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Temperature Compensated AlN/SiO_2 Structures for Lamb Wave Resonators

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***Abstract* — Characteristics of lower symmetric and anti-symmetric modes s_0 and a_0 (velocities, electromechanical coupling coefficients, TCF) were numerically investigated in Lamb wave resonators using AlN and AlN/SiO_2 membranes. Two configurations of AlN/SiO_2 structure were compared, with SiO_2 film located either at the bottom or on top of AlN. All characteristics were calculated as functions of SiO_2 film thickness with normalized AlN thickness varying between 0.1λ and 0.5λ. The influence of uniform Al electrode at the bottom of AlN on the Lamb wave characteristics has been studied. For symmetric mode s_0 it was found that SiO_2 film thickness, which is required for zero TCF, decreases from 60% to 25% of AlN thickness when the latter grows from 0.1λ to 0.5λ. The electromechanical coupling of s_0 mode in the temperature compensated structure depends on the presence of metal film at the bottom of AlN and drops with poor conductivity of this film. The behavior of the reflection coefficient per period of the grating reveals the crucial difference between the analyzed configurations.**

I. Introduction

Lamb wave resonators using AlN thin plates are very attractive for wireless communication systems and other high frequency applications, due to high velocities of Lamb waves and electromechanical coupling up to 3.5%, supported by additional advantages of well developed AlN epitaxial growth and planar technologies and easy integration with IF and RF components if AlN membrane rests on silicon substrate [1-3]. Moreover, temperature compensated high-frequency resonators can be built on AlN with SiO_2 film. In [4] the effect of SiO_2 on the characteristics of the lowest symmetric Lamb mode s0 was investigated assuming that SiO_2 film is located at the bottom surface of AlN membrane (opposite to the top surface with IDTs on it). The thickness of SiO_2, which provides zero TCF of Lamb mode s_0, was theoretically determined and experimentally verified.

It is apparent that temperature compensation can be also obtained if SiO_2 overcoats IDTs and protects the electrode structure from variations of external fields. The typical structure of Lamb wave resonator, with IDTs on the top surface and uniform floating electrode at the bottom, is asymmetric with respect to the middle of the plate along vertical axis. Therefore, one can expect that between two configurations of AlN/SiO_2 resonators, with SiO_2 film either at the bottom or on top of AlN plate, certain difference exists, in terms of Lamb wave characteristics.

The paper is aimed at numerical investigation and comparison of these two configurations of AlN/SiO_2 resonators. The dispersion of the two lowest Lamb modes, s_0 and a_0, propagating under periodic metal grating of IDTs, is investigated and their characteristics (velocities, electro-mechanical coupling, TCF and reflection coefficients) are compared.

II. Method of Investigation

Few numerical techniques have been previously exploited by researcher for theoretical investigation of Lamb waves in AlN resonators. In [1] and [2] the dispersion of Lamb waves was simulated using similar approaches of matrix formalism or Green's functions model applied to eigen mode analysis in AlN, with ignored mass load of electrodes. Such simplified model was able to predict the general behavior of s_0 and a_0 modes with increasing AlN thickness. In particular, high coupling of s_0 mode, up to 3.5%, was predicted when the bottom of AlN membrane is metalized. In [4] the

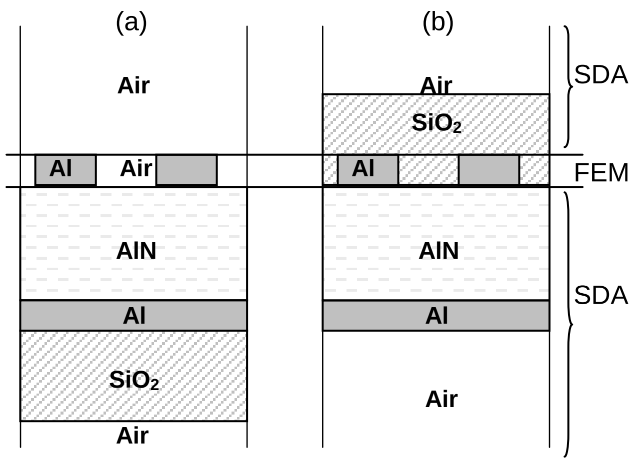

Fig. 1. Two configurations of AlN/SiO_2 structure specified in SDA-FEM-SDA software for numerical investigation of Lamb waves, with SiO_2 at the bottom of AlN (a) or on top of Al grating (b) and Al electrode added at the bottom of AlN.

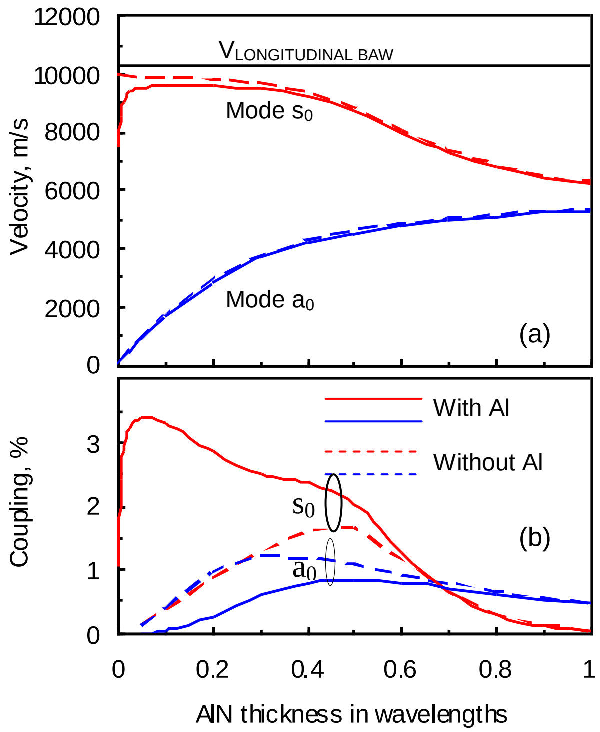

Fig. 2. Velocities in SC grating (a) and electromechanical coupling (b) of Lamb wave modes a_0 and s_0 as functions of AlN plate thickness, when bottom Al electrode is present or absent. Al electrodes of the grating and bottom Al film have the same thickness, h =0.004λ.

same simple model was applied to AlN/SiO_2 composite membranes and provided sufficiently good agreement between the calculated and measured values of TCF. In the recent publication [3] FEM analysis was employed to take into account the finite thickness of Al electrodes. As a result, it was found that mass load of the bottom Al film strongly affects the behavior of a_0 and s_0 modes at very small AlN thicknesses.

In the present paper all simulations were made with the software SDA-FEM-SDA [5] previously developed for analysis of SAW resonators sandwiched between two generally multilayered structures. With half-infinite air in the upper SDA region, half-infinite air overlaid by AlN film in the lower SDA region and Al grating between them (FEM-region), the admittance function of the grating can be calculated and the velocities of Lamb waves can be extracted for arbitrary AlN thickness. If Al electrode of finite thickness is added to the bottom of AlN plate, its influence on Lamb waves can be investigated. Finally, with SiO_2 film added to the lower or upper SDA region, as shown in Fig. 1, two AlN/SiO_2 configurations can be investigated and compared. If necessary, the method allows taking into account additional metal (e.g. Ti) or dielectric layers [6], which are able to improve the resonator performance or required by manufacturing process.

The calculated dispersion of Lamb waves in AlN and TCF behavior in AlN/SiO_2 show good agreement with previously reported dependences. The difference between two AlN/SiO_2 configurations is investigated and discussed. In particular, the behavior of the reflection coefficient κ per wavelength λ=2*p* of Al grating, where *p* is the grating period, is compared for two structures.

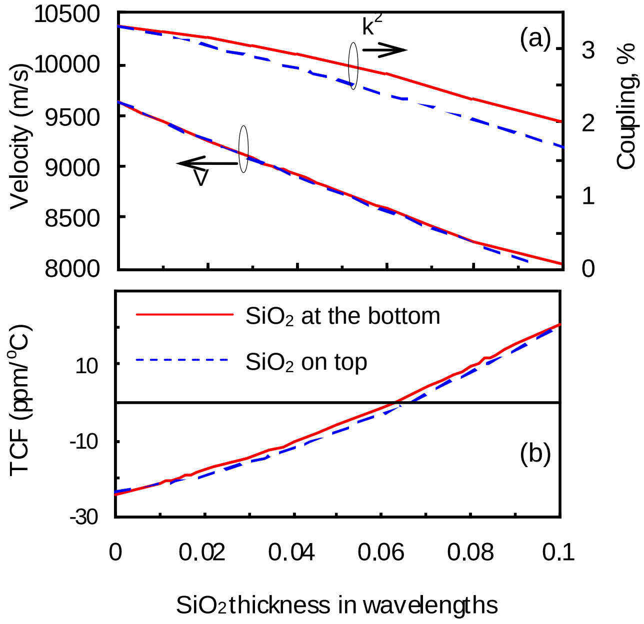

Fig. 3. Velocities, electromechanical coupling (a) and TCF (b) for mode s_0 propagating in two AlN/SiO_2 configurations, as functions of SiO_2 film thickness. Thickness of AlN plate is 0.1λ, thicknesses of bottom Al film and grating electrodes are 0.004 λ.

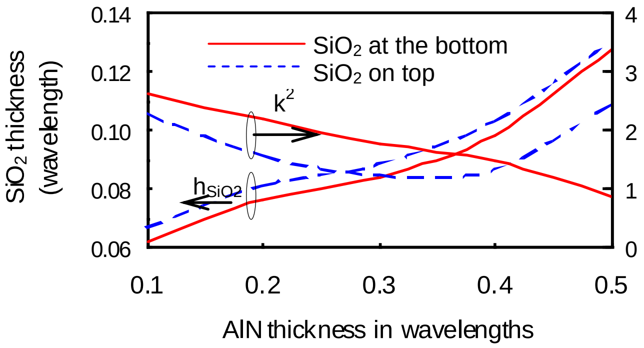

Fig. 4. Optimal thicknesses of SiO_2 film providing zero TCF in two AlN/SiO_2 configurations and electromechanical coupling coefficients in the optimal structures, as functions of AlN plate thickness. Bottom Al film (h=0.004 λ) is taken into account.

III. Numerical Results and Discussion

The propagation velocities *V* in SC grating and electromechanical coupling k^2 of the Lamb wave modes a_0 and s_0 are shown in Fig. 2. These dependences look similar to Fig. 6 of [3], in which FEM analysis was used to take into account finite thickness of Al electrodes and Al film at the bottom.

In Fig. 3 the velocities, coupling coefficients and TCF are shown for s_0 mode as functions of SiO_2 film thickness, in two

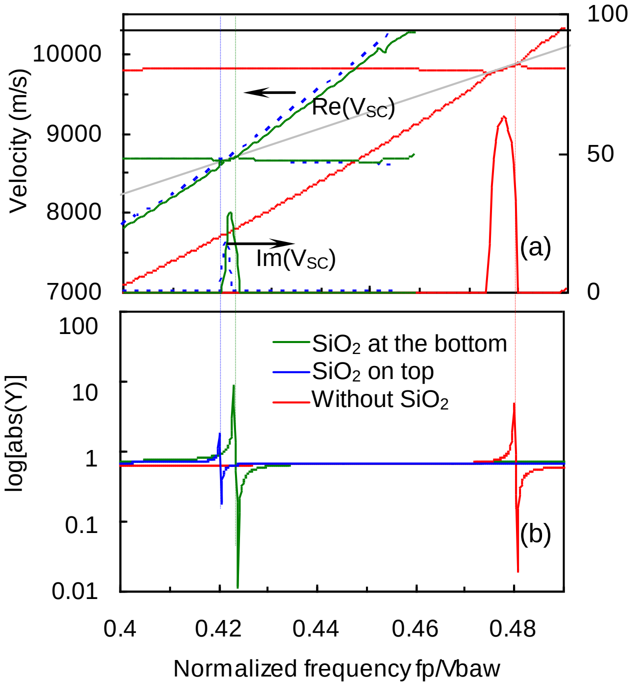

Fig. 5. Velocity dispersion (a) and admittance of the grating (b) referred to mode s_0 propagating in AlN and in two AlN/SiO_2 configurations, without bottom Al electrode. The thicknesses are h_{AlN}=0.1λ, h_{Al}=0.004λ, h_{SiO2}=0.06λ.

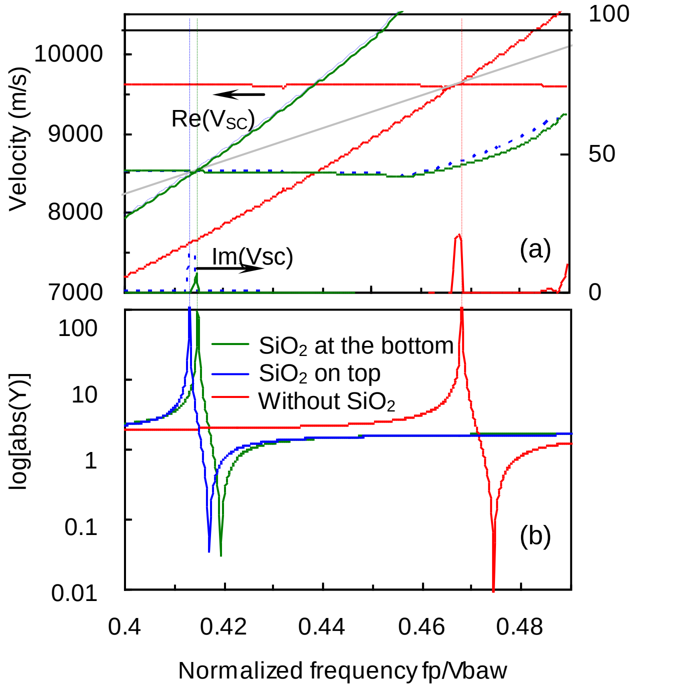

Fig. 6. Velocity dispersion (a) and admittances (b) for the structures similar to shown in Fig. 5 but with Al film added at the bottom of AlN, h_{Al}=0.004λ.

configurations of AlN/SiO_2 structure with h_{AlN}=0.1λ. When SiO_2 overcoats resonator structure, its thickness is measured from AlN surface and the film mass includes only the gaps between the electrodes. This can explain minor differences in V, k^2 and TCF versus SiO_2 thickness dependences, which look very similar in both AlN/SiO_2 configurations. Without SiO_2 the value of TCF is about -25 ppm/ºC. It increases with SiO_2 thickness and crosses zero at h_{SiO2}=0.062λ when SiO_2 is at the bottom and at h_{SiO2}=0.068λ when SiO_2 is on top. The optimal SiO_2 thickness required for temperature compensated resonators grows with AlN thickness, as shown in Fig.4, while the ratio h_{SiO2}/h_{AlN} decreases from 0.6 to 0.25 when AlN thickness grows from 0.1λ to 0.5λ. With increasing SiO_2 thickness k^2 goes down, as expected. However, when SiO_2 overcoats resonator, the coupling shows minimum value at h_{AlN} about 0.35λ and then grows again.

Such behavior of k^2 is not well understood and could be explained, for example, by interaction between s_0 and a_0 modes. The method SDA-FEM-SDA allows accurate simulation of Lamb wave dispersion in a wide range of frequencies and AlN thicknesses. In particular, it was found that s_0, a_0 and all higher order Lamb waves interacts with each other when propagate under the grating and build a complicated dispersion pattern. However, this analysis is beyond the scope of the present paper.

Fig. 5 shows the velocity dispersion and admittance of the grating as functions of the normalized frequency fp/V_{BAW}, for the mode s_0, where V_{BAW}=10287 m/s is the longitudinal BAW velocity in AlN. The normalized thicknesses of AlN, Al grating and SiO_2 are 0.1λ, 0.004λ and 0.06λ, respectively, and there is no bottom electrode. Similar characteristics, but for the structure with bottom Al electrode, h_{Al}=0.004λ, are shown in Fig. 6. In the latter case, k^2 is much higher, in both AlN/SiO_2 configurations, as well as in AlN plate. The Lamb wave velocity decreases with SiO_2 film thickness, independent on SiO_2 position, but the resonance of admittance occurs at lower or upper stopband edges when SiO_2 is located on top or at the bottom of AlN, respectively, indicating different signs of the reflection coefficient.

In the structure without bottom Al electrode (Fig. 5) the Lamb mode s_0 demonstrates stronger interaction with the grating than in the structure with such electrode (Fig. 6),

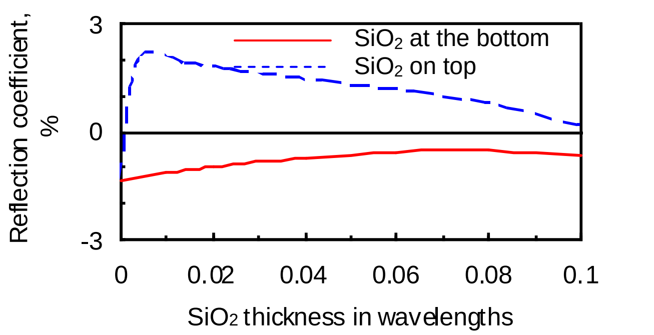

Fig. 7. Reflection coefficients calculated for mode s_0 propagating in two AlN/SiO_2 configurations, as functions of SiO_2 film thickness. Thicknesses of AlN, Al and SiO_2 films are h_{AlN}=0.1λ, h_{Al}=0.004λ and h_{SiO2}=0.06λ.

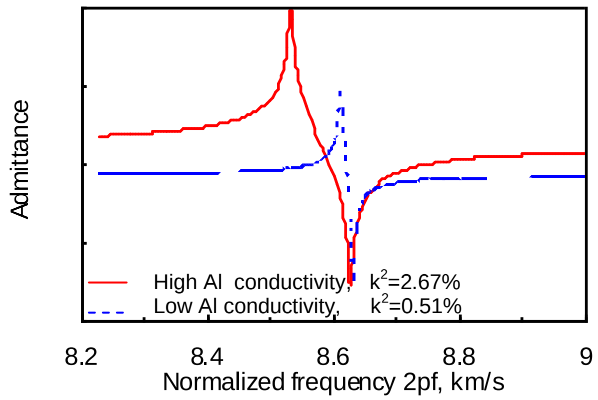

Fig. 8. Admittance of Al grating referred to mode s_0 in AlN/SiO_2 structure with SiO_2 film at the bottom of AlN and Al film between AlN and SiO_2. Infinite and zero conductivity of Al film are compared.

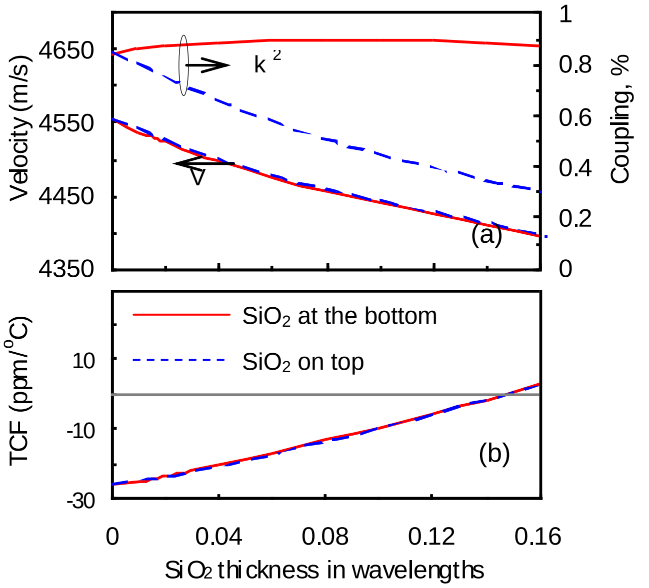

Fig. 9. Velocities, electromechanical coupling (a) and TCF (b) of mode a_0 propagating in two AlN/SiO_2 configurations, as functions of SiO_2 film thickness. Thickness of AlN plate is 0.5λ, thickness of bottom Al film and Al electrodes is 0.004 λ.

especially when SiO_2 film is absent. This conclusion agrees with the behavior of reflection coefficient shown in Fig. 7 as function of SiO_2 thickness. In AlN/SiO_2 structure with SiO_2 at the bottom and zero TCF (h_{SiO2}=0.062λ), the reflection coefficient reaches minimum value, about 0.5% but the coupling is expected to be high, k^2=2.67%. Low experimental value of k^2 observed previously in the temperature compensated structure [4] could be explained by low conductivity of the bottom Al electrode. Fig. 8 illustrates the effect of Al conductivity on the admittance. With its decreasing to zero value the coupling of s_0 mode drops to 0.51%, which is close to 0.56% measured in [4].

The characteristics of Lamb mode a_0 in two configurations of AlN/SiO_2 are compared in Fig. 9. There is almost no difference between the behavior of velocities and TCF in two structures, but the coupling k^2 exhibits strong dependence on the position of SiO_2 film: it stays about 0.8-0.9% with SiO_2 at the bottom but decreases fast if SiO_2 overcoats the grating.

It should be mentioned that when AlN thickness is 0.5λ zero TCF can be obtained for two Lamb wave modes, s_0 and a_0, at nearly the same SiO_2 thickness, about 0.15λ.

IV. Conclusions

Characteristics of lower symmetric and anti-symmetric modes, s_0 and a_0, were numerically investigated in Lamb wave resonators using AlN and AlN/SiO_2 membranes. The results obtained with SDA-FEM-SDA method agree with previously published data.

Two configurations of AlN/SiO_2 structure were compared, with SiO_2 film either at the bottom or on top of AlN. As a result, it was found that

a) electromechanical coupling coefficient k^2 is much stronger when Al electrode is present at the bottom of AlN, in both configurations of AlN/SiO_2 structure and also in AlN membrane, though k^2 drops when Al has low conductivity;

b) velocities of s_0 and a_0 modes decrease with increasing SiO_2 film thickness, in both AlN/SiO_2 configurations;

c) for temperature compensated AlN/SiO_2 structure the ratio between the optimal SiO_2 thickness and AlN thickness varies between 0.6 and 0.25, dependent on AlN thickness;

d) reflection coefficients in the grating show opposite signs in two AlN/SiO_2 configurations and its absolute value decreases with increasing SiO_2 thickness; in the structures with bottom Al electrode Lamb waves demonstrate weak interaction with electrodes of the grating.

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