High Quality Factor Hybrid SAW/BAW Resonators

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***Summary* — We report hybrid SAW/BAW resonators based on arrays of AlN/Mo transducers located atop a silicon substrate. Thanks to an optimized fabrication process, these devices exhibit quality factors up to 3,900 and 1,700 respectively for the pseudo-SAW and pseudo-BAW modes, at frequencies close to 600 MHz and 2.9 GHz.**

Keywords—Hybrid SAW/BAW resonators, High quality factor, AlN

I. Introduction

Resonators consisting of thickness mode transducers positioned at the surface of a non-piezoelectric substrate have been proposed by Plessky *et al.* as a new type of acoustic resonators [1]. The transducers are arranged in a periodic array excited with alternate polarities (Fig. 1(a)). The coupling between collective modes of the transducers and surface modes of the substrate induces so-called "hybrid SAW/BAW" modes. At first, the inertia added by the transducers slows down substrate modes. This leads to a "pseudo-SAW" mode, represented in Fig. 1(b), confined in the vicinity or within the array of transducers. This mode is naturally confined, as its wave velocity is lower than the bulk modes of the substrate and is thus expected to exhibit high quality factors (Q). As demonstrated in Fig. 1(b), the "pseudo-SAW" mode is characterized by a rigid translation of the transducer where a Rayleigh wave propagates on the top surface of the substrate. On the other hand, the thickness resonance of each individual transducer, mechanically loaded by the acoustic impedance of the substrate, promotes a collective mode developing a large electromechanical coupling factor (k^2). This mode is known as the "pseudo-BAW" mode, illustrated in Fig. 1(c). It is characterized by a deformation of the substrate when the transducers extend/compress. The frequency at which this mode occurs is mostly defined by the thickness (e) of the transducers. The condition for this mode to be confined close to the surface is that its effective velocity (V), defined by the product of its frequency (f) and the wavelength ($2p$), remains smaller than the bulk wave velocities in the substrate (5800 m/s) for Si). Considering the influence of these two geometric parameters, the transducer thickness and pitch, indicates that high electromechanical coupling factors (theoretically, close to 6 % for AlN transducers [1]) and high quality factors can only be achieved if the transducers exhibit sufficiently high thickness to pitch aspect ratios (e/p).

Since AlN is a relatively hard and chemically inert material, previous realizations reported experimental difficulty in achieving high aspect ratio transducers. Additionally, many works focused on delay lines. Thus, so far, no work on hybrid SAW/BAW resonators has reported an experimental quality factor [2-4]. In this work, we introduce an optimized fabrication process allowing to define transducers with a periodicity down to 1 µm and thicknesses up to 2 µm, and demonstrate that clean and sharp resonances can indeed be achieved at the theoretically expected frequencies.

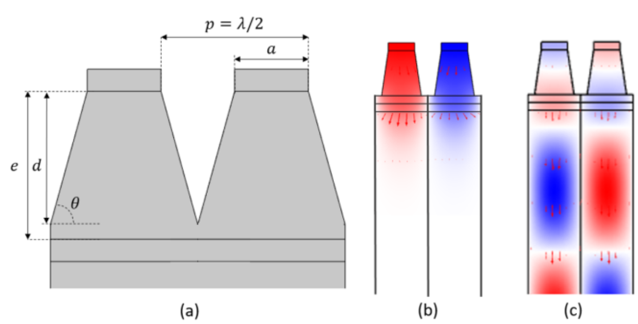


Fig. 1. Finite Element Model (FEM) for a hybrid SAW/BAW: a periodic structure constituted of two pillars with key geometrical parameters indicated (a) and mode shapes (colors correspond to the vertical displacement field) for the pseudo-SAW (b) and pseudo-BAW (c) modes.

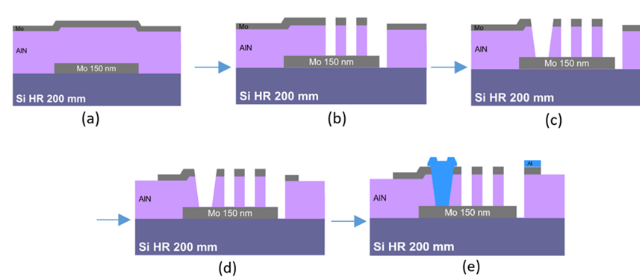
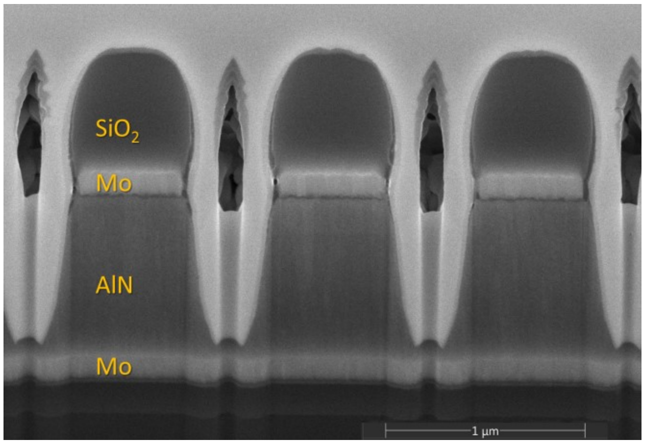
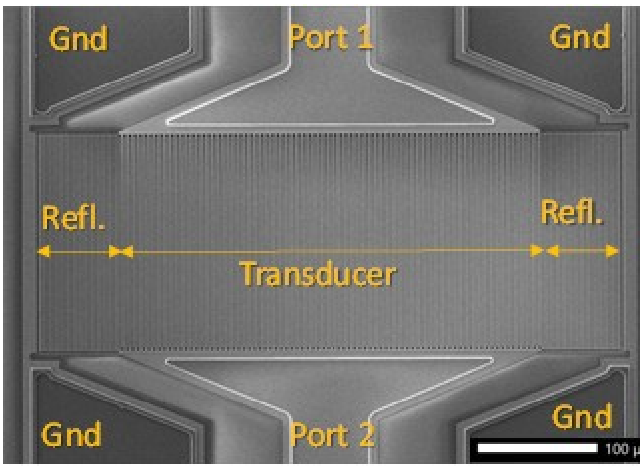


Fig. 2. Five mask process flow for the fabrication of hybrid SAW/BAW resonators: (a) patterning the bottom electrode and deposition of AlN and top electrode, (b) patterning the top electrode and the AlN film to form the transducers, (c) opening vias through the AlN layer for electrical contact towards the bottom electrode, (d) patterning the top electode, (e) Al pads deposition using lift-off.



(a)



(b)

Fig. 3. FIB-SEM cross section of the array of transducers before removal of the etch mask (a) and SEM top view of a resonator after fabrication (b).

II. Fabrication

The fabrication of AlN/Si hybrid SAW/BAW resonators uses a five-mask process flow, illustrated in Fig. 2: a bottom 150 nm Mo electrode common to all transducers is first deposited and patterned. The AlN piezoelectric film, 150 nm top Mo electrode and a SiO_2 hard mask are then subsequently deposited. A combination of UV photolithography and dry-etching defines the trenches separating the transducers. The etch mask is then chemically removed, before patterning a second time the Mo and AlN films, respectively by dry and wet etching in heated phosphoric acid, to open electrical contacts towards the bottom electrode. The top Mo electrode is finally patterned a third time by dry etching to finalize the geometry of the top electrodes. Eventually, Al contact pads are added by lift-off to enable the electrical probing.

Fig. 3. shows SEM images of a resonator with 1µm-thick, and 500 nm-wide transducers spaced by 500 nm. It reveals that the transducers are well-defined, with nearly vertical sidewall angles.

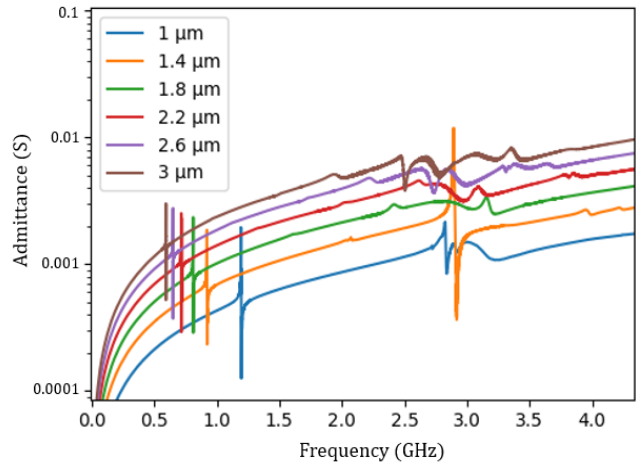


Fig. 4. Electric response of hybrid-SAW BAW resonators with varying transducer pitches.

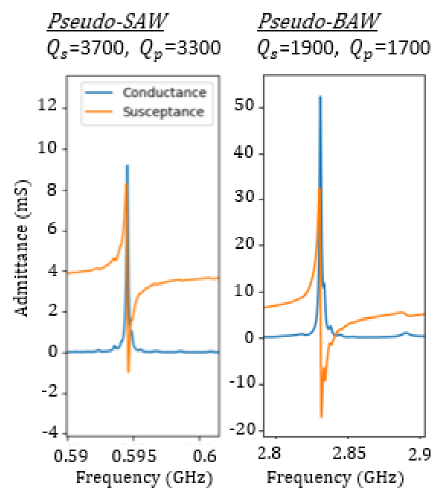


Fig. 5. Magnified view of the electric response in the vicinity of the pseudo-SAW and pseudo-BAW mode resonances for resonators with respective transducer periodicities of 3 and 1 µm.

The two ports resonators are measured on wafer using coplanar GSG probes connected to a vector network analyzer after a proper SOLT calibration. The measured data are deembedded using the measurement of reference devices in which transducers are not connected to the access lines to remove the spurious contribution of pads or feedthrough capacitances. Resonators with varying acoustic apertures, and number of the electrodes were implemented.

III. Results

Resonator responses measured for devices with transducer pitches ranging from 1 to 3 µm are shown in Fig. 4. This indicates that even the smallest dimension transducers exhibit fine resonances. Fig. 5 shows that these resonances can be spurious-free.

A comparison between a calculation of the harmonic admittance using a periodic finite element model (FEM) and the measured electric response is shown in Fig. 6 and extended to

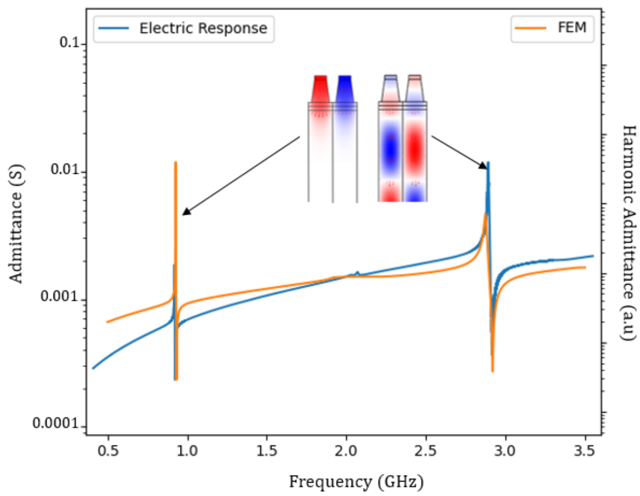


Fig. 6. Comparison betweeen harmonic admittance calculated by the theoratical model and the electrical response of a fabricated device.

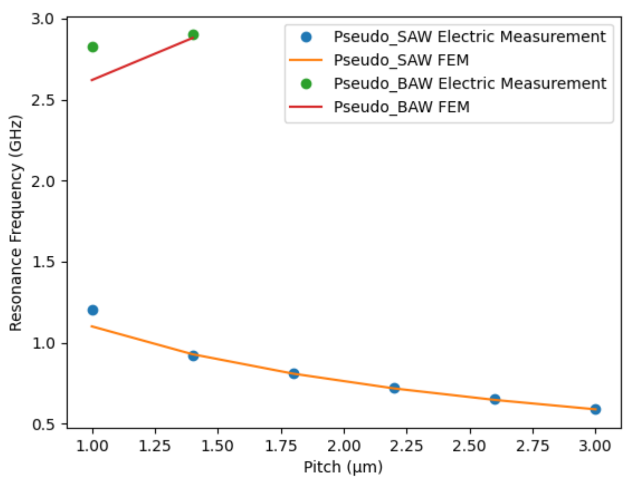


Fig. 7. Extending the comparison betweeen the FEM harmonic admittance and the electrical measurement to various pitch values.

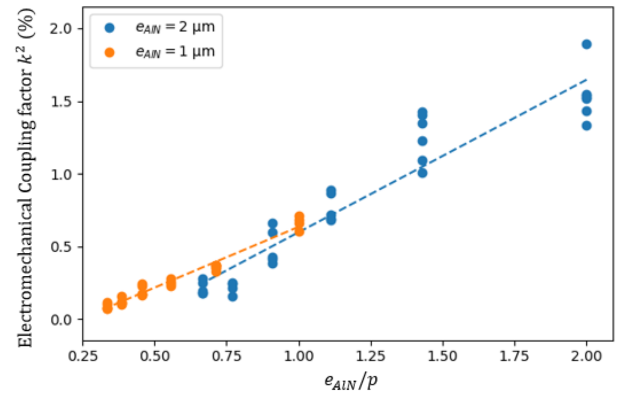


Fig. 8. Influence of the aspect ratio e_{AlN}/p on the electromechanical coupling factor for the pseudo-SAW mode.

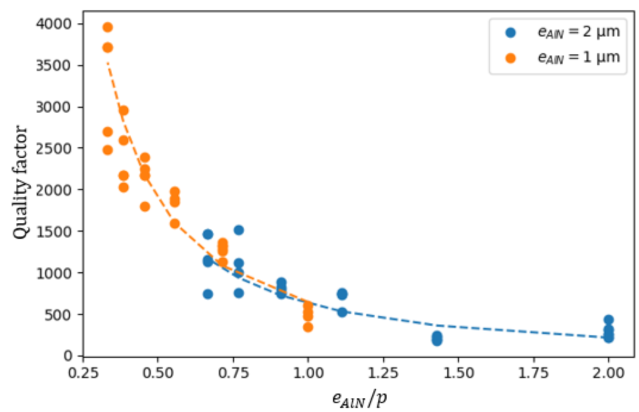


Fig. 9. Influence of the aspect ratio e_{AlN}/p on the quality factor Q for the pseudo-SAW mode.

various pitch values in Fig. 7 keeping the thickness of the AlN layer at 1 µm. The figure shows that the resonance frequencies of the pseudo-SAW and pseudo-BAW modes agree well provided the actual geometry is inferred from Fig 3 (a). This includes a partial etching (d/e_{AlN} in Fig. 1(a)) of 83% of the original AlN thickness, a sidewall angle (θ) of 81° and a coverage ratio (*a/p* in Fig. 1(a)) of 60%. There is, though, one discrepancy at a pitch of 1 µm. This could be the result of a lower manufacturing quality at such small trench dimension making the effect of the slanted walls and the etching ratio more influential.

The lowest resonances, at frequencies between 500 MHz and 1.5 GHz, correspond to the pseudo-SAW mode. Its electromechanical coupling factor improves with increasing transducer aspect ratio, up to 2% for 500 nm-wide and 2 µm-thick transducers. However, its quality factor decreases with increasing aspect ratio, from a maximum 3,600 for 1.5 µm-wide and 1 µm-thick transducers and down to close to 1,000 for 500 nm-wide and 2 µm-thick transducers.

To understand the evolution of the pseudo-SAW mode furthermore, we plot the influence of the transducers height to pitch ratio on k^2 and Q respectively in Fig. 8 and 9 for devices sharing the same relative aperture compared to the wavelength. As the AlN thickness to pitch ratio increases, k^2 increases in an almost linear manner while the quality factor scales almost with the inverse of this parameter. It must be noted that the scattering of data is due to devices with varying number of electrodes being considered altogether, the latter parameter having no clear influence on the electromechanical coupling and the quality factors.

Fig. 5. shows also that when either the second or the third overtones of this fundamental mode approaches 3 GHz, a hybridization occurs between the thickness mode of the transducer and the propagating surface mode, giving rise to the pseudo-BAW mode. Thus, this mode appears only for pitches of 1 and 1.4 µm, unlike the pseudo-SAW, which always exists. Accordingly, the dependences of k^2 and Q on the four available aspect ratios are shown respectively in Fig. 10 and 11. The pseudo-BAW mode exhibits then electromechanical coupling factors up to 2 % and quality factors up to 1,900.

Although the out of phase excitation of neighboring transducers induces destructive interferences preventing a

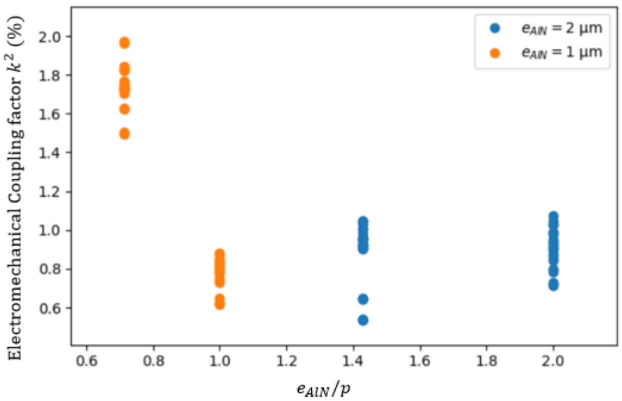


Fig. 10. Influence of the aspect ratio e_{AlN}/p on the electromechanical coupling factor k^2 for the pseudo-BAW mode.

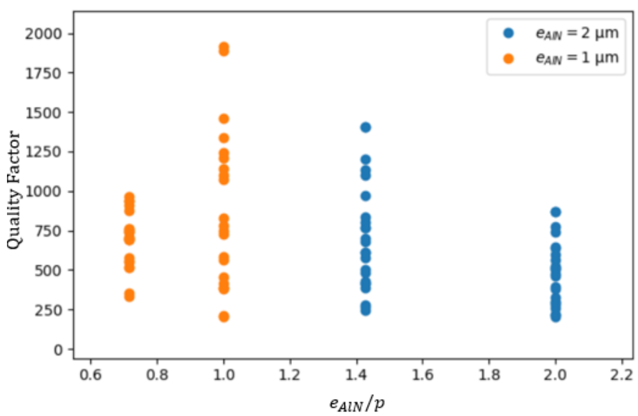


Fig. 11. Influence of the aspect ratio e_{AlN}/p on the quality factor Q for the pseudo-BAW mode.

strong bulk wave radiation [1], some residual leakage into the substrate is still visible in Fig 2(c). It appears on the electric response measurements (Fig. 4) as shoulders close to the second resonance. At low transducers aspect ratios (e_{AlN}/p = 0.7), this even introduces spurious resonances caused by thickness modes of the substrate, which superimpose over the main resonance (as visible in Fig. 12). This may explain the lower quality factors of the pseudo-BAW mode compared to the pseudo-SAW. It also explains the larger distributions in the evaluations of k² and Q in Fig. 10 and 11 respectively, when these spurious contributions become prominent.

Although the quality factors reported for the pseudo-BAW mode are lower than for the pseudo-SAW, the former still exhibits larger Q×f products (4.8×10^{12} Hz) than the latter (2.1×10^{12} Hz). Hence, the pseudo-BAW mode shows promising prospects towards high frequency operation.

IV. Conclusions

We have demonstrated a fabrication process for hybrid SAW/BAW resonators, which enables the definition of AlN/Mo transducers with periodicities down to 1 µm and height to width aspect ratios up to 4. This allowed us to report clean resonator responses and, unlike previous work, to analyze resonator performances. We obtained quality factors up to 3,600 and 1,900 for the pseudo-SAW and pseudo-BAW modes located respectively in the 500 MHz – 1.5 GHz and 2.8 – 3 GHz range. The evaluated electromechanical coupling factors reach up to 2 % for both modes. Future work will aim at further improving performances in terms of electromechanical coupling and quality factors by increasing the transducers aspect ratios and replacing AlN by AlScN as suggested in [2, 5].

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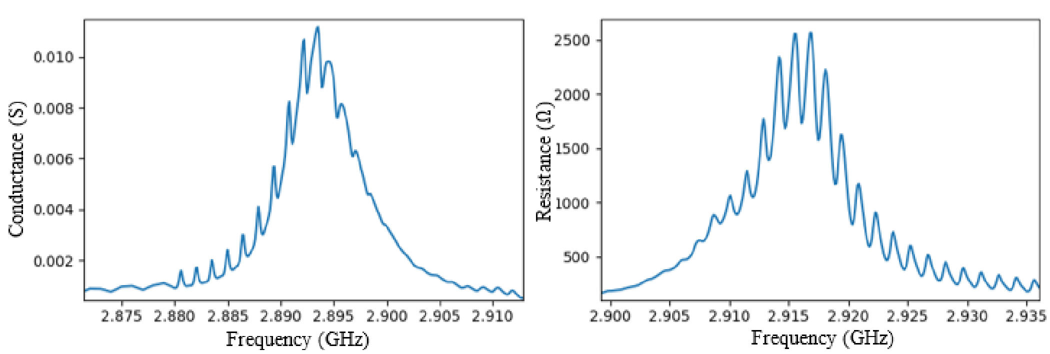

Fig. 12. Example of series (a) and parallel (b) resonances of the pseudo-BAW mode for a device with e_{AlN}/p = 0.7 exhibiting strong contributions from bulk resonances of the substrate.