Temperature Compensated AlN/SiO₂ Structures for Lamb Wave Resonators

Natalya Naumenko
Moscow Steel and Alloys Institute
nnaumenko@ieee.org

Abstract — Characteristics of lower symmetric and antisymmetric modes $s_0$ and $a_0$ (velocities, electromechanical coupling coefficients, TCF) were numerically investigated in Lamb wave resonators using AlN and AlN/SiO₂ membranes. Two configurations of AlN/SiO₂ structure were compared, with SiO₂ film located either at the bottom or on top of AlN. All characteristics were calculated as functions of SiO₂ film thickness with normalized AlN thickness varying between 0.1$\lambda$ and 0.5$\lambda$. 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 SiO₂ film thickness, which is required for zero TCF, decreases from 60% to 25% of AlN thickness when the latter grows from 0.1$\lambda$ to 0.5$\lambda$. 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 SiO₂ film. In [4] the effect of SiO₂ on the characteristics of the lowest symmetric Lamb mode $s_0$ was investigated assuming that SiO₂ film is located at the bottom surface of AlN membrane (opposite to the top surface with IDTs on it). The thickness of SiO₂, 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 SiO₂ 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/SiO₂ resonators, with SiO₂ 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/SiO₂ 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, electromechanical 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

\begin{center}
\begin{tabular}{|c|c|c|}
\hline
 & (a) & (b) \\
\hline
Air & Air & SiO₂ \\
Al & Air & Al \\
\hline
SDA & FEM & SDA \\
\hline
\end{tabular}
\end{center}

Fig. 1. Two configurations of AlN/SiO₂ structure specified in SDA-FEM-SDA software for numerical investigation of Lamb waves, with SiO₂ at the bottom of AlN (a) or on top of Al grating (b) and Al electrode added at the bottom of AlN.
same simple model was applied to AlN/SiO2 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 a0 and s0 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 SiO2 film added to the lower or upper SDA region, as shown in Fig. 1, two AlN/SiO2 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/SiO2 show good agreement with previously reported dependences. The difference between two AlN/SiO2 configurations is investigated and discussed. In particular, the behavior of the reflection coefficient κ per wavelength \( \lambda = 2p \) of Al grating, where \( p \) is the grating period, is compared for two structures.

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 SiO2 film thickness, in two
configurations of AlN/SiO2 structure with $h\text{AlN} = 0.1\lambda$. When SiO2 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 SiO2 thickness dependences, which look very similar in both AlN/SiO2 configurations. Without SiO2, the value of TCF is about $-25$ ppm/$^\circ$C. It increases with SiO2 thickness and crosses zero at $h\text{SiO2} = 0.062\lambda$ when SiO2 is at the bottom and at $h\text{SiO2} = 0.068\lambda$ when SiO2 is on top. The optimal SiO2 thickness required for temperature compensated resonators grows with AlN thickness, as shown in Fig. 4, while the ratio $h\text{SiO2}/h\text{AlN}$ decreases from 0.6 to 0.25 when AlN thickness grows from 0.1$\lambda$ to 0.5$\lambda$. With increasing SiO2 thickness $k^2$ goes down, as expected. However, when SiO2 overcoats resonator, the coupling shows minimum value at $h\text{AlN}$ about 0.35$\lambda$ 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 $f_p/V_{BAW}$, for the mode $s_0$, where $V_{BAW} = 10267$ m/s is the longitudinal BAW velocity in AlN. The normalized thicknesses of AlN, Al grating and SiO2 are 0.1$\lambda$, 0.004$\lambda$ and 0.06$\lambda$, respectively, and there is no bottom electrode. Similar characteristics, but for the structure with bottom Al electrode, $h\text{Al} = 0.004\lambda$, are shown in Fig. 6. In the latter case, $k^2$ is much higher, in both AlN/SiO2 configurations, as well as in AlN plate. The Lamb wave velocity decreases with SiO2 film thickness, independent on SiO2 position, but the resonance of admittance occurs at lower or upper stopband edges when SiO2 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),

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\text{Reflection coefficient, } \%\quad \text{SiO2 at the bottom} \quad \text{SiO2 on top} \quad \text{Without SiO2}
\]

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

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, $h\text{Al} = 0.004\lambda$. 

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

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especially when SiO\textsubscript{2} film is absent. This conclusion agrees with the behavior of reflection coefficient shown in Fig. 7 as function of SiO\textsubscript{2} thickness. In AlN/SiO\textsubscript{2} structure with SiO\textsubscript{2} at the bottom and zero TCF (h_{SiO} = 0.062\textsubscript{2}), the reflection coefficient reaches minimum value, about 0.5\% but the coupling is expected to be high, K\textsuperscript{2} = 2.67\%. Low experimental value of K\textsuperscript{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 of the Al/SiO\textsubscript{2} membrane both configuration and its absolute value decreased to zero when Al electrode is present.

The characteristics of Lamb mode \textit{a}_{0} in two configurations of AlN/SiO\textsubscript{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\textsuperscript{2} exhibits strong dependence on the position of SiO\textsubscript{2} film: it stays about 0.8-0.9\% with SiO\textsubscript{2} at the bottom but decreases fast if SiO\textsubscript{2} overcoats the grating.

It should be mentioned that when AlN thickness is 0.5\textlambda, zero TCF can be obtained for two Lamb wave modes, \textit{s}_{0} and \textit{a}_{0}, at nearly the same SiO\textsubscript{2} thickness, about 0.15\textlambda.

IV. CONCLUSIONS

Characteristics of lower symmetric and anti-symmetric modes, \textit{s}_{0} and \textit{a}_{0}, were numerically investigated in Lamb wave resonators using AlN and AlN/SiO\textsubscript{2} membranes. The results obtained with SDA-FEM-SDA method agree with previously published data.

Two configurations of AlN/SiO\textsubscript{2} structure were compared, with SiO\textsubscript{2} film either at the bottom or on top of AlN. As a result, it was found that

a) electromechanical coupling coefficient K\textsuperscript{2} is much stronger when Al electrode is present at the bottom of AlN, in both configurations of AlN/SiO\textsubscript{2} structure and also in AlN membrane, though K\textsuperscript{2} drops when Al has low conductivity;

b) velocities of \textit{s}_{0} and \textit{a}_{0} modes decrease with increasing SiO\textsubscript{2} film thickness, in both AlN/SiO\textsubscript{2} configurations;

c) for temperature compensated AlN/SiO\textsubscript{2} structure the ratio between the optimal SiO\textsubscript{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\textsubscript{2} configurations and its absolute value decreases with increasing SiO\textsubscript{2} thickness; in the structures with bottom Al electrode Lamb waves demonstrate weak interaction with electrodes of the grating.

REFERENCES


