WAFER-TO-WAFER TRANSFER PROCESS OF BARIUM STRONTIUM TITANATE METAL-INSULATOR-METAL STRUCTURES BY LASER PRE-IRRADIATION AND GOLD-GOLD BONDING FOR FREQUENCY TUNING APPLICATIONS

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ABSTRACT

This is the first report on successful direct transfer of barium strontium titanate (BST) grown on a sapphire substrate at high temperature (~650 °C) to a target substrate at low temperature. The key point of the transfer process is the pre-irradiation of frequency-tripled Nd:YVO_4 laser to a laser adsorption layer beneath the BST layer through the transparent substrate, which weakens BST/Pt adhesion by thermal effect. The bonded substrates separated at BST/Pt interface near sapphire by slight impact to sapphire. After forming an upper Pt electrode on the transferred BST, voltage tuning of the dielectric constant was confirmed.

KEYWORDS

Wafer-to-wafer bonding, Laser assisted transfer process, Barium strontium titanate, Metal-insulator-metal variable capacitor

INTRODUCTION

Radio frequency (RF) filters based on surface acoustic wave/bulk acoustic wave (SAW/BAW) resonators have been widely used in mobile communications because of their excellent features such as small size, wide bandwidth and low insertion loss. However, frequency tuning is basically difficult for SAW/BAW resonators, because the resonant frequency is determined by acoustic velocity and dimensions such as interdigital transducer (IDT) pitch or film/plate thickness, all of which are difficult to change widely.

Recently, a tunable RF filter which is composed of SAW/BAW resonators connected with variable capacitors (VCs) in parallel or series has been proposed [1]. Both passband width and center frequency can be controlled by applying voltage to the VCs. Thin film VCs using ferroelectrics such as barium strontium titanate (BST) is promising for this use because of its excellent tunability of dielectric constant (several hundred % or higher) even in GHz range [2]. However, direct deposition of BST on temperature-sensitive substrates such as SAW substrate is basically difficult because high deposition temperature (>650 °C) is required to obtain BST with high capacitance tunability. To overcome similar problems, film transfer technique using laser lift-off process was proposed, and direct transfer of PZT films [3, 4] and AlGaN films [5] has been successfully performed. The predicted mechanism of laser lift-off is the thermal decomposition of interfacial materials by the irradiation of laser. Volume expansion by the decomposition may cause film peeling. However, it did not work for BST due to high melting point and difficulty of thermal decomposition [3].

Our new idea for delaminating BST films is weakening adhesiveness between BST and a substrate by laser, not relying on decomposition. The key point of the laser transfer process is the pre-irradiation of frequency-tripled Nd:YVO_4 laser through a transparent sapphire substrate to a Pt layer inserted between BST and the substrate before bonding. Then, the BST/Pt layer which is still attached on the substrate but with weakened is bonded with Au pads on a target substrate at low temperature. The bonded sapphire substrate is easily separated at BST/Pt interface after cooling down by slight impact to the sapphire substrate, and the BST patterns are transferred to the target substrate.

EXPERIMENTAL

BST transfer process

Figure 1 illustrates the BST transfer process. First, Pt/BST/Pt layers are deposited on a sapphire substrate by RF magnetron sputtering at high temperature, and an Au layer is also deposited by RF magnetron sputtering (Fig. 1-a). Next, photoresist patterns are formed, (Fig.1-b) and then Au and upper Pt are etched by ion beam milling (Roth & Rau Ionsys 500, MicroSystems Inc.) (Fig. 1-c). After that, the BST film is wet-etched by a mixture of HNO_3 and buffered HF (Fig. 1-d) [6]. The lower Pt layer is also etched by ion beam milling (Fig. 1-e). The photoresist and Au layer are removed by wet process to complete metal-insulator-metal (MIM) structures (Fig. 1-f).

For BST transfer, frequency-tripled Nd:YVO_4 laser is irradiated to the lower Pt through the sapphire substrate (Fig. 1-g). Figure 2 shows an experimental setup for laser irradiation. Laser power is measured by thermopile detector (Newport 818P-110-19). The specification of the laser is shown in Table 1. Scanning speed and pitch are 10 mm/s and 25 μm, respectively. After pre-irradiation, the MIM structures on sapphire are bonded to a borosilicate glass with Au layer by metal-metal (Au-Pt) bonding (Fig. 1-h). The Au and Pt surface on both wafers are activated by Ar plasma treatment [7]. The bonding temperature, pressure and time are 140 °C, 12.5 MPa and 20 min, respectively. After cooling down, the sapphire substrate is released by slight mechanical impact (Fig. 1-i). Finally, top Au/Pt electrodes are formed on the transferred BST patterns by lift-off process (Fig. 1-j). Figure 3 shows the SEM (scanning electron microscope) image of the completed BST MIM structures.

Evaluation

To evaluate BST/Pt adhesiveness by laser pre-irradiation, tape test was employed. An adhesive tape is applied to the MIM structures after laser pre-irradiation, and then peeled in vertical direction as shown in Fig. 4. For quantitative evaluation, transfer ratio is defined as

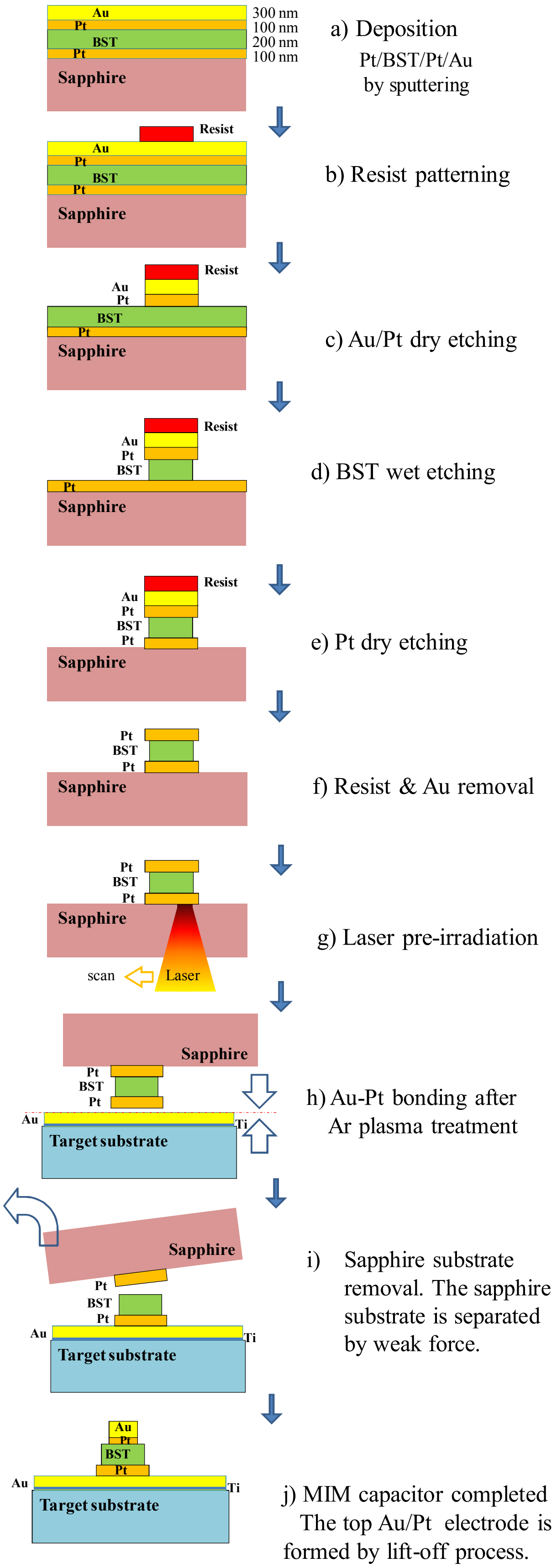

Figure 1: BST transfer process with laser pre-irradiation. BST MIM structures prepared on sapphire at high temperature are transferred to a target substrate with an assist of backside laser irradiation.

Table 1: Specifications of the laser

Polarization, Mode	Liner, TEM_{00}
Wave length (nm)	355
Pulse width (ns)	20
Frequency (kHz)	50
Spot diameter (µm)	20

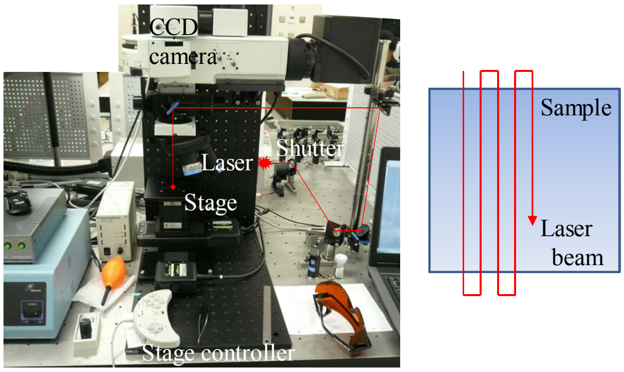

Figure 2: Experimental setup for laser irradiation and the trajectory of laser beam by stage motion.

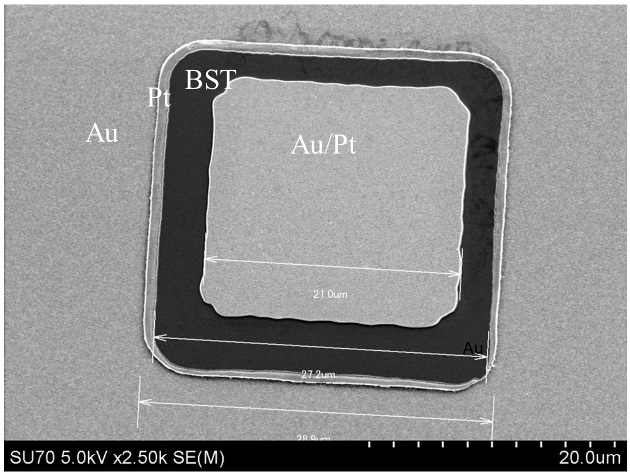

Figure 3 SEM image of the Au/Pt/BST/Pt/Au MIM structure shown in Fig. 1-j. The Au/Pt top electrode was evaporated on the transferred BST film. The bottom electrode was formed by Au-Pt bonding. No visual damage was observed in the BST capacitor.

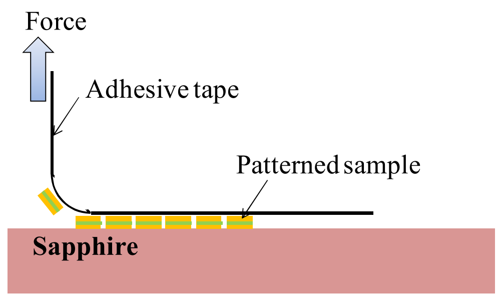

Figure 4: Adhesive tape test for measuring adhesion force.

$$\text{Transfer Ratio} = \frac{\text{Number of transfered patterns}}{\text{Number of total patterns}} \quad (1)$$

After the MIM structures are transferred to the target substrate, transferred patterns are observed using an optical microscope and a SEM. The capacitance of the transferred BST is evaluated using a network analyzer (Agilent E5071B).

RESULTS AND DISSCUSSION

BST transfer test

First, the influence of pre-irradiation for BST film transfer was investigated by the adhesive tape test. Figure 5 shows transfer ratio after tape peeling as a function of laser power. No BST pattern was transferred below the laser power of 0.9 W, but transfer ratio jumped up above 1 W and reached 100 % at 1.1 W. No apparent defect in the transferred BST patterns on the tape was found around a laser power of 1 W.

Based on the adhesive tape test result, BST patterns were transferred from a sapphire substrate to a glass substrate according to the process shown in Fig. 1, and MIM capacitors were fabricated.

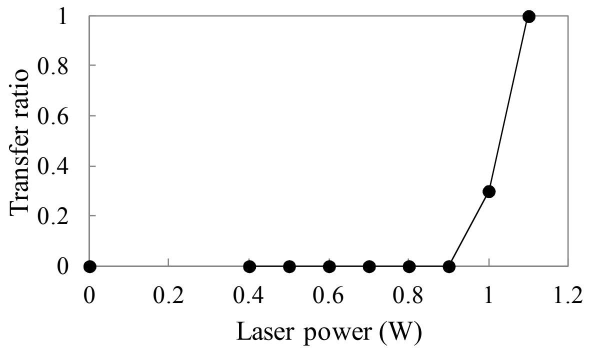

Figure 5: Dependency of BST transfer ratio on laser power investigated by adhesive tape test (see Fig. 4). The sample was the BST MIM structure shown in Fig. 1-g.

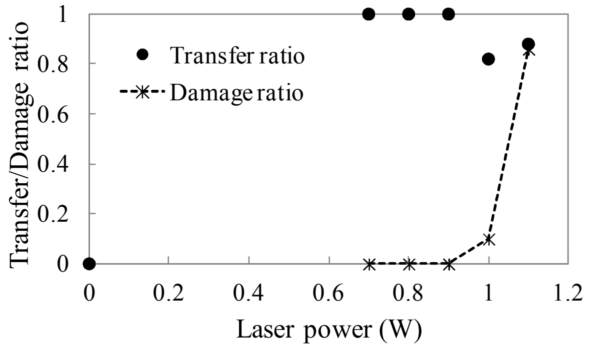

Figure 6: Dependency of BST transfer ratio on laser power. Damage ratio is defined for laser-damaged BST patterns like transfer ratio in Eq. (1). The transfer was possible at laser power higher than 0.7 W. Strong Au-Pt bonding helps the delamination of BST near threshold laser power compared to Fig. 5.

Figure 6 shows transfer ratio as a function of laser power. As is the case with the adhesive tape test, no BST transfer was found without laser pre-irradiation, while all BST patterns were transferred to the glass substrate above the laser power of 0.7 W. Figure 7 shows typical BST patterns transferred to the glass substrate at 0.8 W. No defect was found in the transferred BST. When the laser power was raised above 1 W, however, damage in the transferred BST patterns increased. As a result, a process window for perfect damage-less BST transfer was found between 0.7 W and 0.9 W in laser power.

The delamination interface was between BST and Pt on the sapphire substrate. This is suitable for capacitor fabrication, because capacitance can easily controlled by the upper electrode area. In addition, there is no risk of electrical short through the sidewall of the MIM capacitor, if the top electrode is somewhat smaller than the transferred BST. On the other hand, the delamination interface was between Pt and BST near the bonding interface without laser pre-irradiation. The weakest interface might shift from the upper Pt/BST to the lower Pt/BST by laser pre-irradiation.

The mechanism of the laser lift-off process can be explained by the thermal decomposition of laser-irradiated material including laser ablation. In this case, however, the laser is shielded by Pt, which may not be decomposed due to its high boiling temperature. Therefore, we think that thermal effect such as thermal expansion mismatch between Pt and BST might be the main reason to weaken adhesiveness between them.

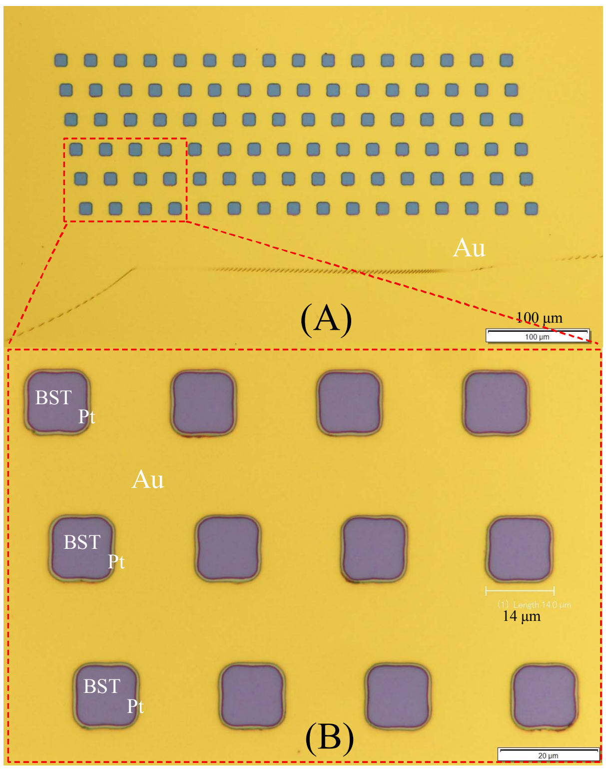

Figure 7: Transferred BST/Pt structures. The pattern size is 15 μm square and the thickness of BST is 180 nm. No visual damage was observed in the BST/Pt structures. (Laser Power = 0.8 W, Scan pitch = 25 μm)

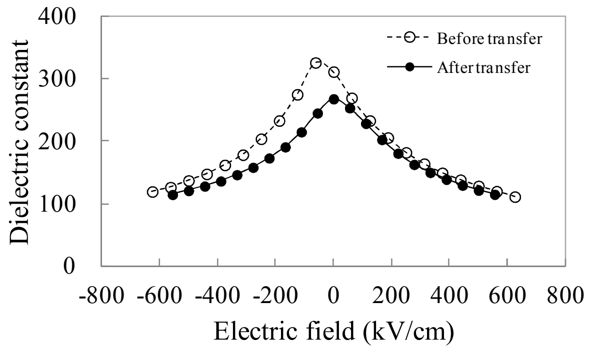

Figure 8: Relationship between electric field across BST and dielectric constant before and after film transfer, measured at 1 GHz.

BST variable capacitor

The characteristic of the BST VCs before and after transfer was evaluated at 1 GHz. Figure 8 shows the dielectric constant of BST as a function of electric field across BST. The transferred BST VCs have a tuning ratio of 2.3, which is comparable with or a bit smaller than that of the VC before transfer. It should be noted that the BST VCs measured before and after transfer were on the same substrate but in different regions, and the distribution of dielectric constant on the substrate must be taken into account of. Higher tuning ratio may be obtained by optimizing the BST deposition condition.

CONCLUSION

For the wafer-to-wafer transfer of the film which has high decomposition temperature, we proposed the novel process in which laser is applied in advance to a laser absorbing (metal) layer beneath the film to be transferred. In this study, 15 μm square BST patterns on a sapphire substrate were successfully transferred to a target glass substrate by laser pre-irradiation to a Pt underlayer through the sapphire substrate. When laser power was 0.7 W to 0.9 W, the perfect transfer of BST patterns without damage were achieved. The delamination interface was between BST and Pt on the sapphire substrate. This is convenient for MIM capacitor fabrication. The transferred BST capacitor had a tuning ratio of 230 % in dielectric constant. This transfer process can be widely applied to the integration of heteroelements to temperature sensitive substrates.

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