Wafer Bonding of Polycrystalline Spinel with $LiNbO_3/LiTaO_3$ for Temperature Compensation of RF Surface Acoustic Wave Devices

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This paper proposes use of polycrystalline spinel for the temperature compensation of radio frequency (RF) surface acoustic wave (SAW) devices. Spinel can be bonded with $LiTaO_3$ (LT) and $LiNbO_3$ (LN) wafers by using adhesive and direct bonding techniques. A series of RF SAW resonators were fabricated on the LT(LN)/spinel structure, and their performance, including the temperature coefficient of frequency (TCF), was measured. For comparison, SAW resonators employing Si and sapphire in place of spinel were also fabricated. The result indicated that the polycrystalline spinel offers TCF improvement better than other materials.

Keywords: spinel, wafer bonding, SAW resonator, temperature compensation, temperature coefficient of frequency

1. Introduction

Lithium tantalate (LT) and lithium niobate (LN) have been widely used as the piezoelectric material for radio frequency (RF) surface acoustic wave (SAW) devices. Although LT and LN are highly piezoelectric, their temperature stability is rather poor.

The temperature stability is characterized by the temperature coefficient of frequency (TCF)*1. One possible technique for its improvement is use of the wafer bonding of LT/LN with a supporting substrate with a low coefficient of thermal expansion (CTE)(1)-(5), and the technique has already been applied to the mass production(3).

As the supporting substrate, use of glass, silicon and sapphire has already been investigated. It was shown that sapphire is most feasible among them for the TCF improvement owing to its high stiffness and small CTE. Nevertheless the high price of sapphire wafers prevented wide use of this technique.

Table 1 shows nominal properties of polycrystalline spinel. This material possesses a large Young's modulus and small CTE comparable to sapphire. On the other hand, the wafer price may be cheaper than that of sapphire because spinel wafers can be prepared by the simple press and sintering process and can be cut and polished relatively easily.

This paper proposes use of the polycrystalline spinel in place of sapphire for the temperature compensation of RF SAW devices.

First, it is shown that spinel can be bonded in high quality with LT/LN wafers using the adhesive and direct bonding techniques. Then we discuss performance of wafer-bonded RF SAW resonators. It is shown that the polycrystalline spinel offers TCF improvement for better than the other materials, including sapphire, when the direct bonding is applied.

2. Bonded Wafer Preparation

Wafer bonded SAW devices were prepared with the following three steps:

1) Bonding of 4 inch spinel and LN/LT wafers
2) Grinding and polishing of LN/LT layer after dicing of the bonded wafer
3) Electrode formation

2-1 Bonding of 4 inch spinel and LN/LT wafers

Here, two wafer bonding methods were examined, i.e.,

Table 1. Properties of polycrystalline spinel

Properties	Spinel	Glass	Silicon	Sapphire
Chemical formula	$MgAl_2O_4$	SiO_2	Si	Al_2O_3
Crystal class	Polycrystal	Non-crystal	Single crystal	Single crystal
Density (g/cm^3)	3.58	2.20	2.33	3.98
Young's modulus (GPa)	280	70	120	470
Knoop hardness (kgf/mm^2)	1400	600	1150	2000
Coefficient of thermal expansion (ppm/°C)	7.3	0.6	3.4	7.7
Thermal conductivity (W/mK)	16.9	1.4	163	33.0

adhesive bonding and direct bonding. Although the adhesive bonding seems cost-effective, it is unclear whether the adhesive is stable against the heat cycle during and after the device fabrication. On the other hand, the direct bonding is expected to be stable. However, very flat and clean substrate surfaces are required.

(1) Adhesive bonding

We examined three types of adhesives, i.e., UV cure, thermo setting and room temperature setting. Since CTE difference between spinel and LN/LT is large (>10 ppm/°C), the thermo setting one is hardly applicable to the 4 inch wafer bonding. On the other hand, weak adhesion of the room temperature setting one resulted in peeling apart of the bonding during the SAW device fabrication. As for UV cure type, no bending and peel apart were observed as we paid attention not to cause temperature increase during the UV irradiation$^{(6)}$.

Photo 1 shows a cross sectional view of an adhesively bonded wafer. Thickness of the adhesive layer is about 3 μm uniformly throughout the wafer.

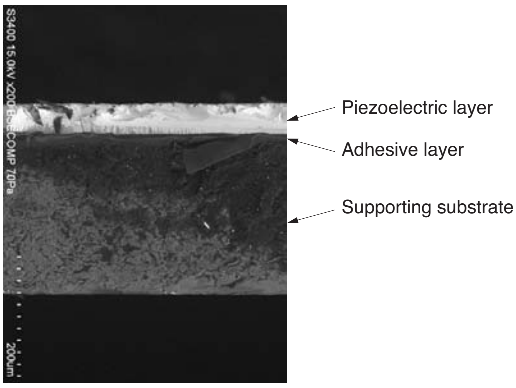

Photo 1. Cross sectional view of adhesively bonded wafer

(2) Direct bonding

We examined the room temperature bonding$^{(7), (8)}$ and plasma bonding. Since the room temperature bonding offered better bonding strength than the plasma one, the room temperature one was chosen for the following experiments.

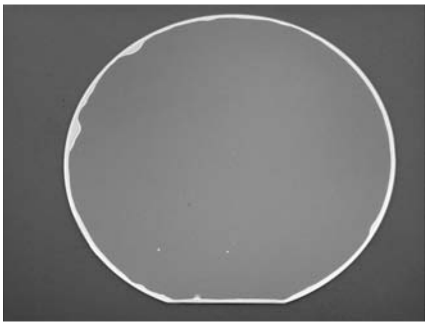

Photo 2. Directly bonded 4 inch wafer (LT/spinel)

Wafers are required to have very flat surfaces to be well bonded. Optimization of wafer polishing and bonding conditions allows us to bond 4 inch polycrystalline spinel and LN/LT wafers tightly as shown in **Photo 2**.

2-2 Grinding and polishing of LN/LT layer after dicing of the bonded wafer

Bonded wafers were diced into 10 x 20 mm^2 tips, and then their LN/LT layers were thinned by grinding. Finally, their top surfaces were polished to the optically flat level. Here, the thickness ratio is defined as the thickness of supporting substrate to the LN/LT layer (**Fig. 1**).

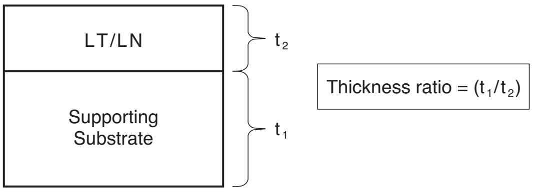

Fig. 1. Structure of sample after grinding and polishing

2-3 Electrode formation

One-port SAW resonators were fabricated on the bonded wafers using the combination of the direct electron beam lithography and lift-off process. **Table 2** shows the design parameters for the resonators.

Table 2. Design of SAW resonator

Properties	SAW resonator
Electrode material	Cu
Electrode thickness (nm)	200
Pitch p_I (μm)	3.6
Aperture (μm)	54 (15λ)
Number of IDT finger pairs	60
Number of reflector electrodes	40

3. Experimental Results

First, we investigated the influence of the chosen supporting substrate material on the TCF performance. Temperature dependence of the resonance frequency was measured for fabricated SAW resonators, and the TCF was evaluated from its gradient. The temperature range was from +10°C to +80°C. In this experiment, 64°YX-LN was chosen as the piezoelectric material. The thickness ratio was approximately 6.

Table 3 shows the measured TCFs. It is seen that use of spinel can improve TCF by more than 20 ppm/˚C, and this value is better than (at least comparable to) those of the other materials, including sapphire, when the direct bonding was employed.

The table also shows measured TCFs for SAW resonators which are fabricated on wafers by adhesive bonding. In this case, TCF improvement is relatively small and less dependent on the difference of the supporting substrate material. This weakened TCF improvement may be due to the stress relaxation in the adhesive layer. Thinning the adhesive layer may resolve this problem.

Next, we investigated the influence of the thickness ratio on the device performance including TCF. In this experiment, 42˚YX-LT and polycrystalline spinel were chosen as the piezoelectric and supporting substrate materials, respectively, and were bonded by the direct bonding.

Table 3. Measured TCF of wafer bonded SAW devices with the thickness ratio of 6

Supporting substrate	TCF (ppm/˚C)	
	Direct	Adhesive
Spinel	-61	-68
Sapphire	-63	-70
Silicon	-68	-71
None	-82	

Figure 2 shows the variation of measured TCF. TCF was improved from -42 to -18 ppm/˚C by using the 42˚YX-LT/spinel structure at the thickness ratio of 15. This value is obviously better than the reported results when Si or sapphire was used as the supporting substrate$^{(3),\,(5)}$.

TCF becomes worse when the ratio is 20. We believe this phenomenon is not intrinsic but is resulted from the distortion caused by grinding and polishing the thin 42˚YX-LT structure (~30 μm).

Table 4 shows the variation of the effective SAW velocity V_r (= $f_r p_I$) and the effective electromechanical coupling factor K^2 with the thickness ratio. Here, K^2 is defined by

$$K^2 = (\pi f_r / 2f_a) / \tan(\pi f_r / 2f_r) \cdots\cdots\cdots\cdots (1)$$

where f_r and f_r are the resonance and anti-resonance frequencies, respectively, and p_I is the IDT pitch.

The variation of V_r is small and the value does not exhibit clear dependency. We expect that this variation is mainly caused by that of the Cu thickness. On the other hand, K^2 slightly but obviously increased after the wafer bonding. This phenomenon was also reported in another paper$^{(4)}$. This may be caused by the static internal stress generated during the bonding.

Table 4. Estimated SAW resonator properties

Thickness ratio	TCF ppm/˚C	K^2 %	V_r m/s
none	-42	7.1	3658
2.5	-34	8.1	3690
5	-27	8.4	3654
10	-22	8.8	3640
15	-18	8.8	3643
20	-21	8.1	3672

Figure 3 shows the input impedance of the wafer-bonded SAW resonator using wafer-bonded 42˚YX-LT/spinel structure with the thickness ratio of 15. High Q resonance is seen at 1,011 MHz. The impedance ratio more than 60 dB is achieved. A spurious resonance can be seen at 1,021 MHz. This is due to the leaked bulk acoustic wave generated by the leaky nature of the SAW propagating on 42˚YX-LT and reflected at the bonded interface. This response should be suppressed for practical use. Weak resonances are seen at frequencies lower than the main resonance. They are transverse resonances, which are intrinsic in the present resonator structure.

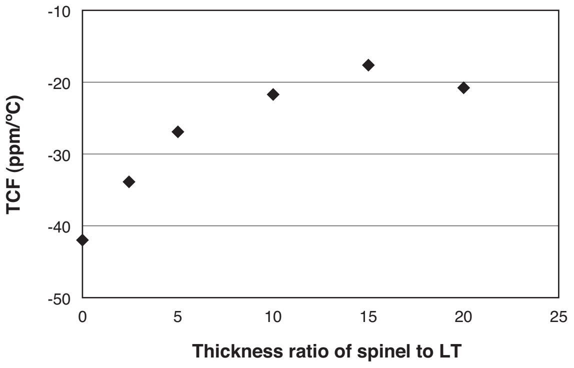

Fig. 2. Measured TCF as a function of the thickness ratio

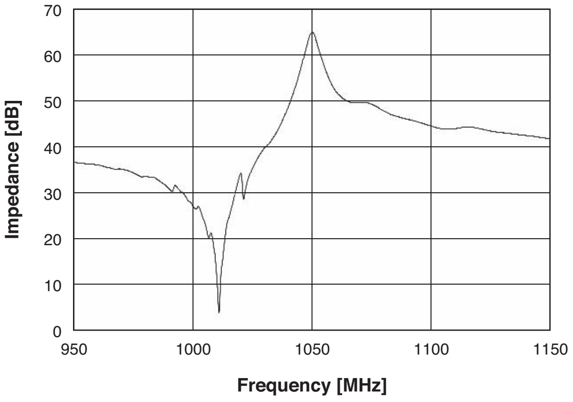

Fig. 3. Impedance characteristic of SAW resonator on 42˚ YX-LN/spinel structure with thickness ratio of 15

4. Conclusion

This paper proposed use of polycrystalline spinel as the supporting substrate for temperature compensated RF SAW devices.

It was shown that the spinel can be bonded well with LT/LN wafers by using the adhesive and direct bonding techniques. It was also shown that the spinel offers TCF improvement better than sapphire when the direct bonding is applied.

Because of the high TCF improvement capability and low wafer price, we believe that polycrystalline spinel is useful as the supporting substrate for high performance RF SAW duplexers and filters employing the wafer bonding technology.

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Technical Term

*1 TCF (Temperature Coefficient of Frequency): A rate at which frequency changes with temperature.

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