A High-Performance NS-SAW Resonator Using 30° YX-Lithium Niobate

Shuxian Wu, Zonglin Wu, Hangyu Qian, Feihong Bao*, Feng Xu, and Jie Zou*
School of Information Science and Technology
Fudan University
Shanghai, China
*e-mail: baofh@fudan.edu.cn, jiezou@fudan.edu.cn

Gongbin Tang*
Institute of Novel Semiconductors
Shandong University
Jinan, China
*e-mail: gongbin.tang@sdu.edu.cn

***Abstract*—With the popularity of 5G technique, large bandwidth devices are urgently needed to meet the enormous transmission requirements. Recently, the shear horizontal (SH) surface acoustic wave (SAW) resonators with large effective coefficient (k^2_{eff}) attracted wide attention, however, obtaining a high quality-factor (Q) is still a great challenge due to the bulk acoustic wave radiation into the substrate. In this work, a 30° YX-$LiNbO_3/SiO_2/Si$ Non-leaky Stack SAW (NS-SAW) resonator with SH mode is proposed. Large velocity difference between the SH-SAW wave in $LiNbO_3$ layer and the slow shear bulk acoustic wave in SiO_2/Si substrate helps to reduce the bulk wave leakage. Numerical simulations by finite element method (FEM) are implemented to optimize the cut angle of $LiNbO_3$ film and the thickness of each layer. The fabricated NS-SAW resonators yield a k^2_{eff} of 24.4% and a Bode-Q_{max} of 1092. Compared to the reported similar-type SAW resonators, the NS-SAW resonator shows the best level of figure of merit (*FoM*=266) when k^2_{eff} is more than 20%, presenting great potential for designing the wide bandwidth devices in 5G wireless communication.**

Keywords—Surface acoustic wave; effective coupling coefficient; quality factor; shear horizontal.

I. Introduction

With the rapid popularization of fifth generation (5G) mobile communication, internet of things (IoT), autonomous vehicles, artificial intelligence and so on, high-performance acoustic devices have attracted more and more attention [1-5]. The effective coupling coefficient (k^2_{eff}) of the commercially popular surface acoustic wave (SAW) or bulk acoustic wave (BAW) technology is 6%-13%, limiting the filters bandwidth (BW) to up to 6%. For the bands wider than 6%, such as Band 41 and Band 28, split-band solution or inductor-aided technology is generally adopted, which consumes much more space and introduces additional loss. Emerging 5G communication standards require low-loss and wide-bandwidth filters, in which the key technology is acoustic resonators. Therefore, a large number of theories for obtaining high-performance resonators with large k^2_{eff} or high quality-factor (Q) have been widely studied [6-12].

Traditional shear-horizontal (SH) SAW propagates on the substrate as a leaky wave, leading to strong acoustic energy leakage and the limited Q. Recently, the SH-SAW resonators

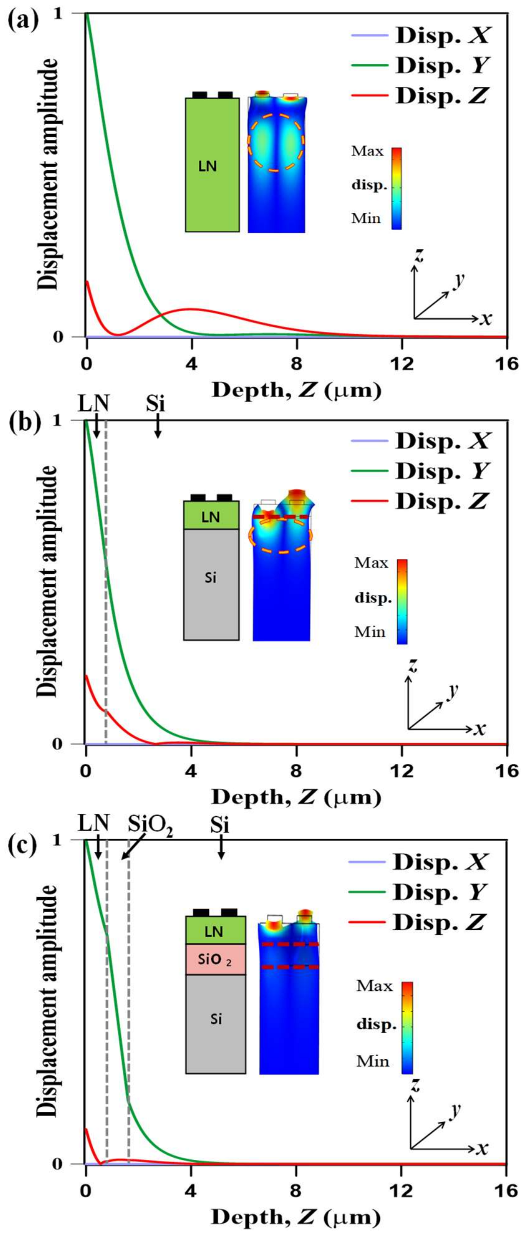

Fig. 1. Comparison of simulated displacements of (a) 30° YX-LN substrate (b) 30° YX-LN/Si (c) 30° YX-LN/SiO_2/Si. The insets are the mode shapes at resonant frequency simulated by periodic structures.

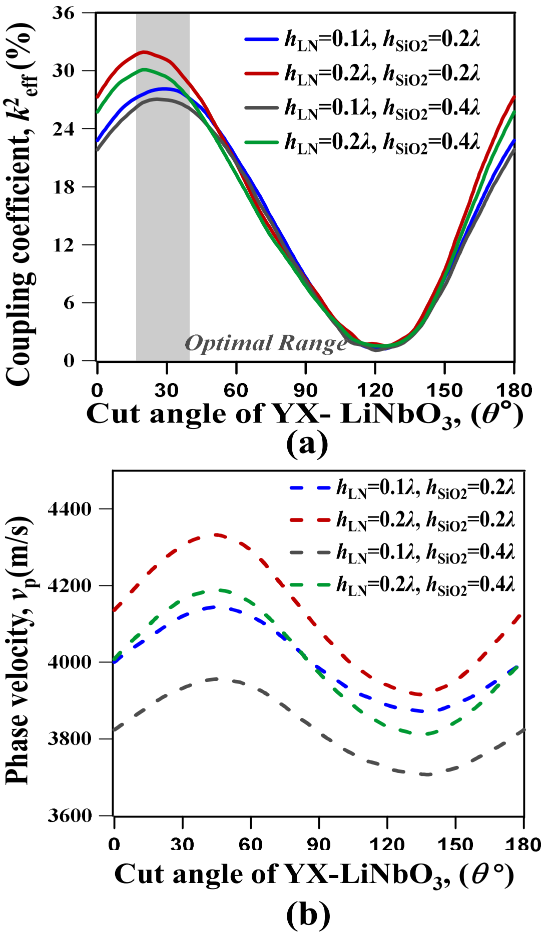

Fig. 2. (a) k^2_{eff} and (b) v_p vary with cut angles of $LiNbO_3$ in the case of different combinations: h_{LN}=0.1λ, h_{SiO2}=0.2λ; h_{LN}=0.2λ, h_{SiO2}=0.2λ; h_{LN}=0.1λ, h_{SiO2}=0.4λ and h_{LN}=0.2λ, h_{SiO2}=0.4λ. It is found that the largest coupling coefficient can be obtained when θ is around 30°, in which the phase velocity is also very high (>3800m/s). Thus, θ=30° is as the optimized cut angle.

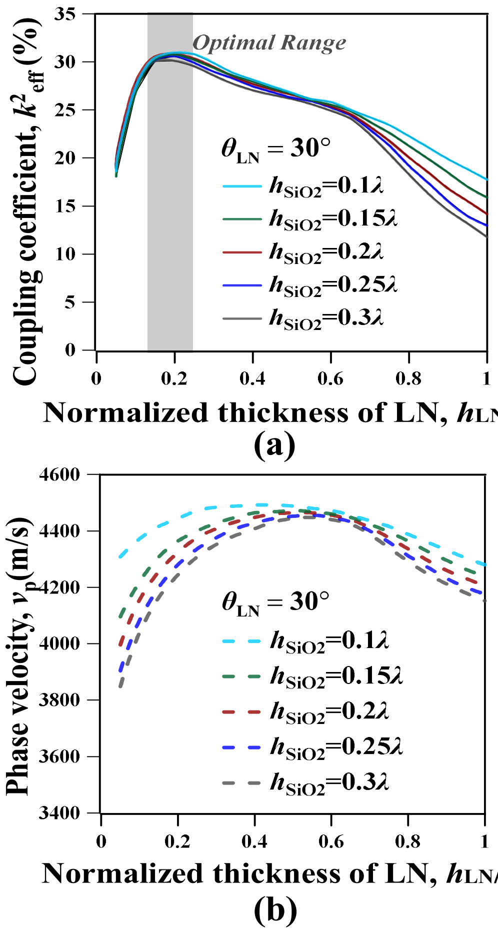

Fig. 3. (a) k^2_{eff} and (b) v_p vary with different thicknesses of h_{LN} and h_{SiO2} in the case of the cut angle of LN is 30°. When h_{LN}/λ=0.2, the largest coupling coefficient is obtained, so we choose h_{LN}/λ=0.2 as the optimal thickness. Since h_{SiO2} has very little effect on k^2_{eff}, h_{SiO2}=0.2λ is selected to reduce the difficulty of the process.

with $LiTaO_3$ (LT) and $LiNbO_3$ (LN) film using a piezoelectric-on-insulator (POI) structure were proposed by researches [13-20]. Among them, multilayered SAW resonators were studied extensively and have been attempted to improve the performance [17-20]. Nevertheless, the achieved *Q* are still not enough to meet the requirements of practical applications.

To alleviate the above problem, a Non-leaky Stack SAW (NS-SAW) resonator with 30° YX-$LiNbO_3$(LN)/SiO_2/Si structure is proposed in this work. Since the acoustic velocity of shear horizontal (SH) wave in piezoelectric layer is lower than the slow shear bulk wave velocity in Si substrate, the SH wave has too weak coupling with the slow shear bulk wave to leak acoustic energy into Si substrate. SiO_2 film with positive temperature coefficient of frequency (*TCF*) can improve the frequency stability. By using finite element method (FEM), the k^2_{eff} and the acoustic wave phase velocity (v_p) of NS-SAW resonator were calculated as the functions of LN cut angle (θ), LN layer thickness (h_{LN}) and SiO_2 layer thickness (h_{SiO2}) to optimize the stack structure. The proposed NS-SAW resonators are fabricated by advanced smart-cut technology. The measured results yield the k^2_{eff} of 24.4% and the Bode-Q_{max} of 1092. Namely, the proposed resonators achieve a large k^2_{eff} and a high *Q* simultaneously, showing great advantage to design wideband filters in 5G communication system.

II. Simulations and Stack Optimization

In this work, a non-leaky stack SAW resonator with 30° YX-LN/SiO_2/Si is proposed, and the material aluminum (Al) is as the electrodes in interdigital-transducer (IDT). Fig. 1 depicts the displacements of three resonators in *x*, *y*, and *z* directions, including: (a) 30° YX-LN substrate, (b) 30° YX-LN/Si and (c) 30° YX-LN/SiO_2/Si. Herein, the resonators of (b) and (c) are with λ = 4.5 μm, h_{LiNbO3}/λ = h_{SiO2}/λ=0.2, h_{Al}/λ = 7.5%, where h_{LiNbO3}, h_{SiO2} and h_{Al} represent the thickness of each layer, and λ is the wavelength. Since the SH-SAW wave velocity in LN layer is much lower than the slow shear bulk acoustic wave velocity in SiO_2/Si substrate, the displacement in *z* direction is reduced and the shear bulk wave leakage is weaker than the other two SAW resonators. The k^2_{eff} of resonators derived by

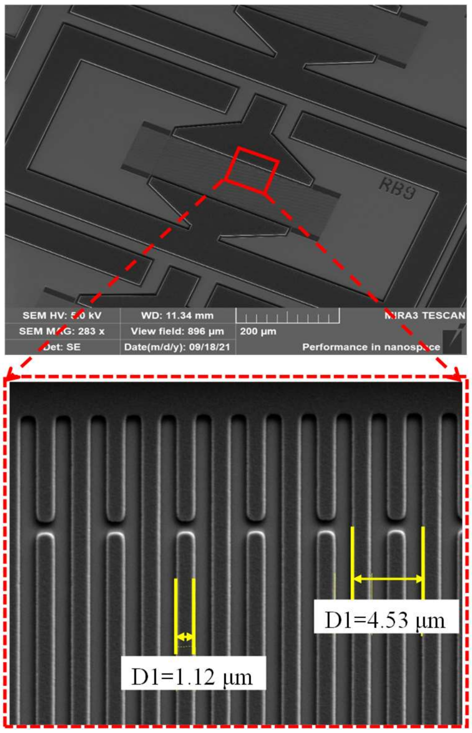

Fig. 4. The SEM image of NS-SAW resonator and the enlarged picture of IDT. The clear profile of IDT is observed, and the fabricated accuracy is identified by checking SEM results, where the designed wavelength is 4.5 μm and the metallization ratio is 0.5.

the *IEEE* standard definition is related to the capacitance ratio by taking the 2nd Taylor series [21], expressed as:

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

The phase velocity of SH wave is represented as $v_p = f_s \cdot \lambda$, where f_s is resonant frequency.

By FEM simulations, Fig. 2 shows the calculated k^2_{eff} and v_P for NS-SAW resonator with different LN cut angles. From Fig. 2(a), it is observed that the largest k^2_{eff} is obtained when LN cut angle (θ) is around 30°. Based on the above results, the optimization of h_{LN} and h_{SiO2} is presented when θ is set as 30°, and the results are shown in Fig. 3. Different colors indicate different thicknesses of SiO_2 layer. It is obvious that the largest k^2_{eff} value are obtained when $h_{LN} = 0.2\lambda$. When h_{LN} is 0.2λ, the k^2_{eff} of resonator is almost equal at the h_{SiO2}/λ from 0.1 to 0.2, suggesting that the h_{SiO2} has little effect on k^2_{eff}. To reduce the difficulty of fabrication process, h_{SiO2} is designed as 0.2λ in this work.

III. Measurement Results

The NS-SAW resonators are fabricated by using smart-cut technology, including ion-implantation, wafer bonding and lift off process. Then, S parameters are measured by a GSG probe and an Agilent E5071C vector network analyzer (VNA) in ambient temperature and dry environment. Fig. 4 shows the top view of fabricated tilted resonators and the enlarged picture by Scanning-Electron-Microscope (SEM). The metal electrodes in IDT are located on the upper surface of LN. The clear profile of fingers is observed, and the fabricated accuracy is identified by checking SEM results, where the designed wavelength and measured wavelength are 4.5 um and 4.53 um, respectively, and the metallization ratio is 0.5.

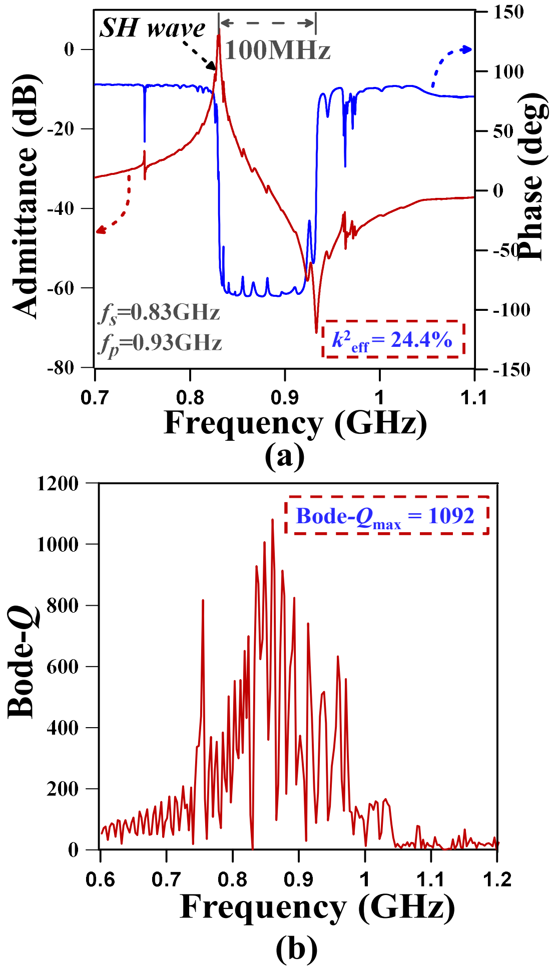

Fig. 5. (a) Admittance and phase response of the fabricated NS-SAW resonator. It is observed that the k^2_{eff} of 24.4% is obtained. (b) Bode-Q curve. The maximum Bode-Q (Bode-Q_{max}) is as high as 1092, thereby figure of merit (*FoM*) is calculated as 266.4, which is the highest value among the same-type SAW resonators when k^2_{eff} >20%.

The measured admittance/phase response at the resonant frequency of 0.83 GHz is depicted, shown in Fig. 5 (a). The extracted k^2_{eff} is 24.4% and the bandwidth is 100 MHz. In Fig. 5 (b), the Bode-Q curve is derived from the directly probed S parameters, calculated as [22],

$$\text{Bode-}Q = \frac{2\pi f \tau |S_{11}|}{1-|S_{11}|^2}, \quad (2)$$

where f is frequency, τ is group delay. It is observed that the maximum of Bode-Q (Bode-Q_{max}) is about 1092 and the figure of merit (FoM=$k^2_{eff}\cdot$ Bode-Q_{max}) is 266.

IV. Conclusions

In summary, a NS-SAW resonator with 30° YX-LN/SiO_2/Si substrate is proposed. By FEM simulations, both the cut angle of LN and the thickness of each layer were optimized to obtain a larger k^2_{eff}. As a result, the NS-SAW resonators have been designed as θ = 30° and h_{LN}/λ=h_{SiO2}/λ=0.2. The fabricated resonators have been presented an excellent performance with the k^2_{eff} of 24.4% and the Bode-Q_{max} of 1092. The results show that the highest FoM has been obtained among the similar-type SAW resonators when their k^2_{eff} >20%, showing an attractive potential for 5G applications.

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