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Research Article

Micro-Temperature Sensor Based on Quartz Tuning Fork Resonator

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Abstract: In this study, a low cost quartz tuning fork temperature sensor adopting H-shaped tuning fork resonator to address miniaturization, high resolution and high stability has been designed, developed and tested. The quartz tuning temperature sensor is designed using flexural vibrating mode with a new thermo-sensitive cut. The quartz tuning fork temperature sensor consists of two prongs connected at one end of crystalline quartz plate with thin-film metal electrodes deposited on the faces, which is used to produce vibration in response to alternating voltages and detecting the resonance frequency in the meantime. When an external temperature is change, there is a shift in its natural frequency. Finite Element Method (FEM) is used to analyze the vibratory modes and optimize the structure of the sensor. The resonance frequency of tuning fork is about 37 kHz with a sensitivity of rough 80 ppm/°C. The experimental results shown that a temperature accuracy of 0.01°C and a resolution of 0.005°C within temperature range from 0 to 100°C, respectively.

Keywords: Finite element method, quartz, resonance frequency, temperature senor, tuning fork

INTRODUCTION

Precise temperature measurement is an important part of modern technology. Over the past two decades, several advances have been made in micro-machined sensor and actuators, a number of research works were focused on quartz sensors, theoretically and in terms of micro fabrication. Piezoelectric materials provide a direct transduction mechanism to convert signals form mechanical to electrical domains and vice versa. Due to benefit like high sensitivity, small size, mechanical robustness and cost effective fabrication, piezoelectric resonators have widely been utilized for temperature measurement sensors. To demonstrate the approach, the temperature sensor is made to the analysis of the orthotropic plates made of Y-cut and LC-cut crystal quartz. Quartz thermometers have a very linear output characteristic over the temperature range between -40 and +230°C, respectively. The measurement resolution of temperature is 0.1°C.

In order to miniaturize construction of sensor and reduce the power consumption, one of the advantageous resonator types of tuning-fork shape was used for design the resonators. A miniature resonator as a temperature sensor was described by Dinger and Ueda. The low resonance frequency of tuning-fork allows low power consumption of CMOS electronics and miniaturized by the use of photolithography and etching technology are very attractive properties for sensor applications (Benes *et al*., 1995; Eernisse *et al*., 1998; Errol and Wiggins, 2001; Tadigadapa and Mateti, 2009; Hempel and Lucklum, 2008; Antoni, 2008). Design parameters of tuning fork geometry, tine tip and tine surface electrode shape and thickness were based on theoretically modeled optimum values using FEM.

Temperature sensor using a quartz resonator is inherently insensitive to noise because the output is a frequency shift caused by an external temperature. The output can easily be converted into a digital signal which can be directly connected to a micro-controller without an A-D converter. The temperature sensor also has a fast response and a high sensitivity. Mechanical resonators utilizing the flexural modes generally have lower resonance frequencies (KHz) than Thickness Shear Mode (TSM) or Surface Acoustic Wave (SAW) devices. Among different mechanical resonators, quartz tuning forks are more attractive due to their low power consumption, low cost, high resolution, high precision, long stability and full-digital frequency output signal.

In this study, new experiments have been carried out on quartz tuning fork resonator to highlight the existence of high thermo-sensitive cut. The optimal selection of quartz crystal cuts is carried out which yields the best performances. It concerns tuning fork resonators vibrating in flexure mode with clamped-free boundary conditions. A theoretical model is also developed and the simulation using FEM results are compared with the experimental results.

SENSOR DESIGN

In this study, micro-machined quartz tuning fork resonators vibrating in a flexural mode are adopted. Quartz crystal usually is defined by its crystallographic

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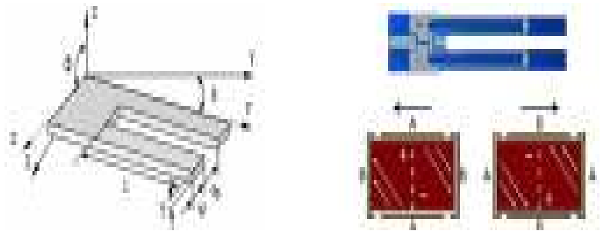


Fig. 1: Crystallography o and the electrodes

axes (X, Y, Z). The resonance frequency-temperature characteristic of the thermo-sensitive quartz tuning fork resonator is importantly depend on the working mode of vibration and the cut angle of the quartz plate and the piezoelectric parameters like electromechanical coupling coefficients should be taken into consideration. Thus it is necessary to select the optimal crystal cut which yields the best performance for quartz tuning fork temperature sensor. The optimal crystal cut for quartz tuning fork temperature sensor is defined as shown in Fig. 1.

In this analytical model, Let us consider cantilever of thickness T, width W and length L. Tuning fork crystals have been mathematically analyzed as a cantilever beam vibrating in a flexural mode and an analytical solution of the equation of motion for tuning forks has been obtained with pertinent boundary conditions. The derivation used in his model is based on Bernoulli beam model where shear effect are neglected and without taking into the piezoelectric effect. The resonant frequencies formula below:

$$f = \frac{\lambda^2}{4\pi\sqrt{3}} \frac{w}{L^2} \sqrt{\frac{1}{3\rho s_{22}}} \tag{1}$$

where,

S_{22} : The flexible coefficient

ρ : The density of the quartz crystal

λ : The solution of an Eigen frequency equation that depends upon the boundary conditions

For a fixed-free beam the Eigen frequency equation is $1+\cos\lambda \cosh\lambda = 0$.

Two prongs connected at one end make a resonator whose resonance frequency is defined by the properties of the material from which it is made and by its geometry. Under normal operation the tuning fork is excited at its natural frequency and closed loop electronics maintain the device in resonance frequency, the electrodes are designed as shown in Fig. 1. The material constants and the design parameters of quartz tuning fork resonator are shown in Table 1 and 2.

Table 1: Material constants of quartz

C_{11}^E	C_{12}^E	C_{13}^E	C_{14}^E	C_{33}^E	C_{44}^E
0.86474	0.0699	0.1191	-0.1791	1.072	0.5794
C_{66}^E 1011N/m^2	$\varepsilon_{11}^S/\varepsilon_0$	$\varepsilon_{33}^S/\varepsilon_0$	e_{11}	e_{25} C/m^2	P kg/m^3
0.3988	4.43	4.63	0.171	0.0403	2650

Table 2: Design parameters of quartz and the dimension of the tuning fork

Part	Design parameter	Symbol	Eigenvalue
Crystal blank	Arm length	L	2.368 mm
	Width	W	0.218 mm
	Thickness	T	0.12 mm
	Gap	Gp	0.10 mm
	Cutting angle	Φ/θ	$118°/18°$
	Base length	L1	4.00 mm
Face electrode	Thickness	te	3000 $A°$
	Width	we	0.178 mm
Side electrode	Thickness	ts	2000 $A°$
Tine tip electrode	Thickness	tt	5000 $A°$

The cutting angle of flexural quartz crystal is expressed by new cut ZY(θ/Φ), it is the principal affecting the quartz tuning fork temperature sensor. In this study, although the frequency-temperature characteristic of the tuning fork temperature sensor is nearly linear, it is not exactly so. A better model is a second-order polynomial in temperature as:

$$f(T) = f(T_0)(\alpha\Delta T+\beta\Delta T^2+\gamma\Delta T^3) \tag{2}$$

With

$$\Delta T = T - T_0$$

$$\alpha = \frac{1}{f}\frac{\partial f}{\partial T}; \quad \beta = \frac{1}{2!\,f}\frac{\partial^2 f}{\partial T^2} \quad \gamma = \frac{1}{3!\,f}\frac{\partial^3 f}{\partial T^3} \tag{3}$$

where,

$f(T)$: Any one of frequency at measured temperature T

$f(T_0)$: Reference temperature T_0

α : The first-order temperature coefficient of frequency constant $f(T_0)$

β : Second-order temperature coefficient of frequency constant $f(T_0)$

Consequently, on one hand let us consider a quartz plate with angles of cut vibrating in Bulk Acoustic Waves (BAW) operating in flexural modes. The resonance frequency-temperature characteristic of the thermo-sensitive quartz tuning fork resonator is importantly depend on the working mode of vibration and the cut angle of the quartz plate. The dependence of the frequency versus temperature is an essential characteristic to resonator which controls the frequency. On the other hand the thermal sensitivity of BAW resonators and of piezoelectric parameters like electromechanical coupling coefficients should be taken into consideration. The ideal quart tuning fork temperature sensor has to achieve the following specifications:

- The change in the resonant frequency measurement range should be high.

- The resonant frequency temperature dependence has be unique.
- The electromechanical coupling should be high.
- The range of temperature should be width.

For an ideal thermo-sensitive cutting angle, we often choose the value of first-order temperature coefficient of frequency should be as large as possible and the value of second-order temperature coefficient of frequency should be as small as possible in order to raise the output of signal and to improve its linearity. The first-order temperature coefficient is larger, the value of cutting θ should become larger accordingly, by the mean time the Equivalent Series Resistance (ESR) will become larger. The oscillation circuit will stop working by the lager ESR. The ESR is a function of the cutting angles θ and Φ. It has been experimentally determined the cutting angles θ and Φ must be in the ranges of 118° and 18°. According to fundamental analysis, flexural mode tuning fork temperature sensor have a high sensitivity which can reach about 80×10-6/°C, its dynamic resistance value is reasonable and can be worked in wide temperature range and low power consumptions.

The present study uses Finite-Element Model (FEM) software (ANSYS) to carry out the numerical simulation of micro tuning fork type temperature sensor. The analysis is based on the finite element modeling including the piezoelectric effect. The piezoelectric equations of e form are expressed as:

$$\{T\} = [c^{E}]\{S\} - [e]^{T}\{E\}$$

$$\{D\} = [e]\{S\} - [\varepsilon^{S}]\{E\} \qquad (4)$$

{T}, {D}, {S}, {E}, [cE], [e] and [εS] are stress, electric flux density, strain, electric field, stiffness, electro-mechanical coupling constants and permittivity, respectively. The effect of the temperature change on the parameters is assumed as the result of the changes of some physical constants due to the temperature change. Though the values of [cE], [e] and [εS] may change with the temperature, only [cE] among others is chosen to be effective.

In FEM analysis, the resonance frequency and vibration mode analysis are carried out by harmonic analysis. Considering solid material with losses, stress, electric potential distribution and equivalent circuit parameters as shown in Fig. 2 could also be obtained by FEM analysis as described elsewhere. Therefore in the present research, various tuning fork design parameters and their levels have been laid out by well-known Taguchi's design of experiment method. An example of electrode designs of the resonator is also illustrated in Fig. 3. The shaded areas indicate electrodes of the resonator. Arrows in the Fig. 3b express directions of applied or generated electrical field.

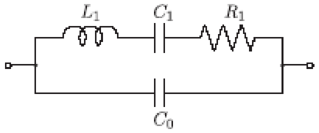
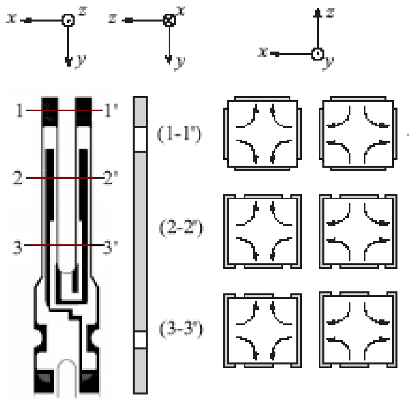


Fig. 2: Equivalent circuit of the quartz tuning fork resonator



(a) (b)

Fig. 3: The electrodes of the double-ended tuning fork quartz resonator (a) outside view, (b) cross section

For the analysis by FEM, a complex structure is converted into a mesh and the finite element tuning fork model (vibration mode from first order to forth order) as shown in Fig. 4, where the nodes have a mass and every element between two nodes is combination a spring and a damper. The spring and damping constants of the connecting elements are chosen such that together they exhibit the same behavior as the whole structure.

The dependence of the individual crystal parameter sensitivity on various design parameters can be comprehensively analyzed by FEM and detailed information on geometry of tuning fork blanks and electrodes. The piezoelectricity phenomenon is integrated in the computation depending on the element choice. From FEM analysis, it is shown that the tine width and the tine tip electrode thickness are major factors affecting the resonance frequency of tuning fork. Also, the resonance frequency is inversely proportional to the square of the tine length. After Reasonable configuration the electrode and structure of the quartz tuning fork, the resonance frequency is about 34 kHz by FEM analysis in forth vibration mode-flexural that is

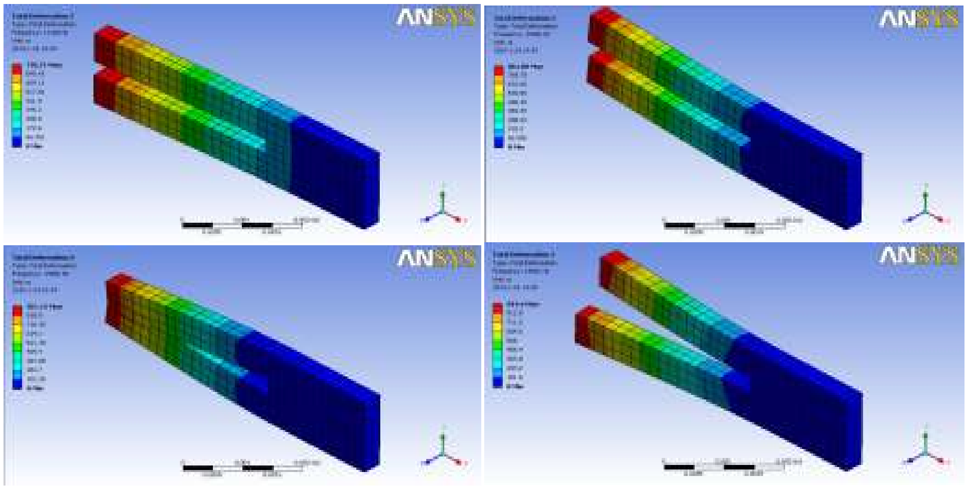


Fig. 4: Vibration mode

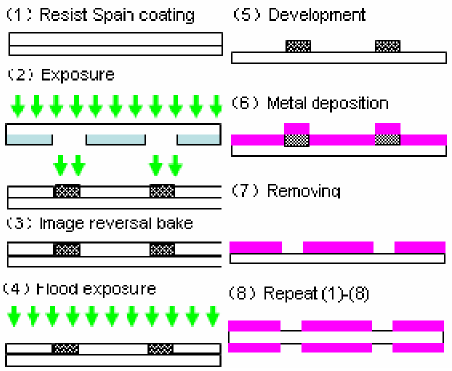


Fig. 5: Fabrication process chart

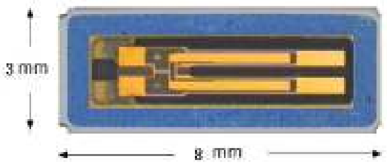


Fig. 6: Mount structure of tuning fork resonator

lower than the 37 kHz by theoretical analysis. In this mode, the quartz tuning fork temperature sensor has high sensitivity and fast respond time.

Tuning fork resonators were fabricated from single crystalline ZY-cut quartz wafers by lithography followed by wet etching according to the scheme of Fig. 5. Process flow is wafer clean, tuning fork shape etching, electrode shape etching, inspection and assembly. Patterns of the electrodes are designed using software and make the Cr-glass mask. A gold layer is deposited on the cleaned sample through a sputtering method. Photo-resist is spin coated on the sample and exposed to light through the mask on the both sides of the sample. Gold-etch and chromium-etch are used, two nickel wires are then glued on the gold electrodes, on the each side of the tuning forks, with Ag conducting spray.

The tuning fork appears as a metallic cylinder 8 mm in height by 3 mm in diameter, holding a two-terminal electronic component and filled with Helium of 90 Pa, as shown in Fig. 6. It not only keeps the long term stability but also resolve the problem of response time and Q value.

EXPERIMENTAL RESULTS

Figure 7 demonstrates the principle of sensor calibration experiment. The resonators are installed in standard capsules of package Φ3×8 holders and filled with Helium of 90 Pa. The temperature sensor is deposed into a temperature oven, which is heated using Hot Controller, providing the temperature range from 0 to 100ºC, respectively. The water's temperature is measured by thermometers directly. At the same time, the frequency of the quartz tuning fork temperature sensor is connected to oscilloscope (RIGOL DS5102ACE) and frequency counter (Agilent 34411A). This information can be read out from Oscilloscope and high precise frequency counter in terms of Resonant Frequency. Measures are done between 0 and 100°C by 2°C step. The data measured is send to the personal computer via USB; the PC computed the temperature, saves the frequency and temperature data in files on a hard disk and shows their values as graphics on the screen. For each point we had a minimum of 20 separately measured values, the averages of which were used in further analyses of experimental results.

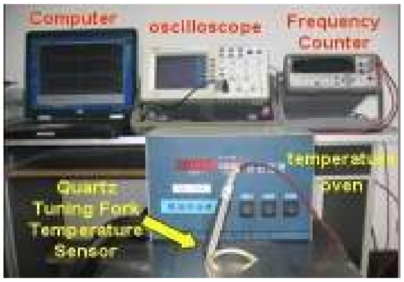


Fig. 7: Experimental setup for temperature experiment

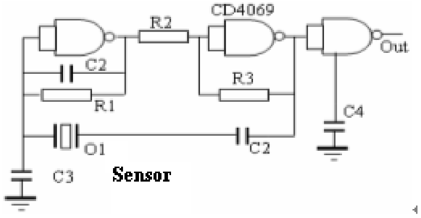


Fig. 8: The circuit of an oscillation

In order to eliminate the mutual interference and decrease power consumption, an optimized integrated circuit with low-power shot (CMOS CD4069) was chosen for the oscillator measurement as show in Fig. 8. This circuit possessed advantage such as simple configuration, stable performance, as well as its wide adjustment range for parameters of electronic components.

The parameters of the electronic components of the circuit were optimized in this study. Results showed that a circuit with following parameters as C1 = 30 pF, C2 = 20~40 pF, C3 = 20 pF, R1 = R2 = 500Ω, R3 = 2K could give stable oscillation. To eliminate the mutual interference, a capacitance C4 = 10 uF was added between each circuit power input terminal and ground to insulate the interfering oscillation wave from other circuit. Then the following measure should be taken:

- Eight oscillator circuits were designed and assembled separately. Each circuit was shield with a copper box and ground respectively.
- Owing to the nuance existing among the same kind of electronic components in different circuits, the parameter of electronic components should be adjusted separately to obtain a stable oscillation for each oscillator.

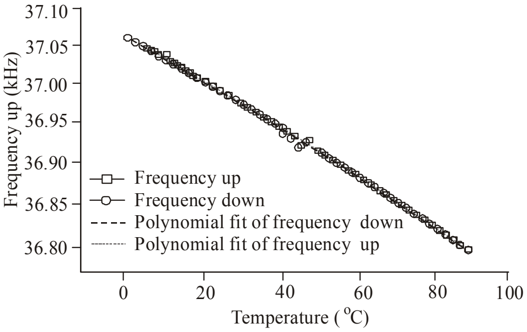


Fig. 9: Frequency versus temperature behaviors

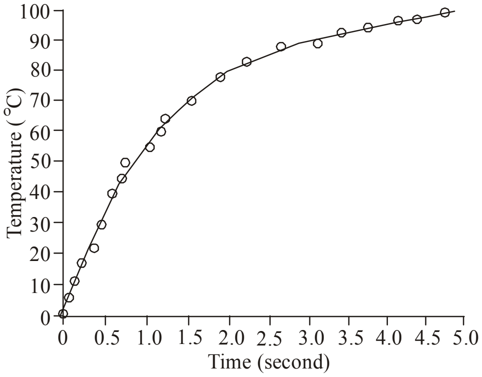


Fig. 10: Respond time of sensor

The experimental temperature variation with the frequency variation of quartz tuning temperature from 0 to 100°C is linear and is shown in Fig. 9. The increase temperature process is plotted in a red line, while the temperature process is plotted in a blue line. As the results, the hysteresis of the sensor is calculated to be 0.4% and the nonlinearity is calculated to be 0.5%. Sensitivity of the sensor is 80 ppm/°C. The typical parameters of quartz tuning fork temperature sensor are shown in Table 2. Figure 10 presents the time response of the quartz tuning fork temperature sensor. The response time of the proposed micro quartz tuning-fork temperature is determined to be 5 s in the relative temperature range from 0 to 100°C, respectively.

CONCLUSION

The study successfully demonstrated a new micro thermo-sensitive quartz tuning-fork resonator based temperature sensor. In design of quartz tuning fork temperature sensor, selecting the cut type of quartz tuning fork resonator according to the each anisotropic nature of quartz tuning fork resonator, which uses doubly rotated ZYtw (118°/18°) -cut with working at flexural vibration mode ensure the temperature coefficient up to 80 ppm/ºC and has a linear temperature-frequency relationship. The flexural vibration mode is analyzed by the theoretical analytical model and FEM method.

The temperature test results show that the precision of the temperature sensor designed in this study exhibits a accuracy of 0.01ºC, the hysteresis nearly can be neglected in the temperature range is from 0 to 150ºC. Further, this frequency-based technique has the advantage of being immune to amplitude noise in the measurement system-a feature not shared by thermocouple, thermistor, or RTD based temperature sensing techniques. Lastly, remote temperature sensing is possible by using an antenna to pick up the frequency of the electromagnetic waves emitted by the sensor.

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