Enhancement of Effective Electromechanical Coupling Factor by Mass Loading in Layered SAW Device Structures

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1. Introduction

The effective electromechanical coupling factor $K_e^2$ is a key parameter to determine the realizable filter bandwidth. Recently, Scandium-doped AlN (ScAlN) films have drawn much attention due to the strong piezoelectricity1-3). The authors reported that large SAW velocity $V$, small propagation attenuation, and large $K_e^2$ of about 6.1% are simultaneously achievable when the film is combined with a high velocity base substrate such as single crystal diamond (SCD) and 6H-SiC for the Sezawa mode even for operation in the 3 GHz range 2,3).

In many cases, $K_e^2$ of the SAW is much lower than that of the bulk wave even when the same piezoelectric material is chosen. This is because the SAW field distribution does not match well to the electric field generated by the interdigital transducer (IDT), and thus $K_e^2$ can be sometimes enhanced when heavy electrodes are used and/or the IDT is inlaid in the layered substrate.

This effect is well known also for the bulk acoustic wave (BAW) devices4), and is widely used in practical device design.

This paper describes drastic enhancement of $K_e^2$ by mass loading in layered SAW device structures such as the Cu IDT/ScAlN film/Si substrate structure, and existence of this phenomenon is verified experimentally.

2. Simulation

SAW properties on the Cu electrode/Sc0.43Al0.57N film/Si structure were analyzed by the software SYNCL5), which calculates the input admittance of the infinitely long IDT on the structure as a function of the driving frequency $f$. The Sc0.43Al0.57N film thickness is set at 0.5 $\lambda$, where $\lambda$ is the SAW wavelength. This thickness gives the maximum $K_e^2$ when the Cu electrode thickness $h_{Cu}$ is zero.

Fig. 1. Model structure used for simulation

Fig. 2 shows effective SAW velocity $V$ and $K_e^2$ as a function of $h_{Cu}/\lambda$. These values were estimated using the following formulas:

\[ V = \lambda f_i \]  
\[ K_e^2 = \left( f_r^2 / 2 f_a^2 \right) / \tan(\pi f_r^2 / 2 f_a), \]  

respectively, where $f_i$ and $f_r$ are the resonance and anti-resonance frequencies.

It is seen that $V$ decreases monotonically with $h_{Cu}/\lambda$ for the fundamental and second modes. On the other hand, $K_e^2$ for the Sezawa mode increases with $h_{Cu}/\lambda$, and takes a maximum value of 9.1% at $h_{Cu}/\lambda=0.15$, which is more than three times larger than the value when $h_{Cu}/\lambda=0$. In contrast, $K_e^2$ for the Rayleigh mode decreases with $h_{Cu}/\lambda$. This enhancement is caused by variation of the SAW field distribution to fit with the electric field excited by the IDT. Such $K_e^2$ enhancement also occurs in SAWs on semi-infinite piezoelectric substrates6). But it is more prominent for the present case because only the limited region, i.e., piezoelectric film, is responsible for the wave excitation.

This phenomenon occurs in various layered SAW structures. More calculations can be found in Ref. 7.

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3. **Experiment**

For experimental verification of this phenomenon, a series of one port SAW devices were on the ScAlN film/Si substrate structure, and $K_e^2$ was evaluated using Eq. (2). The device parameters are given in Table I. The Sc content $r$ estimated by the X-ray fluorescence spectrometry was circa 22%.

<table>
<thead>
<tr>
<th>Table I. Design parameters</th>
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<tr>
<td>ScAlN thickness, $h_{ScAlN}$</td>
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<tr>
<td>Wavelength, $\lambda$</td>
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<tr>
<td>Finger width, $w$</td>
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<tr>
<td>Aperture, $W$</td>
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<tr>
<td>Numb. of IDT finger pairs</td>
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<td>Numb. of Reflector fingers</td>
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<td>Cu electrode thickness, $h_{Cu}$</td>
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Fig. 3 shows variation of $K_e^2$ of the second mode with $h_{Cu}$. It is seen that $K_e^2$ increases monotonically with $h_{Cu}$ and $K_e^2$ is about 2% when $h_{Cu}/\lambda \sim 0.1$. The value is about three times larger than that when $h_{Cu}/\lambda \sim 0.01$. But the value is much smaller than that shown in Fig. 2(b). This is because of low $r$ in the used ScAlN film. It results in not only reduction of the piezoelectricity but increase of the SAW velocity. Larger $V$ tends to increase the Cu thickness giving maximum $K_e^2$. For example, the Cu thickness of 0.6 $\lambda$ is necessary for the AlN/Si structure.

4. **Conclusion**

This paper describes drastic enhancement of $K_e^2$ by mass loading in layered SAW device structures.

It is quite interesting about the SAW characteristics on high Sc content Cu IDT/ScAlN film/Si substrate structure.

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**Reference**