Hybrid resonant structures for wireless sensor applications

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Abstract: **In this work, we report on an original approach for increasing the coupling factor of Harmonic Bulk Acoustic Resonators (HBARs). It consists in adding a layer onto the top electrode to optimize the operation of the device. We avoid using metal layers and used an extra Aluminum Nitride (AlN) film to optimize the excitation energy localization in the stack and try and preserve the Q factor of the structure. We present simulation results demonstrating the efficiency of the optimization approach. Based on these simulations, test devices have been manufactured and tested, demonstrating the possibility to gain more than a factor of 2 on the coupling along the proposed approach. Finally, the possibility to wirelessly interrogate these resonators is demonstrated.**

I- Introduction

Radio-frequency acoustic wave resonators are widely used for various applications such as frequency sources, filters, and sensors for wired or wireless purposes. The latter application benefits from the linear nature of piezoelectricity to allow for remote control of the sensor without boarded energy supply. We have investigated the possibility to exploit Harmonic Bulk Acoustic Resonators for the fabrication of high quality and stability sources [1], taking advantage of Aluminum Nitride (AlN) atop thin silicon plate structures to achieve a spectral separation of the modes compatible with this kind of application. This also allows to isolate one mode within the ISM (Indsutrial, Scientific, Medical) bands (434, 866, 915 MHz, 2.45 GHz) for the fabrication of wireless temperature sensors. One of the main problems we have been facing for the wireless interrogation of these devices was related to the small coupling coefficient of the resonance, even when using the best accessible AlN [2].

A first approach to improve these weak coupling values was proposed by Shih-Yung Pao et al [3]. Their investigations were focused on the combination of different electrodes for various configurations of piezoelectric film/substrate. The authors pointed out that thick top electrodes yield better coupling coefficients than thin ones. This approach however also yielded a notable degradation of the quality factor of the resonance. Analyzing the mechanical behavior of a classical bulk wave resonator shows that the coupling between the electrical excitation and the piezoelectric medium is maximum when the maximum stress locates in the middle of the said medium. As a consequence, we do understand that Shih-Yung Pao et al. empirical solution consists in increasing the stress within the piezoelectric layer, then yielding larger electromechanical coupling coefficients of the resonances.

In this work, we report on an original optimization process for which a structure capable to preserve the quality of the resonance is introduced. It consists in adding a layer onto the top electrode to optimize the operation of the device. We then avoid using metal layers and used an extra AlN film to optimize the excitation energy localization in the stack. We present simulation results demonstrating the efficiency of the optimization approach for the first modes of the structure, allowing to better benefit from the intrinsic coupling capabilities of the film. Based on these simulations, test devices have been manufactured and tested, demonstrating the possibility to gain more than a factor of 2 on the coupling along our approach. Experimental measurements are reported, also showing the need for an accurate control of the top layer machining, capable to give rise to parasitic contributions. The possibility to wirelessly interrogate these optimized resonators finally is demonstrated.

II- Harmonic Bulk Acoustic Resonators (HBARs)

We first briefly recall the basic principle of HBAR. Harmonic bulk resonators also called over-moded resonators (OMR) consist in a composite structure coupling a thin piezoelectric transducing layer deposited on a thick propagation material (fig.1). The waves emitted by the transducer propagates back and forth (from top to bottom surfaces). Even and odd harmonics are excited as well, as they all respect the boundary conditions. The resonance frequency of the n^{th} mode is given at first order by the simple relation $f_n=nV/2e$ where the effective thickness e corresponds to the one of the whole composite plate (piezoelectric layer plus substrate) and V is the equivalent velocity of the mode (composition of the substrate and film velocities). The mode polarization is forced by the transducer piezoelectric coupling whereas V mainly depends on the elastic properties of the substrate. The latter is advantageously a single crystal exhibiting reduced acoustic losses to favour strong Q factors of the resonances. The electrical response of such a

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device then is composed of numerous resonance contributions. The choice of the thickness of the different stacked layers is achieved for favoring the mode for which the half wavelength will correspond to the piezoelectric layer thickness. As we intend to use these resonators for oscillator or wireless sensor applications, we have consider substrate dimensions allowing for a large spectral separation. Finally, the possibility to accurately set one resonance within ISM band widths (434, 866 MHz or 2.45 GHz) has been consider as a main design parameter.

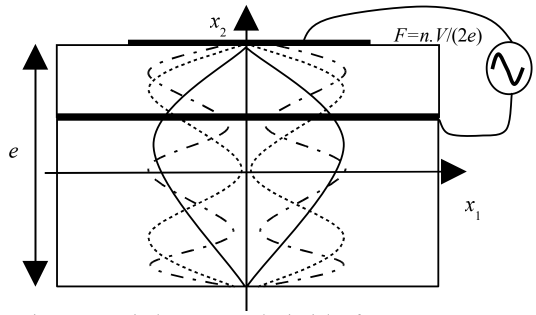


Figure 1 : Typical structure and principle of a HBAR or OMR resonator

Numerous research and industrial groups have developed advanced techniques for the fabrication of reliable piezoelectric layers for RF applications. AlN appears as the most robust and trustable material in that purpose [2]. It can be deposited on various materials and especially on silicon. With a coupling factor of its longitudinal bulk wave close to 7%, it is well suited for the transducer function of HBARs. Furthermore, the use of the fundamental mode of AlN for the fabrication of resonators in the 434 or 866 MHz ISM bands requires quite thick layers (13.2 and 6.6 µm respectively) which are beyond reach of most technological facilities. The fundamental mode of AlN films could eventually be used for the 2.45 GHz ISM band, but the modest Q factors generally measured in such confgurations (rarelly in excess of 1500) are poorly suited for resonator-based wireless interrogation. Everything sounds to indicate that HBAR may solve all those poblems.

III- AlN/Si HBARs

A. Simple devices

In a previous work, we fabricated AlN/Silicon HBAR for oscillators applications, in which we used a 30µm thick as propagating medium and an AlN layer as transducer. The devices were built on a 4" thick SOI wafer (30µm thick Si plate above a 500µm thick Si substrate, SiO_2 thickness near 500nm). We used a high quality AlN layer deposited by pulsed-DC sputtering [2] on a C-oriented Ti/Pt (20/100 nm) electrode on the top side of the SOI wafer (the one corresponding to the 30µm thick Si plate). After AlN deposition, a top Pt electrode is deposited and the backside silicon is removed via Deep Reactive Ion Etching (DRIE) to take advantage of the well-controlled thickness of the top silicon layer, yielding a fundamental longitudinal mode near 120 MHz (assuming an equivalent longitudinal wave velocity of about 8000 m.s^{-1} along the stack Si/Pt/AlN/Pt). This yields harmonic modes each 120 MHz, yielding a spectral separation expected to ease the choice of the resonance frequency for wireless interrogation. Although a thicker Si plate would ease reaching the 434 MHz, we have used these devices for our demonstration, even if notably far from the targetted band, without any loss of generality as the system is linear (the results can be transposed to any frequency band).

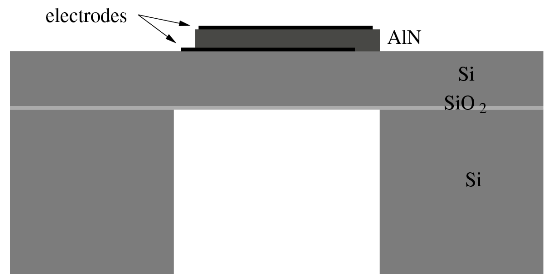


Figure 2 : Initial AlN/Silicon HBAR structure. The AlN film is 2µm thick, the silicon 30µm thick and metallization consists of 100 nm Pt layers

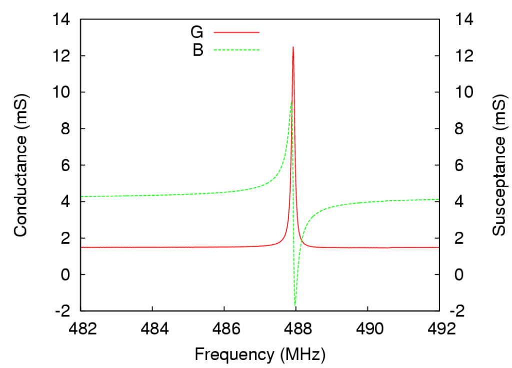


Figure 3 : Admittance (measured) of the 4th mode of the structure of fig.2, resonance frequency f_r = 487.925 MHz, electromechanical coupling K_s^2 = 0.06%, quality factor Q = 5500

The Temperature Coefficient of Frequency (TCF) of this mode was measured near –30 ppm/K corresponding to a linear temperature-frequency drift. Even if this drift was a bit too strong for matching the ISM band and the considered temperature range (0 to 160°C), the ease with which this result was obtained and the very small size of the corresponding device pushed to investigate further this solution for temperature sensing purpose. We did extract from these measurements the principal characteritics of the corresponding mode. We found a quality factor of about 5500 (principaly conditioned by silicon) and a modest coupling factor near 0.06%. Using a 1D model coupled with a model updating approach then allowed to estimate intrinsic parameters of the involved materials, and more particularly the electromechanical coupling factor of the fundamental longitudinal mode of the AlN layer above 6%.

B. Optimised devices

Starting from these values, we decided to identifiy the geometrical dimensions of an AlN/Silicon composite structure composite to reach the coupling value of a SAW resonator built on quartz, as we knew theses characteristics complied with the wireless interrogation constraints. The following curve shows the evolution of the coupling coefficient versus silicon thickness (substrate) for a resonance near 441 MHz (the mode just above the tested one), assuming a wavelength close to 20µm. One finds out that approaching the Rayleigh wave electromechanical coupling on Quartz (1‰) practically imposes to exploit the fundamental mode of the structure (cf fig.4).

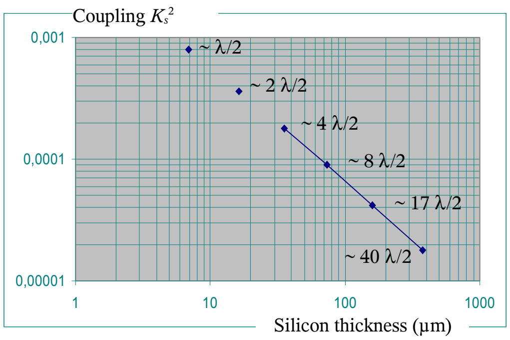


Figure 4 : Characterization of the coupling factor of the mode corresponding to a resonance near 441 MHz versus silicon thickness (wavelength λ= 19.135µm)

We then decided to address the problem of such small electromechanical coupling factors when using a reasonably well coupled AlN layer. The solution is related to the localization of the elastic energy within the stack, which plays a fundamental role in the excitation efficiency of the different modes of the structure and hence on the corresponding coupling strength.

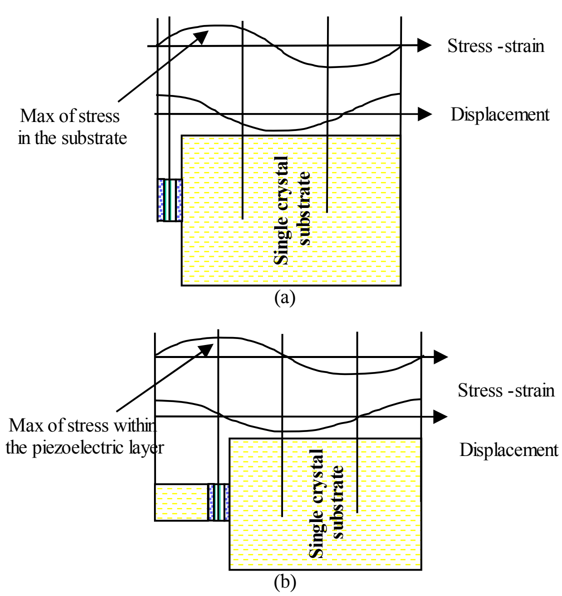


Figure 5 : Scheme of the elastic energy (stress-strain) localization within the whole material stack (a), impact of the matching top layer on the matching of the max stress and the piezoelectric layer (b)

The idea then consists in placing the maximum of the stress distribution right in the middle of the transducer layer to benefit from the actual piezoelectric coupling properties of the film, similarly to what is achieved for BAW resonators operating on their fundamental resonance. Figure 5 shows a scheme of the energy location in the structure without and with a matching layer to illustrate the proposed approach. There is various strategies to address the problem. Figure 6 shows the evolution of the electromechanical coupling factor when considering the piezoelectric layer placed in such a way that it is submitted to the maximum stress for odd modes, like in the case of a single piezoelectric plate excited by in-regard electrodes. This is achieved by adding an extra silicon plate above the piezoelectric layer. The consequence of this approach is to notably increase the K_s^2 of the regarded mode, allowing for reaching the expected operating point for modes of order above or equal 4.

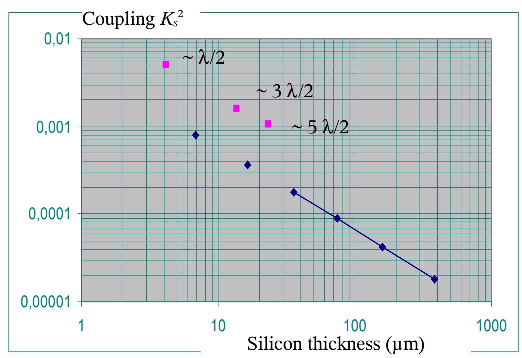


Figure 6 : Characterization of the coupling factor of the mode corresponding to a resonance near 441 MHz versus silicon thickness (wavelength λ= 19.135µm) accounting for a silicon matching layer above the top electrode

Figure 7 shows more directly the impact of the presence of the matching layer on the admittance of the resonator near the considered mode. This result is obtained using our 1D model [4] but even the simplest Mason-like simulation tool would yield the same observations.

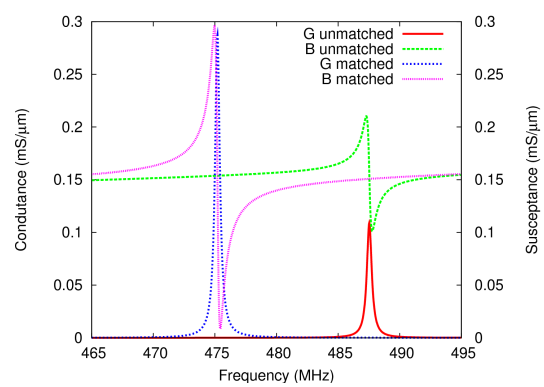


Figure 7 : Calculated admittances of the 4[th] mode of the structure of fig.2 (unmatched) and of the same structure equipped with a 2µm thick AlN matching layer (matched)

We assume here a 30µm thick silicon substrate (accounting for a 1.5µm thick silica layer underneath), coated by a 2µm thick AlN transducer deposited on a 100 nm Pt bottom electrode, the top electrode being the same. The matching layer here simply consists in a 2µm thick AlN layer atop the later electrode. The initial coupling is in the vicinity of 0.068% (without matching layer) for a mode resonating near 485 MHz.

When adding the matching layer, the resonance of course drops down to 475 MHz but also the coupling reaches 0.18%, i.e. near 3 times the initial value. Although these figures are deduced from the resonance/antiresonance separation, the increase of coupling clearly appears on the conductance peak, as the Q factor is not degraded by the presence of the matching layer.

To summarize, the proposed structure consists of a single crystal substrate on which a piezozlectric transducer (Pt/AlN/Pt) is deposited, the initial stack being completed by a top layer acting as a matching layer which helps concen,trating the elastic energy within the piezoelectric layer. We precognize the use of a high acoustic and dielectric quality material to keep the resonance quality factor of the HBAR structures. It may consist of the same material as the top electrode but deposited metals are not known for their excellent acoustic properties. Consequently, the use of the same material as used for the piezoelectric layer has been considered for the experimental validation.

IV- Experimental assessment

The fabrication of test vehicles for demonstrating the interest of the proposed structure has been performed using the simple devices presented above. The final device corresponds to the scheme of fig.8. The matching layer consist of an AlN layer deposited along the same process described in II and then patterned to fit the top electrode surface. The silicon substrate as well as the insulating silica layer are etched afterwards. ALN matching layer is machined using a TetraMethyl-Ammonium-Hydroxide (TMAH) based wet-etch process. This step reveals particularly critical as illustrated by fig.9 (a,b), showing underetch effects near the AlN top layer edges. It actually turns out that lateral etching of the AlN layer using this process is notably faster than surface etching, yielding the observed phenomena. Consequently, the transducing AlN layer also has been slightly etched, yielding a notable degradation of the whole structure.

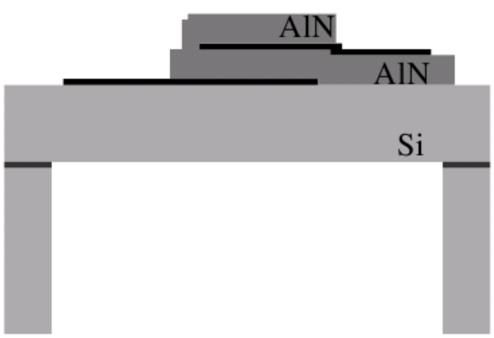
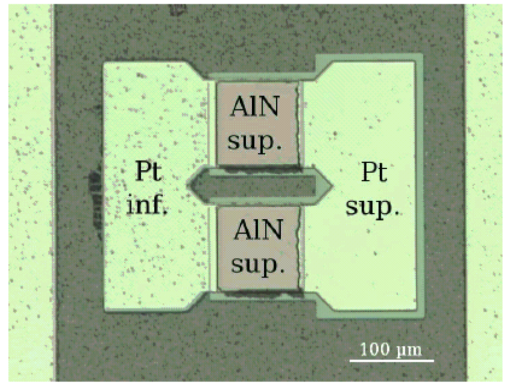
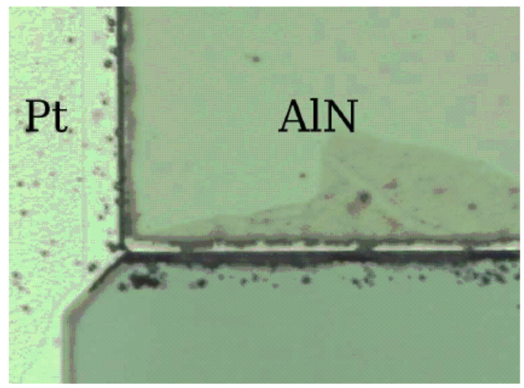


Figure 8 : Optimized AlN/AlN/Silicon HBAR structure. AlN films are about 2µm thick, the silicon 30µm thick and metallization still consists of 100 nm Pt layers

The fabricated devices have been electrically characterized and the analysis of experimental admittances (fig.10) shows that the matching layer actually operates as expected, yielding coupling factors in excess of 0.2%, i.e. more than 3 times the intial value. We also observe a predicable Q factor reduction considering the observations of fig.9.



(a)



(b)

Figure 9 : SEM top views of the machined structures – two resonators in parallel (a) – after the top matching layer patterning,.close view of the underetch effects (b)

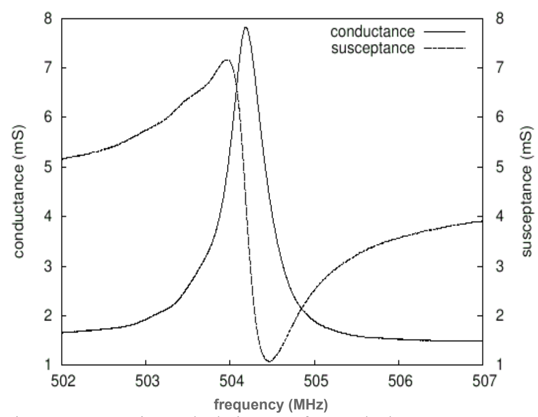


Figure 10 : Experimental admittance of a matched HBAR, resonance frequency 504.2 MHz, K_s^2 = **0.22%,** Q = 1350 – the Q reduction attributed to matching layer under-etch and surface degradation

IV- Wireless interrogation

Finally the best resonators were diced and encapsulated in standard ceramic pakages. A quarter-wavelegnth antenna was then connected to the packaged device to check our capability to wirelessly interrogate such devices. Due to the difficulty to well match the 434 MHz centered ISM band, we have adapted our interrogation electronics [5] to operate between 482 et 485 MHz. The curves of Figure 11 present the electrical response at the amplitude detection circuit output. Three different interrogation distances have been tested, proving the possibility to wirelessly interrogate the devices at a distance of 1 meter. We of course illustrate the well-known phase rotation phenomenon (which can be simulated by simply adding a transmission line of variable length in the HBAR model [6]).

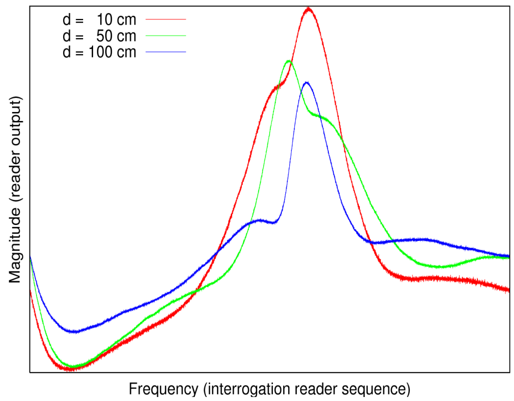


Figure 11 : Experimental assessment of wireless interrogation of a HBAR device

From these mesurements, we can establish the possibility to wirelessly interrogate HBARs in the 434 MHz ISM band similarly to what is achieved using SAW resonators. The reader electronic set-up did not required any change (apart the central operating frequency) and, provided a better control of the central frequency and of the quality factor of our resonators, HBARs could advantadgeously replace SAW resonators for various applications, allowing for a notable size reduction without sacrifying the system efficiency. One problem to address now is the fabrication of HBAR allowing for differential measurements to get rid of any phase rotation or aging effects (and more generally to reject correlated paralmeter variations) as arising in real applications and to allow for measuring absolute physical parameters.

V- Conclusion

We have proposed a new structure allowing for optimizing the characteristics of HBARs and particularly the electromechanical coupling factor to favour their use for wireless sensing operations. We have explained the role of the eleastic energy localisation within the material stack and how this parameter could be optimized to notably increase the coupling strength of any mode of the structure, with a particular focus on resonance near the 434 MHz centerd ISM band. We have experimentally demostrated the efficiency of the proposed approach, gaining a factor 3 on the actual K_s^2 of AlN/Si-based HBARs. We finally have shown the pôssibility to wirelessly interrogate these devices at distances in the meter range. Further work now will be dedicated to the development of differential structure to prove the possibility to replace SAW devices by compact HBAR structures for various wireless sensing applications.

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