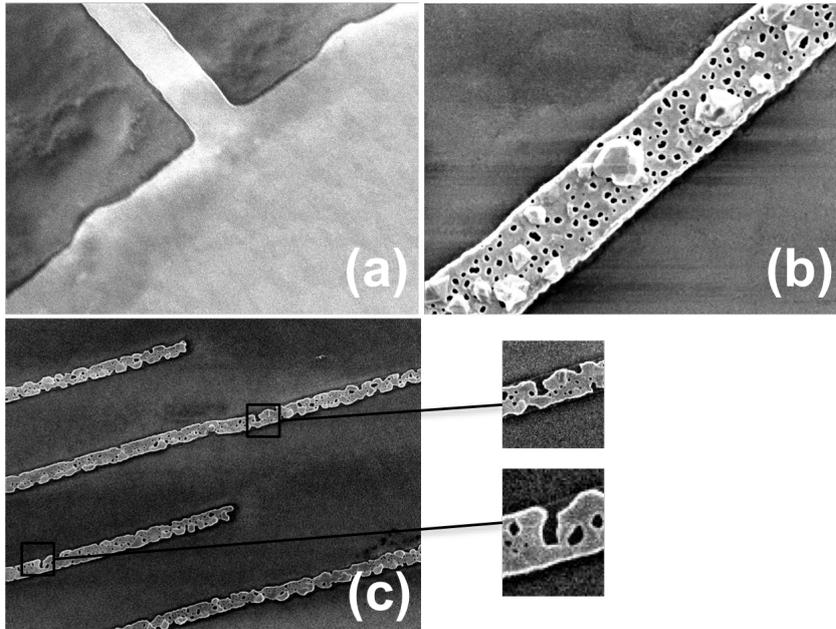


Figure 3

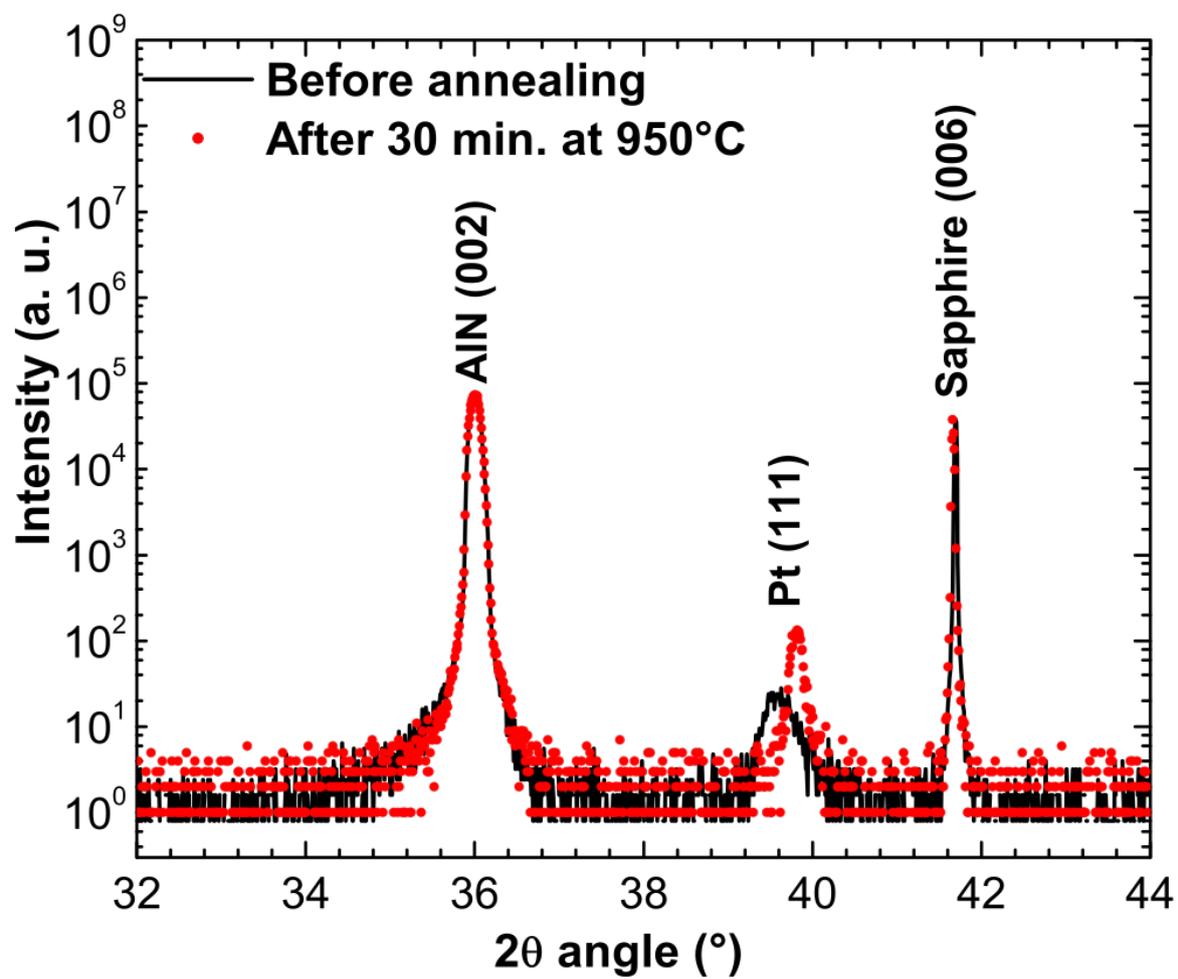


Figure 4

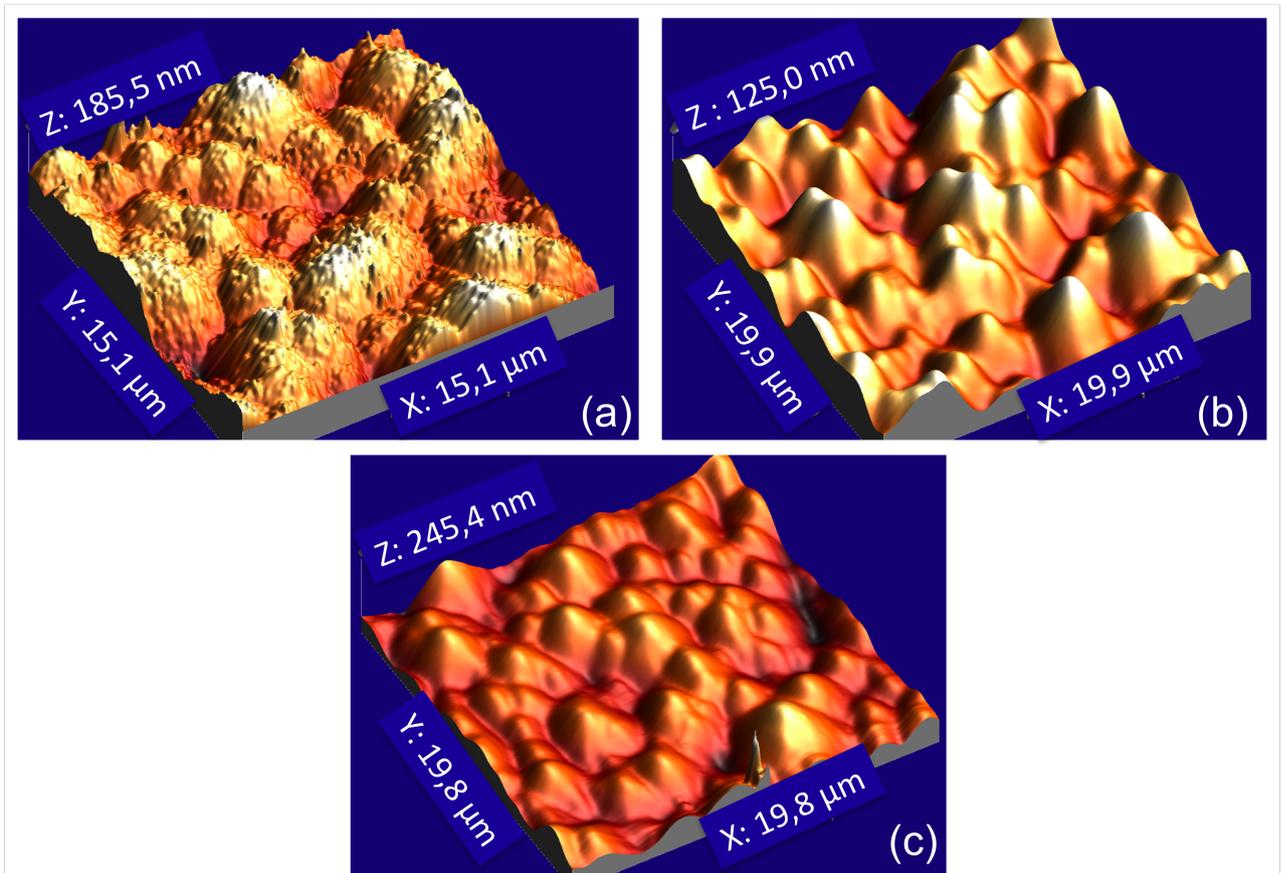


Table I. Summary of the results

Device state	Before heating	30 min. at 800°C	30 min. at 900°C	30 min. at 950°C
$S_{21}$ insertion losses (dB)	-36.0	-36.5	-38.0	-42.0
Operating frequency (MHz)	397.33	397.2	396.95	396.47
FWHM of (002) AlN RC	0.16°	0.16°	0.16°	0.16°
Surface Roughness Rms (nm)	32	-	24	27