# On the Lateral Excitation Of Shear Modes in AlN Layered Resonators

M. Clement, E. Iborra, J. Olivares, M. de Miguel-Ramos, J. Capilla, J. Sangrador

*Abstract*— **In this paper we describe the fabrication and frequency characterization of different structures intended for the lateral excitation of shear modes in AlN *c*-axis-oriented films, which are at the same time designed to minimize the excitation of longitudinal modes. Laterally excited resonators were built on partially metallic ($SiO_2$, W) and insulating (SiOC, $Si_3N_4$) acoustic mirrors built on silicon substrates, and on insulating mirrors ($SiO_2$, $TaO_x$) built on insulating glass plates. $TiO_x$ seed layers were used to stimulate the growth of highly c-axis oriented AlN films, which was confirmed by XRD and SAW measurements. Coplanar Mo electrodes of different geometries were defined on top of the AlN films to excite the shear modes. All the structures analyzed displayed a clear longitudinal mode, corresponding to an acoustic velocity of 11000 m/s, but a null or extremely weak shear response corresponding to a sound velocity of around 6350 m/s. The simulation of the frequency response based on Mason's model confirms that the shear resonance is extremely weak. The observed longitudinal modes are attributed either to the field applied between the electrodes and a conductive plane (metallic layer or Si substrate) or to the electric field parallel to the c-axis in the edges of the electrodes or in tilted grains. The low excitation of shear modes is attributed to the very low values of electric field strength parallel to the surface**

## I. INTRODUCTION

Biosensors are an essential type of sensors for those applications that require a precise and selective detection of biological agents present mainly in liquid solutions. Bulk acoustic wave (BAW) resonators operating in the shear mode are good candidates for such applications since shear waves are not attenuated significantly in liquid environments. This is due to the fact that the displacement of particles in such transverse waves is perpendicular to the direction of the energy transfer, and therefore parallel to the surface in contact with the viscous medium. Quartz crystal microbalances (QCM) are being used routinely in biological sensing applications [1]. However, their large size and incompatibility with silicon-based integrated circuit technologies have driven during the last ten years the development of shear BAW resonators based on AlN and ZnO thin films [2-4]. The hexagonal wurtzite structure is the preferred crystalline structure of AlN and ZnO polycrystalline films, which tend to grow with the *c*-axis normal to the surface, as long as enough energy is supplied to the film during its growth. This orientation enables the ease excitation of longitudinal thickness modes by applying an electric field normally to the parallel plate capacitor. However, the excitation of shear modes requires the applied electric field to be perpendicular to the propagation direction of the acoustic wave. Many efforts have been devoted to the growth of AlN and ZnO films with the c-axis tilted with respect to the normal [2-7]; in such films, an electric field applied normally to the parallel plate capacitor provides a mixed shear and longitudinal excitation. However, achieving polycrystalline films exhibiting a homogeneous c-axis tilt across the wafer is still a pending matter. A straightforward solution for the excitation of shear-thickness modes has been proposed recently; the procedure, called lateral excitation (LE), simply consists in applying an electric field between two coplanar electrodes defined on top of a piezoelectric film grown with the *c*-axis normal to its surface. This way, a shear wave is exited owing to the shear coupling through the $e_{15}$ piezoelectric coefficient [8-16].

In this work we investigate the possibility of achieving AlN shear resonators operating in the thickness mode by lateral excitation. We analyze the frequency response of different structures specifically designed for the lateral excitation of shear modes in AlN films oriented with the c-axis normal to the surface. The results are compared to those achieved by exciting AlN films exhibiting a tilted c-axis through an electric field normal to the film sandwiched between two metallic electrodes.

## II. EXPERIMENTAL

To investigate the influence of both the electrode geometry and the nature of the acoustic reflector in the excitation of shear modes three different solidly mounted resonators (SMRs) ranging from partially conducting to fully insulating were fabricated and characterized. The three types of substrates shown in Fig. 1 were used to support the AlN layer and the coplanar electrodes. Substrates of type I consisted of a high resistivity silicon substrate covered by a partly conducting Bragg mirror formed by a set of five alternated tungsten (W) and silicon dioxide ($SiO_2$) layers. Substrate type II consisted of the same Si semiconducting substrate, this time covered by a fully insulating acoustic reflector composed of five alternated layers of silicon oxycarbide (SiOC) and silicon nitride ($Si_3N_4$). Finally, substrates of type III were composed exclusively of insulating materials; as substrates we used Corning glass plates 500 µm-thick which were covered with five insulating layers of $SiO_2$ and tantalum oxide ($TaO_x$).

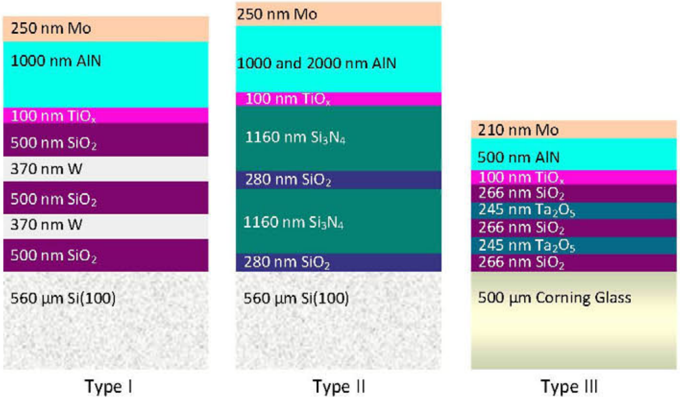


Fig. 1. The three types of substrates used to fabricate the LE-Shear mode resonators

The piezoelectric AlN film was deposited directly on top of the mirror without bottom electrode. Titanium oxide ($TiO_x$) seed layers were used to promote the growth of highly c-axis oriented films [17]. Finally, a molybdenum (Mo) layer was grown on top of the AlN film and patterned into coplanar electrodes of different geometries shown in figure 2.

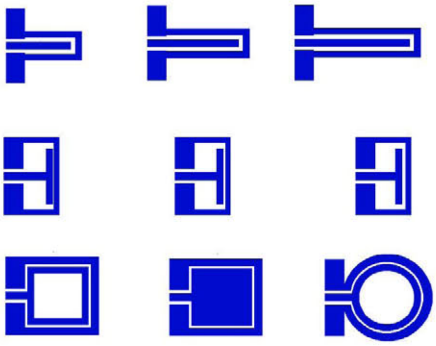

Fig. 2. Geometries of the coplanar electrodes used for lateral excited devices.

Except for the substrates of type II (provided by CEA-Leti) the different W, Mo, $SiO_2$, $TaO_x$, $TiO_x$ and AlN layers were deposited by pulsed-DC reactive magnetron sputtering process. High-purity W, Mo, Si, Al, Ta and Ti targets 150 mm-in-diameter were sputtered using $Ar/O_2$ or $Ar/N_2$ mixtures of different compositions. Before AlN deposition the substrates were degassed close to the AlN deposition temperature (400°C). Then, the surface of the $TiO_x$ seed layers were soft etched by means of a short bombardment (60 s) with $Ar^+$ or $N_2^+$ ions from an RF glow discharge generated near the substrate. Once the surface prepared, the AlN films were sputtered on top of the seed layers using a 3:7 $Ar{:}N_2$ admixture at a total pressure of 1.2 mTorr, a pulsed-DC power of 1.2 kW and a platen temperature of 400°C. An RF bias of -77 V was applied to the substrates to tune the stress in the AlN films. The thickness of the different layers was adjusted to achieve required shear frequency.

In order to assess the piezoelectric activity of the AlN films grown on insulating substrates, SAW delay lines were also fabricated on the surface of the AlN films by defining interdigital transducers (IDTs) on the Mo film. The scattering parameters $S_{ij}$ of the SAW delay lines were measured between 100 kHz and 700 MHz with an Agilent 8753-ES network analyzer. The experimental spectra were fitted using our own simulation program described in a previous work [18], which enabled us to confirm the piezoelectric activity of the films and to derive an electromechanical coupling factor $k^2_{SAW}$ only dependent on the AlN material properties.

The frequency response of the LE shear resonators was assessed by measuring the $S_{11}$ reflection coefficient between 10 MHz and 10 GHz with an Agilent network analyzer PNA-5230A and compared to the frequency response predicted by the simulation with Mason's model, which included both longitudinal and shear modes.

## III. Results and Dicussion

Since *c*-axis oriented AlN films of high quality are hardly achieved in non-metallic substrates, their piezoelectric activity was previously checked through the frequency response of SAW delay lines built on top of the films. These revealed that despite being grown on the $TiO_x$ seed layers, all the films exhibited a significant piezoelectric activity with values of the electromechanical coupling factor $k^2_{SAW}$ ranging between 0.6% and 1.2%, which have been associated to coupling factors $k^2_{BAW}$ in BAW resonators operating in the longitudinal thickness mode ranging from 3% to 5% [17, 19].

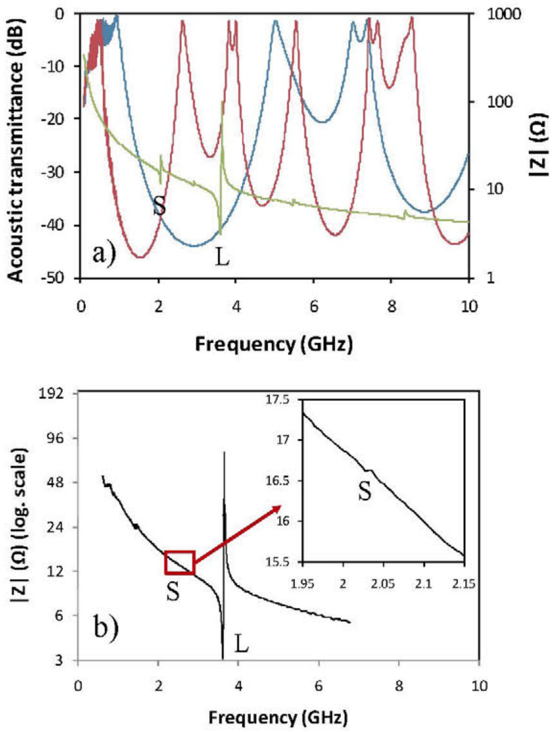


Fig. 3. LE-SMRs of type I. a) Simulation of |Z| (green) and acoustic mirror transmittance for the longitudinal mode (blue) the and shear mode (red). b) Measured |Z| of a typical device.

Figures 3 a), 4 a) and 5 a) show the simulated transmittance of the different Bragg reflectors used in each structure for the longitudinal and shear modes along with the simulated frequency response of the corresponding LE-SRMs. For the simulations we have used a value of $k^2_{shear}$ considerably greater than the measured one to highlight the position of the resonance frequency corresponding to the shear mode. We observe than in all cases the two acoustic modes are effectively trapped in the AlN film. Figures 3 b), 4 b) and 5 b) show the actual measured frequency response of the LE-SMRs of type I, II and III.

On the one hand, the experimental data of Figs. 3 b), 4 b) and 5 b) highlight in all cases the presence of a significant resonance $f_l$ at the frequency corresponding to the longitudinal mode, which appears surprisingly even when the fully insulating substrate of type III is used; in this case, however, the electromechanical coupling factor $k_l^2$ is considerably lower than in the cases that metallic or semi-conducting layers are present under the AlN film. On the other hand, the experimental data barely reveal the presence of the experimental shear resonance $f_s$. This, when present, appears at around $f_l$/1.78 and is either extremely weak (substrates I and II) or completely non-existent for the SMRs built in glass substrates (type III). It is also worth noting that the excitation of the shear modes is not enhanced either by reducing the gap between the two electrodes or by increasing their length or modifying their shape.

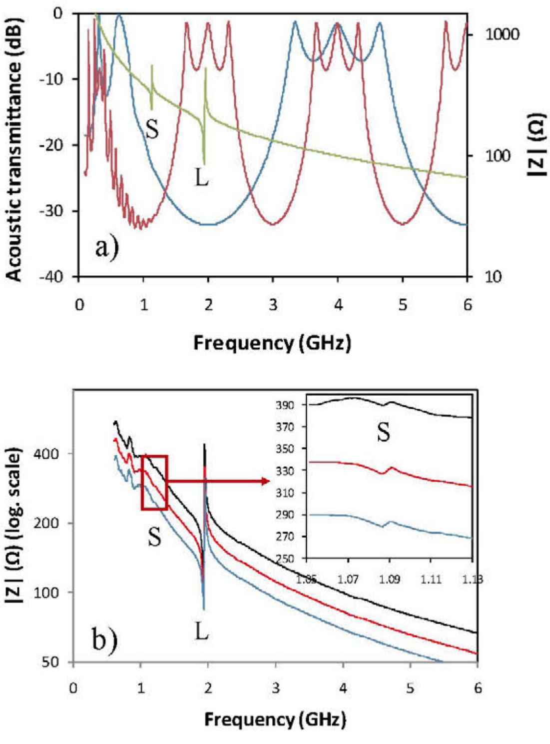


Fig. 4. LE-SMRs of type II. a) Simulation of |Z| (green) and acoustic mirror transmittance for the longitudinal mode (blue) the and shear mode (red). b) Measured |Z| for three typical devices of different lengths.

The excitation of the longitudinal modes can be explained by the fact that, regardless the type of substrate, the field under the electrodes is vertically aligned with the c-axis oriented grains, which produces to a greater or lesser extent the excitation of the longitudinal wave [20]. As for the lateral excitation of the shear wave, although part the electric field strength is located in the gap between the two electrodes and is parallel to the surface, this is too weak to generate the expected shear mode.

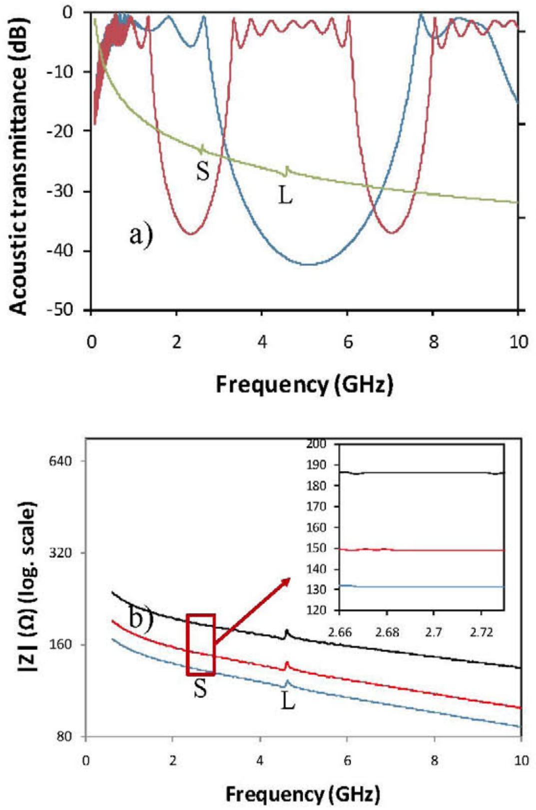


Fig. 5. LE-SMRs of type III. a) Simulation of |Z| (green) and acoustic mirror transmittance for the longitudinal mode (blue) the and shear mode (red). b) Measured |Z| for three typical devices of different lengths.

Finally, it is very interesting to analyze how shear waves are actually excited by the two methods mentioned in the introduction. Fig. 6 depicts the frequency response of a LE-SMR of type II compared to that of a resonator in which an AlN layer with the c-axis tilted 25° with respect to the normal and sandwiched between two molybdenum electrodes is excited through a electric field normal to the surface. As can be clearly observed, the excitation of shear modes is far more efficient in AlN tilted films. Actually, the resonator containing tilted grains has an electromechanical coupling factor $k^2_{shear}$ of 2.4 %. In contrast, the corresponding $k^2_{shear}$ value for this LE-SMR is only 0.01%, which barely produces any variation in the Z modulus.

In summary, none of the three types of structures analyzed provide any convincing evidence that shear modes are successfully stimulated by lateral excitation. Similar results were achieved by Gorisse et al. [20] in AlN LE membrane-based AlN resonators. This could be attributed to 1) the low intensity of the electric field existing between the two coplanar electrodes separated at least 10 μm from each other, which is significantly greater than the thickness of the films (< 2 μm), or 2) the lower piezoelectric activity of the films grown on insulating substrates. This last reason is not very likely, since the SAW assessment has confirmed a sufficient piezoelectric activity. A careful examination of some previously reported works dealing with the lateral excitation of shear modes in structures of similar dimensions suggests that either the reported shear resonances are very weak or that they might actually correspond to longitudinal modes, according to the simulations that we have carried out with Mason's model.

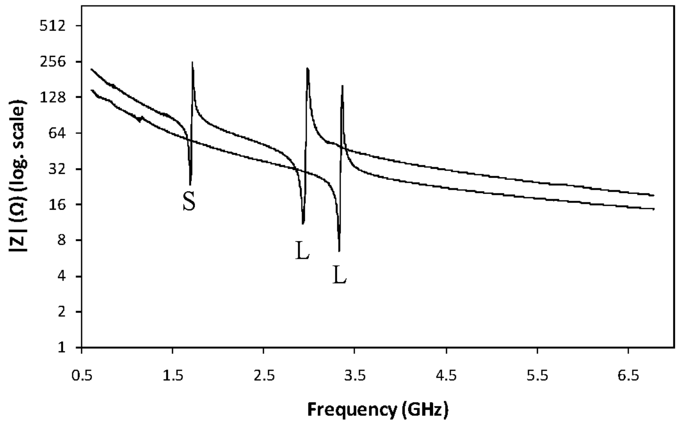


Fig. 6. Frequency response of a laterally-excited SMR of type II (red line) compared with that of a parallel plate resonator containing a polycrystalline AlN film with the c-axis inclined 25° with respect to the normal (blak line).

## IV. Conclusion

After examining carefully the frequency response of a large set of laterally-excited resonators built on different substrates ranging from partially conducting to fully insulating, we have reached the conclusion that shear waves can be hardly excited by lateral excitation; only extremely weak shear modes could be detected in all cases, whereas significant longitudinal modes were systematically excited, even in fully insulating substrates. Additionally, neither the presence of conducting layers in the underlying substrate prevents the excitation of extremely weak shear modes, nor the use of fully insulating substrates eliminates the excitation of longitudinal ones. The excitation of shear modes with perpendicular electric fields in AlN tilted films is far more efficient than the lateral field excitation.

## Acknowledgment

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