Temperature Compensated $LiTaO_3$/sapphire SAW Substrate for High Power Applications

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***Abstract*—A new temperature-compensated SAW substrate for high power applications was developed based on bonded $LiTaO_3$/sapphire. Because of its small thermal expansion coefficient, large Young's modulus, and large electric resistivity, sapphire is an ideal material for a support substrate. In addition, the large thermal conductivity of sapphire brings efficient heat dissipation. Surface activated bonding was used and optimized to strongly bond $LiTaO_3$ and sapphire without any damage or bow.**

Keywords-SAW; $LiTaO_3$; sapphire; temperature compensation; surface activated bonding; heat dissipation; US-PCS;

I. INTRODUCTION

SAW filters are now widely used in mobile phones because of their small size and excellent frequency characteristics. Recently, SAW filters have been used for more difficult situations, including high power applications, such as duplexers. In high power applications, SAW filters have major problems. The first problem is high Joule's heat caused by the high input power. In high power applications, like duplexers, RF powers of watt level are applied to SAW filters. Therefore, a large amount of Joule's heat is generated, causing frequency drift of the SAW filters. Conventional SAW filters using a $LiTaO_3$ substrate have large temperature coefficients of frequency (TCFs) of about -40 ppm/°C, and the frequency drift is about 9 MHz from -30 to 85°C in the 1.9 GHz range. In addition, high Joule's heat causes early migration breakage of the inter-digital transducer (IDT) electrode material. Therefore, conventional SAW filters have a difficult time securing power durability in high power applications. The second problem is the increasing power density due to miniaturization. There is strong demand for miniaturization of SAW filters. Therefore SAW dies are being made as small as possible, causing power density to rapidly increase. As a result, without adequate heat dissipation, further increasing of the temperature of SAW dies occurs, and it can easily overheat. In addition, the US-Personal communications service (US-PCS) system has only a 20 MHz guard band, despite the 1.9 GHz range. Therefore, when developing filters or duplexers for that system, frequency drift due to temperature changes is a significant problem.

$LiTaO_3$ and $LiNbO_3$ have excellent SAW frequency characteristics, with large electro mechanical coupling factors (k^2) and low propagation loss, but they have poor temperature characteristics, with large TCFs. Since the early stages of developing SAW filters using $LiTaO_3$ or $LiNbO_3$, various temperature compensation methods have been investigated for practical use. A few of them are now used, but they degrade the frequency characteristics of SAW filters and fail to improve the heat dissipation.

The thick SiO_2 method, which is one of the most common conventional temperature-compensation methods for SAW filters, uses a SiO_2 layer on the IDT [1-3]. This method provides the capability of achieving a TCF of 0 ppm/°C, but degrades the value of k^2 and increases the propagation loss. Moreover, controlling the SiO_2 thickness is very difficult, resulting in low-productivity SAW filters. Furthermore, this method doesn't improve heat dissipation.

Another common conventional method uses a bonded $LiTaO_3$/glass substrate [4], with the glass functioning as a support substrate on the back of the $LiTaO_3$. Compared with the thick SiO_2 method, there is less k^2 degradation and lower propagation loss. However, the $LiTaO_3$ thickness must be kept thin to improve the TCF, because of the small Young's modulus of glass. At the same time, spurious responses caused by bulk waves reflecting at the bonding interface degrade the frequency characteristics of SAW filters when $LiTaO_3$ is thin. Moreover, this method degrades heat dissipation because of the small thermal conductivity of glass. In this method, selection of a proper support substrate is important.

As we previously reported [5-6], to obtain temperature-compensated SAW filters with good frequency characteristics, a new temperature compensation method using a bonded $LiTaO_3$/sapphire substrate was developed. Sapphire has excellent characteristics for effective temperature compensation and good frequency performance. In this paper, the frequency and temperature characteristics of SAW filters with the bonded $LiTaO_3$/sapphire method and techniques for bonding $LiTaO_3$ and sapphire are described.

II. SELECTION OF SUPPORT SUBSTRATE

There are so many candidate materials for the support substrates of the bonded $LiTaO_3$/support-substrate method. The method uses the support substrate to suppress the thermal expansion of $LiTaO_3$. Therefore, the support substrate material must have a smaller thermal expansion coefficient (TEC) than $LiTaO_3$ and, if possible, a larger Young's modulus. In addition, to improve heat dissipation, the support substrate must have large thermal conductivity. Moreover, to avoid degradation of frequency characteristics, the support substrate must have large electric resistivity. The properties of some candidate materials are listed in Table 1. Some types of glass have very small TECs (e.g., fused quartz has a TEC of about 0 ppm/°C) and are regarded as promising candidates. As mentioned above, however, glass has a small Young's modulus (about 70 GPa) and provides little improvement in the TCF. Silicon also has a small TEC of about 3 ppm/°C and a larger Young's modulus (about 160 GPa) than glass. Therefore, silicon can more effectively suppress the thermal expansion of $LiTaO_3$ and improves the TCF more. In addition, because of its large thermal conductivity of 160 W/m/K, silicon improves the heat dissipation remarkably. However, because of its small electrical resistivity, silicon degrades the frequency characteristics of SAW filters. Sapphire has a TEC of about 5 ppm/°C and a very large Young's modulus of about 470 GPa. Hence, it can effectively suppress the thermal expansion of $LiTaO_3$ and significantly improve the TCF. In addition, because of its large thermal conductivity of 42 W/m/K, sapphire can improve the heat dissipation. Furthermore, sapphire has a very large electric resistivity of over 10^{12} Ωm and does not degrade the frequency characteristics of SAW filters, unlike silicon.

Consequently, sapphire is an ideal material for the support substrate.

Table 1: Properties of candidate materials for support substrate and of $LiTaO_3$. (Properties of glass taken from [4]. Listed TEC of $LiTaO_3$ is value in SAW propagation direction.)

Material	TEC [ppm/°C]	Young's modulus [GPa]	Thermal conductivity [W/m/K]	Electric resistivity [Ω m]
Glass	4.5	66	1	10^{10}
Sapphire	5	470	42	$> 10^{12}$
Silicon	3	160	160	$< 10^{3}$
$LiTaO_3$	16.1	230	2	10^{12}

III. BONDING $LiTaO_3$ AND SAPPHIRE

We selected sapphire as an ideal support substrate for the bonded $LiTaO_3$/support substrate method. However one significant problem occurred. How can we bond $LiTaO_3$ and sapphire without any damage or bow? These two materials have large thermal expansion and lattice mismatches. In addition, these two materials have large Young's moduli. In general, thermal stress generated in the bimetallic structure like $LiTaO_3$/support-substrate increases in proportion to the temperature change, the thermal expansion mismatch, and the Young's moduli. Therefore, conventional bonding techniques cannot be used to bond $LiTaO_3$ and sapphire, because they usually include heating process such as anodic bonding. We used a surface activated bonding (SAB) technique to bond $LiTaO_3$ and sapphire. This technique was originally developed by groups including Prof. Suga of the University of Tokyo and Dr. Takagi of National Institute of Advanced Industrial Science and Technology to bond metal and metal or silicon and silicon [7-8]. The features of SAB are room temperature bonding, with no heating process required to have strong bonding, and the generation of an amorphous layer between bonded materials. SAB is based on the fact that clean surfaces are capable of forming strong bonds with other atoms. The process of SAB is shown in Fig. 1.

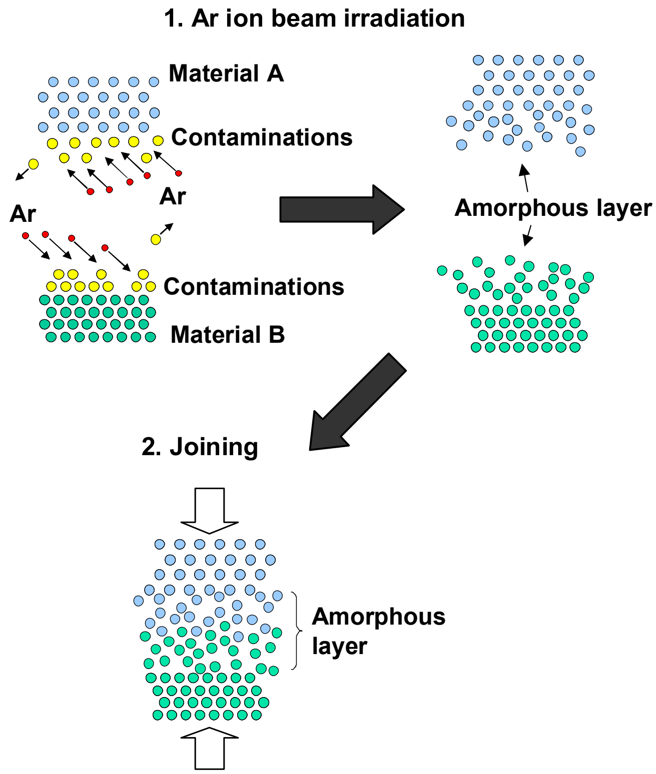

Figure 1: Process flow of surface activated bonding

First, irradiate the surfaces with an Ar ion beam in a vacuum to remove contamination and make active the surfaces. As this happens, an amorphous layer is generated on each surface. Then, the two surfaces are joined. They bond spontaneously with no pressure or load required.

SAB was originally developed for bonding metal to metal or semiconductors like silicon to other semiconductors. It was believed that bonding oxide to oxide like SiO_2 was difficult using SAB [9]. Therefore, SAB must be optimized to create strong $LiTaO_3$/sapphire bonding. We investigated the effect of the amorphous layer thickness on the $LiTaO_3$/sapphire bonding strength. As shown in Fig. 2, an amorphous layer thickness of 0.5 to 2 nm had a bonding strength of about 9 MPa. With an amorphous layer thickness of less than 0.5 nm, bonding strength was weak. This is probably because of insufficient surface activation and residual contamination. With an amorphous layer thickness of more than 2 nm, bonding was also weak. Here, this is probably because of enhanced surface roughness caused by excessive Ar irradiation. A transmission electron microscopy (TEM) image of a $LiTaO_3$ and sapphire bonding interface is shown in Fig. 3. The image shows atomic level bonding occurred and an amorphous layer was generated at the bonding interface

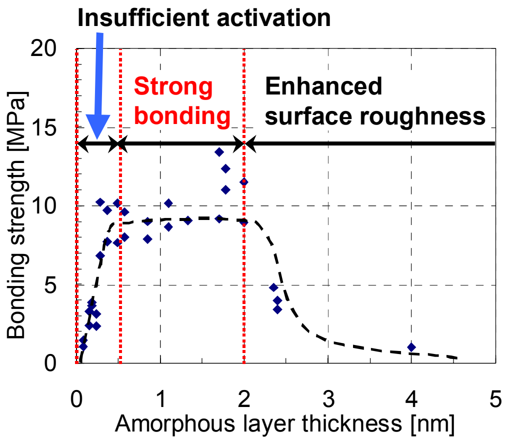

Figure 2: Bonding strength of $LiTaO_3$/sapphire as function of amorphous layer thickness measured by tensile test

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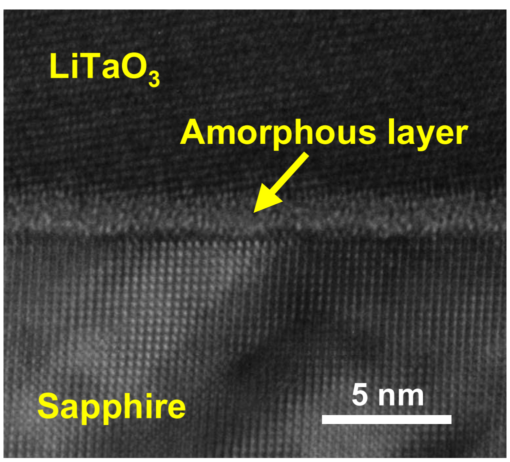


Figure 3: TEM image of $LiTaO_3$/sapphire bonding interface

IV. Frequency and Temperature Characteristics

US-PCS Tx filter using bonded $LiTaO_3$/sapphire substrate was designed and fabricated. As we previously reported [6], the $LiTaO_3$ thickness of bonded $LiTaO_3$/sapphire substrate strongly affects spurious responses caused by bulk waves reflected at the bonding interface. Frequency characteristics of US-PCS Tx filters are shown in Fig. 4. Each $LiTaO_3$ thickness was from 10 to 40 μm. As shown in Fig. 4, the frequency characteristics at the pass band are almost the same, however, spurious responses generated at higher frequencies decreased as the $LiTaO_3$ thickness increased. A $LiTaO_3$ thickness of 40 μm sufficiently suppressed spurious responses for practical use. The temperature characteristics of the US-PCS Tx filters shown in Fig. 4 measured at –3.5 dB attenuation of the higher frequency side of pass band are shown in Fig. 5. A slight tendency for the TCF to degrade as $LiTaO_3$ thickness increases can be observed. However, even if the $LiTaO_3$ thickness is 40 μm, the temperature characteristics were greatly improved in comparison with conventional SAW filters with TCFs of about –40 ppm/°C.

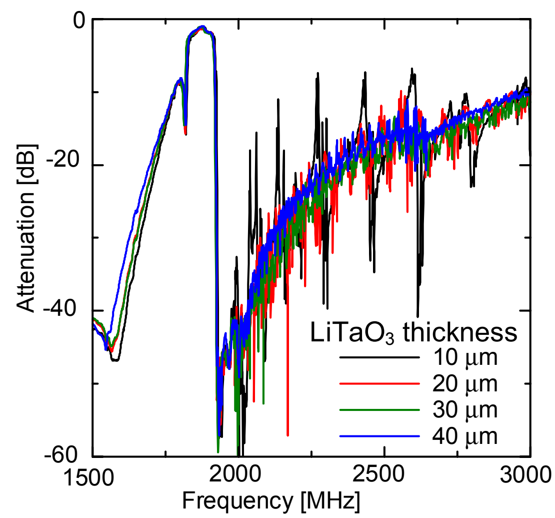


Figure 4: Effect of $LiTaO_3$ thickness on frequency characteristics of US-PCS Tx filters using bonded $LiTaO_3$/sapphire substrate

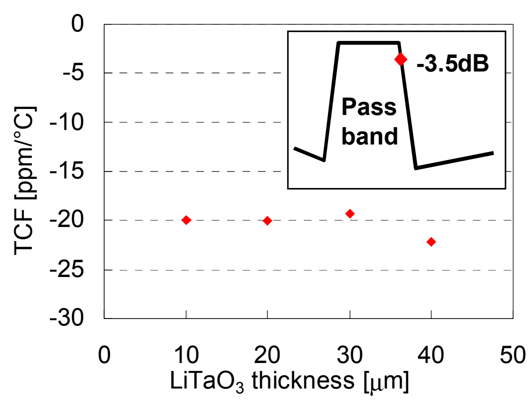
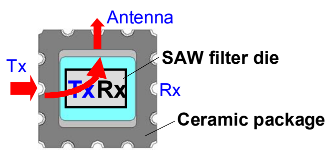


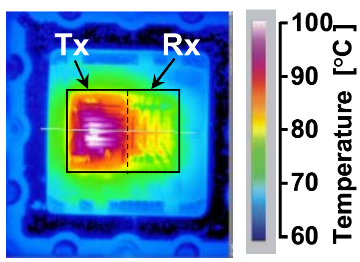
Figure 5: Effect of $LiTaO_3$ thickness on temperature characteristics of US-PCS Tx filters using bonded $LiTaO_3$/sapphire substrate

V. Heat Dissipation

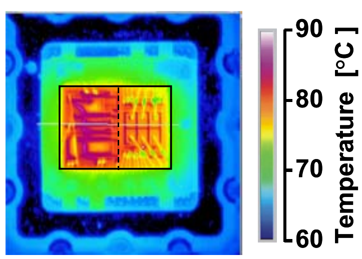
We measured the temperature distribution in the SAW filter die by applying 0.8 W of RF power from the Tx port of the US-PCS duplexers. Thermal images of the SAW filter dies observed using an infrared sensor are shown in Fig. 6. The ambient temperature was 60°C. For the conventional $LiTaO_3$ substrate, shown in Fig. 6(b), the heat generated in the Tx filter was confined within the Tx region, such that the highest temperature reached as high as 100°C. For the bonded $LiTaO_3$/sapphire substrate, shown in Fig. 6(c), the heat generated in the Tx filter dissipated throughout the die so that the highest temperature did not exceed 90°C. From these observations, we confirmed that the power durability was improved with the bonded $LiTaO_3$/sapphire substrate, in addition to improving the TCF.



(a) Observed device



(b) $LiTaO_3$ substrate



(c) Bonded $LiTaO_3$/sapphire substrate

Figure 6: Thermal images of SAW filter dies

VI. CONCLUSION

We developed a new temperature compensation method using a bonded $LiTaO_3$/sapphire substrate for high power applications. We found that sapphire is an ideal material for a support substrate because of its small thermal expansion, large Young's modulus, large thermal conductivity, and large electric resistivity. Using this substrate, excellent temperature characteristics and heat dissipation were realized. Surface activated bonding techniques were used and optimized to strongly bond $LiTaO_3$ and sapphire. Surface activated bonding takes place at room temperature and creates atomic level bonding with an amorphous layer. As a result, strong bonding occurred without any damage or bow regardless of the large thermal expansion and lattice mismatches between $LiTaO_3$ and sapphire. Using these techniques, we developed SAW filters for high power applications, such as US-PCS duplexers.

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