Design, fabrication and characterization of SAW devices on LiNbO₃ bulk and ZnO thin film substrates

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ABSTRACT

In this paper, surface acoustic wave (SAW) devices with various designs were fabricated on two types of piezoelectric substrates of LiNbO₃ bulk material and thin piezoelectric ZnO film on silicon. Different sizes, orients and types of SAW devices were laid out on the same mask to compare their RF performance with a same fabrication. Devices were fabricated using lift-off technology with a double photoresist technique to achieve a steeper and narrower SAW pattern with a depth-to-width ratio of 1.27 and a steep resist angle of 85°. The devices were then characterized using RF probe station together with vector network analyzer. RF performance was also verified by 2D computer simulation implementing both electrical and piezoelectric physics models using the same device dimensions in the mask layout. RF response of 128°Y LiNbO₃ from experiments agrees with simulation fairly well while the devices on ZnO/Si have larger frequency distribution due to process variation of the ZnO thin film on silicon wafer. Quality factor of 34,000 was obtained from the SAW device fabricated in LiNO₃ substrate and this Q value has a strong dependency on the number electrodes of IDT fingers and reflectors. Temperature dependency was also measured for future wireless sensor application. The temperature coefficient of frequency of 16μm wavelength devices of LiNbO₃ substrate was −87.5 ppm/°C and was −72.41 ppm/°C for 12μm wavelength devices.

1. Introduction

Surface acoustic wave (SAW) devices are receiving a lot of attention since after R.M. White and F.W. Voltmer invent the interdigital transducer (IDT) in 1965 [1]. With the correct IDT design, SAW devices can achieve plenty of functions as electronic devices such as RF filters and wireless sensors. Propagation characteristics such as phase, frequency and acoustic velocity will be influenced by ambient temperature, stress and other physical factors, and this factor founds the basis to build various sensors. By detecting the receiving electric signal, the physical parameters are efficiently measured or calculated [2,3]. With the advantages of small volume, high sensitivity, diverse types and convenient process, SAW sensors can be widely used in the areas of measurement [4].

To achieve these goals, research work on design and process optimization on SAW device is necessary by various mask options and fabrication technologies. In this paper, different types of SAW devices with variations in dimension and other parameters were designed and verified by computer simulation via a combined electro-acoustic multiphysics model. Both thin film and bulk piezoelectric materials were used as the substrate to build the SAW devices. A double photoresist technique was proposed to facilitate the lift-off process on small IDT patterns. Devices are characterized using a vector network analyzer together with a GSG RF probe station. Piezoelectric qualities of the thin film and bulk substrate materials are characterized and verified by X-ray diffraction (XRD).

2. Design and simulation

The key design parameters of a standard SAW resonating device contain the acoustic aperture (W), the IDT finger pairs (Np), number of electrodes per reflector (Ng) and the reflector-IDT separation (Lg) are also illustrated.

Various IDTs with wavelength λ ranging from 12 to 40μm were designed. With other parameters W, Np, Ng and Lg are listed in Table 1. Cu is chosen because of its slower oxidation on the surface than Al at the room temperature, which is suitable for the probe test.

SAW devices were laid out in different angles to study the orientation dependence on S11, bandwidth and temperature frequency coefficient on different substrate. The mask design is illustrated in Fig. 1.
2.1. SAW device simulation

Structures for simulation is illustrated in Fig. 2. For the simplicity of the SAW device the left and right boundary are set as periodic condition while the top and the bottom side a fixed constraint boundary. The dimension of the IDT follows the design parameters above. Two types of substrate materials of bulk LiNO3 and thin film ZnO on silicon are used in simulation and the IDT electrode material is chosen as copper. The physical parameters for simulation such as density, coupling matrix, elasticity matrix and relative permittivity are basic materials library in the simulator.

Fig. 3 shows the admittance response of SAW devices with the IDT electrode width ranging from 3μm to 10μm, corresponding to the wavelength of 12μm to 40μm. The simulated resonant frequency ranges from 96.5MHz to 320MHz. According to the formula [4] below, the acoustic velocity was calculated as 3848 m/s agreeing with theoretical value of the 128° YX LiNO3:

\[ f_0 = \frac{V_{SAW}}{\lambda} \]  

The value \( V_{SAW} \) in this formula is the acoustic velocity of the chosen substrate.

The results of SAW simulation on ZnO/Silicon were shown in Fig. 4. The thickness of ZnO thin film was about 1μm. The resonant frequency ranges from 116 MHz to 340 MHz.

Unlike the bulk LiNO3, the average acoustic velocity of ZnO/Si structure is not a constant, it depends on the thickness to wavelength ratio of the SAW devices. Detailed discussion is in the following chapter together with the experimental comparison.

3. Device fabrication

There are two methods to create the IDT patterns. One is the etching technique; the other is the lift-off. Lift-off technique is selected here to build the SAW devices yet thicker photoresist is preferred to facilitate the lift-off process. A double photoresist technique is used to achieve a thick photoresist layer (~3.99μm) in order to create a distinct minimum finger width (3μm) in IDT. The double photoresist technique is shown in Fig. 5. Initially, a 1.3μm PR layer is coated on the substrates then exposed thoroughly without mask. Then another PR layer is coated onto this exposed PR to form a thick PR layer. Because the mutual dissolution between two PRs, the final thickness ranges from 3.8μm to 4.2μm. The exposure time is reduced to only the half of conventional time since the bottom PR layer was already exposed. Therefore, in the double photoresist technique, decreasing exposure time can achieve a shaper trapezoid angle slope. With the help of mutual of dissolution of exposed resist and unexposed residue, the bottom resist can be developed easily.

The resulting PR pattern using the double photoresist technique is shown in Fig. 6 under the optical microscope and the scanning electron microscope. The thickness of photoresist was approximately 3.9μm. The maximum of depth-to-width ratio was nearly 1.27. From the first figure, the pattern was clean and of no damage. An 85–90°slope angle was observed easily in the top left corner of the SEM figure.

After the photoresist patterning, the substrates were placed into the magnetron sputtering chamber to for metal layer deposition. After sputtering, the substrates are soaked in acetone aided by ultrasonic vibration to remove the PR to form the IDT patterns in the SAW devices shown in Fig. 7. The roughness of the edge of the electrode is from 0.04μm to 0.39μm due to the uneven lift-off process which may cause the noise in the frequency response in later RF measurements.

4. XRD of piezoelectric materials

The X-ray diffraction instrument is used to characterize the piezoelectric properties of ZnO thin film and LiNbO3. The diffraction angle measured by XRD has connection with C axis orientation the piezoelectric lattice plane [7]. The XRD results of Zinc Oxide thin film and LiNbO3 crystal are shown in Fig. 8. For the Zinc Oxide thin film, the grazing angle was 34.24° close to the theory value of (0 0 2) 2θ 34.42°. The diffraction angle of LiNbO3 is 34.97° corresponding to (1 1 0) plane with a slightly variation from the 34.8°.
with Keysight E5063 ENA series Network Analyzer are used for RF characterization. S11 parameter is measured to characterize one-port resonating SAW sensors. S11, also named as network reflection coefficient, is the specific value of the power of the reflect wave and the power of the input wave that reflects the extent of network loss \[8\]. The S11 of SAW resonators fabricated on the LiNbO3 substrate is shown in Fig. 9. The resonant frequency of SAW resonators of different wavelengths ranged from 96MHz to 320MHZ. Fig. 9(b) compares the experimental data with the previous simulation results. Experimental data agree with simulation quite well.

RF results on SAW devices fabricated on the ZnO/Si substrate is shown in Fig. 10(a). The resonant frequency ranged from 136.6MHz to 266.5MHz for different SAW device design with different wavelengths. Fig. 10(b) shows the relationship between calculated acoustic speed according to formula (1) and wavelength together with the simulation result. Unlike the bulk LiNO3, the average acoustic velocity of ZnO/Si structure is not a constant; it depends on the thickness to wavelength ratio of the SAW devices. Reducing the wavelength down to the thickness of ZnO thin film saturates average acoustic velocity, an indication that the acoustics speed of ZnO/Si composite layers is the combination of ZnO thin film and the silicon substrate. This average speed is an average acoustic speed of combining both vertical and horizontal acoustic speed ingredients in ZnO and silicon. It is also seen that the experiment data agree with the theoretical simulation fairly well.

4.2. Dependence on different orientation of the SAW design

SAW devices built on LiNO3 may have different RF behaviors due to their orientation difference. The result of resonant frequencies for different orientation angle $\theta$ is shown in Fig. 11(a). Resonant frequencies range from 176MHz to 193MHz when SAW layout rotates from 0° to 360°, while devices with 180° orientation difference have similar resonant frequencies. Fig. 11(b) shows the SAW propagation velocity in relation to orientation. SAW velocity reaches its maximum when propagated along with the X axis and minimum when oriented with 45°.

4.3. Dependence on different $N_p$ and $N_g$

The result of frequency response and Q values of different finger
pairs and reflectors are shown in Fig. 12. As seen increasing the number of IDT finger pairs \((N_p)\) from 300 to 600 incurs a 0.135 MHz resonant frequency shift and a slightly \(Q\) factor improvement from 27,673 to 33,808. \(Q\) factor is calculated from \(-3\) dB bandwidth as [10]:

\[
Q = \frac{f_0}{\Delta f_{-3dB}}
\]

(2)

When SAW device becomes smaller (1/10 in width) a much smaller \(Q\) value (less than 1/10) is observed, indicating a strong dependency of \(Q\) value on the size of the SAW device, i.e. the numbers of finger pairs and reflectors.

4.4. Temperature sensitivity analysis

Temperature was adjusted by a hot plane made by silicone placed on the Cascade probe station. The temperature is monitored by a Pt-PtRh thermocouple fixed on the hot plane. The test system is shown in Fig. 13.

Fig. 14 showed \(S11\) response of SAW devices on the LiNbO\(_3\) substrate at different temperature. The resonant frequency at room temperature \((25°C)\) was 240.6 MHz for the SAW devices with wavelength 16 \(\mu\)m. The frequency shifts 800 kHz when temperature ramps from 25 °C to 63 °C and follows a nearly linear relationship with the temperature coefficient of frequency (TCF) of \(-87.5 \text{ ppm/°C}\). The sensitivity of temperature shift was \(-21.053 \text{ kHz/°C}\), which was larger than \(5.83 \text{ kHz/°C}\) reported in [2]. The \(S11\) response with temperature of
12 μm SAW device is similar with a TCF of −72.410 ppm/°C and sensitivity of −23.08 kHz/°C

5. Conclusions

To compare and optimize the SAW device performance on frequency response and temperature sensing capabilities, various designs on layout and both bulk and thin film piezoelectric substrates of LiNO3 and ZnO/Si were used to fabricate the SAW sensors. A new double photoresist technique was presented and shown to be effective to help the lift off process for a clear-cut and a sharp PR angle. Frequency response of the SAW devices were verified and compared with numeric simulation. In LiNO3 X-cut SAW device has the best resonant performance than those in other SAW orientations. The equivalent acoustic speed of the ZnO/Si is dependable on the relative dimensions of the electrode width and the thin film thickness of ZnO on silicon substrate. Quality factor up to 34,000 was obtained on SAW devices built on LiNO3 substrate. Temperature TCF of the SAW devices built on LiNO3 similar is close −70 ppm/°C and frequency response sensitivity close to −20 kHz/°C

Fig. 8. (a) The XRD spectrum of ZnO thin film and LiNbO3 crystal in relation to their piezoelectric lattice orientations.

Fig. 9. (a) Measured S11 parameter of different SAW wavelengths (b) relationship between wavelength and its resonant frequency.

Fig. 10. (a) Measured S11 of SAW devices on ZnO/Si. (b) Comparison between simulation and experiment, and its resonant frequency or SAW propagation velocity.
Fig. 11. (a) Resonant frequency and acoustic wave velocity in relation of SAW orientation. $\theta$ is the angle between $+x$ axis and the rotating SAW device and $\Delta \theta$ is defined as the angle between the SAW propagation and $X$ axis.

Fig. 12. S11 together with the corresponding Q values of the SAW devices in different numbers of IDT finger pairs and the reflectors. The wave length is 12 $\mu$m.

Q values of various $N_p$ and $N_g$

<table>
<thead>
<tr>
<th>$N_p$</th>
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<td>1693</td>
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<td>300</td>
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<td>27673</td>
</tr>
<tr>
<td>600</td>
<td>400</td>
<td>33838</td>
</tr>
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Fig. 13. Test systems for temperature sensitivity studies.

Fig. 14. (a) S11 parameter measured under different temperatures on the SAW devices with wavelength 16 $\mu$m; (b) the relationship between the temperature and its resonant frequency.
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References


Further reading


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