Super-high sensitivity FBAR temperature sensor based on size effect of Ti insertion layer

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Abstract

The temperature sensitivity is one of the critical parameters for the thin film bulk acoustic resonator (FBAR) based temperature sensors. In this work, FBARs with Au/Fe$_{0.8}$Ga$_{0.2}$/Ti/AlN/Mo structure are developed. The size effect of the Ti insertion layer on the temperature sensitivity of the devices is systematically investigated. The devices were fabricated by MEMS process and characterized by a network analyzer under variable temperatures. It is found that the temperature sensitivity of the devices is strongly related to the thickness of the Ti insertion layer. A super–high temperature sensitivity up to 546 kHz °C$^{-1}$ was obtained with 20 nm Ti inserted thin film; that feature can even reach 825 kHz °C$^{-1}$ for some devices, showing great potential for ultra-sensitive temperature monitoring. Mason model is used to analyze the extraordinary characteristics of the device and finite element method (FEM) is used to analyze the strain distribution in the device. The supreme performance of the temperature sensor can be explained by the size effect of the temperature coefficient of Young’s modulus (TCE) of Ti film, which means that the TCE was enhanced when the thickness of the Ti film is around 20 nm. This work provides a new approach for the design of high sensitivity temperature sensor based on FBAR.

1. Introduction

Temperature monitoring plays an essential role in scientific research and industrial production. The sustainable development of modern industry puts forward higher requirements for temperature control. Novel techniques are inquired, e.g., for implantable [1] and high temperature [1, 2] applications, wireless and passive temperature sensors have obvious advantages because they do not need other electronic components. At present, there are many related types of researches, such as wireless temperature sensors based on the surface acoustic wave (SAW) device [3, 4], micro-antenna [5, 6], and super surface antenna [7]. FBAR has the advantages of small size, high operating frequency [8, 9] and higher quality factor [10, 11]. The higher working frequency significantly reduces the size of the antenna as it typically operating over 2 GHz, and FBAR based wireless passive sensors have been developed [12, 13]. In addition, the output of temperature for FBAR based sensors is frequency, which can be readily converted to digital signals [14], and not easily affected by external circuit noise, present unique advantages in the sensing field.

FBAR is a transducer with a piezoelectric film sandwiched by two thin-film electrodes. The common piezoelectric materials used include AlN, PZT and ZnO; among them, AlN has attracted much attention due to its excellent physical properties, such as high longitudinal acoustic velocity (11400 m s$^{-1}$), and CMOS compatibility [11, 15]. The resonant frequency of FBAR varies approximately linearly with real-time changing...
temperature, making it suitable for temperature sensing, and the temperature coefficient of the frequency (TCF) of AlN is about $-25$ ppm °C$^{-1}$ [16, 17]. The mechanism of FBAR temperature sensor is that the TCE of common materials is negative, and the longitudinal acoustic wave velocity decreases with increasing temperature. The temperature sensitivity of the device can be improved by using large TCE materials or increasing the thickness ratio of material with higher TCE in the device [18]. The TCE of most metals is larger than that of AlN, such as Al [19]. In 2009, Kao et al raised TCF to $-34.5$ ppm °C$^{-1}$ by increasing the thickness ratio of Al electrodes in AlN FBAR, corresponding to a temperature sensitivity of 82.8 kHz °C$^{-1}$ [20]. By doping Sc in AlN, the TCE of AlN can be increased, and the temperature sensitivity of the sensor can also be improved [21]. In 2021, Wang et al prepared an FBAR based on Mo/Al$_{0.7}$Sc$_{0.3}$N/Mo with a working frequency of $\sim2.8$ GHz, a TCF of $-39.6$ ppm °C$^{-1}$ and a temperature sensitivity of 110.9 kHz °C$^{-1}$ [22]. In addition to using the materials with high TCE, some structural designs can also be used to improve the temperature sensitivity of the device. In 2012, Ding et al had improved the temperature sensitivity from 13 kHz °C$^{-1}$ to 25 kHz °C$^{-1}$ by changing the cavity of the FBAR temperature sensor from open to sealed [23]. In 2020, Zhao et al prepared a dual-frequency FBAR temperature sensor, and the sensitivity is 64.8 kHz °C$^{-1}$ [15]. However, limited by the piezoelectric thin films (AlN, ZnO, etc.) and the device structure, the sensitivity of FBAR temperature sensor is still limited, far behind the patch antenna sensors (580 kHz °C$^{-1}$) [3], which limits the use ability of such devices in the area that requires high sensitivity. In 2012, Liang et al verified the size effect of TCE by molecular dynamics simulation and experiment, which demonstrated the TCE of nano-scale thin films will increase with the decrease of film thickness [24, 25].

Ti is an excellent functional material with high modulus, and the modulus is sensitive to temperature [26, 27]. From the size effect of TCE, it is expected that the temperature sensitivity of FBAR can be significantly improved by inserting a layer of nano Ti film into the FBAR. In this work, the influence of the size effect of the Ti insertion layer on the sensitivity of the FBAR temperature sensor is studied. Mo is used as the lower electrode of FBAR, AlN as the piezoelectric resonance layer, and Fe$_{0.8}$Ga$_{0.2}$ as the upper electrode. The Ti insertion layer is located between AlN and FeGa. The temperature sensitivity is obtained by measuring the change of resonant frequency with temperature. The devices were fabricated by MEMS technology and characterized by a network analyzer and temperature control platform.

2. Experimental details

The fabrication process of the devices is as follows. Firstly, AlN seed layer of 30 nm and Mo bottom electrode of 250 nm were deposited on (100) high resistance Si wafer (280 μm) through DC sputtering method (fxp, SPTS), the pressure of the reaction chamber is fixed at 0.7 mTorr, the sputtering power was set to be 6 kW and the substrate was heated to 200 °C. After patterning the bottom electrodes, 1000 nm AlN piezoelectric layer was deposited by DC reactive magnetron sputtering (fxp, SPTS) at 3.4 mTorr. The upper electrode (Ti/FeGa/Au, 20/200/10 nm) was deposited on the AlN piezoelectric layer through DC magnetron sputtering (Lab18, Lesker), where Ti is used as the insertion layer and Au the passivation layer to prevent the oxidation of FeGa. Then, the upper electrodes and the AlN were patterned by ion beam etching and inductively coupled plasma etching, respectively. Next, a Si$_3$N$_4$ insulating layer with a thickness of 400 nm was grown by PECVD and selectively removed by RIE. After that, to reduce the series resistance of the device, the Ni/Au layer with a thickness of 20/200 nm was stacked on the coplanar waveguide(CPW) pads by a lift-off process. Finally, the back-trench was released by the Bosch process. For the convenience of description, the device is named sensor-X, where the

![Figure 1. Micrograph (a) and fabrication flow chart (b) of the FBAR devices.](Image 220x670 to 316x769)
character ‘X’ denotes the thickness of the Ti insertion layer, e.g., sensor-20 represents a device with 20 nm inserted Ti thin film.

Figure 1(a) shows the microscopic image of the device, and the fabrication flow is shown in figure 1(b). For comparison, FBAR devices with Ti insertion layers of 50 nm and 100 nm (denoted as sensor-50 and sensor-100) and FBAR device without Ti insertion layer (sensor-0) were also fabricated.

The crystal orientations of the films were analyzed by X-ray diffraction (XRD, D8, Bruker), and the surface roughness and the step height of the nano insertion layers were characterized by atomic force microscope (AFM, Dimension ICON, Bruker). The thickness of metal films with thickness greater than 100 nm were measured by Profilometer (DektakXT, Bruker), and the thickness of the dielectric films were measured by an ellipsometer (M-2000, J.A.Woollam). A focused ion beam (FIB, Scios, FEI) was used to observe the cross section of the device. A vector network analyzer (VNA, ZVA40, Rohde & Schwarz) was used to obtain the S-parameters of the
devices. Figure 2 shows the setup of the testing system, the wafer is placed on a temperature controlled plate, and the devices are measured by a GSG probe with the port connected to the VNA.

3. Results and discussion

Figure 3(a) is the XRD pattern of the films with the scan range of 20°–65°. There is no obvious diffraction peak of Ti can be observed, which indicates that there is no prominent preferred orientation of Ti. Figure 3(b) shows the rocking curves of AlN and Mo, the FWHM for AlN (002) and Mo (110) are 1.95° and 1.48°, respectively. The Mo layer with an orientation of (110) is preferred for the deposition of the c-axis AlN; both materials with this optimized orientation are critical to obtain high-performance FBAR devices [11].

The properties of the films are closely related to their morphology. Figure 4 shows the AFM images of Ti and FeGa films with a scan area of 5 μm × 5 μm. In figure 4(a), with the thickness of Ti layer is ~20 nm, the film tends to be amorphous rather than with a dense state, and the roughness Ra = 2.62 nm. Figures 4(b) and (c) show the surface morphology of the Ti layer with thicknesses of 50 nm and 100 nm, with Ra of 1.24 nm and 1.45 nm, respectively, which means the films are fully formed. Figure 4(d) is the AFM morphology of FeGa at
200 nm on 20 nm Ti substrate, and the roughness of the film is ∼2.3 nm. Compare figures 4(c) and (d), it can be found that the grain size of FeGa is much larger than that of Ti. When FeGa is deposited is above the thin Ti layer (20 nm), it is almost impossible for the FeGa to enter a gap smaller than itself between Ti grains, and some porous transition zones may occur at the interface.

Figure 5 shows the SEM images of the resonance region. Figure 5(a) is a cross-sectional view, and the thickness of each layer is basically consistent with the design thickness. Figure 5(b) shows the enlarged picture of the white circle in figure 5(a). The distribution of Ti is discontinuous, which is the same as that observed in AFM test in figure 4(a). Figure 5(c) is a top view of the resonant region. The gap in the figure is obtained by FIB etching, the red circle in the figure indicates the position of figure 5(a) in the resonant region.

Figure 6(a) shows the S11 and impedance spectra of the sensor-20. The resonant frequency of the device is 2.57 GHz, with an effective electromechanical coupling coefficient of 5.8%. The Mason model was used to fit the measure curves; the resonance frequency of the experimental and calculation one is basically consistent, while the deviation of the amplitude is mainly attributed to the serial resistance introduced by the composite metal pads. The parameters of the Mason model for the device are shown in table 1. The thickness was adjusted according to the SEM results. The acoustic impedance of Ti and FeGa are calculated based on Young’s modulus and density [28, 29]. Previous experimental results show that Young’s modulus of Ti and FeGa are 167.5 GPa and 195 GPa, and the density 7400 kg m⁻³ and 4500 kg m⁻³, respectively. Figure 6(b) shows the stress distribution of the device calculated by the finite element method at the resonant frequency, the stress is mainly in the AlN regions, and the Ti insertion layer is located in the region with high stain.

FBAR devices with different Ti insertion layers were fabricated and their frequency response under various temperatures was studied, the only variable parameter is the thickness of the Ti insertion layer. The temperature sensitivity of devices can be obtained by characterizing the relationship between S11 parameters and temperature. As expected, the resonant frequency of the sensors shifts down with increasing temperature, as shown in figure 7. Sensor-0 exhibits high linearity for temperature sensing; the calculated temperature sensitivity is 132 ± 21 kHz °C⁻¹, as shown in figure 7(b). The Mason model was also employed to calculate the theoretical temperature sensitivity, and the obtained sensitivity was 123 kHz °C⁻¹, which was consistent with
the measurement results. The whole material parameters are shown in table 1, with the thickness of the Ti and FeGa layers adjusted to 0 nm and 204 nm.

When inserting a thin Ti layer between the piezoelectric film and the FeGa top electrode, the temperature sensitivity of the sensor changes significantly. Figure 8(a) shows the typical relationship between the $S_{11}$ spectrum of sensor-20 and temperature, and the summary of the frequency response under various temperature is shown in figure 8(b). As the temperature increases from $30^\circ$C to $80^\circ$C, the resonant frequency of the device decreases about 28.3 MHz, corresponding to the temperature sensitivity of 546 kHz$^\circ$C$^{-1}$, three times higher than that without Ti insertion layer. Notably, a super-high temperature sensitivity up to 825 kHz$^\circ$C$^{-1}$ can be obtained (figures 8(c), (d)) for some devices with 20 nm insertion layer, featuring the great potential for high-sensitive temperature monitoring. The extraordinary performance of the sensors may cause by the slight deviation of film thickness among different devices on the same wafer, which will be further investigated. The characteristics during cooling are also shown in figures 8(b) and (d), which are basically consistent with those at
heating up. During the measurement (10 min), the sensor shows good stability, and the frequency fluctuation is less than 5 kHz.

Table 2 summarizes the performances of assorted temperature sensors based on resonant frequency. Within our knowledge, the sensor reported in this paper has the highest sensitivity and the smallest size. The only difference between sensor-0 and sensor-20 is the thickness of the Ti insertion layer, which is considered the principal reason for the sensitivity difference. The temperature dependence of FBAR devices is mainly caused by the changing of coefficient of thermal expansion (CTE) and TCE of each structural layer. Since the TCE is much larger than CTE, e.g., the Ti has a CTE of $\sim 8.6 \text{ ppm C}^{-1}$ in the temperature range of 20°C–100°C while the TCE is $\sim 93.22 \text{ MPa} \text{ C}^{-1}$ (equal to $\sim 760 \text{ ppm C}^{-1}$) [27, 36], the contribution of TCE is mainly considered in the calculation. When the thickness of the Ti layer reaches 10–20 nm, a remarkable size effect of the Young’s modulus for the thin-film will occur. With elevating temperature, the cohesive energy between atoms decreases sharply, leading to an abrupt increment of TCE for the Ti layer [24]. Furthermore, the

![Figure 8. Temperature dependence of $S_{11}$ and resonant frequency of sensor-20. (a) (b) typical device, (c) (d) the most sensitive device.](image)

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substantial change of Young’s modulus also results in the dramatic change of the acoustic velocity and impedance\cite{28}. The combining effects of CTE and TCE finally lead to the abnormally large TCF of sensor-20. Based on the typical TCF data obtained from the measurement, the 20 nm Ti insertion layer represents a strikingly high TCE of $-7830$ ppm $^\circ$C$^{-1}$, about 10.3 times that of polycrystalline Ti.

To further clarify the influence of Ti thickness on the temperature sensitivity of the sensor, devices with inserted Ti layers of 50 nm and 100 nm were also prepared. The average temperature sensitivity for sensor-50

![Figure 9. Relationship between frequency variation and temperature of devices with different Ti thickness (a) and the temperature sensitivity of the sensor under various Ti film thickness (b).](image)

Table 2. Comparisons of devices used for wireless temperature sensing.

| Device type | Year  | T (°C) | Working frequency | Sensitivity kHz/°C | References |
|-------------|-------|--------|-------------------|-------------------|------------|
| FBAR        | 2007  | 10–80  | 1.8 GHz           | 51.8              | [14]       |
| FBAR        | 2009  | 10–80  | 2.4 GHz           | 82.8              | [20]       |
| SAW         | 2015  | 40–150 | 439 kHz           | 5                 | [4]        |
| Patch antenna | 2015 | 20–1050 | 5.1 GHz          | 410–580          | [5]        |
| Micro antenna | 2018 | 28–1100 | 2.4 GHz         | 95.6              | [7]        |
| Slot antenna | 2020 | 25–300 | 2.3 GHz           | 133               | [6]        |
| FBAR        | 2020  | 20–50  | 886 MHz           | 42                | [12]       |
| SAW         | 2020  | 20–120 | 613 MHz           | 93.4              | [33]       |
| SAW         | 2020  | 20–1100| 416 MHz           | -15               | [2]        |
| SAW         | 2020  | 20–200 | 85 MHz            | 5.16              | [34]       |
| SAW         | 2020  | 20–450 | 455 MHz           | 26                | [35]       |
| FBAR        | 2021  | 20–220 | 2.8 GHz           | ~111              | [22]       |
| FBAR        | 2021  | 20–80  | 2.5 GHz           | 847               | This work  |
and sensor-100 are 190 kHz °C⁻¹ and 244 kHz °C⁻¹, respectively. The TCEs of the Ti films were fitted by the Mason model, and the calculated value for the 50 nm and 100 nm Ti are −880 ppm °C⁻¹ and −830 ppm °C⁻¹, respectively, slightly larger than the value of polycrystalline Ti reported in literature [27].

Figure 9(a) summarizes the relationship between the frequency variation and temperature of sensors with different Ti thickness, which shows good linearity and the frequency change is dependent on the thickness of Ti film. Figure 9(b) shows the relationship between the temperature sensitivity of the sensor and the thickness Ti insertion layer, the results analyzed by the Mason model are also presented. From the Mason model, since the Ti layer represents a negative TCE, the sensitivity of the sensor increases gradually when the thickness of the Ti layer increases from 50 nm to 700 nm, a peak sensitivity of 397 kHz °C⁻¹ can be obtained. As the thickness increases from 700 nm to 1000 nm, the mass-loading effect of the top electrode dominates, which results in the off-shift of frequency when temperature increases and eventually lead to the reduction of temperature sensitivity. Compared with experimental results, when the thickness of the Ti layer is 50 nm and 100 nm, the practical sensitivities are close to those predicted by the Mason mode. However, for the Ti layer of 20 nm, the sensitivity reaches 546 kHz °C⁻¹, which is much larger than the calculated value (141 kHz °C⁻¹). From previous analysis, this anomaly phenomenon is mainly related to the scale effect of Ti thin-film. The sensors adopt materials with high melting point, which are expected to viable for high temperature sensing applications. Through the packaging of sensors and the construction of test system applicable to high temperature, the high temperature characteristics of sensors can be obtained, which needs further research.

4. Conclusion

This paper explores the size effect of the Ti nano films on the improvement of the sensitivity of the FBAR temperature sensor. FBARs with Au/Fe₀.₈Ga₀.₂/Ti/AlN/Mo structure were fabricated by the MEMS process, and the influence of the Ti insertion layers was investigated. It is found that when the thickness of the inserted Ti layer increases from 50 nm to 700 nm, the temperature sensitivity of the sensors increases monotonically. However, high sensitivity of 546 kHz °C⁻¹ can be obtained when the Ti layer reduces to 20 nm, and a super-high sensitivity up to 825 kHz °C⁻¹ for such devices was recorded. The leading high-performance of the sensors is contributed to the size effect of the Ti insertion layer caused by the ultra-large TCE of the amorphous film. The superb performance of the FBAR sensors in this work provides a new approach for developing ultra-high sensitive temperature sensors.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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