Tilted Interdigital-transducer in NS-SAW Resonator for Transverse Mode Suppression

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***Abstract*—Multilayered shear-horizontal surface acoustic wave (SAW) resonators have attracted wide attention due to its high performance. However, the transverse modes appeared in spectrum will degrade the stability of the resonators. In this work, a tilted interdigital-transducer (IDT) method is proposed for a non-leaky stack SAW (NS-SAW) resonator using 30° YX-$LiNbO_3/SiO_2$/Si substrate to solve the above problem. In simulations, the IDT are optimized by designing different tilted angles. When the tilted angle is about 16°, the low-order transverse modes between resonant frequency (f_s) and anti-resonant frequency (f_p) are suppressed successfully. In particular, the high-order transverse modes between f_p and the stopband frequency are also removed and the admittance plots become smoother. The measurement results verify that the tilted IDT method is effective to suppress the transverse modes of NS-SAW resonators.**

Keywords—surface acoustic wave; shear horizontal; lithium niobite ($LiNbO_3$); tilted angle; transverse modes suppression.

I. Introduction

Surface acoustic wave (SAW) devices have occupied an irreplaceable role in radiofrequency (RF) front-end application relying on its advantages of small volume, low price and feasibility of mass production [1-4]. With the rapid development of the artificial intelligence and internet of things (IoT), the demand for improving big data transmission capacity has increased sharply to support fifth-generation (5G) communication technology. Therefore, it is essential to improve the performance of SAW resonators, such as a large effective coupling coefficient (k^2_{eff}), a high quality-factor (Q), and spurious free in spectrum, and various methods have been studied in the past decade [5-11].

It is also reported that using plate wave devices to improve k^2_{eff} by optimizing the thickness of the plate, selecting different Euler angles, and using different modes of waves [7-9]. In recent years, multilayered structure resonators with lithium niobate ($LiNbO_3$) or lithium tantalate ($LiTaO_3$) bonded to a supportable substrate have been studied to improve the acoustic performance and mechanical stability of SAW resonators [10-11]. In our previous work [12], a 30° YX-$LiNbO_3/SiO_2$/Si Non-leaky Stack SAW (NS-SAW) resonator with shear horizontal (SH)-SAW mode is proposed. By using a high acoustic velocity substrate and optimizing the stack, the SH-SAW wave is confined well in piezoelectric layer and the energy leakage into the substrate is reduced, yielding a large k^2_{eff} and a high Bode-Q. However, some transverse modes appeared in NS-SAW resonators due to the coupling effect of the main mode and the other excitation modes, thereby introducing the unwanted ripples.

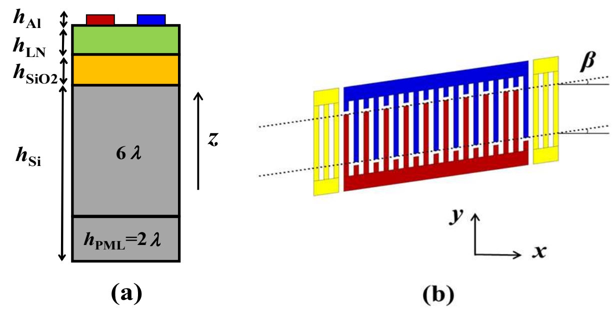

Fig. 1. (a) 2-D cross-sectional view in 3-D NS-SAW simulation model. (b) Conceptual diagram of the tilted IDT with a tilted angle β.

To suppress the transverse modes of acoustic resonators, several methods have been reported [13-19]. The principle of suppression is trying to match the shape of the excitation with that of the main mode. The apodization interdigital-transducer (IDT) is an approach to suppress the transverse modes [13-14], however, the Q is deteriorated. The dummy electrode technology suppresses the transverse modes by changing the transverse structure of the resonator [15]. Another common method to suppress the transverse modes is a piston mode technique, which is aimed to obtain a rectangular excitation by modifying the wave velocity profile of the resonator to match the shape of main mode [9] [16-18]. Besides, a tilted transducer has been proposed for I.H.P. SAW resonators using $LiTaO_3$ material [19]. However, there are still no detailed research about the optimization of tilted angle, the different orders transverse modes and so on. In this work, to suppress the transverse modes of proposed NS-SAW resonator, a tilted interdigital-transducer (IDT) deposited on the surface of the substrates is designed and the tilted angle of IDT is optimized. Both the simulation and measurement results show that the best tilted angle for achieving spurious-free response is 16°.

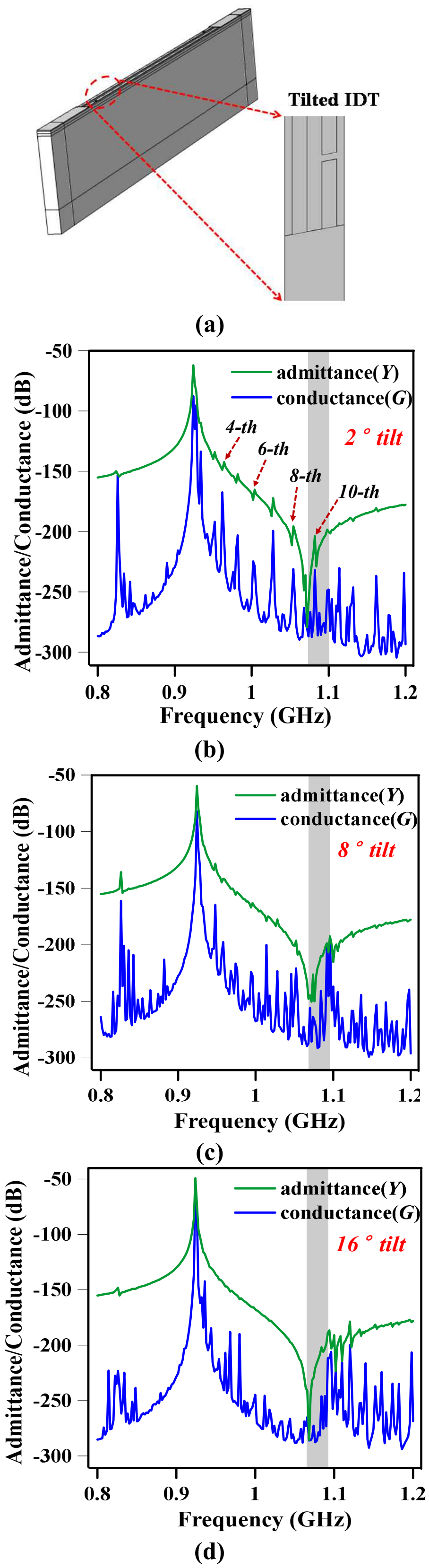

Fig. 2. (a) 3-D model in simulations. Admittance and conductance of the simulated 30°YX-$LiNbO_3$/SiO_2/Si NS-SAW resonators with (b)2° tilted IDT. (c) 8° tilted IDT. (d) 16° tilted IDT. The suppression effect of transverse modes is the best when the tilted angle is around 16°.

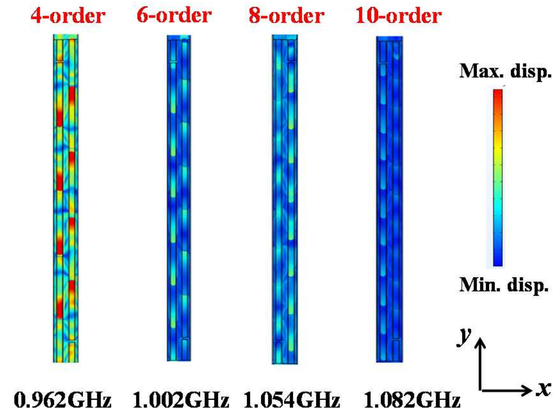

Fig. 3. The displacement distributions at different frequencies in *y*-direction when β=2°, and the transverse modes with different orders are observed clearly.

II. Transverse Modes in NS-SAW Resonator

Fig. 1(a) shows the 2-D view in 3-D model of NS-SAW resonator with 30° YX-$LiNbO_3$(0.2λ)/SiO_2(0.2λ)/Si substrate, and the thickness of Si layer is set to 8λ (6λ for wave propagation and 2λ for perfect match layer, PML), where λ=4um is the wavelength. The metal aluminum (Al) is chose as the electrodes in interdigital-transducer (IDT) with the thickness of 7.5%λ. Due to the SH-SAW wave velocity in LN layer is lower than the slow shear bulk acoustic wave velocity in SiO_2/Si substrate, the acoustic energy leakage into substrate is reduced. The k^2_{eff} of resonators derived by the *IEEE* standard definition [20] is expressed as:

$$k_{\text{eff}}^2 = \frac{\pi}{2}\frac{f_{\text{S}}}{f_{\text{P}}}\frac{1}{\tan(\frac{\pi}{2}\frac{f_{\text{S}}}{f_{\text{P}}})}. \tag{1}$$

To analyze the transverse modes in NS-SAW resonators, the tilted interdigital-transducer (IDT) resonators are also designed. The conceptual diagram of the IDT with tilted angle (β) is drawn in Fig.1 (b), where β is the angle between the connection line of both sides of the IDT in the aperture direction and the propagation direction of acoustic wave. Besides, the power flow angle (PFA) is defined as the angle between directions of phase velocity and group velocity, and it is determined by the material properties and resonator structure. It has been found that some transverse modes will be generated when the group velocity of acoustic wave does not coincide with the phase velocity in most propagation directions. Namely, if the IDT tilted angle is close to the PFA of resonators, the transverse modes would be suppressed.

Fig. 2(a) shows the 3-D simulation model of tilted IDT resonators by finite element method (FEM), where the aperture length of IDT is 20λ, the length of dummy fingers is 1.5λ, and the gap in IDT end is 0.15λ. Fig. 2(b) - (d) show the admittance/conductance of the simulated NS-SAW resonators with the tilted angles (β) of 2°, 8° and 16°, respectively. By comparing the results of Fig. 2(b) - (d), when the tilted angle reaches about 16°, the low-order transverse modes are suppressed, and the high order transverse modes is disappeared.

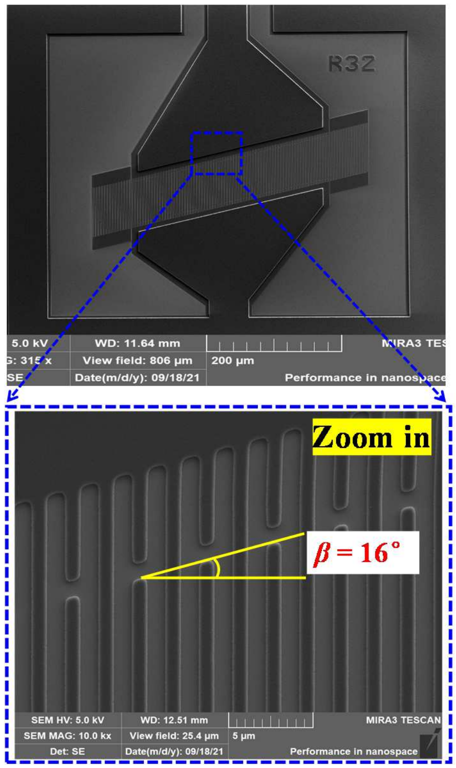

Fig. 4. SEM image of NS-SAW resonator with the IDT tilted angle of 16° and the enlarge image of IDT fingers.

In Fig. 3, the displacement distributions in y-direction at different resonant frequency positions are depicted when β=2°. It can be seen that the transverse modes with different orders are observed, and the magnitude of the displacement becomes smaller as the frequency increases.

III. Fabrication and Mesurement Results

The NS-SAW resonators are fabricated using the advance smart-cut process, including ion implantation, wafer bonding, and lift off. First of all, a single crystal LN wafer implanted with He ions is bonded to a Si substrate using thermal oxidation. Then, the bonded wafer is put into an annealing furnace for LN substrate separation, and the surface of LN film is polished to reduce the roughness of surface. After that, the metal IDT is evaporated on the obtained wafer by lift off process. The S-parameters of fabricated resonators are measured by a GSG probe and a vector network analyzer.

The SEM image and the enlarged picture of the tilted resonator are shown in Fig. 4. To analyze the suppression effect of transverse modes of NS-SAW resonators with different tilted angles, the admittance and conductance responses are depicted, as shown in Fig. 5. It is observed that both the low-order and the high-order transverse modes are suppressed, which is very useful for designing spurious-free resonators. Moreover, the longitudinal modes below the resonant frequency are also weakened and the admittance curve becomes smoother. Furthermore, the k^2_{eff} and Bode-Q_{max} [21] with different tilted angles are calculated from the probed S-parameters, and the performance comparison is shown in Table I. It is noteworthy

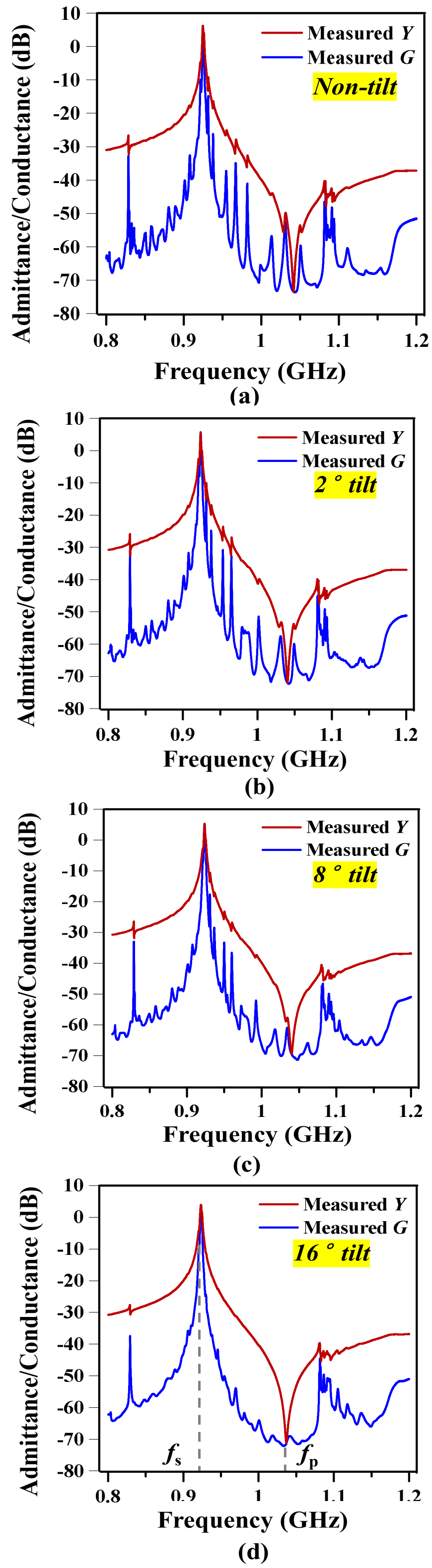

Fig. 5. Admittance and conductance of the fabricated NS-SAW resonators with different IDT tilted angles: (a) non-tilted IDT. (b) 2° tilted IDT. (c) 8° tilted IDT. (d) 16° tilted IDT. It is seen that when the tilted angle is designed about 16°, not only the low-order transverse modes between f_r and f_a is suppressed, but also the high-order transverse mode is removed and the admittance plot becomes smoother.

Table I. PERFORMANCE COMPARISON OF TILTED RESONATORS

Tilted Angle	**Measured k^2_{eff} (%)**	**Measured Bode-Q_{max}**
0°	24.8	1107
2°	24.8	1117
8°	24.8	976
16°	24.3	603

that the tilted resonators have a comparable k^2_{eff} to the non-tilted resonators, however there is some reduction of Bode-Q value as the angle increases.

IV. CONCLUSIONS

In summary, a tilted IDT method is proposed for the 30° YX-$LiNbO_3/SiO_2/Si$ NS-SAW resonators. To analyze the suppression effect of transverse modes, the resonators with different tilted angles are carried out by 3-D FEM simulations. Both the results of simulations and measurements show that when the tilted angle is 16°, not only the low-order transverse modes are suppressed successfully, but also the high-order transverse modes are almost disappeared. Meanwhile, the longitudinal modes are also weakened. Therefore, this work is instructive for designing non-ripples, wideband and low loss filters.

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