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Direct Bonding of $LiTaO_3$/Si at Room Temperature Using Self-sputtered Bonding Method

自己スパッタ接合法を用いた常温による $LiTaO_3$/Si 直接接合

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1. Introduction

$LiTaO_3$ and $LiNbO_3$ have been widely used for surface-acoustic-wave (SAW) devices in mobile communication systems, as these materials have high piezoelectric properties. However, as the materials have large temperature coefficient of frequency (TCF), various temperature compensation techniques are currently being studied to reduce the TCF. It has been reported that the TCF characteristics was improved by directly bonding the $LiTaO_3$ or $LiNbO_3$ wafer bonded to a support substrate with a low coefficient of thermal expansion (CTE), and the temperature compensated (TC) SAW devices have been already put to practical use by the directly bonded $LiTaO_3$/sapphire wafers [1]. Si and glass have been also investigated as the support substrate. The conventional bonding method requires heating process to achieve strong bonds. Since the thermal expansion mismatch between oxide materials such as $LiTaO_3$ and $LiNbO_3$ and semiconductors is large, various problems such as cracking, bowing and so on occur during the heating process. Since surface activated bonding (SAB) is a bonding method carried out at room or low temperature [2, 3], the method is suitable for bonding between the dissimilar materials with large thermal expansion mismatch. However, it is difficult to directly bond oxide materials to Si by SAB method [4]. In this paper, we propose the novel bonding process for directly bonding oxide materials to Si at room temperature. We have developed the suitable apparatus for our proposed process and examined the direct bonding of $LiTaO_3$/Si wafers. We have evaluated the surface energy and the tensile strength and investigated the bonding interface by transmission electron microscopy (TEM). Moreover, the elemental composition across the bonding interface has been analyzed by energy-dispersive X-ray spectroscopy (EDS).

2. Self-sputtered Bonding (SSB) Method

In our proposed bonding process, as shown in **Fig. 1,** only the lower wafer' surface is etched by Ar plasma, and the thin film of the lower wafer's material is deposited on the upper wafer's surface during the etching process. The surface of the lower wafer is activated during Ar plasma etching, and the surface of the film deposited on the upper wafer remains activated due to high vacuum process. The upper and lower wafers are then immediately brought into contact. Therefore, we call this bonding process "Self-sputtered Bonding (SSB)" method. **Figure 2** shows the bonding apparatus which we developed for SSB method. The apparatus is comprised of bonding process chamber and load/unload rock chamber. The specification is shown in **Table I**. Since the apparatus has two radio frequency (RF) power supplies for the upper and lower wafer, each wafer's surface can be individually sputtered, also. The lower wafer can be approached to the upper wafer to contact in the bonding chamber after plasma process.

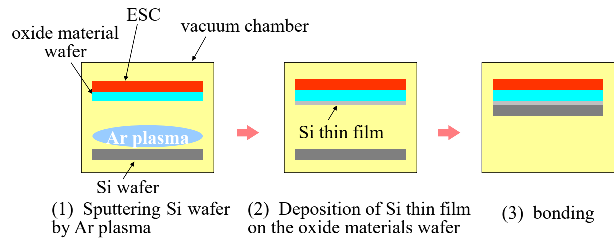

Fig. 1 Bonding process by SSB method.

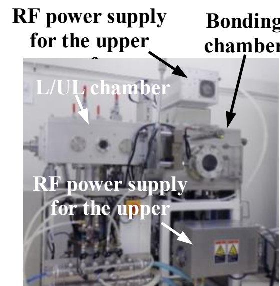

Fig. 2 Bonding apparatus.

Table I. Specification of the apparatus.

Max. wafer diameter	8 inch
Background vacuum pressure	$< 1\times10^{-5}$ Pa
RF power for the upper wafer	1000 W
RF power for the lower wafer	500 W
Max. press load	500 kgf

3. Bonding Experiments

4-in 42° Y-X $LiTaO_3$ wafer (thickness of 350 μm, Yamajyu ceramics) and 4-in Si blanket wafer (thickness of 525 μm) were prepared for this experiments. The $LiTaO_3$ wafer was held by the electrostatic chuck (ESC) to turn the surface down. The Si wafer was placed on the lower side in the same vacuum chamber. Only Si wafer was etched by Ar plasma produced RF power supply for lower wafer. RF power and irradiation time was 300 W

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and 2.5 min, respectively. The background vacuum pressure was lower than approximately 2 × 10^{-5} Pa before the plasma process. The $LiTaO_3$ and Si wafers were then immediately brought into contact with a bonding press force of 80 kgf.

4. Results and discuss

4.1 Bonding results

Figure 3 shows the boned $LiTaO_3$/Si wafers. A void was confirmed, which was caused by the residue on the $LiTaO_3$ wafer's surface owing to insufficient cleaning before bonding; however, it seems that the SSB method yielded a good bonding. The surface energy of the bonded wafer was evaluated by the crack-opening method [5]. The surface energy of wafers bonded by the normal SAB method was approximately 1 J/m^2. However, as shown in **Fig. 4a**, a fracture from the $LiTaO_3$ wafer in the bonded wafers by SSB method occurred when the blade was inserted toward the bonding interface. The bonding strength was also measured by a tensile test. The specimen for the tensile test was prepared by cutting the bonded wafers into 8 × 8mm^2 sections. The bonding strength was found to be approximately 16 MPa, but the specimen fractured at the glue interface and not at the bonded interface as shown in **Fig. 4b**. This means that the bonding strength of the $LiTaO_3$/Si interface is higher than the measured value.

4.2 TEM observation and EDS analysis of $LiTaO_3$/Si bonding interface

Figure 5a shows the cross-sectional TEM image of the $LiTaO_3$/Si bonding interface. No microvoids or gaps are observed at the bonding interface, but the intermediate layer is visible. The thickness of this layer was approximately 8 nm. The bonding interface is assumed to be below the center of the intermediate layer as shown in Fig. 5a. The layer above the bonding interface is assumed to be deposited during Ar plasma process, and the lower is assumed to be damaged formed by Ar plasma irradiation [6]. The elemental composition across the $LiTaO_3$/Si bonding interface was measured by EDS. **Figure 5b** shows the Si, O, Al, Fe, Ar, and Ta concentrations across the interface. Although O and Ar were slightly detected in the intermediate layer, the layer seems to be amorphous Si layers.

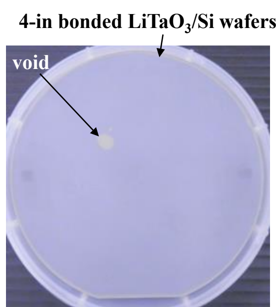

Fig. 3 Bonded $LiTaO_3$/Si wafers by SSB method

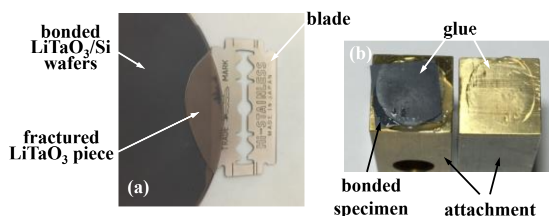

Fig. 4 (a) Fracture image of the bonded $LiTaO_3$/Si wafer by opening-crack method. (b) Image of $LiTaO_3$/Si bonding specimen fractured by tensile test.

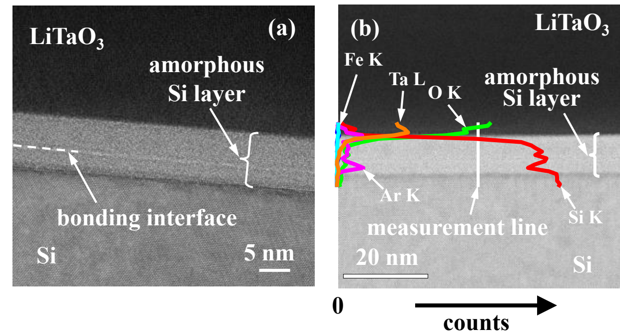

Fig. 5 (a) High resolution TEM cross sectional image of the bonding interface. (b) EDS line analysis along the white line on TEM image.

5. Conclusion

We have demonstrated a novel bonding method, SSB method, to directly bond oxide material to Si at room temperature, and developed the bonding apparatus for the method. We showed the bonding strength of the bonded $LiTaO_3$/Si wafers by the method was higher than that by SAB method. Our proposed method promises to directly bond Si to the oxide materials or the undesirably damaged materials by surface activation at room temperature.

References

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