A High Sensitivity Temperature Sensor Using High-*Q* NS-SAW Resonator

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***Abstract*——In this paper, a temperature sensor based on non-leaky stack surface acoustic wave (NS-SAW) resonator is proposed. Specifically, $LiNbO_3$ (LN)/SiO_2/Si multilayered structure is adopted to reduce the acoustic energy leakage of SAW resonator, and a high quality-factor (*Q*) is reached for improving the sensitivity of SAW type temperature sensor. To systematically explore the temperature-dependent frequency response of the proposed design, simulation and experimental investigations were performed, revealing that LN-based NS-SAW resonator owns a high *Q* compared with other sensors and resonators. Meanwhile, the acceptable temperature coefficient of frequency (*TCF*) and great linearity of our device offer a big advantage for sensing applications. Accordingly, a high sensitivity temperature sensor with −26.01 ppm/°C *TCF* and 862 Bode-Q_{max} is obtained simultaneously.**

Keywords—Surface acoustic wave; Lithium Niobate; temperature sensor; quality-factor; temperature coefficient of frequency.

I. Introduction

With the growing demands for temperature sensor technology in scientific research and industry, conventional wired sensors may become inadequate on some special occasions. For instance, thermocouple is not capable in the sealed temperature environment since the wired signal leads across different temperature areas would cause the leakage of heat. Meanwhile, extreme temperature test conditions would make a big impact on the metal cable leading to the damage of sensors. A normal alternative is using infrared thermometer or thermal imager, which still shows some drawbacks such as vulnerability to light, vapor, electromagnetic interference, etc.

One of the promising approaches to producing a novel temperature sensor is to take advantage of the frequency drifting phenomenon of surface acoustic wave (SAW) resonator. That makes such temperature sensors suitable for the cases where the wired connection is out of option[1]–[3]. Some traditional piezoelectric materials with excellent heat resistance such as Quartz[4] and Langasite (LGS)[5] are largely used in radio frequency (RF) signal filter design for better stability of performance in different environments. Conversely, materials highly sensitive to the change of temperature including $LiNbO_3$ (LN) and $LiTaO_3$ (LT) are more desirable to compose a temperature sensor. Generally, the temperature sensors based on SAW resonators have the advantages of small size, ease of mass production, and high integration. However, the relatively low quality-factor (*Q*) of conventional SAW resonators limits the application for fabricating the high sensitivity temperature sensor.

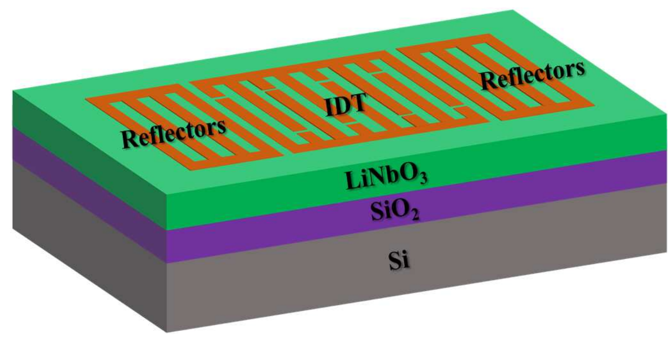

Fig.1. Illustration of the proposed NS-SAW resonator for temperature sensor application.

In this paper, the problem mentioned above has been improved by a SiO_2/Si stack on the SAW device. LN is selected for its good piezoelectric properties and commercialization potential. The non-leaky stack surface acoustic wave (NS-SAW)[4] resonator based on the structure that thin-film LN is bonding on SiO_2/Si substrate is adopted to improve the *Q* of resonator, so that the temperature sensor using this resonator could reach a high sensitivity eventually.

II. NS-SAW Resonator Design and Simulation

A. Operating principle

The 3-D geometry of the proposed NS-SAW resonator is illustrated in Fig. 1. Principally, the electrical signal could activate surface acoustic wave through the interdigital transducer (IDT) located on the center of the device. Then, the IDT transforms the wave into a modulated electrical signal sent back to the external measurement device such as Vector Network Analyzers (VNA) by the piezoelectric effect. Once the structural parameters of the SAW resonator are determined, a unique frequency would correspond to a certain temperature. In other words, temperature detection could be conducted by measuring the frequency response of SAW resonator, therefore, the design of resonator dominates the performance of temperature sensor.

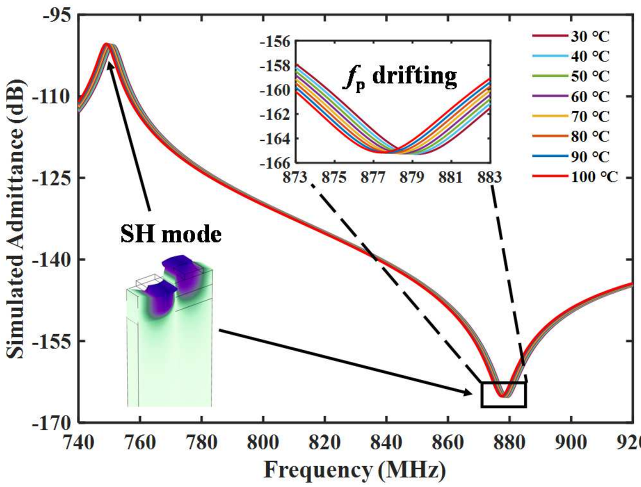

Fig.2. Temperature-dependent frequency drifting performance and wave mode simulated by FEM model according to the proposed NS-SAW resonator.

B. *Resonator Simulation*

A 2.5-D cross-section finite element method (FEM) model of the proposed resonator based on the NS-SAW structure is established to investigate the wave mode and frequency drifting when temperature is varying from 30 °C to 100 °C as shown in Fig. 2. Simulation is based on method proposed in [5], [6]. At resonant frequency f_s and anti-resonant frequency f_p, Shear-Horizontal (SH) wave mode is excited as the mode shape inset in Fig. 2 shows. Meanwhile, it could be seen that the leakage of energy reduces majorly below piezoelectrical layer. Besides, an obvious frequency drifting phenomenon could be observed in Fig. 2. In this case, with the temperature rising, the frequency response drifts towards to lower frequency direction. To work as a temperature sensor, resonant frequency or anti-resonant frequency is normally picked as the target signal to be distinguished in signal processing step.

III. Fabrication and Measurement

A. *Fabrication and measurment environment*

One-port SAW resonators were fabricated on a 30° YX-LN substrate. This LN thin film is bonding on Si wafer which is supposed to be deposited SiO_2 layer first. The metal layer for IDT is located on the top of the LN, in which Aluminum (Al) and Titanium (Ti) are selected as its materials. Ti is used for increasing the adhesion and reducing the ohmic loss. The Scanning Electron Microscope (SEM) image of fabricated SAW resonator is shown in Fig. 3. The main design parameters for this resonator could be found in Table I. Especially, dummy finger design of IDT is adopted in our device to reduce the end effect of transducers.

In our measurement, the resonators were activated and measured by an Agilent E5071C VNA with G-S-G probes in an ambient pressure environment. A vacuum chuck working together with a temperature controller is utilized to hold the device and raise the temperature from 30 °C to 110 °C.

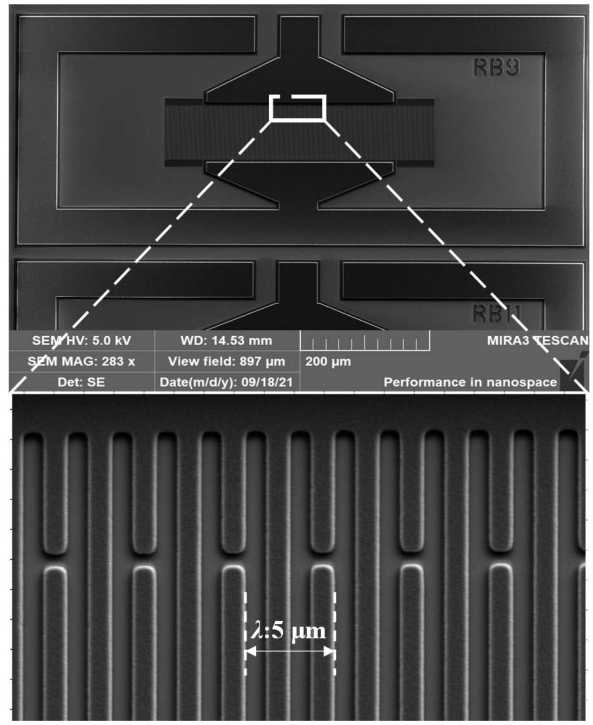

Fig.3. SEM image of the fabricated SAW resonator and close-up view of IDT fingers.

Table I. Parameters of The NS-SAW Resonator

Parameter name	value
IDT fingers number (N_t)	150
Gratings number (N_r)	30/side
IDT finger width ($a=\lambda/4$, λ=5μm)	1.25 μm
Pitch of fingers ($p=\lambda/2$)	2.5 μm
LN thickness	800 nm
SiO_2 thickness	800 nm

B. *Measurement results*

Fig. 4 shows the admittance curve and quality-factor curve both derived from the measured S_{11} data. The method of calculating quality-factor Q is inconsistent, in this work, a frequency-dependent Q is adopted and named as Bode-Q[7], given by the formula:

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

where f is the frequency and τ is the group delay of S_{11} parameter. Meanwhile, the Bode-Q_{max} of this resonator reaches 862, which is almost 100 times larger than the LC tank type temperature sensor[8], and over 5 times larger than AlN based[9] and LN based[2] SAW temperature sensor. Furthermore, this resonator even owns higher Bode-Q_{max} than other LN based SAW resonators with similar multilayered structure[10]–[12] as the Table II lists. Such large quality-factor is significant to enlarge the sensing rang. Therefore, a high sensitivity temperature

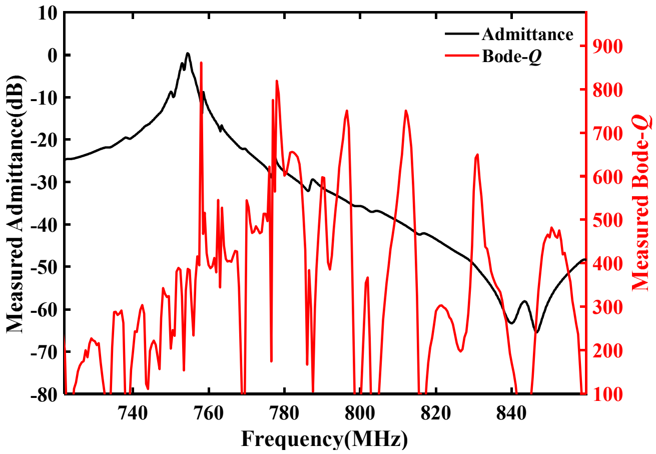

Fig.4. Measured admittance and Bode-Q were derived from S_{11} data collected by Agilent E5071C VNA.

Table II. QUALITY-FACTOR COMPARISON OF TEMPERATURE SENSORS/RESONATORS AT ROOM TEMPERATURE

Ref.	Structure	Q_{max}	Year
[8]	PDMS, Si/Glass	8.5	2015
[9]	Pt/AlN/Sapphire	132	2013
[2]	128°YX-LN	160	2019
[10]	YX-LN/SiO2/Si	251	2020
[11]	15°YX-LN/SiO2/Si	280	2021
[12]	15°YX-LN/SiO2/SiC	330	2021
This work	**30°YX-LN/SiO2/Si**	**862**	**2022**

sensor with strong anti-interference ability could be conducted by this NS-SAW resonator.

The measured admittances-frequency curves of resonator at different temperatures are shown in Fig. 5. To be more exact, the clear frequency drifting phenomenon could be observed. f_p drifts 1.77 MHz when temperature changes from 30 °C to 110 °C. Note that the ripple mixing in the admittance-temperature curve is generated by spurious mode and it could be suppressed by optimizing the design of IDT.

To quantify the temperature stability of SAW device, a commonly used first-order temperature coefficient of frequency (TCF_{1st})[13] is introduced as its definition is shown below:

$$TCF_{1st} = \frac{1}{f_0} \cdot \frac{f_1 - f_0}{T_1 - T_0}, \quad (2)$$

where f_1 and T_1 are target frequency and temperature at the measuring point respectively. f_0 and T_0 are the parameters at reference point. In this case, we set 30 °C as T_0, and f_p as target frequency. Then we can get the TCF_{1st} at f_p from Fig. 6.

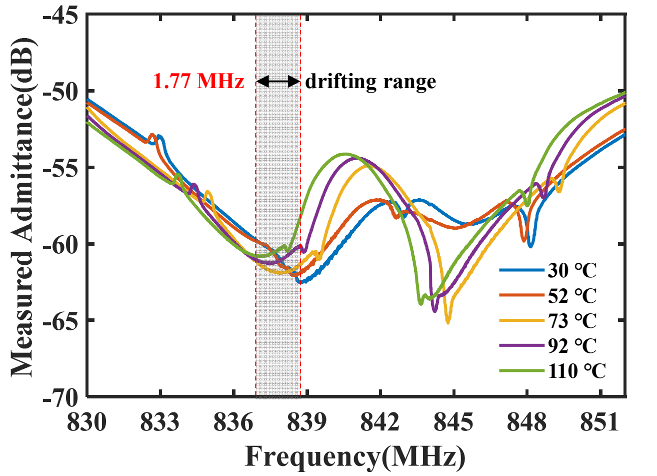

Fig.5. Frequency drifting phenomenon at anti-resonant frequency f_p when temperature T_1 varies from 30 °C to 110 °C.

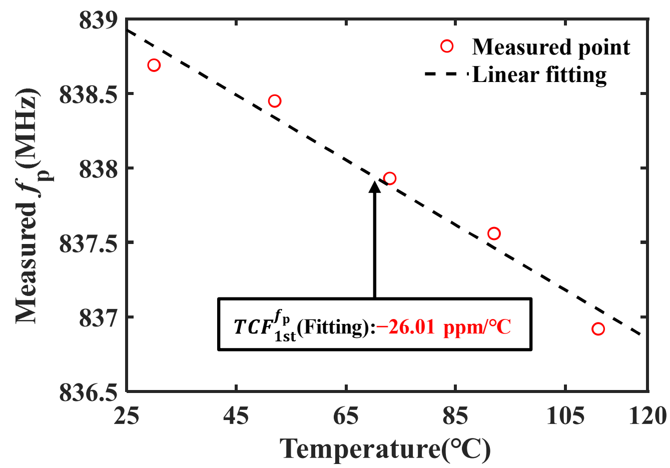

Fig.6. Calculated TCF_{1st} at anti-resonant frequency f_p based on linear fitting curve.

Fig. 6 contains the measured data extracted from Fig. 5 and a linear fitting curve to calculate the TCF_{1st} at f_p. It shows that a −26.01 ppm/°C of TCF_{1st} at f_p is achieved by our design. This result is acceptable when compared with other SAW temperature sensors[2], [9], [14]–[16] shown in Table III. Besides, high linearity means a great constant performance which offers a big advantage for sensing applications.

Table III. *TCF* COMPARISON OF TEMPERATURE SENSORS/RESONATORS AT ROOM TEMPERATURE

Ref.	Structure	*TCF* (ppm/°C)	Year
[9]	Pt/AlN/Sapphire	-34	2013
[2]	128°YX-LN	-115	2019
[14]	41°YX-SiO2/LN	-36	2019
[15]	Mo/AlN/Mo/Si	-27,2	2021
[16]	AlN/Pt/LGS	-14.55	2021
This work	**30°YX-LN/SiO2/Si**	**-26.01**	**2022**

IV. Conclusions

In this paper, a high quality-factor NS-SAW resonator with the 30° YX-LN/SiO_2/Si structure is proposed to compose a high sensitivity temperature sensor. FEM simulation and frequency response measurement on the fabricated device show that SiO_2/Si stack improves the Q of resonators which leads to an 862 Bode-Q_{max} practically. Besides, this resonator shows great linearity for the temperature sensor with an acceptable first-order *TCF* of −26.01 ppm/°C. Therefore, a high sensitivity temperature sensor could be achieved by NS-SAW resonator theoretically.

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