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Temperature characteristics of langasite surface acoustic wave resonators coated with SiO_2 films

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ABSTRACT

In this paper, the SiO_2 temperature compensation layers were deposited on LGS SAW resonators. The temperature characteristics of SAW resonators with different thicknesses of SiO_2 coating layers were investigated from room temperature to 450 °C. The results show that the SAW velocity, the turnover temperature, the first and second order temperature coefficients of frequency (TCF_1 and $|TCF_2|$) increase as the SiO_2 films thickness increasing. The Q factor of the SAW resonator decreases greatly due to the poor quality of the SiO_2 film. Zero TCF_1 is achieved when the SiO_2 coating layer is about 0.25 μm. The results show that the LGS SAW resonators can be temperature compensated by SiO_2 coating layer.

1. Introduction

Nowadays, various sensors based on surface acoustic wave (SAW) technology offer high potentials for sensor applications because of their excellent performances. The most outstanding advantages of SAW sensors are wireless and passive operation. Then the wireless SAW sensors can be operated in harsh-environments, such as high temperature or high pressure environment [1]. SAW sensors were widely studied and used for several years, such as SAW high temperature sensors [2], gas sensors [3] and liquid sensors [4]. In a typical SAW device, SAW are generated and then propagate at the surface of a piezoelectric crystal or a thin film. The characteristics of SAW devices are strongly dependent on the piezoelectric substrate. Among various piezoelectric materials, LGS (langasite, $La_3Ga_5SiO_{14}$) is thought as one of the most attractive materials for high temperature applications. This piezoelectric material shows temperature compensated orientations and up to six times higher electromechanical coupling coefficients (K^2) than quartz [5]. In addition, compared with 573 °C α-β transition temperature in quartz, the melting point of LGS material is 1470 °C without any phase transition phenomenon [5]. Congruent $LiNbO_3$ (LN) crystals have large K^2 but poor temperature stability. Between 300 °C and 600 °C, congruent LN shows strong O losses. Furthermore, this material is known to exhibit pyroelectricity [6]. Congruent LN SAW devices were investigated by Hauser [7], and the lifetime of the devices is about 10 days at 400 °C, 1 day at 425 °C, 2 h at 450 °C, and shows shorter-time stability up to 500 °C. The pyroelectric effect of $LiTaO_3$ (LT) has been a burden to achieving higher yields and lower costs for SAW devices [8]. Besides, according to ref. [6,9], LT has low Curie temperature located at 720 °C. Sensitivity remains high up to about half of Curie temperature. Thus, quartz, LN and LT offers no apparent advantage for high-temperature acoustic sensors. AlN/Sapphire bi-layer structure is expected an alternative to LGS, but AlN suffers from oxidation above 700 °C in air. AlN can only be operated for high temperature under low-O environments [10]. Besides, LGS remains the most advanced piezoelectric materials for high temperature SAW applications as large wafers are commercially available [11] and its high temperature surface stability has been thoroughly studied [12]. These properties make LGS to be an appropriate material for future high temperature SAW devices. It should be noted that these are also some limitations in LGS. LGS-based devices are limited by their low electrical resistivity (about 10^6 Ohm·cm at 600 °C), so the maximum wireless operating temperature is limited to below 600 °C [13].

When SAW resonators are used in certain practical applications such as strain sensors and gas sensors, it should be expected that the resonance frequency of the device doesn't change with ambient temperature variation. However, the temperature coefficients of frequency (TCF) of many piezoelectric materials are not zero. The TCF for LGS (0°, 138.5°, 26.6°) cut is close to 0 at room temperature and becomes negative as temperature increasing. When the temperature reaches up to 500 °C, the TCF for this propagation direction decreases to about -40 ppm/°C [14]. Besides, according

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to ref [15], the TCFs of LGS SAW resonators are slightly different as h/λ varying, where h is the thickness of electrodes and λ is the wavelength. There are two methods to avoid the temperature effect in SAW devices. One is differential measurement [16] and the other is temperature compensation technique. But differential measurements generally need more than one device, which results in large dimension of the sensors. So, it is necessary to study temperature compensation technique in SAW devices. One of strategies for temperature compensation used in LN and LT SAW devices is to integrate materials with positive TCF films. SiO_2 is the most commonly used film. Yamanouchi [17] had researched the SAW properties of SiO_2/128° Y-X LN structure. The TCF of the SAW devices with SiO_2/Al/LN structure had been improved from -80 ppm/°C to -10 ppm/°C by Kadota [18]. 500 nm and 1000 nm-thick of SiO_2 films were deposited on the X-cut plate, 112° Y rotated LT by Hickemell [19]. It was found that the TCF of a bare SAW device was -20 ppm/°C and the TCF of the SAW device coated with 1000 nm-thick SiO_2 film decreased to -16 ppm/°C. A series of SAW devices using fluorine doped SiO_2/Cu/LN structure were fabricated and their performances were evaluated by Matsuda [20]. The TCF was improved by 7 ppm/°C when fluorine content was 3.8 atomic %.

To the best of our knowledge, there are few studies on the temperature compensation of LGS SAW devices, though SAW devices based on LGS piezoelectric material were reported widely. In this work, SAW resonators based on LGS substrate were fabricated and SiO_2 films with different thicknesses were deposited on the bare SAW devices. The goal of this study is to explore the temperature behaviors of the SAW resonators coated with SiO_2 films. Additionally, temperature coefficients of frequency, turnover temperatures, K^2 and quality factors (Q factors) of the LGS SAW resonators coated with SiO_2 films are reported.

2. Experiments and method

The LGS substrates with Euler angles (0°, 138.5°, 26.6°) used in this work were purchased from SICCAS, Shanghai. The SAW resonators had a typical one-port SAW resonator structure which consisted of an interdigital transducer (IDT) and two reflector banks. Each IDT contained 101 equal-interval-finger electrodes with finger width of 2 μm, yielding an acoustic wavelength of 8 μm. Each reflector bank contained 400 short-circuited grating, 2 μm finger width. The wavelength aperture was 100 wavelengths. The electrodes consisted of a 10 nm-thick Ti adhesion layer and a 100 nm-thick Au film, and were patterned by lift-off and photolithography techniques on LGS substrate. Finally, the SiO_2 films were deposited on the surface of the SAW resonators by plasma enhanced chemical vapor deposition (PECVD) with 70 W. The deposition rate was about 150 nm/min. In this work, the thickness of the SiO_2 films was in the range from 0.18 μm to 1.8 μm. The SiO_2 films were only deposited on the surface of the IDT. Before PECVD depositing, a mask shielded the electrode pads from SiO_2 deposition, so there were not SiO_2 films on the electrode pads surface. Before measurement, all SAW devices were annealed at 500 °C for 30 min in pure N_2 environment to improve their thermal stability. As an example, a SAW resonator coated with 0.3 μm-thick SiO_2 film was shown in Fig. 1.

The thicknesses of the SiO_2 films were measured by a profile meter (Dektak 150, Veeco). The scattering parameters (S_{11}) of the prepared SAW resonators were measured from room temperature to 450 °C in a heating box by an Agilent E5071C vector network analyzer (VNA). The VNA and the SAW resonators were connected by a high temperature coaxial cable and a PC was utilized to record the measurement data. A scanning electron microscope

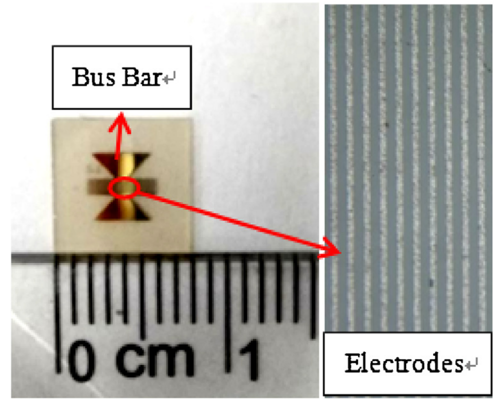

Fig. 1. Photo of a SAW resonator coated with 0.3 μm-thick SiO_2 film.

(SEM) (JSM-7500 F, JEOL, Tokyo, Japan) was used to characterize the microstructure of the samples.

The prepared SAW resonator was electrically characterized mainly in terms of surface acoustic wave velocity v_s, relative resonance frequency shift, K^2 and Q factor. The v_s is calculated by

$$v_s = \lambda \cdot f_r \tag{1}$$

where λ and f_r are the wavelength of surface acoustic wave and resonance frequency, respectively.

The relative resonance frequency shift due to temperature change is defined as

$$\frac{\Delta f_T}{f_{rt}} = \frac{f_T - f_{rt}}{f_{rt}} \times 100\% \tag{2}$$

where f_T and f_{rt} are the resonance frequencies of the SAW devices at temperature T and room temperature, respectively.

The K^2 can be calculated by [21]

$$K^2 = \frac{\pi}{4N} \cdot \frac{G_m(f_r)}{B_s(f_r)} \tag{3}$$

where N is the number of IDT finger pairs and equals 100 in this work. The $G_m(f_r)$ and $B_s(f_r)$ are the motional conductance and static susceptance of the SAW device at resonance frequency f_r, respectively. Then, the Q factor is extracted by using the phase slope method and defined as [22]

$$Q = \frac{\omega_r}{2} \cdot \left| \frac{d\phi}{d\omega} \right| \tag{4}$$

where ω_r is the angular resonance frequency, and φ is the phase.

3. Results and discussion

Fig. 2 shows the measured S_{11} curves of the SAW resonators without SiO_2 film and with 0.9 μm-thick SiO_2 film at room temperature. The resonance peaks of the SAW resonators can be observed clearly and we can find the resonance frequencies of these two SAW resonators are 334.25 MHz and 343.55 MHz, respectively. The resonance frequency difference is about 10 MHz. It indicates that the SiO_2 film has a great influence on the resonance frequency of the SAW resonator.

Fig. 3 shows the SAW velocities of the SAW resonators coated with SiO_2 films. From Fig. 3, we can observe that the SAW velocity increases from 2674 m/s to 2825.7 m/s when the thickness of SiO_2 films increases from 0 μm (without SiO_2 film) to 1.8 μm. This can be interpreted as that the SiO_2 overlay have a high acoustic wave velocity (about 3158 m/s [4]), which is higher than LGS substrate (2700 m/s [10]). More acoustic wave energy will be concentrated into the SiO_2 coating layer with increasing thickness of SiO_2 films,