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Design, modeling, fabrication and studying the responses of the SAW devices for temperature measurement

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Abstract

In this paper, a complete analysis of a surface acoustic wave (SAW) sensor is reported with the capability of temperature sensing. An inexpensive material polydimethylsiloxane (PDMS) is used in temperature sensing. This SAW sensor is coated with PDMS solution to increase the sensitivity of the SAW temperature sensor. This PDMS solution is very sensitive towards the temperature. PDMS is positive coefficient of elasticity. Permittivity of this material is decreases with temperature. The permittivity change is based on the principle of clausius-Mosotti equation. That is density of sensing layer is decreases with temperature. Hence the capacitance formed is changed to decrease with temperature. As a result frequency increases with temperature. Simulation of the equivalent model of temperature sensor is done through TINA software. We have taken all initial electrical equivalent parameters of R02101 in T039 case as given by the manufacturer. Sensor is tested from 25^0C to 75^0C temperature and observed a good sensitivity of 860 KHz/0C shift

Keywords and phrases: SAW sensor, surface acoustic wave, temperature sensor, PDMS

1 Introduction

Temperature is the most critical parameters which affect everything. Food storage, medicine storage and any health as well as industrial related product is kept on the particular temperature. If the temperature is not maintain at desired storing temperature, the quality of the product will be degrades. It is too major parameters to control and hence, temperature measurement is also an important task. There are so many temperature sensor is developed to detect the temperature. So far, many temperature sensor has been reported which is based on resistive[1]–[3], capacitive [4]–[8], inductive[9], and combined as LRC resonator[10], [11]. The resistive temperature sensor is not very use to detect high temperature due to its self heating problem. To compensate its self effects there are two measure methods can be employed either use of its self heating in temperature sensing or a signal condition circuit to compensate its self heating effects. Resistance thermo detector (RTD) is the common example of the resistive type temperature sensor. A Wheatstone bridge circuit is used to compensate its self lead heating issue. A capacitive type sensor has also a disadvantage like dielectric property has been changed with temperature. Laser technology is very fancy to use in temperature detection. This technology is not affected by any self heating issue. Work has also been reported to avoid power consumption of the sensor in the remote location sensing. Passive wireless sensors (PWS) have so gained attention during the past ten years as a result of its benefits, such as battery-free operation and distant operation, which are very beneficial for sensor networks, and long-term monitoring in hostile environments. Surface acoustic wave based temperature sensor is quite randomly used in temperature sensing[12]–[16]. Because of the SAW's highly compact construction and reliable electrical characteristics at high temperatures. However change in electrical parameters of SAW due to temperature is used in temperature sensing. SAW sensor will respond the shift in central frequency with temperature. This paper presents the SAW based temperature sensor. A PDMS solution is used as a sensing layer to increase the sensitivity of sensor. All the working principle with simulation and experimental analysis is illustrated step by step in proceeding sections below.

2 Principle of SAW temperature sensor

A piezoelectric crystal substrate is used as a surface to make the SAW device. When, the temperature of the surface changes, the reflected wave velocity of the SAW changes. The wave velocity will be proportional to the temperature changes. The relationship between resonance frequency and temperature can be illustrated as:

$$f_T = f_{T_0}\left(1 + a_1\left(T - T_0\right) + a_2\left(T - T_0\right)^2 + \ldots\ldots\ldots\ldots\ldots\right) \tag{1}$$

f_T and f_{T_0} is the resonant frequency at temperature T and T_0 respectively. Where, a_1 and a_2 are first and second order temperature coefficient respectively. Second and higher order temperature coefficient is too small value for most of the piezoelectric and hence it is to be neglected. Then equation (1) can be reduced as:

$$f_T = f_{T_0}\left(1 + a_1\left(T - T_0\right)\right)$$
$$\Rightarrow f_T = f_{T_0} + f_{T_0}a_1\left(T - T_0\right)$$
$$\Rightarrow f_T - f_{T_0} = f_{T_0}a_1\left(T - T_0\right)$$
$$\Delta f = f_0 a_1 \Delta T \tag{2}$$

Here we can see that Δf is directly proportional to ΔT and the temperature is directly measured from frequency change $\left(\Delta f\right)$. Basic SAW schematic is shown in the figure1.

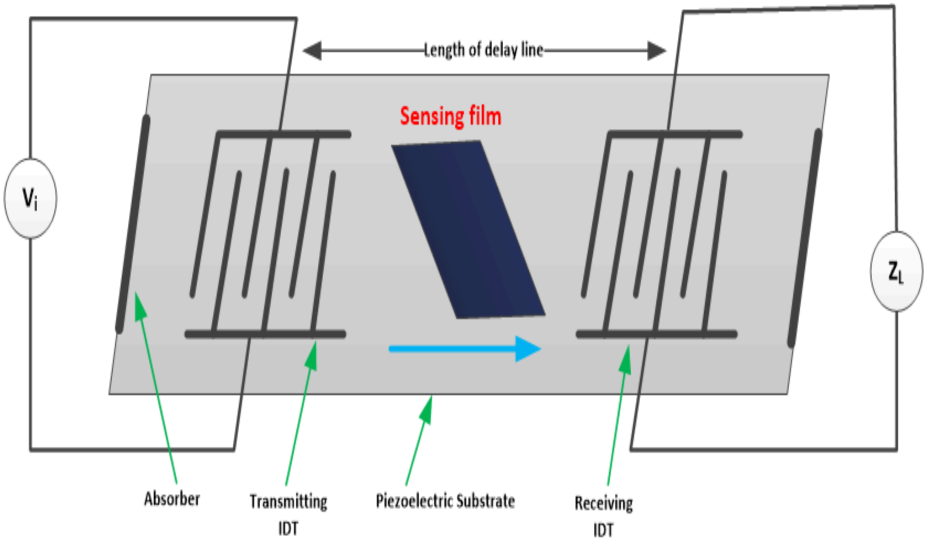

Figure 1: A Schematic diagram of SAW sensor

The distance between each bars of the IDT is l_b and wavelength λ and it is related as described below.

$$\lambda = 2l_b \tag{3}$$

2 Electrical equivalent modeling

The SAW device can be used in either one port or two port mode of operation as shown in figure 2 and figure 3 respectively. In both network, lumped elements $\left(L_m, R_{m,}\ and\ C_m\right)$ are used to designed electrical model of SAW resonator. These element L_m, R_m, and C_m represents the inertia, damping and elasticity property of the resonator respectively. The all three lumped elements of model is temperature dependent. Resistance $\left(R_m\right)$ represents the damping effect of the resonator. The value of inductance $\left(L_m\right)$ and resistance $\left(R_m\right)$ increases while capacitance $\left(C_m\right)$ decreases with temperature. In this paper we focused on the elasticity property of SAW. PDMS material is very sensitive towards the temperature. Its elasticity property is changed with temperature. So, to increase the elastic property of SAW, we introduce the PDMS material to enhance the temperature sensing application. The central frequency or resonance frequency of the resonator can be shifted down due to mass loading effect of PDMS coating on SAW surface. The resonance frequency can be determined by (4).

$$f_r = \frac{1}{2\pi\sqrt{L_m C_m}} \tag{4}$$

Resistance value is related to inverse of the quality factor (Q factor) of the resonator. The R_m value increases and Q factor decreases with temperature. The relationship between resistance and quality factor for the resonator can be calculated by the expression (5).

$$Q = \frac{2\pi f_r L_m}{R_m} \tag{5}$$

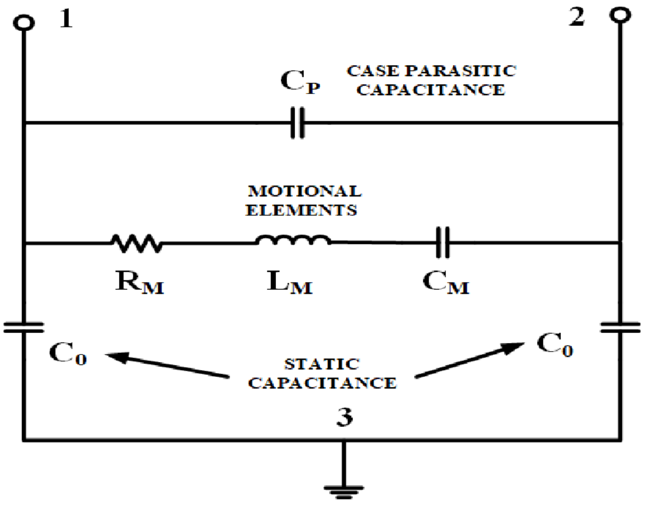

Figure 2: Equivalent RLC model of SAW resonator near resonance

The two port model is illustrated at resonance with combination of input/output non motional capacitance$(C_{01}\ and\ C_{02})$, motional elements (L_m, R_m, C_m) and ideal transformer. The capacitance C_{01} and C_{02} corresponds to static capacitances including case parasitic capacitance. The ideal transformer is linked to conversion of mechanical to electrical energy.

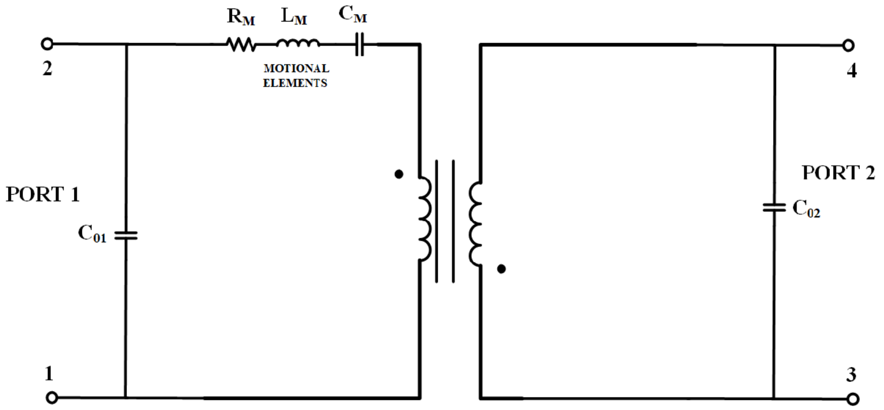

Figure 3: Equivalent circuit model of two port SAW

Nodal admittance matrix for the equivalent circuit can be expressed as below

$$Y_{11} = j\omega C_{01} + \frac{1}{R_m + j\left(\omega L_m - \frac{1}{\omega C_m}\right)} \tag{6}$$

$$Y_{12} = Y_{21} = \frac{1}{R_m + j\left(\omega L_m - \frac{1}{\omega C_m}\right)} \tag{7}$$

$$Y_{22} = j\omega C_{02} + \frac{1}{R_m + j\left(\omega L_m - \frac{1}{\omega C_m}\right)} \tag{8}$$

At resonance condition, above parameters can be expressed as:

$$Y_{11} = j\omega C_{01} + \frac{1}{R_m} \tag{9}$$

$$Y_{21} = Y_{12} = \frac{1}{R_m} \tag{10}$$

$$Y_{22} = j\omega C_{02} + \frac{1}{R_m} \tag{11}$$

The value of R_m, C_{01}, and C_{02} can be evaluated from $\mathrm{Re}(Y_{11})$, $\mathrm{Im}(Y_{11})$, and $\mathrm{Im}(Y_{22})$ at the resonance respectively. The other parameters L_m and C_m can be extracted from analytical expression of SAW resonance frequency and Q factor.

2 Extraction of equivalent parameters

The Y parameters are calculated from TINA software simulation. The value of concerned parameters can be extracted as:

$$R_m = \mathrm{Re}\left(\frac{1}{Y_{11r}}\right) \tag{12}$$

$$C_{01} = \mathrm{Im}\left(\frac{Y_{11r}}{2\pi f_r}\right) \tag{13}$$

$$C_{02} = \mathrm{Im}\left(\frac{Y_{22r}}{2\pi f_r}\right) \tag{14}$$

The values of f_r and Q is calculated from the experiments carried out on the SAW sensor under test. The value for L_m and C_m can be found out from the equation (14) and (15) as illustrated below.

$$L_m = \frac{QR_m}{2\pi f_r} \tag{15}$$

$$C_m = \frac{1}{(2\pi f_r)^2 L_m} \tag{16}$$

At resonance frequency $(f = f_r)$, the real part of Y_{11} is maximum. Quality factor (Q) is the ratio of resonance frequency to the half power bandwidth (B) .

$$Q = \frac{f_r}{2B} \tag{17}$$

3 Simulation of SAW Temperature sensor

Simulation of any equivalent model is necessary to optimize the size and performance. So we have done simulation of SAW sensor through TINA software. SAW resonator R02101 in T039 case is taken for all simulation as well as experimental work. This resonator is having the base central frequency at 433.93 MHz. Due to mass loading effect, the central frequency becomes 204.5 MHz after PDMS coating on the substrate of the resonator. All initial electrical equivalent values are taken from manufacturer, which are listed in table I. The colpitts oscillator is used to interface the SAW sensor as shown in the fig.4. Simulation is done with all initial condition of the resonator at room temperature as shown in the fig.5. The result of the simulation is shown in the figure 6.

Sr. No.	Characteristics	symbol	Typical value	Units
1	Motional Resistance	R_M	18	ohm
2	Motional Inductance	L_M	86	µH
3	Motional Capacitance	C_M	1.6	fF
4	Static Capacitance	C_p	1.7	pF
5	Case Parasitic Capacitance	C_0	0.5	pF
6	Frequency Temperature Coefficients	FTC	0.037	ppm/$^0C^2$

Table 1: Properties equivalent SAW RLC model with absolute frequency 433.93 MHz

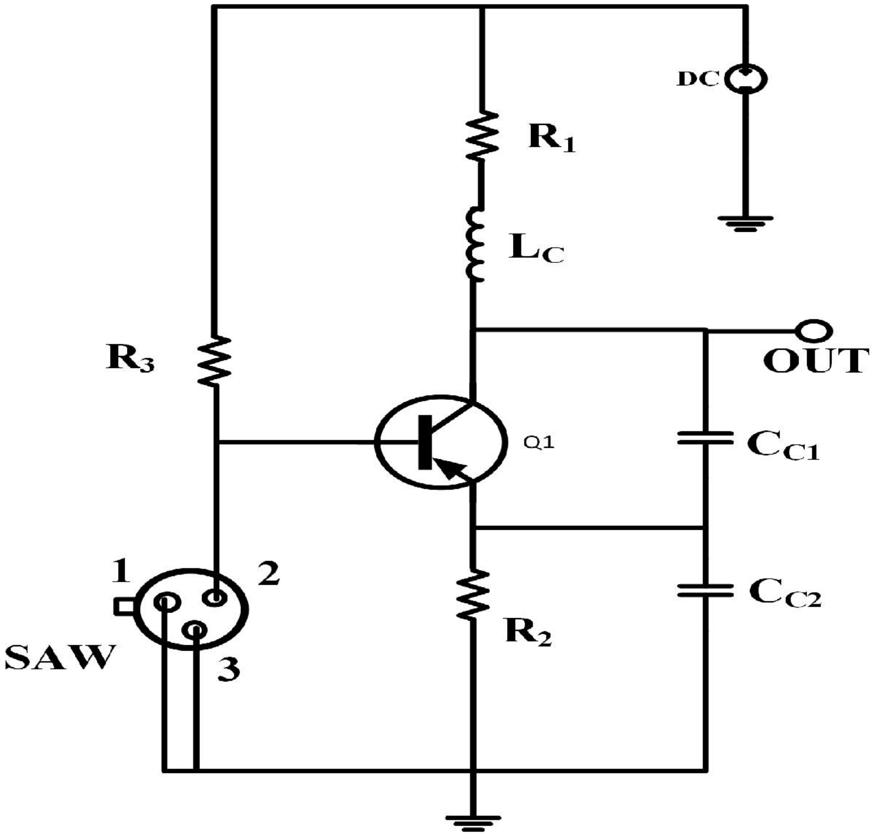

Figure 4: Colpitt Oscillator schematic with surface acoustic wave (SAW) based device

Sr. no.	components	symbol	value	units
1	Transistor	Q1	BFR93 A	
1	Resistor 1	R_1	22	Ω
2	Resistor 2	R_2	47	Ω
3	Resistor 3	R_3	33	KΩ
4	Inductor	L_C	36.2	nH
5	Capacitor 1	C_{C1}	4.7	pF
6	Capacitor 2	C_{C2}	18	pF

Table 2: SAW RLC oscillator parameters at absolute frequency 433.93 MHz

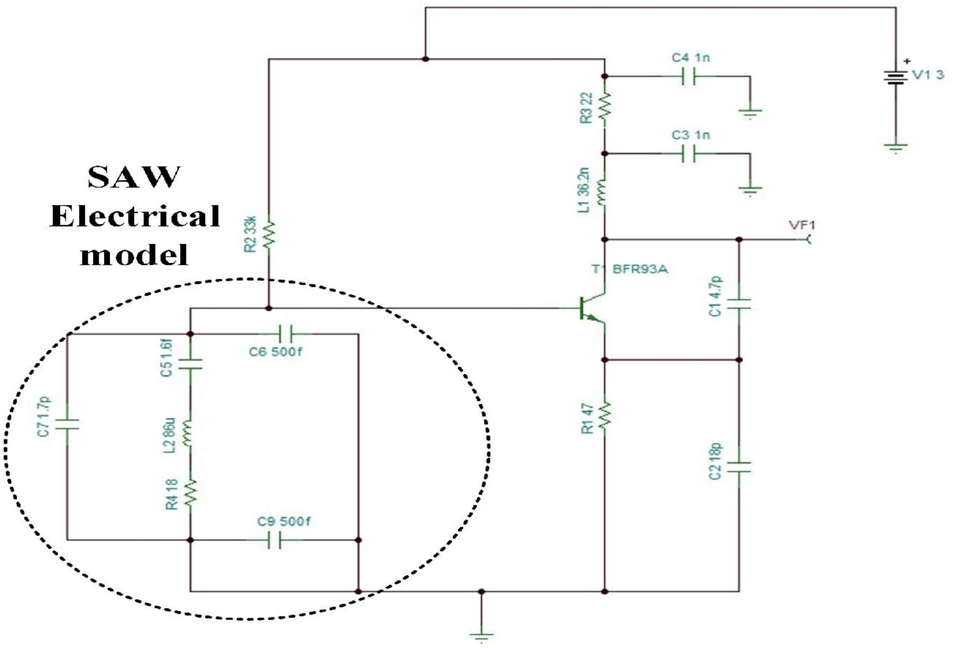

Figure 5: Colpitts Oscillator simulation with TINA software

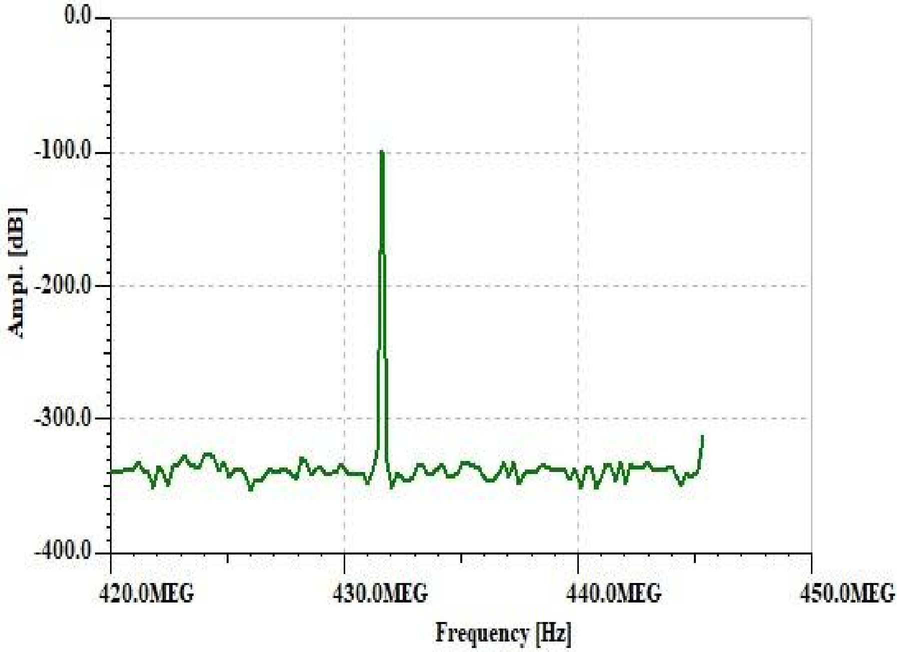

Figure 6: Oscillator simulation response at 433.9 MHz with TINA software

4 Experimental study of SAW temperature sensor

4.1 PDMS solution of SAW temperature sensor

PDMS solution is used to enhance the sensitivity of the sensor. This solution is hydrofobic in nature, so there is no effect of moisture around the sensor. The mechanical property of the solution is to increase its elasticity with temperature[17]. When temperature is changed, the motional capacitance of SAW sensor is changed and hence the central frequency accordingly shifted. When PDMS is coated on SAW resonator it becomes a layer between and over the IDT structures of SAW substrate surface. This will cause to form a capacitance. This capacitance is with parallel to the motional capacitance of SAW resonator. As a result, the overall capacitance will increase and hence the frequency shift is observed. So a coating is enhancing the temperature sensing using SAW device. A PDMS coated SAW sensor is shown in the figure 7.

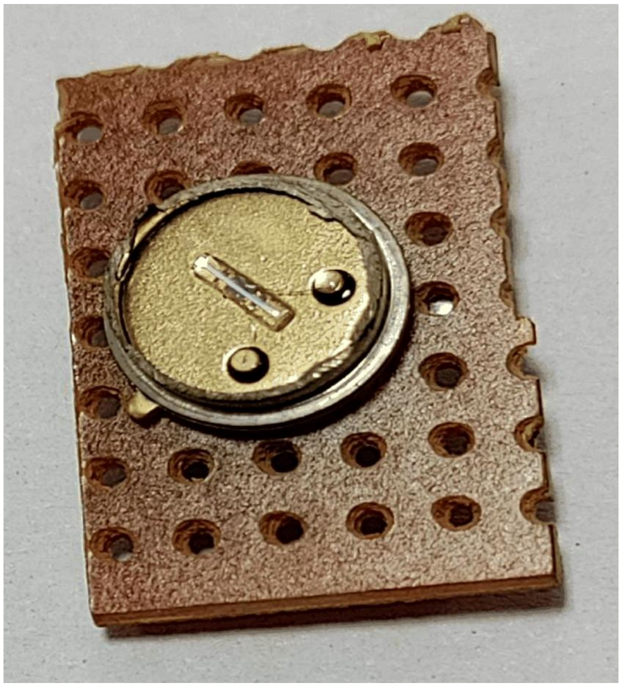

Figure 7: A SAW temperature sensor with PDMS coating

4.2 SAW temperature sensor fabrication and measurement

A SAW resonator R02101 in T039 case is taken for temperature sensing application. The upper cap of the resonator is cut out properly. A thin film sensing layer of PDMS is deposited on the piezoelectric substrate of the resonator through drop casting method. After coated of the sensor it is put in the furnace for curing the layer at 100^0C for 1 hour. Shielded cable is used to connect resonator to SMA connector as shown in the figure 8. A complete experimental setup is built in the lab to take the reading of sensor response on vector network analyzer as shown in the figure 10. The boiling point of the transformer oil is approximately 425^0C. Hence it is used in experimental study of temperature sensing. So that it is used to increase the temperature around environment the sensor.

Figure 8: A SAW sensor zig with SMA connector (a) front view (b) back

PDMS coated SAW sensor is put in test tube with thermometer for temperature reference as shown in the figure 9. Borosilicate glass is filled with transformer oil and test tube is completely dipped into this glass. Filament type heater is used to heat the glass. The sensor is responded while increasing the temperature of the oil.

5 Results and discussion

A frequency response of SAW temperature sensor with temperature is shown in the figure 11. Scattering (S) parameter response is taken on VNA with temperature increase from 25^0C to 75^0C. A frequency shift with temperature is shown in the figure 12. As we see that central frequency increases with temperature and it is varied linearly.

It is observed that PDMS enhance the sensitivity of the sensor as shown in the figure 11. Due to its elastic behavior caused by its property with temperature, the PDMS layer's dielectric will deform as temperature changes. Capacitance and dielectric constant are directly related. The capacitance created by the IDT structure printed on the substrate of the SAW surface will decrease because the dielectric constant of PDMS lowers with temperature. The centre frequency will rise with temperature as a result of the decrease in capacitance.

Figure 9: A SAW temperature sensor put in the test tube

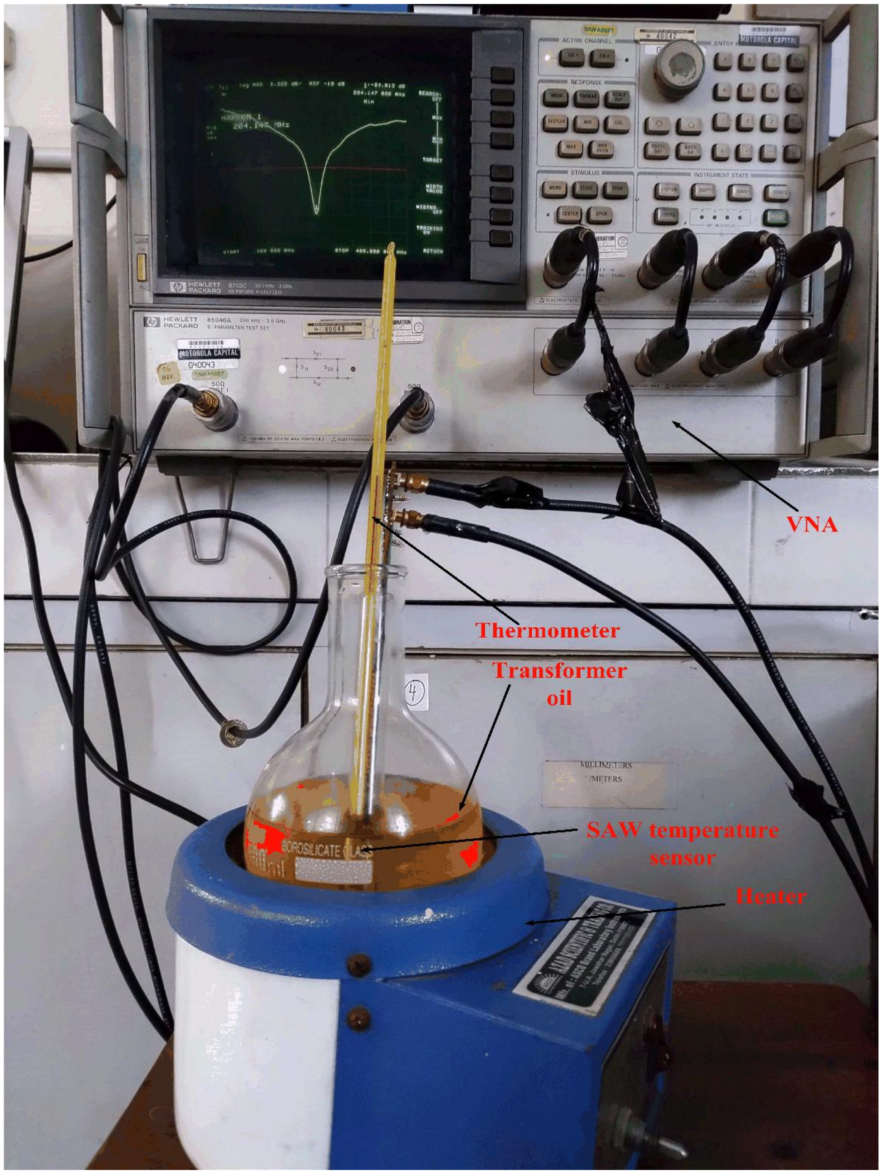

Figure 10: A complete setup for measuring S-parameter response of SAW sensor

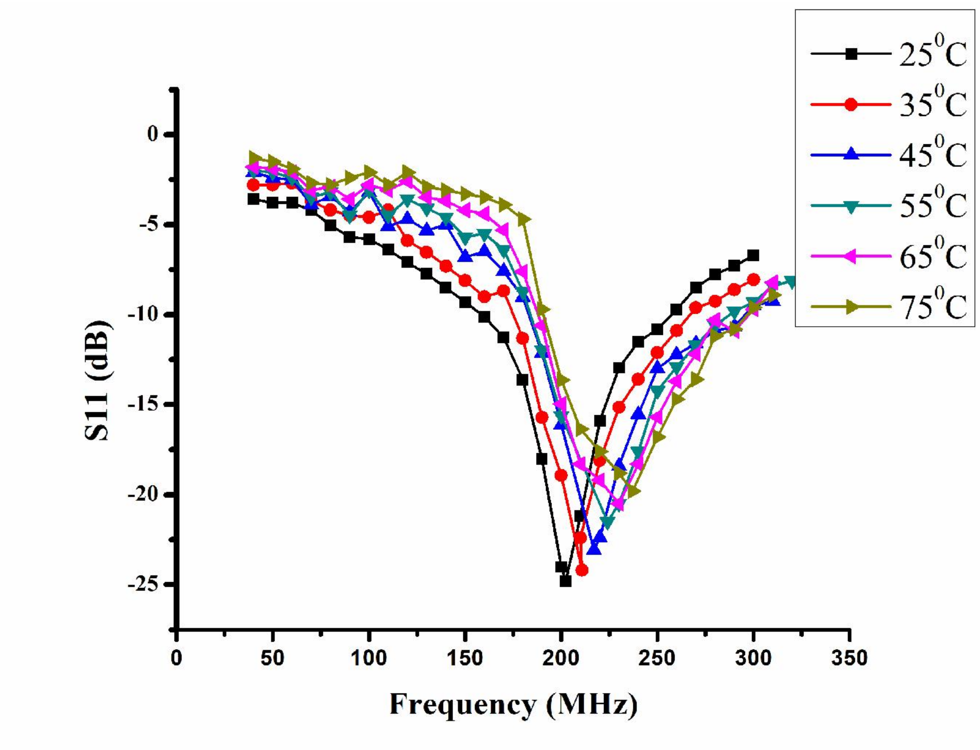

Figure 11: S-parameter response of SAW sensor

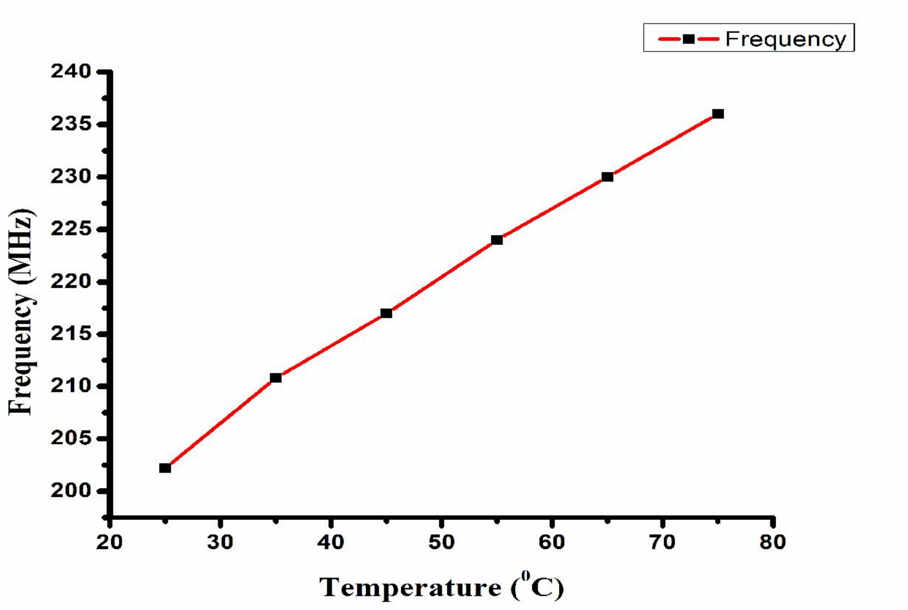

Figure 12: A frequency shift with temperature

5 Conclusions

Temperature has an impact on all of the admittance parameters while resonance occurring. SAW sensor with PDMS coating has good temperature responsiveness. We made use of PDMS's temperature-sensitive feature. So, in the SAW temperature sensor, we employed PDMS as the dielectric. The dielectric constant of PDMS decreases with increasing temperature, which also causes a decrease in capacitance. When capacitance falls with temperature, frequency rises, and vice versa. A good linearity response is shown by the sensor. The sensitivity of the sensor is calculated as 860 KHz/^{0}C. The temperature sensing performance of SAW sensor is depends of different parameters such as resonance frequency$\left(f_r\right)$, quality factor$\left(Q\right)$, and conductance$\left(G\right)$. The absolute sensitivity is calculated by partial derivates of dependent parameters with respect to temperature as shown in (18), (19), and (20).

$$S_f = \frac{\partial f_r}{\partial T} \qquad (18)$$

$$S_Q = \frac{\partial Q}{\partial T} \qquad (19)$$

$$S_G = \frac{\partial G}{\partial T} \qquad (20)$$

References

[1] M. Ahmed, M. M. Chitteboyina, D. P. Butler, and Z. Celik-Butler, “Temperature sensor in a flexible substrate,” *IEEE Sens. J.*, vol. 12, no. 5, pp. 864–869, 2012, doi: 10.1109/JSEN.2011.2166064.

[2] R. Ambrosio, M. Moreno, J. Mireles, A. Torres, A. Kosarev, and A. Heredia, “An overview of uncooled infrared sensors technology based on amorphous silicon and silicon germanium alloys,” *Phys. Status Solidi Curr. Top. Solid State Phys.*, vol. 7, no. 3–4, pp. 1180–1183, 2010, doi: 10.1002/pssc.200982781.

[3] G. Matzeu, A. Pucci, S. Savi, M. Romanelli, and F. Di Francesco, “A temperature sensor based on a MWCNT/SEBS nanocomposite,” *Sensors Actuators, A Phys.*, vol. 178, pp. 94–99, 2012, doi: 10.1016/j.sna.2012.02.043.

[4] M. R. R. Khan and S. W. Kang, “Fast, Highly Sensitive Interdigitated Capacitor Sensor to Detect Wide Range of Temperatures Using Graphene-Oxide-Containing Dielectric Membrane,” *IEEE*

Sens. J., vol. 18, no. 7, pp. 2667–2674, 2018, doi: 10.1109/JSEN.2018.2807395.

[5] A. D. DeHennis and K. D. Wise, "A wireless microsystem for the remote sensing of pressure, temperature, and relative humidity," *J. Microelectromechanical Syst.*, vol. 14, no. 1, pp. 12–22, 2005, doi: 10.1109/JMEMS.2004.839650.

[6] H. Y. Ma, Q. A. Huang, M. Qin, and T. Lu, "A micromachined silicon capacitive temperature sensor for wide temperature range applications," *J. Micromechanics Microengineering*, vol. 20, no. 5, 2010, doi: 10.1088/0960-1317/20/5/055036.

[7] L. Toygur, A. C. Patil, J. Guo, X. Yu, and S. L. Garverick, "A 300°C, SOI transimpedance amplifier with application to capacitive temperature sensing," *Proc. IEEE Sensors*, pp. 3–6, 2012, doi: 10.1109/ICSENS.2012.6411504.

[8] C. H. Cai and M. Qin, "High-performance bulk silicon interdigital capacitive temperature sensor based on graphene oxide," *Electron. Lett.*, vol. 49, no. 7, pp. 457–458, 2013, doi: 10.1049/el.2012.4141.

[9] Y. Ji, Q. Tan, H. Wang, W. Lv, H. Dong, and J. Xiong, "A Novel Surface LC Wireless Passive Temperature Sensor Applied in Ultra-High Temperature Measurement," *IEEE Sens. J.*, vol. 19, no. 1, pp. 102–112, 2019, doi: 10.1109/JSEN.2018.2872915.

[10] H. Kairm *et al.*, "Concept and model of a metamaterial-based passive wireless temperature sensor for harsh environment applications," *IEEE Sens. J.*, vol. 15, no. 3, pp. 1445–1452, 2015, doi: 10.1109/JSEN.2014.2363095.

[11] J. M. Boccard, T. Aftab, J. Hoppe, A. Yousaf, R. Hutter, and L. M. Reindl, "High-Resolution, Far-Field, and Passive Temperature Sensing up to 700 °c Using an Isolated ZST Microwave Dielectric Resonator," *IEEE Sens. J.*, vol. 16, no. 3, pp. 715–722, 2016, doi: 10.1109/JSEN.2015.2487606.

[12] H. H. Motors, A. Binder, and R. Fachberger, "Wireless SAW Temperature Sensor System for," vol. 11, no. 4, pp. 966–970, 2011.

[13] H. Guo *et al.*, "A temperature and humidity synchronization detection method based on microwave coupled-resonator," *Sensors Actuators, B Chem.*, vol. 261, pp. 434–440, 2018.

[14] D. Huang and T. Li, "Design of RF temperature measurement system of delay linear SAW temperature sensor based on FPGA," *Proc. - 2020 Int. Conf. Comput. Eng. Appl. ICCEA 2020*, no. 1, pp. 520–524, 2020, doi: 10.1109/ICCEA50009.2020.00115.

[15] H. Weng, F. L. Duan, Z. Xie, S. Liu, Z. Ji, and Y. Zhang, "LiNbO 3 -Based SAW Sensors Capable," vol. 20, no. 21, pp. 12679–12683, 2020.

[16] G. Crupi, G. Gugliandolo, G. Campobello, and N. Donato, "Measurement-Based Extraction and Analysis of a Temperature-Dependent Equivalent-Circuit Model for a SAW Resonator: From Room down to Cryogenic Temperatures," *IEEE Sens. J.*, vol. 21, no. 10, pp. 12202–12211, 2021, doi: 10.1109/JSEN.2021.3066345.

[17] U. Salmaz, T. Islam, and S. Sohail, "A Novel Linear Capacitive Temperature Sensor Using Polydimethylsiloxane," *IEEE Trans. Instrum. Meas.*, vol. 69, no. 10, pp. 7887–7894, 2020, doi: 10.1109/TIM.2020.2986120.

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