Effects of Coating Layers on Properties of LGS SAW Resonators

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ABSTRACT

Surface acoustic wave (SAW) sensors are very sensitive to the external environment, when the devices are working in a complex environment, SAW sensors must be protected. This paper reports the study of SAW resonators based on coating layer/LGS substrate package-less structure. AlN, Al₂O₃ and Si₃N₄ thin films were selected as protective coating layer materials. The SAW resonators with different thicknesses of coating layers were simulated and fabricated. The device performances in terms of SAW velocity, quality factor (Q factor) and electromechanical coupling coefficient (K²) were determined from the measured S₁₁ parameters. The SAW velocity is 2500 m/s in the SAW resonators without any coating layer and with the increase of the thickness of coating layers, the SAW velocity increases. K² and Q factor decrease as the thickness of Al₂O₃ and Si₃N₄ coating layers increasing. For AlN coating layer, K² and Q factor of the SAW resonators with 0.2 µm-thick AlN coating layer are greater than the SAW resonators without any coating layer. When the thickness is more than 0.2 µm, K² and Q factor decline as other two kinds of coating layers devices.

INTRODUCTION

Surface acoustic wave (SAW) sensors are wireless and very sensitive to the external environment, so SAW sensors such as temperature, strain and gas sensors are particularly utility and widely used in every environment [1]. However, because of sensitivity characteristics, SAW sensors must be protected from surface scratching, oxidation and chemical degradation, especially when SAW sensors are working in a complex environment. These factors probably cause bare surface electrode to be short or destroyed. From 1980, to be packaged in hermetic enclosures was the typical method to overcome these problems [2-6], but the packages were generally larger in comparison to the size of the SAW sensors and packaging brings more cost and device complexity in production. Though people had attempted to reduce the price of packing, the progress was not so obvious as our wish, so package-less structures were becoming more attractive. Meantime,
depositing coating layers on SAW sensors was one of the efficient ways to protect the electrode of the package-less SAW sensors in harsh environment.

LGS (langasite, \( \text{La}_3\text{Ga}_5\text{SiO}_{14} \)) is a piezoelectric material that shows following advantages: temperature compensated orientations, up to six times higher piezoelectric coupling than \( \text{SiO}_2 \), and about 25% lower phase velocity than \( \text{SiO}_2 \). In addition, comparison with 573 °C \( \alpha-\beta \) transition temperature in \( \text{SiO}_2 \), melting point of LGS material is 1470 °C without any phase transition phenomenon, which can support that LGS substrate can be explored for high temperature applications [7-10]. However, it is found that there are few studies on the LGS SAW sensors with coating layers. In this work, SAW resonators based on LGS substrate were fabricated and \( \text{AlN, Al}_2\text{O}_3 \) and \( \text{Si}_3\text{N}_4 \) protective coating layers with different thicknesses were deposited on the same SAW devices. The goal of this report is to explore the influences of coating layers on the electric performances of SAW resonators.

**SIMULATION**

Finite element method simulations were carried out using COMSOL to investigate the performances of the SAW sensors. 2D simulation was performed by periodic condition on left and right sides of the device in order to simulate an infinite ideal sensor plate.

The mode of SAW was identified with an Eigen mode simulation, thus, the SAW velocity was calculated by

\[
v = \frac{\lambda \cdot f}{(1)}\]

where \( \lambda \) was the SAW propagation wavelength, and \( f \) was the Eigen frequency result from the simulation. The electro-mechanical coupling coefficients (\( K^2 \)) for SAW sensors were calculated by [11]

\[
K^2 = 2 \times \frac{v_0 - v_m}{v_0} (2),
\]

where the \( v_0 \) and \( v_m \) were phase velocities when the electrical boundary conditions were respectively assumed to be electrically free and short.

**EXPERIMENT**

The SAW resonators reported in this work used LGS piezoelectric single crystal as substrate and 100 nm-thick Au film was used as both electrode and sensing film. Each SAW resonator was fabricated by lift-off photo-lithography on the LGS cut with Euler angles of \( (0^\circ, 138.5^\circ, 26.6^\circ) \). Each interdigital transducer (IDT) contained 101 equal-interval-finger electrodes and 100 wavelengths aperture. Each reflector bank contained 400 short-circuited grating. Finally, the different thicknesses of \( \text{Al}_2\text{O}_3 \), \( \text{AlN} \), \( \text{Si}_3\text{N}_4 \) coating layers were deposited on Au film. The thickness included 0.2 µm, 0.5 µm, 1 µm, 1.2 µm, 1.5 µm and 2 µm for all kinds of coating layers. Before measurement, the SAW resonators were annealed at 500 °C for 3 minutes in pure \( \text{N}_2 \) to improve their thermal stability. As an example, a prepared SAW resonator with 0.2 µm-thick AlN coating layer is shown in Fig. 1.
RESULTS AND DISCUSSION

The $S_{11}$ parameters of the SAW resonators were measured at room temperature by a Agilent E5071C vector network analyzer (VNA). The VNA and the SAW resonators were connected by insulated coaxial cables and a PC was utilized to record the measurement data. The prepared SAW resonators were characterized in terms of the SAW velocity ($v_s$), quality factor (Q factor) and $K^2$ to evaluate the performances of the SAW devices. The $v_s$ was calculated by

$$v_s = \frac{\lambda}{f_r}$$ \hspace{1cm} (3),

where $\lambda$ was the length of SAW and $f_r$ was the resonant frequency.

The $K^2$ of a SAW device was deduced from the following equation [1],

$$K^2 = \frac{G_a}{8f_rC_tC_rN}$$ \hspace{1cm} (4),

where $G_a$ was the radiation conductance, $C_t$ was the capacitance of an IDT pair, $N$ represented the number of IDT finger pairs, and $f_r$ was the resonant frequency. Then, the experimental $K^2$ was calculated by the equation with the measured $S_{11}$ parameters and the Q factor was extracted using the phase slope method and defined as [12]

$$Q = \frac{\omega_r}{\frac{d\phi}{d\omega} \left| \frac{d\phi}{d\omega} \right|}$$ \hspace{1cm} (5),

where $\omega_r$ was the angular resonant frequency, and $\phi$ was the phase.
Figure 2. SAW velocity as the thickness of Al₂O₃ and Si₃N₄, AlN coating layers.

From Fig. 2, we can observe that, both of the experimental results and the simulated results, as the thickness of AlN, Al₂O₃ and Si₃N₄ coating layers increasing, SAW velocity increases for all. Without any coating layer, SAW velocity is 2500 m/s and with 2.0 µm coating layers, SAW velocity increases to 2750 m/s. The main reason for this phenomenon is that SAW propagation velocity in coating layers is higher than that in LGS substrate. In this structure, the coating layer is a kind of guided wave structure, and as the thickness of coating layers increasing, more SAWs are propagated in coating layers [13]. It can be also found that when the thickness of coating layers is greater than 1.5 µm, the influence of the thickness of coating layers to SAW velocity begins to decline, which is originated from coating layers mass effect. This effect causes SAW energy to scatter into LGS substrate, then the propagation of SAW is restrained and the resonant performance declines significantly.

It also can be seen that, from the simulated results, with the same thickness of coating layers, SAW velocity is highest in Al₂O₃ and lowest in Si₃N₄, though the different is not obvious. However, in the experimental results, this phenomenon disappears. This is because that the different thicknesses of coating layers have different qualities, which causes that the different thicknesses of coating layers have different material parameters. Due to limited condition, these concrete material parameters cannot be given in detail. Therefore, the curve trends of the experimental data and the simulated data are consistent, but the experimental data and the simulated data show subtle differences.
Fig. 3 shows the relationship between $K^2$/Q factor and the thickness of coating layers. We can observe that, from the simulated results, $K^2$ and Q factor decrease as the thickness of coating layers increasing. The experimental results are consistent with the simulated results and the deviation is due to the material parameters used in the simulation. The simulated parameters are for ideal material, and there is a deviation between simulated material parameters and actual material parameters in the experiments. The coating layers have a obvious influence on the resonance performances of the devices. When the thickness of coating layers is more than 0.2 $\mu$m, $K^2$ and Q factor decrease obviously. When the thickness is greater than 1.5 $\mu$m, the resonant peaks of the devices are almost covered by noise. When the thickness of Si$_3$N$_4$, Al$_2$O$_3$ and AlN coating layers is 1.5 $\mu$m, Q factor decreases to about 100. The coating layers have this negative effect on the properties of the LGS SAW devices due to mass effect, leading to reduction of the resonance strength of the SAW devices [14].

It also can be seen that, in Fig. 3 (c), when the thickness of AlN is 0.2 $\mu$m, $K^2$ and Q factor are greater than the devices without any coating layer. This result also indicates the above conclusion that in the coating layer/LGS substrate structure, the SAW is inspired not only by LGS substrate, but also by coating layers. The piezoelectricity of the AlN film creates coupling between LGS substrate and AlN coating layers, the efficiency of the electro-mechanical coupling effect increases [11], when the thickness of AlN film is thin. However, when the thickness is more than 0.2 $\mu$m, with the increase of the thickness of AlN, $K^2$ and Q factor decline as Si$_3$N$_4$ and Al$_2$O$_3$ devices, because that coating layers mass effect becomes the main factor instead of AlN piezoelectric effect.
CONCLUSION

SAW resonators with AlN, Al₂O₃ and Si₃N₄ coating layers of different thickness are fabricated and tested in this work. The velocity of SAW increases as the thickness of coating layers increasing. K² and Q factor decrease with the increase of Si₃N₄, Al₂O₃ coating layers thickness, but in AlN coating layer SAW resonators, due to AlN piezoelectric effect, K² and Q factor is highest when AlN coating layer is 0.2 µm, and when the thickness is more than 0.2 µm, K² and Q factor decline as the devices with Si₃N₄ and Al₂O₃ coating layers.

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