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List of Contents

Integration of BST varactors on lithium niobate by film transfer technology for tunable SAW filters

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***Abstract* — A tunable RF bandpass filter employing ferroelectric variable capacitors (VCs) connected in parallel and/or series with surface acoustic wave (SAW) resonators is proposed. Because the direct deposition of ferroelectric materials such as barium strontium titanate (BST) on a SAW substrate such as lithium niobate (LN) at high temperature may cause thermal damage in the BST film due to difference in the coefficient of thermal expansion between them, the BST film depositing on a Si substrate is transferred to a LN substrate at low temperature using surface activated Au-Au bonding. The fabricated metal-insulator-metal (MIM)-type ferroelectric VC on LN showed a change in relative permittivity from 310 to 200 at 1 GHz by applying electric field of 15 KV/mm. The resonance frequency of a 1 GHz SAW resonator was shifted upward by 18 MHz by applying a DC bias voltage of 3 V to the VC connected in series with the SAW resonators. This is the clear evidence that the frequency tuning of a SAW filter is possible using the transferred BST VCs.**

Keywords- Tunable filter, Surface acoustic wave (SAW), Barium strontium titanate (BST), Variable capacitor

I. INTRODUCTION

A tunable wireless front-end is needed for an advanced wireless system for cognitive radio, where unlicensed users are allowed to transmit and receive data over portions of spectra when licensed users are inactive [1, 2]. In particular, widely-tunable RF bandpass filters are strongly required for such systems, because all transmission frequency other than the selected frequency must be cut-off strictly to avoid interference with licensed users. RF filters based on surface acoustic wave (SAW) or bulk acoustic wave (BAW) resonators have been widely used in mobile communications because of their excellent features such as small size, wide bandwidth, sharp cut-off characteristics and low insertion loss. However, frequency tuning is basically difficult for SAW/BAW resonators, because the resonant frequency is determined by dimensions such as interdigital transducer (IDT) pitch and film/plate thickness, all of which are difficult to change widely.

Recently, a tunable RF filter using SAW/BAW resonators connecting variable capacitors (VCs) in parallel and/or series with SAW/BAW resonators in ladder-type configuration has been proposed [3]. Both passband width and center frequency can be flexibly controlled by applying voltage to VCs. Based on this concept, we have developed tunable filters by integrating SAW resonators with electro-statically actuated micro electro mechanical systems (MEMS) VCs [4]. The 3 dB bandwidth was tuned from 146 MHz to 130 MHz by actuating a MEMS variable capacitor connected in parallel to one of the series resonators. There are some advantages of a MEMS VC such as low RF loss and good linearity, whereas its relatively large size is a problem for consumer applications. Low capacitance tunability (C_{max}/C_{min}) and high control voltage of the MEMS VC are also serious problems to meet practical requirements.

Another candidate of VCs for tunable RF application is electric-field tunable dielectrics materials. Barium strontium titanate (BST) is one of the most promising materials for this application because of a strong dependence of permittivity on electric field, high breakdown field and relatively low loss tangent at microwave frequencies [5, 6] High dielectric constant of BST is advantageous to reduce the size of the VCs. However, the direct deposition of BST on a SAW substrate such as lithium tantalate (LT) and lithium niobate (LN) has not been well demonstrated, because high growth temperature (650 °C or higher) might cause thermal damage to the film structure partly due to difference in the coefficient of thermal expansion (CTE) between the substrate and BST.

For the material which is difficult to deposit directly, film transfer technique is the next possible way for hetero-materials integration. This kind of technique is used for an Al-As-Ga-based LED printhead element integrated with a Si-based IC driver using a sacrificial etching process [7]. In this study, we have developed a ferroelectric film transfer process to integrate BST elements on SAW devices at low temperature for tunable RF filter application. This paper reports the design, fabrication and preliminary result of a proof-of-concept tunable SAW filter.

II. PRINCIPLE AND DESIGN

A. Principle

Consider a capacitor, C, is connected to a SAW resonator, SR, in parallel as shown in Fig. 1 (a). When the quality factor, Q, of the resonator is sufficiently high, a simple LCR model shows that the anti-resonant frequency, f_a^e, decreases according to

$$f_a^e = f_a \sqrt{1 - \frac{1}{\gamma + 1} \cdot \frac{C}{C_0 + C}}\,, \quad (1)$$

while the anti-resonance frequency does not change from its intrinsic value. On the other hand, when a capacitor, C, is connected in series to a SAW resonator, SR, as shown in Fig. 1 (b), the anti-resonance frequency, f_a^e, remains unchanged, while the resonant frequency, f_r^e, increases according to

$$f_r^e = f_r \sqrt{1 + \frac{1}{\gamma} \cdot \frac{C_0}{C_0 + C}}\,, \quad (2)$$

where f_r, f_a and C_0 are the resonance frequency, anti-resonance frequency and clamp capacitance of the original resonator, respectively. γ is the capacitance ratio, and C is the capacitance of the additional capacitor.

If a ladder type filter shown in Fig. 2 is constructed using the units shown in Fig. 1 (a) and (b), both rejection poles shift inside, i.e. the passband is narrowed in comparison with the filter without the additional capacitors, as shown in Fig. 3. Equations (1) and (2) suggest that the position of each rejection pole moves downward, when the capacitance of both series and parallel additional VCs increases, while it moves upward with decrease in the capacitance of additional VCs, as shown in Fig. 3. Therefore, the bandwidth and the center frequency can be tuned by changing the capacitance of the VCs. Wider frequency tunability can be realized using the filter configuration where two capacitors are connected to each resonator in series and in parallel. The device configurations and tuning capability are described elsewhere more in detail [3].

B. Device Design

Based on the above principle, the frequency tuning range is absolutely limited within the original bandwidth of the filter without additional capacitors. Therefore, a wideband filter composed of resonators with high electromechanical coupling coefficient, k^2, is necessary to obtain practical frequency tunability. In this study, we adopted Love wave, which is a kind of SAW with extremely high k^2 (~30 %), for resonators. Love wave can be generated on a lightly-rotated Y-cut LN wafer with heavy (e.g. Cu or Au) IDT electrodes [8].

The filter design is basically identical to that using MEMS VCs reported in [4], and the MEMS VCs are replaced by BST VCs in this study. The center frequency is 1 GHz. The dielectric constant of the BST film which we have obtained on a Si wafer changes from 800 to 200 by applying a DC bias voltage of 8 V. Therefore, a 200 nm thick, 15 µm square BST capacitor should have a tuning range from 8 pF to 2 pF. Simple test element groups (TEG) of 1-port SAW resonators with the BST VCs are included on the same die.

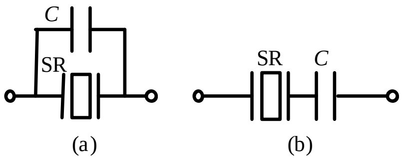

Figure 1. Capacitor, C, connected (a) in parallel and (b) in series to a SAW resonator, SR.

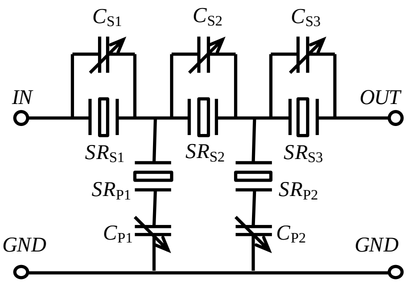

Figure 2. Circuit diagram of a simple tunable filter composed of SAW resonators, SR, and variable capacitors, C.

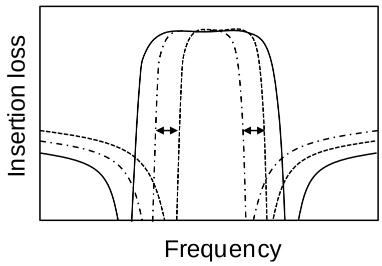

Figure 3. Transmission characteristics of a ladder type SAW filter without additional VCs (solid line), with VCs in series and in parallel at the minimum capacitance (dotted line), and with VCs in series and in parallel at the maximum capacitance (dashed line).

III. FABRICATION

To integrate BST VCs on a LN substrate by film transfer technique, one of the most important process steps is wafer bonding, because large CTE mismatch between LN and Si, on which BST is grown, causes cracking in the LN substrate during a thermal bonding process [9]. Au-Au bonding with argon plasma surface activation method was employed to enhance bonding strength at low temperature [9, 10].

The fabrication process is shown in Fig. 4. First, IDT electrodes of Au/Ti were fabricated on a 15 ° Y LN substrate by electron beam lithography (a), and wiring lines and bonding pads of Au/Ti were fabricated by lift-off process (b). The thickness of the Au/Ti layer for the IDT electrodes and the bonding pads is 100 nm/8 nm and 200 nm/8 nm, respectively. For the deposition of BST, a double-side polished Si substrate of 200 µm in thickness was thermally oxidized. On it, 20 nm thick TiO_2, 200 nm thick Pt and 200 nm thick BST were deposited in this order by sputtering. The deposition temperature of BST was 650 °C. The BST and Pt layers were patterned by HF + HNO_3 wet etching and Xe ion etching, respectively (c). On the patterned BST, 200 nm thick Au pads for bonding were formed by lift-off process (d). The backside oxide layer was patterned into alignment marks using buffered HF.

Before the bonding, the bonding surfaces on both Au/BST/Pt metal-insulator-metal (MIM) structures on the Si substrate and the Au bonding pads on the LN substrate were activated by Ar plasma for 1 min. The BST MIM structures on the Si substrate were aligned and bonded to the Au pads on the LN substrate by applying a pressure of 3 MPa at 130 °C for 20 min in vacuum (e). After bonding the LN and Si substrates, all Si bulk layer of 200 µm thick was etched off by SF_6 plasma (f), and the oxide layer was removed by buffered HF etching (g). Then, the BST MIM structures were covered with a photo-patternable polyimide insulating layer with wiring apertures. Finally, Al electrodes were formed for connecting the BST VCs and the SAW resonators (h). Figure 5 shows the schematic cross-section view and optical micrographs of the completed MIM-type varactor on the LN substrate.

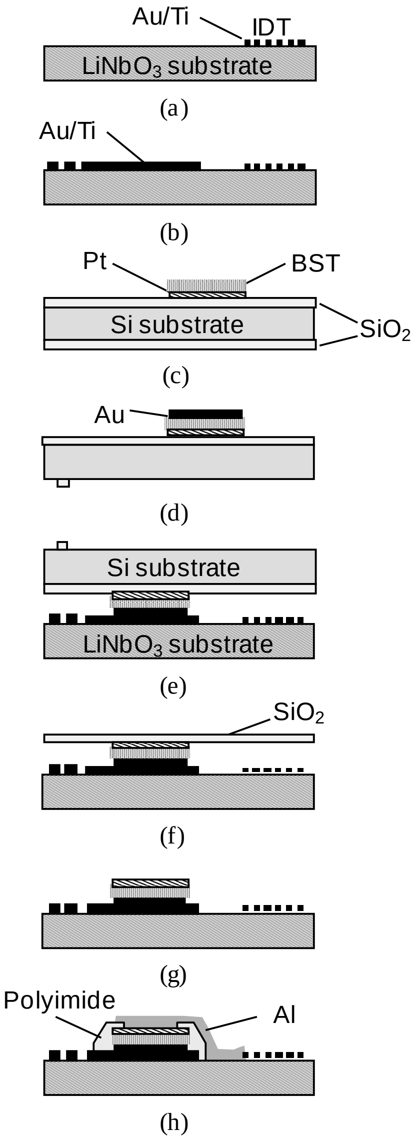

Figure 4. Process flow of the tunable SAW filter using BST VCs.

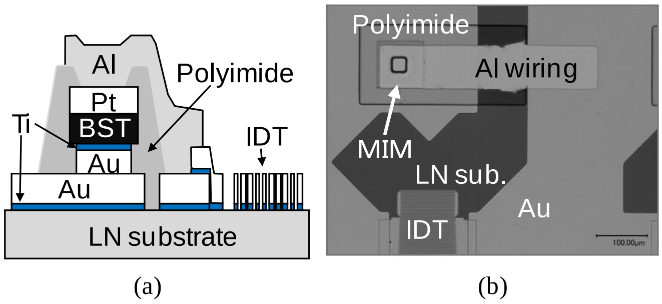

Figure 5. Schematic cross-section view (a) and optical micrograph (b) of the completed BST varactor on LN substrate.

IV. EVALUATION

The capacitance of the BST MIM structures and the fabricated SAW device was characterized using Agilent 5071B network analyzer, Cascade SG/GS-250 RF wafer probes and a modified probe for DC voltage application. Figure 6 shows the dielectric constant of the BST film at 1 GHz (a) just after deposition by sputtering and (b) after transferring, as a function of DC bias voltage. Without applying DC bias voltage, the dielectric constant of BST films before transferred reaches 800, while that after transferred was less than a half of the original value. This deterioration might be caused by the formation of a low permittivity layer on the BST film during Pt patterning. A possible solution is the removal of the damaged BST layer by slight etching. The transferred BST film on LN also showed change in relative permittivity from 310 to 200 with applying 3 V, i.e. an electric field of 15 kV/mm, as shown in Fig. 6 (b), but the capacitance tunability was reduced by transfer. It might be also caused by the low permittivity layer inserted in the MIM structure.

When DC bias voltage higher than 4 V was applied to the transferred BST VC, it was damage by short circuit. The leak path could be caused by sputter-deposited Pt debris on BST sidewalls during Xe ion etching. For Pt patterning, reactive ion etching such as Cl_2 plasma etching should be used instead of Xe ion etching to reduce the Pt residue.

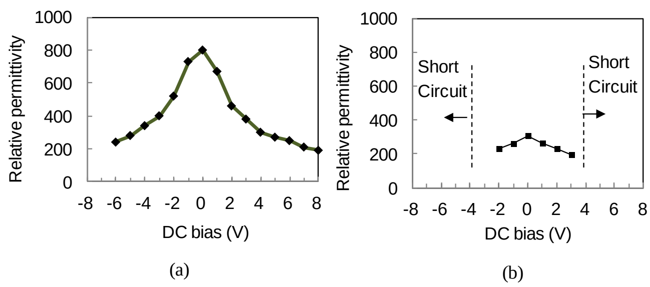

Figure 6. Dielectric constant of BST films as a function of DC bias voltage. (a) As-deposition BST on a Si substrate, (b) Transferred BST on a LN substrate.

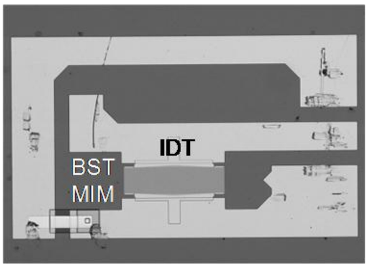

Figure 7. Optical micrograph of a 1-port SAW resonator connected with the BST VC in series.

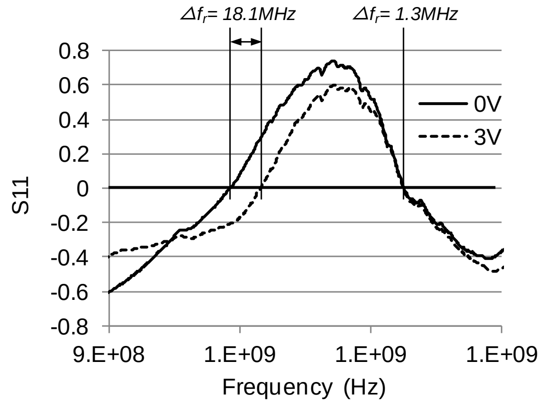

Figure 8. Imaginary part of S_{11} of a 1-port SAW resonator with BST VCs in series with and without DC vias voltage (3 V).

Because no evaluable tunable filter was obtained due to insufficient yield of BST film transfer, the frequency tunability was preliminarily demonstrated using the TEG, which was a 1-port SAW resonator connected with the BST VC in series, as shown in Fig. 7. Figure 8 shows the imaginary part of S_{11} ($\mathrm{Im}(S_{11})$) with and without applying DC bias voltage to the VC. The lower and upper zero-cross points of $\mathrm{Im}(S_{11})$ corresponds to resonance and anti-resonance frequencies, respectively. By applying 3 V to the VC, the resonance frequency moved from 999 MHz to 1018 MHz, while the anti-resonance frequency did not move, as the theory indicates.

V. CONCLUSION

We developed a ferroelectric film transfer technology for tunable RF bandpass filters consisting of SAW resonators and ferroelectric variable capacitors. BST was deposited on a Si substrate at 650 °C, patterned into MIM structures, and then transferred to a LN substrate. The transfer process consists of Au-Au surface activated bonding and Si lost wafer process. The transferred BST MIM structure worked as a VC, and the resonance frequency of a one-port SAW resonator with the transferred BST VC connected in series increased from 999 MHz to 1018 MHz, when a DC bias voltage of 3 V was applied to the VC. This is the first evidence that the frequency tuning of a SAW filter is possible using the transferred BST VCs. The proposed film transfer technology can be applied to other devices and other materials as well as the tunable SAW filter.

ACKNOWLEDGMENT

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