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A study of resonance properties on leaky SAWs using $LiTaO_3/SiC/Si$ structure

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1. Introduction

Current communication technologies for 5G and beyond require higher frequency ranges, narrow-gap bands, and high-performance radio frequency (RF) acoustic wave filters. In surface acoustic wave (SAW) devices, which commonly used acoustic wave devices, thinning of the piezoelectric substrate to concentrate the energy on the device surface has been attracting attention. Accordingly, bonding substrate technology is used to realize this development.[1)]

In addition, owing to problems of transmission distance, the bonding substrate approach is implemented in high-power environments, where the heat-generation conditions inside the terminal are severe. In this study, we focused on silicon carbide (SiC), which is attracting attention as a high-power semiconductor, and proposed an RF device characterized by a structure that uses SiC between the piezoelectric $LiTaO_3$ (LT) layer and silicon (Si) support substrate.

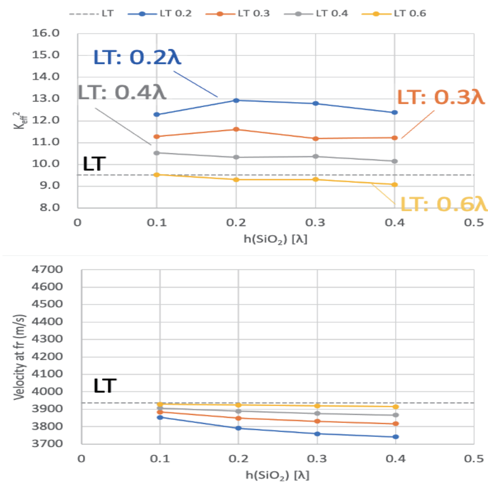
2. Methods

2.1 FEM models

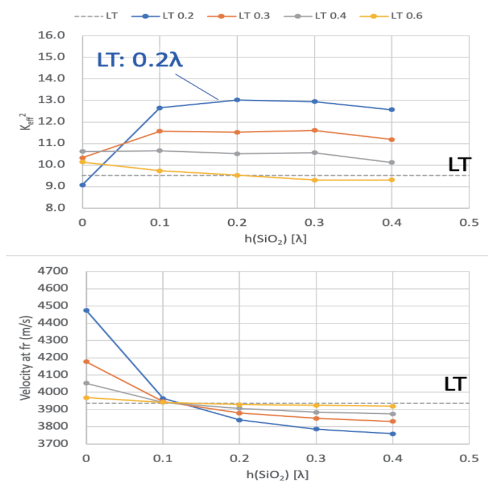
In the conventional structures, a silicon oxide (SiO_2) film was used for the intermediate layer.[1,2)] Therefore, first, the properties of leaky SAW (LSAW) were evaluated conducting a finite element method (FEM) simulation and compared with respect to the following structures: (a) 42°Y-LT-single, (b) 42°Y-LT/SiO_2/Si(111), (c) 42°Y-LT/SiO_2/3C-SiC, and (d) 42°Y-LT/3C-SiC/Si(111). All analysis models employed an infinite-period aluminum (Al) interdigital transducer (IDT) electrode pair with a wavelength (λ) of 4.444 μm and film thickness of 0.08λ on the LT substrate surface. The mechanical and dielectric losses of the materials were not considered.

2.2 Simulated results of resonance properties

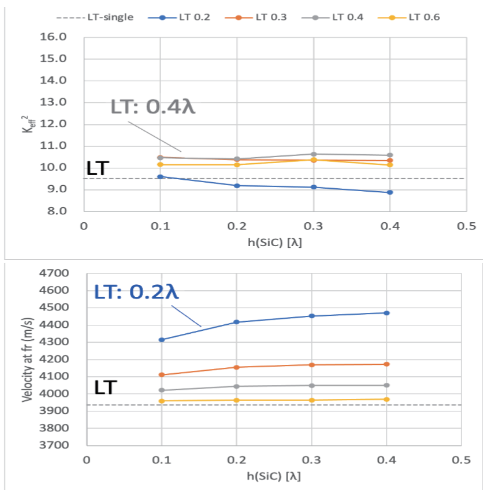
For each structure, the characteristic values, such as resonance frequency characteristics and effective electromechanical coupling coefficient K_{eff}^2, were compared and evaluated. **Figure 1** shows the phase velocity V and the K_{eff}^2 with respect to the intermediate layer thickness normalized by the wavelength λ for each structure.



1a. Structure (b): LT/SiO_2/Si(111)



1b. Structure (c): LT/SiO_2/3C-SiC



1c. Structure (d): LT/3C-SiC/Si(111)

Fig. 1 Simulated V and K_{eff}^2 values for each structure.

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The phase velocities of structures (b) and (c), which used SiO_2 as the intermediate layer, tended to be lower than that of (a) LT-single, with only structure (d) exhibiting a higher phase velocity.

The K_{eff}^2 value of structure (b) reached a maximum value of 12.9% at LT = 0.2λ. Further, (c) yielded a maximum value of 13.0% at LT = 0.2λ, and (d) yielded 10.6% at LT = 0.4λ. Compared to K_{eff}^2 of LT-single (9.5%), that of (b) and (c) were 3.4% larger, whereas that of (d) was 1.1% larger than that of LT-single.

The trends of these characteristics are similar for (b) and (c), although the supporting substrates are different. Thus, it can be concluded that the difference in the intermediate layer had a greater effect on the resonance characteristics than the difference in the support substrate did.

2.3 Simulated results of TCF

The LSAW resonant frequency temperature coefficient (TCF) for each structure is shown in **Fig. 2**. The TCF is the sum of the temperature coefficient of velocity (TCV) and thermal expansion coefficient (TEC).

$$TCF = TCV + TEC.$$

For the bonded substrates, the TEC of the supporting substrate was dominant. Therefore, the TEC values of the LT and the intermediate layers were replaced with that of the support substrate.

Regardless of the support material in the composite substrate being the same, the TCF behavior with respect to the LT-normalized thickness differed significantly owing to the differences in the properties of the intermediate layer material. In structure (b) and (c), the TCF behaviors approached zero as the normalized plate thickness of the LT decreased. However, structure (d) exhibited the opposite TCF behavior.

Notice that resonance frequency temperature coefficient (TCFr) and anti-resonance frequency temperature coefficient (TCFa) of the bonded substrate structure are asymptotic to a certain degree. Here, if the TEC of the LT-single is replaced with that of Si and then the TCFr and TCFa values of the LT-single are calculated, the aqua-blue dotted line in Fig. 2 is obtained. Consequently, it is considered that TCFr and TCFa asymptotically approach this line.

3. Conclusions

Our new structure LT/SiC/Si possesses the following characteristics:

1) The effective electromechanical coupling coefficient K_{eff}^2: 10.6% is obtained at LT thickness 0.4λ. A coupling coefficient higher than 9.5% was obtained for the LT-single, and a broadband characteristics can be expected. However, the value of this coefficient for our new structure was smaller than that obtained with conventional structures.
2) The phase velocity V: 4050m/s is obtained at LT thickness 0.4λ, which is higher than that of LT-single or other conventional structures. A higher frequency can be expected compared with that observed in a conventional structure.
3) TCF: The absolute value of TCF of the new structure using an SiC intermediate layer can be reduced by 40% compared to that of LT-single. This primarily depends on the TEC of the supporting substrate. However, when the intermediate layer is made of SiO_2, which has a positive temperature coefficient as observed in the conventional structure, the layer thickness condition reached to 0-TCF can be obtained by canceling the negative temperature coefficient of LT.
4) In addition, high heat dissipation of SiC can be expected owing to the thermal conductivity of the material. This is expected to result in a high power-handling resistance.[3)]

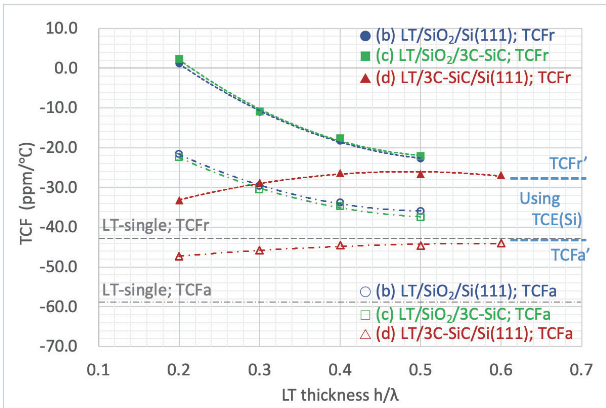

Fig. 2 Simulated TCF for each structure, with intermediate layer thicknesses of (b), (c) SiO_2 of 0.2λ, and (d) SiC of 0.4λ.

Accordingly, even with the same supporting substrate, the properties tend to differ depending on the material used for the intermediate layer and its thickness. Therefore, the design of the intermediate layer is crucial.

References

1) T. Takai, *et al.*, IEEE Trans. Ultrason., Ferroelect., Freq. Control, **66**, 1006 (2019).
2) Zonglin Wu, *et al.*, Proc. EFTF-IFCS 2022, 5233.
3) N. Watanabe, *et al.*, JSAP, Autumn, C105-13, 2022. [in Japanese]