SAW Resonators on 15°YX-$LiNbO_3$/SiO_2/Sapphire Substrate with Excellent Electromechanical Coupling

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***Summary*—In this work, the shear horizontal surface acoustic wave (SH-SAW) resonators were demonstrated on 15° YX-$LiNbO_3$/SiO_2/sapphire ($LiNbO_3$-on-sapphire, LNOS) substrate. Compared to the reported gigahertz SAW resonators based on piezoelectric heterogeneous substrates, the fabricated resonator in this work exhibits a state-of-the-art electromechanical coupling coefficient (k^2) of 42.2%, a maximum Bode-Q (Q_{max}) of 1457 and an excellent figure of merit ($k^2 \times Q_{max}$) of 615. Besides, several methods for suppressing transverse modes were implemented and compared. Tilted interdigital-transducers combined with the apodization technique can suppress the transverse modes more thoroughly while maintaining decent Q values. Overall, SAW devices based on the LNOS substrate have great potential for RF filters with low insertion loss, steep skirts, and wide bandwidth.**

***Keywords*—Surface acoustic wave resonator; $LiNbO_3$-on-insulator; sapphire; RF loss; electromechanical coupling coefficient; transverse mode**

I. Introduction

Acoustic devices including surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices have been widely used for radio frequency (RF) signal processing. With the development of mobile communication systems, the fifth-generation (5G) New Radio (NR) bands require filters with low insertion loss, steep skirt and wide bandwidth, which place higher requirements on the quality factor (Q) and electromechanical coupling coefficient (k^2) of resonators. For instance, the fractional bandwidth (FBW) of the N77 band (3300-4200 MHz) is 24%, which requires that the k^2 of the resonators constituting the ladder-type filters is not less than 50% [1-2].

In recent years, shear horizontal SAW (SH-SAW) devices based on piezoelectric heterogeneous substrates have attracted much attentions due to their improved performance. The SH-SAW resonators based on $LiTaO_3$/SiO_2/Si ($LiTaO_3$-on-insulator, LTOI) substrates achieve ultra-high Q values and small temperature coefficient of frequency (TCF) [3]. After that, several alternative support substrates have been introduced to reduce RF loss [4-5] and mechanical loss [6-7]. However, the k^2 of the LTOI based SAW resonator is around 10%. In contrast, $LiNbO_3$ films combined with stacked substrates may be one of the promising solutions for broadband filters due to the large k^2 of $LiNbO_3$ [8-12].

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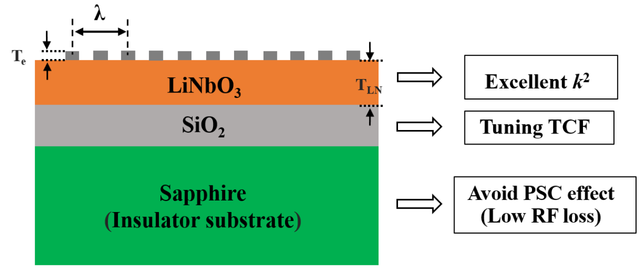

Fig. 1. The schematic of SAW devices on the LNOS substrate.

In this work, the $LiNbO_3$/SiO_2/sapphire ($LiNbO_3$-on-sapphire, LNOS) substrate was designed and prepared. The cut angle of $LiNbO_3$ was chosen to be 15° for maximum k^2, and a sapphire insulator substrate was used here to avoid RF-loss. The fabricated SH-SAW resonator on the LNOS substrate shows an ultra-high k^2 of 42.2%, and the figure of merit (FoM=$k^2 \times Q_{max}$) is very close to the state-of-the-art [4].

II. Simulation and Design

In order to obtain the maximum k^2, SH-SAW resonators on $LiNbO_3$/SiO_2/sapphire substrates (as schematically shown in Fig. 1) with different cut angles of $LiNbO_3$ film were simulated using the finite element analysis (FEA). Notably, sapphire was selected as support substrate to avoid parasitic surface conduction (PSC) effects and reduce RF loss [5]. Figs. 2(a) and (b) show the simulated resonant frequency (f_r), anti-resonant frequency (f_a) and the extracted k^2 of LNOS based SAW resonators, respectively. Where the k^2 is given by $k^2=\pi^2/8\times(f_a^2-f_r^2)/f_r^2$ [13]. When the cut angle θ is around 15°, the k^2 reaches its maximum value.

III. Experimental Results and Discussion

Subsequently, the 15° YX-$LiNbO_3$/SiO_2/sapphire substrate was prepared by ion-cutting process, including ion

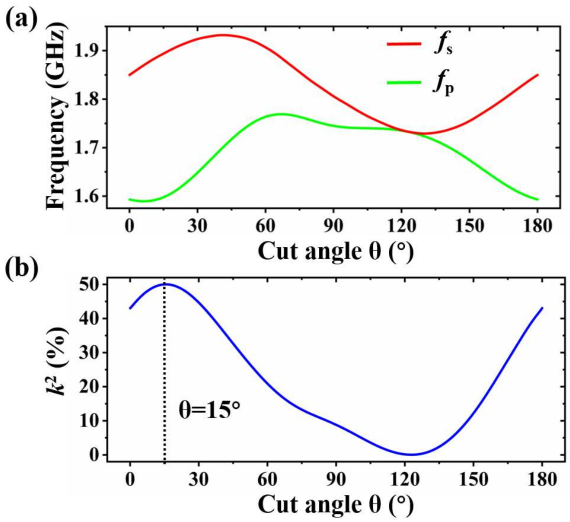

Fig. 2. (a) Simulated f_s and f_p of LNOS based SAW resonators with different cut angle θ.(b) Extracted k^2 of LNOS based SAW resonators with different cut angle θ.

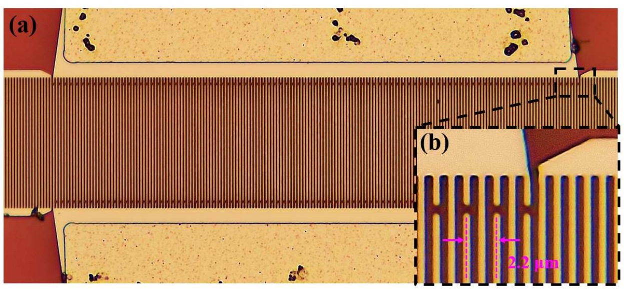

Fig. 3. (a) The optical microscope image and (b) zoomed-in image of a fabricated LNOS based SAW resonator.

implantation, wafer bonding, annealing and chemical mechanical polishing (CMP) [14]. The thickness of $LiNbO_3$ and SiO_2 are 600 nm and 500 nm, respectively. Several SH-SAW resonators on the LNOS substrate were fabricated using electron-beam lithography, metal evaporation, and the lift-off process. The interdigital-transducers (IDT) and reflectors consist of Ti/Au/Ti/Al/Ti with thicknesses of 2 nm, 20 nm, 2 nm, 95 nm and 3 nm, respectively. Figs. 3(a) and (b) show the optical microscope images of a fabricated LNOS based SAW resonator. This resonator comprises 90 pairs of IDT electrodes and 25 pairs of reflectors on both sides. The wavelength (λ) is 2.2 μm, and the duty factor is 50%.

The frequency responses of the fabricated LNOS based SAW resonators were characterized using a vector network analyzer (Keysight E5071C) with a terminal impedance of 50 Ω at room temperature in air. Figs. 4(a) and (b) show the measured admittance, conductance, Bode-Q and fitted Bode-Q curves of a fabricated LNOS based SAW resonator with ordinary IDT, respectively. This resonator exhibits an excellent k^2 of 42.2%, Q_{max} of 1457 and an FoM of 615. The excellent performance of LNOS based SAW resonators is attributed to the large piezoelectric coefficient of $LiNbO_3$ and the great insulating properties of the sapphire support substrate. It should be noted that the measured k^2 is slightly smaller than the

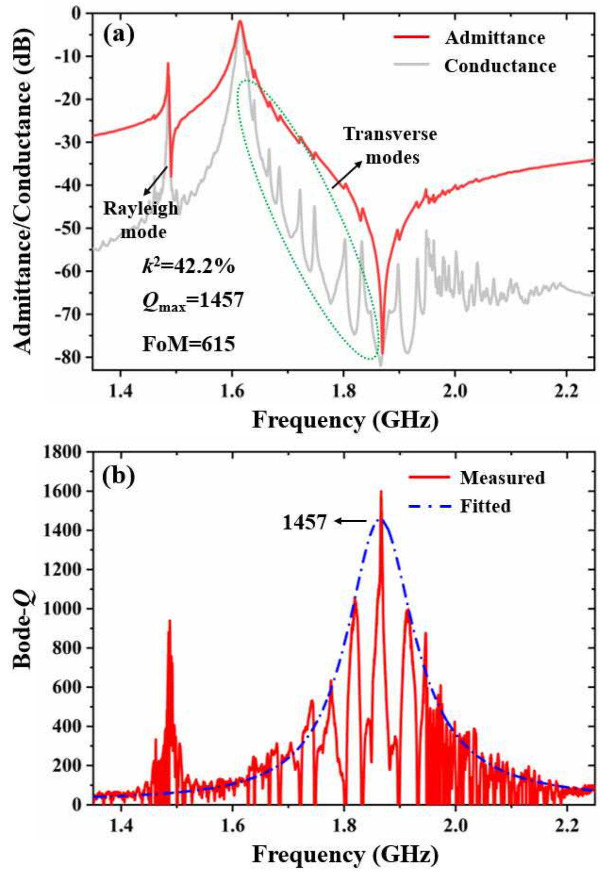

Fig. 4. (a) Measured admittance and conductance curves of the LNOS based SAW resonator. (b) Measured Bode-Q and the fitted curves of the LNOS based SAW resonator.

simulated results. There are several reasons that may cause the difference between the simulated and the measured results, where the imperfect preparation processes of the LNOS substrate and electrodes may be the most important factors. The k^2 of the LNOS based SAW resonators may be further improved by optimizing the related fabrication process.

The conductance curve in Fig. 4(a) shows strong transverse modes that will cause ripples in the passband of the filters. In order to suppress above transverse modes, four methods were implemented and compared in this work. Fig. 5 shows the optical microscope images of the fabricated SAW resonators with different designs, the wavelengths of above resonators are all 2.2 μm. In addition to the universal IDT designs, tilted IDT [15], piston mode structure [16-17], apodization technique [18-19], tilted IDT combined with the apodization technique have also been used for transverse modes suppression. The measured results of above resonators are shown in Fig. 6, and the above four methods are all effective. Where the tilted IDT combined with the apodization technique can suppress the transverse modes more thoroughly while maintaining decent Q values. As for the Rayleigh mode, which can be suppressed by changing the ratio of the thickness (including T_{LN}, T_e, etc.) to wavelength [20-21] or the cut angle of $LiNbO_3$ [22]. Fig. 7 shows the measured admittance curve of the LNOS based SAW resonator

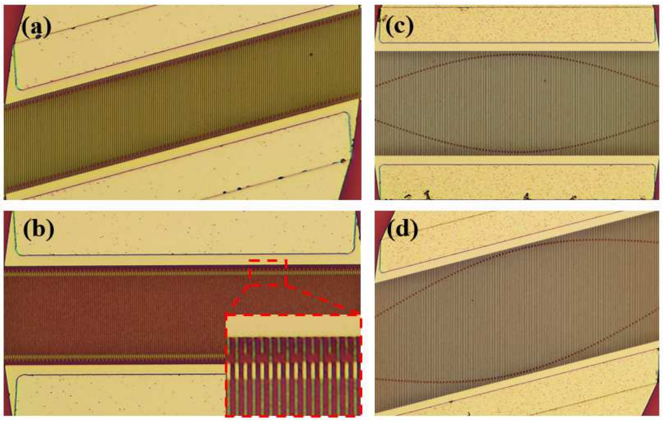

Fig. 5. Optical microscope images of LNOS based SAW resonators with different designs for suppressing transverse modes. (a) Tilted IDT, (b) piston mode structure, (c) apodization technique, (d) tilted IDT combined with the apodization technique.

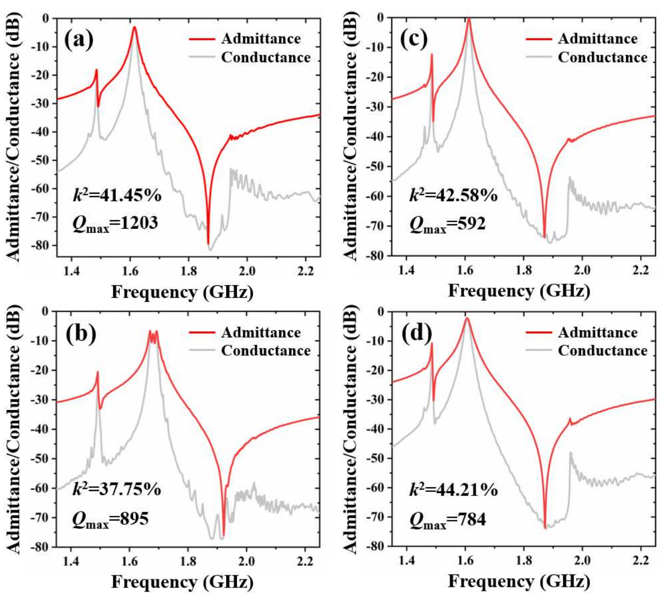

Fig. 6. Measured admittance and conductance curves of LNOS based SAW resonators with different designs. (a) Tilted IDT, (b) piston mode structure, (c) apodization technique, (d) tilted IDT combined with the apodization technique.

with λ=1.2 μm, and the Rayleigh mode is well suppressed at the suitable T_{LN}/λ and T_e/λ.

Fig. 8 shows the comparison of this work with other SAW resonators on piezoelectric heterogeneous substrates [3-12, 23]. The LNOS based SAW resonator in Fig. 3 exhibits the largest k^2 among all reported gigahertz SAW resonators based on heterostructures, and its FoM is very close to the state-of-the-art [4]. After further optimization of the design and the fabrication process, SAW devices with enhanced performance can be expected.

IV. Conclusions

This work demonstrates the SH-SAW resonator on the LNOS substrate with an ultra-high k^2 of 42.2%, Q_{max} of 1457, and an FoM of 615. Where the k^2 exceeds all reported gigahertz SAW resonators based on heterostructures, and the FoM is very close to the state-of-the-art. The transverse modes and Rayleigh

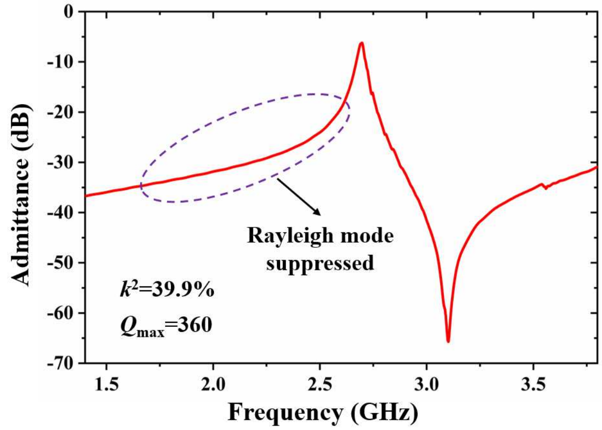

Fig. 7. Measured admittance curve of the LNOS based SAW resonator with λ=1.2 μm.

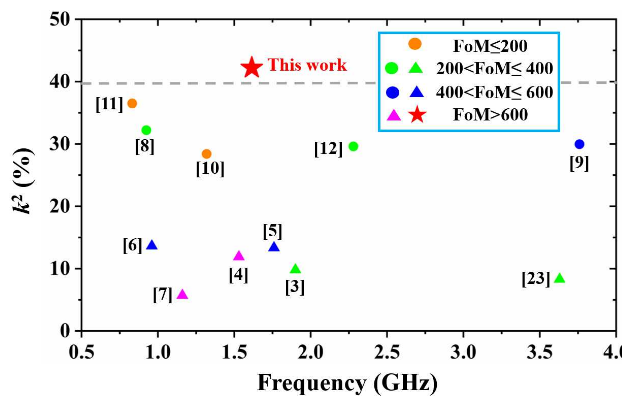

Fig. 8. A comparison of the LNOS based SAW resonator with other SAW resonators on piezoelectric heterogeneous substrates.

mode were also suppressed. After further optimization, the LNOS based SAW devices have great potential as low loss and broadband filtering solutions for 5G-NR bands.

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