On the dispersive behaviour of AlN/Si High Overtone Bulk Acoustic Resonators

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***Abstract*—Harmonic Bulk Acoustic Resonators are build on a SOI to allow for a good spectral separation of the device resonance. SOI is etched back to allow for the fabrication of well defined resonance in the vicinity of 2.45 GHz. Thermal sensitivity close to –25 ppm/K also was measured. The analysis of experimental data obtained for resonance taking place in the whole stack allows for emphasizing a dispersive behavior of the harmonic modes of the structure.**

I. INTRODUCTION

The fabrication of compact high stability frequency sources devoted to on-board applications may be stabilized by acousto-electric devices such as SAW and BAW resonators. Many architectures have been proposed to improve the quality factor of such devices which directly influence the phase noise figure of the oscillator [1]. We recently have reported on properties of HBAR built on 127 µm thick AT-cut quartz plates excited by a C-oriented aluminium nitride (AlN) thin film. The interest of this configuration mainly consisted in the good spectral separation of the excited harmonics, with loaded Q factors as high as 30000 at 400 MHz [2].

In this work, we have used a high quality AlN layer deposited by sputtering onto a very thin (30 µm thick) silicon plate to improve one step further the spectral separation and to fabricate oscillators at frequencies close to 2.4 GHz. The substrate consists in a 4" thick SOI wafer. The aluminium nitride then is deposited by pulsed direct current reactive sputtering onto a platinum electrode. The top electrode is then patterned to achieve the expected impedance at resonance. The fabricated devices exhibit a fundamental longitudinal mode resonance near 120 Mhz and well defined and coupled harmonics in the vicinity of 2.45 GHz, allowing for the fabrication of oscillators in this frequency range. A dispersive behaviour was experimentally observed concerning the main characteristics of the resonator (resonance frequency, coupling, quality factor). These characteristics changes with the mode order along a modal distribution similar to those of plate modes or lamb waves. A theoretical analysis of these devices provides similar results which should allow for explaining this phenomenon. Finally, these resonators have been fully characterized and are expected to be used to stabilize an oscillator close to 2.45 GHz.

II. PRINCIPLE AND DESIGN OF ALN/SI HBAR

Figure 1 and 3 show the general structure of the implemented devices. It consists in classical HBAR structures built on a 4" SOI wafer. for this specific application (high quality RF source manufacturing), we use a high quality AlN layer deposited by sputtering [3] on the top side of the SOI wafer (the one corresponding to the 30µm thick Si plate). After AlN deposition, the backside silicon is removed via Deep reactive ion etching (DRIE) to take advantage of the controlled thickness top silicon layer, yielding a spectral separation of about 120 MHz (assuming an equivalent longitudinal wave velocity of about 8000 m.s-1 along the stack Si/Pt/AlN/Pt). Such a spectral separation of the harmonic modes is expected to ease the choice of resonance frequency in the considered spectral domain. We though expect to be able to stabilize an electrical oscillator in the vicinity of 2,45 GHz using our AlN/Si HBAR.

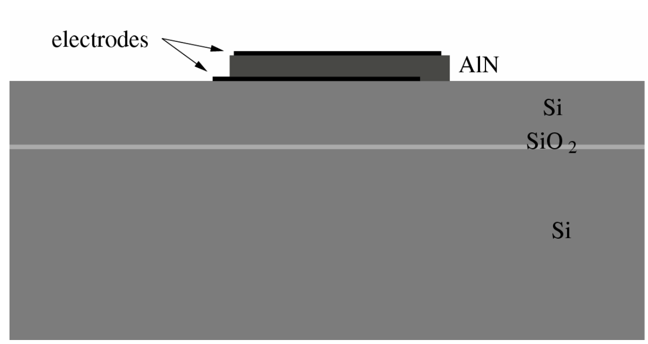

Figure 1. HBAR conifguration exploiting the whole SOI thickness (before DRIE)

The following plot shows the predicted admittance of the first configuration. AlN thickness is 2µm, Pt electrode are 150nm thick, silicon plate thickness set to 30µm with a residual 500nm thick SiO_2 layer beneath. Surface of the electrode is set to 100µm². The spectral distance between two resonance is 8 MHz, yielding a quite fuzzy spectral definition and almost no chance to specifically select any mode in the peak forest. On the contrary, once the Back side SOI silicon is removed (fig.3), the spectral separation allows for an easier mode selection, as shown in fig.4.

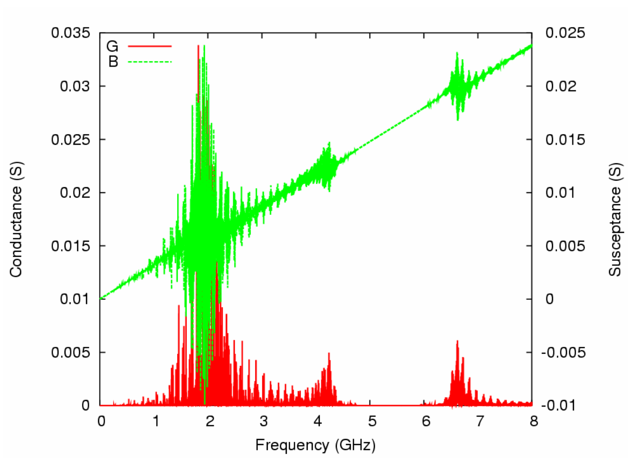

Figure 2. Theoretical admittance of the structure of fig.1. We note a strong mode coupling near 2 GHz and smaller contributions between 6 and 7 GHz.

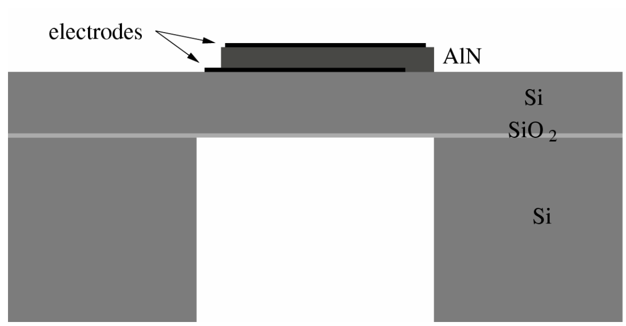

Figure 3. Final structure of the AlN/Si HBAR

III. HBAR FABRICATION AND CHARACTERIZATION

AlN is deposited in a pulsed direct current regime on a C oriented platinum layer to favor its growth along the C axis. As suggested in fig.1 and 2, the top electrode is patterned to meet different impedance values in the vicinity of the principal resonance. Figure 5 shows a SEM view of one single port resonator, allowing to appreciate the quality of the micro-machining achieved at the EPFL. In order to fully characterize the capabilities of the implemented material and structures to support high quality factor and spectral purity resonance, we have first measured the HBAR response over the whole SOI stack before etching the silicon backside by DRIE along the Bosch process. We then were able to measure the different contributions of the HBAR.

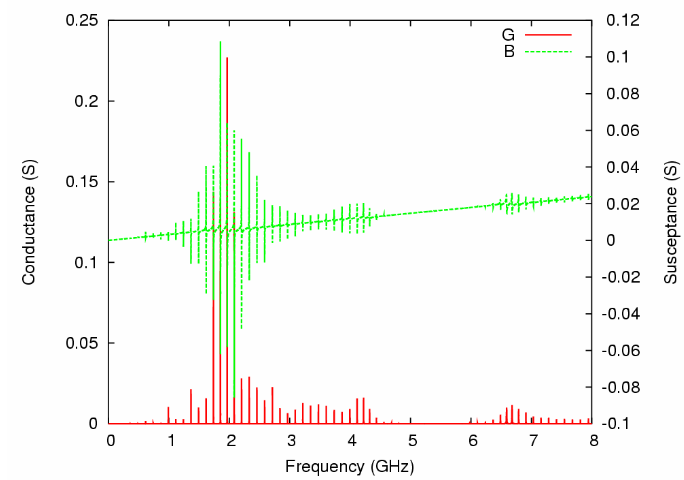

Figure 4. Theoretical admittance of the structure of fig.2. Same optima appears with a better spectral separation of the modes

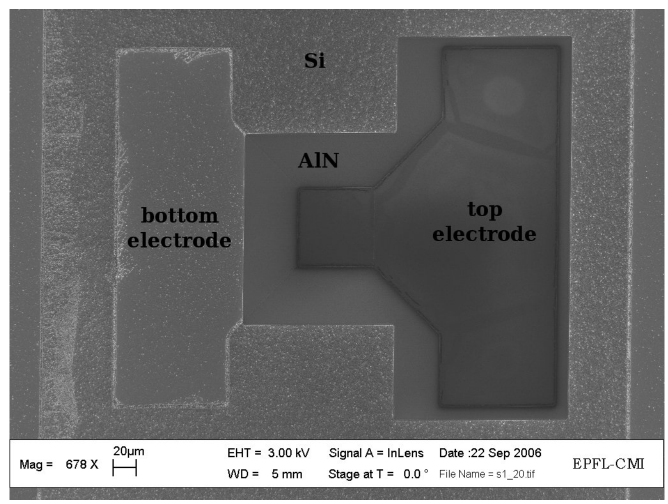

Figure 5. SEM view of a 50 Ω AlN/Si HBAR. AlN has been etched to access the bottom electrode.

Figure 6 shows a wide range experimental admittance of the device of fig.5. It actually exhibits a behaviour quite comparable to the one predicted in fig.4 (but with larger losses), with the most coupled modes located in the 1.5-2 GHz range, an also significantly coupled modes near 6.5 GHz as predicted. Measurements have been focused near 480 MHz and 2.5 GHz to illustrate the response quality of the device. The corresponding experimental admittances are plotted in fig.7 and 8 respectively. We particularly emphasize the very good spectral separation of harmonics (fundamental frequency close to 120 Mhz) as well as rather good quality factors, corresponding to QF products around 5.10^{12} for frequency in the range 1-3 GHz. Typical figure of merit were found equal to 6000 at 485 Mhz, 4000 at 1.2 Ghz and 2000 at 2.45 GHz. Finally, temperature coefficient of frequency of the mode near 485 MHz. Although the frequency of the resonators within the plate are somehow dispersed (488 to 489.5 MHz), the TCF of the different tested devices appear very coherent and comparable, yielding a linear temperature coefficient near –25.7 ppm/K. The results of this last characterization are plotted in fig.9.

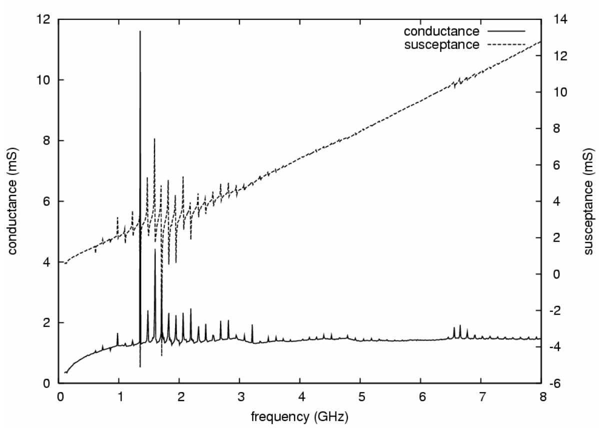

Figure 6. Experimental admittance of AlN/Si HBAR on a wide frequency range. Optimum of excitation is obtained near 1.8 and 6.7 GHz

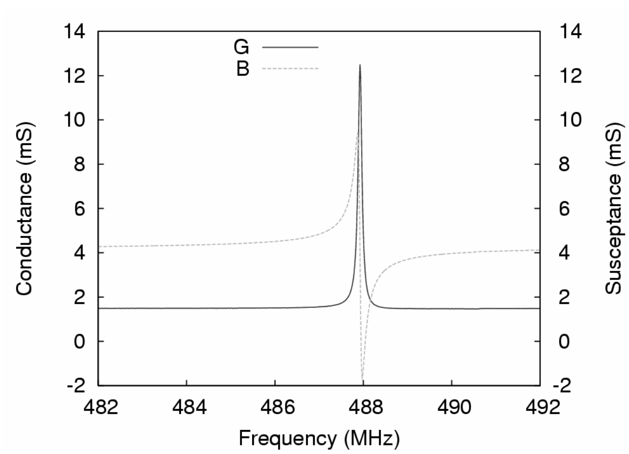

Figure 7. Close-up admittance measurement in the vicinity of th 485 MHz resonance. Q=6000

IV. EVIDENCE OF HBAR DISPERSIVE BEHAVIOUR

Systematic measurements have been achieved on the numerous devices available. Particularly, we have measured the coupling coefficient and the resonance frequency for different harmonics of the whole stack before backside silicon etching. Intermediate coupling coefficients were measured for low order modes (from 0.2 to 0.5%) wheras this figure drops down when increasing the mode ordre (in the 0.1% for resonance in the range 2.4-2.5 GHz). However, the most unexpected result emphasized by these systematic measurements is the fact that coupling coefficients are found to be distributed along the frequency on separated curves globaly following the same law along frequency. Figure 10 shows an extended plot of the K_s^2 for the analyzed modes, with a superimposition of theoretical predictions obtained using our 1D model.

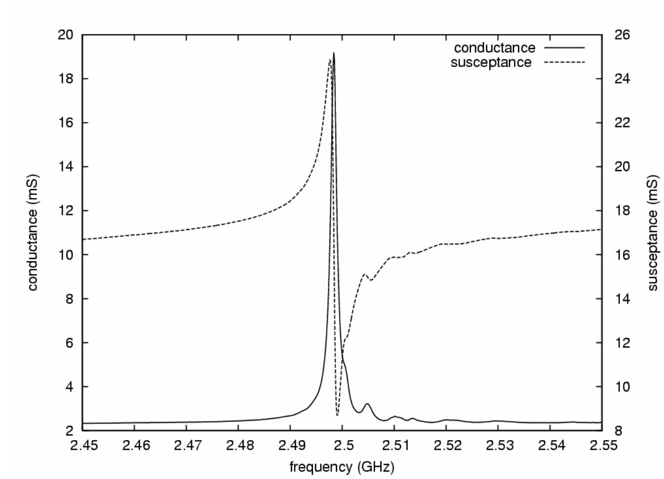

Figure 8. Close-up admittance measurement in the vicinity of th 2.5GHz resonance. Q=2000

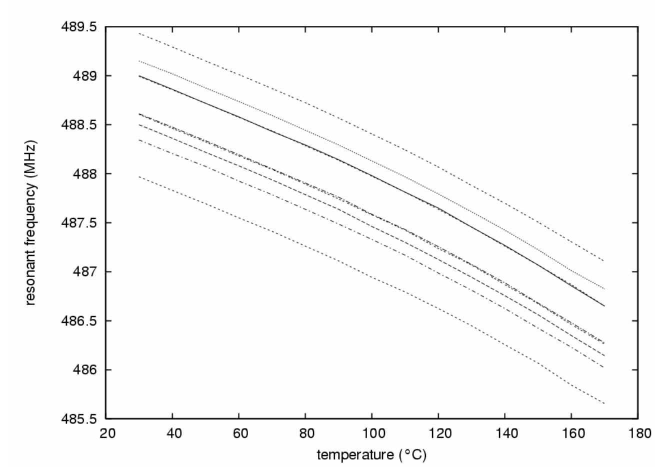

Figure 9. Temperature induced frequency drift, the 1st dergree TCF is found equal to –25.7 ppm/K

Figure 11 shows a focused view of the same curve for low frequencies, emphasing the observed phenomenon. Many hypotheses can be emitted to explain this phenomenon. Reinhardt explained in [4] that the fundamental mode and each of its harmonics exhibit a kind of optimal energy matching for different geometrical configuration, yielding the curve superimposition pointed in fig.10 and 11. It is then possible as shown on these graphs to find out this phenomenon theoretically. However, if it seems rather simple to extract the mode characteristics along the thickness of the plate in the case discussed by Reinhardt, the situation in which many layers are stacked yields more difficulties to identify which is responsible of what effect, yielding the quite poor theory/experiment matching of fig.10 and 11. Concerning the equivalent mode velocity, we found that experimental data more or less followed the dispersion behavior theoretically predicted (fig.12). Increasing the thickness of the plate is known to decrease the velocity of the mode from the AlN longitudinal mode velocity to the one of the silicon. However, in our case we don't change the thickness of the whole stack. We then conclude that as in the case of Lamb wave and more generally for dispersive propagation, we should be able to point out a dependence of the harmonics characteristics along an equivalent frequency-thickness product, allowing for a more accurate prediction and a better design of HBARs made on complicated stacked wafers.

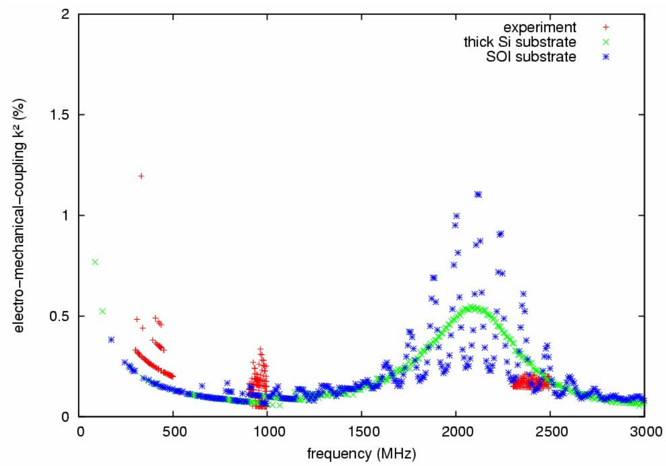

Figure 10. Dispersive behaviour of the coupling coefficient versus resonance frequency of the HBAR structure of fig.1

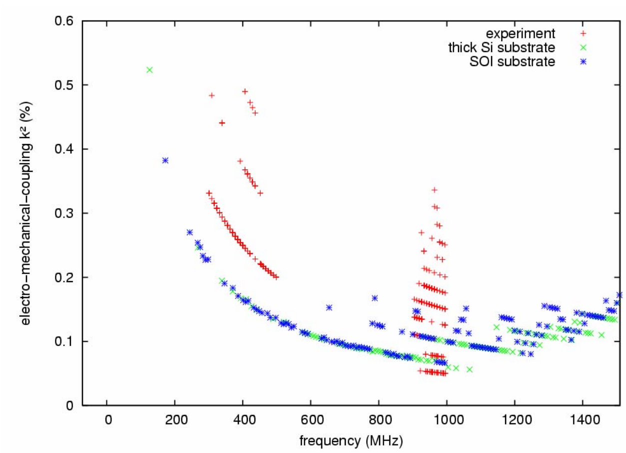

Figure 11. Focus of fig.10 on the low frequency experimental and theoretical Ks²

More work is under development to fully understand why modes assumed to follow an harmonic distribution for a given structure as our exhibit some kind of discrete distribution along different harmonics characteristics. Everything happens like some harmonics can better take place in the stack than others (harmonics of harmonics), but we hardly see a physical reason explaining that. For instance, there is no relation between phase of the mode along the thickness of the plate and the evolution of the characteristics. We then expect to find some more robust explanation in the analysis of the energy distribution along the stack, this work being presently under development.

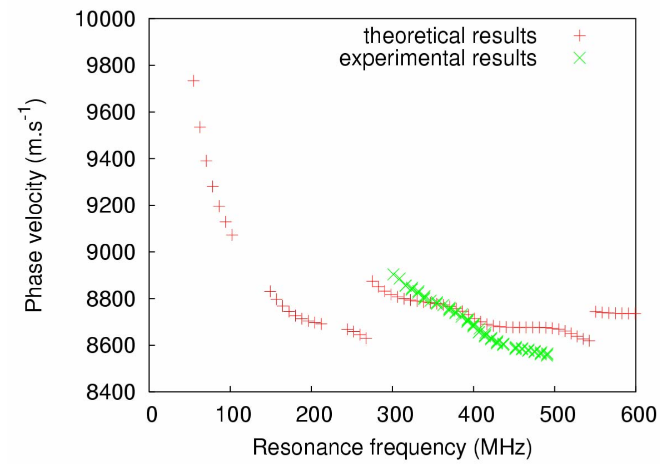

Figure 12. Equivalent phase velocity versus resonance frequency, comparison between theory and experiment.

V. CONCLUSION

HBAR resonators have been fabricated on a SOI wafer to well control the spectral separation of the excited harmonics mode and to favour well coupled high Q resonance in the vicinity of 2.45 GHz. These resonators are expected to stabilize high stability resonators in this frequency range. QF products in the vicnity of 5.10^{12} were measured in the range 1-3 GHz. The systematic exploitation of measured characteristics of harmonics on the whole material stack allowed for pointing a dispersive behaviour of the HBAR, also found theroretically but not in perfect agreement with experiments. More work is currently undertaken to propose a comprehensive and efficient analysis of this dispersion phenomenon.

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