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High-precision low-power quartz tuning fork temperature sensor with optimized resonance excitation[*]

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Abstract: This paper presents the design, fabrication, and characterization of a quartz tuning fork temperature sensor based on a new ZY-cut quartz crystal bulk acoustic wave resonator vibrating in a flexural mode. Design and performance analysis of the quartz tuning fork temperature sensor were conducted and the thermal sensing characteristics were examined by measuring the resonance frequency shift of this sensor caused by an external temperature. Finite element method is used to analyze the vibratory modes and optimize the structure of the sensor. The sensor prototype was successfully fabricated and calibrated in operation from 0 to 100 °C with the thermo-sensitivity of 70×10^{-6}/°C. Experimental results show that the sensor has high thermo-sensitivity, good stability, and good reproducibility. This work presents a high-precision low-power temperature sensor using the comprehensive thermal characterization of the ZY-cut quartz tuning fork resonator.

Key words: Tuning fork, ZY-cut quartz, Quartz micromachining, Thermal sensing, Temperature sensor
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1 Introduction

Recent advances in materials and micromachining technology have offered exciting new technologies for detection in high performance sensors. Piezoelectric materials provide a direct transduction mechanism to convert signals from mechanical to electrical domains, and vice versa. Transducers using piezoelectric materials can be configured as sensors when the design of the device is optimized for the generation of an electric signal. Piezoelectric materials have attractive electromechanical properties for realizing micromachined sensors and actuators (Trolier-McKinstry and Muralt, 2004; Setter *et al.*, 2006; Friedt and Carry, 2007; Tadigadapa and Mateti, 2009). Quartz crystal resonators are widely used as frequency control devices which are designed to be as insensitive to the environment as possible, and can also be designed as sensors to be highly sensitive to environmental parameters such as temperature, pressure, force, and acceleration, which can exhibit unsurpassed resolution and dynamics (EerNisse *et al.*, 1988; EerNisse and Wiggins, 2001; Guo *et al.*, 2010; Gil *et al.*, 2011; Pisani *et al.*, 2011). Those sensors are inherently insensitive to noise because the output is a frequency signal and can easily be converted into a digital signal that can directly be connected to a micro-controller without an AD converter.

The resonant frequency temperature dependence of quartz resonators has been used for the measurement of temperature for a long time. Early in the 1960's, it was recognized that many of the crystallographic orientations, called 'cuts', ignored by the advancing frequency-control fields, were useful as temperature sensors (Wade and Slutsky, 1962; Smith and Spencer, 1963; Hammond *et al.*, 1964; Spassov, 1992; Spassov *et al.*, 1997). The advantage of these sensors is the great thermo-sensitivity, which makes it

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possible to determine the temperature with an accuracy of 0.001 °C. The disadvantage of the quartz resonator as a temperature sensor with the frequency of MHz-level is a relatively long period of time for transmission of heat between the measured object and the resonator. Those temperature sensors based on resonators that vibrate with thickness shear modes are rather cumbersome on account of larger volume and higher power consumption.

In this paper, we discuss the use of the quartz tuning fork (QTF) to overcome the above difficulties. QTF is commercially produced piezoelectric oscillators which are meant to be used as frequency standards in watches. Extensive literature describes their usage for a large number of other additional applications. Due to their high mechanical quality factor Q (10^3–10^5), QTF is very sensitive to environmental changes (Ctistis *et al.*, 2011). QTFs do not require an excitation current; hence, self-heating will not occur. The anisotropy of quartz and usage of different types of vibrations make it possible for the control of parameters such as temperature, force, mass, pressure, acceleration, and humidity. QTFs have proven to be extremely useful as sensors for temperature (Dinger, 1982; Ueda *et al.*, 1986; He *et al.*, 2003; Tsow and Tao, 2007; Jayapandian *et al.*, 2012), humidity (Zhou *et al.*, 2007), force (Castellanos-Gomez *et al.*, 2011), density (Zeisel *et al.*, 2000), and gyroscopes (Guo *et al.*, 2010; Wu *et al.*, 2012). Recent QTF resonators have been designed using finite element method (FEM) and fabricated using the micro-electro-mechanical systems (MEMS) technology, which has many advantages, such as small size, low cost, low power, high sensitivity, and high stability. They also have compatibility with the integrated circuit process and can be operated at an ultra low voltage (3 V) while consuming only microwatts of power (Lee, 2002; Lee *et al.*, 2004; Beeby *et al.*, 2000; Wakatsuki *et al.*, 2003). In addition, a major advantage of QTF in many applications is that to drive those piezoelectric devices, no magnetic fields are needed, and they are insensitive to magnetic fields (Rychen *et al.*, 2000; Clubb *et al.*, 2004).

In this study, we extend the use of QTF as sensors for thermal applications. The QTF was mechanically driven by self-excitation using tuning fork electrodes. We proposed and demonstrated a high-accuracy low-power QTF temperature sensor vibrating in a flexural mode. The basis of the QTF temperature sensor is that an environmental temperature change leads to a change in the measured frequency change of the QTF temperature sensor. New experiments have been carried out on the QTF resonator to highlight the existence of a high thermo-sensitive cut. It concerns tuning fork resonators vibrating in a flexure mode with clamped-free boundary conditions for low power consumption. A theoretical model is also developed and the results of simulation using FEM are compared with the experimental results.

2 Sensor design

The QTF temperature sensors are tuning fork quartz crystals using a new cut and vibrating in a flexural mode. Their frequency is both extremely sensitive to temperature and highly linear. This high sensitivity offers the ability to detect fine changes in temperature and this frequency-based technique has the advantage of being immune to amplitude noise in the measurement system in comparison with thermocouples, thermostats, and resistance temperature detectors.

Since quartz is an anisotropic medium, it is necessary to select the optimal crystal cut which yields the best performance for a QTF temperature sensor. Table 1 lists the temperature coefficients of the resonance frequencies for different quartz crystal cuts at ambient temperature (Vig *et al.*, 1996; He *et al.*, 2003).

Table 1 Temperature cofficients of the resonance frequency for various quartz cuts

Quartz crystal cut	Temperature coefficient of frequency ($\times10^{-6}$/°C)	Reference
AC-cut	20	
LC-cut	35.4	
SC-cut (b-mode)	90	Vig *et al.* (1996)
SC-cut (dual mode)	−25.5	
ZYtw-cut	60	
NLSC-cut	80–100	He *et al.* (2003)

To attain a higher thermal sensitivity, the optimal crystal cut for a QTF temperature sensor is experimentally defined. A new type of thermo-sensitive cut type, ZY-cut (rotate angle θ around the X-axis and rotate angle ϕ around the Y-axis), is adopted to develop the QTF temperature sensor (Fig. 1).

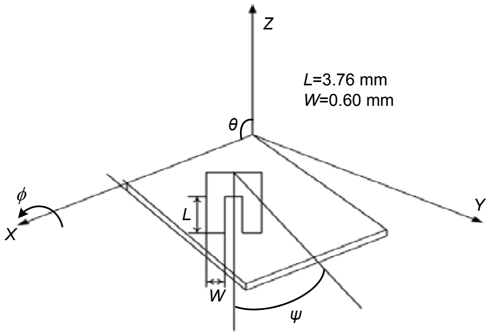

Fig. 1 Orientation of the quartz tuning fork (QTF) resonator

The temperature frequency characteristic of QTF is dependent mainly on the cutting angles θ and ϕ, which is written mathematically as $Tf=F(\theta, \phi)$. The temperature frequency characteristic of each resonator can be represented by a polynomial of nth order and has the form of different cuts. According to Bechmann's systematic investigation, the temperature-frequency characteristic can be expressed by a 3rd order polynomial as (Benes *et al.*, 1995)

$$\frac{f(T)}{f(T_0)}=\left(1+\alpha(T-T_0)+\beta(T-T_0)^2+\gamma(T-T_0)^3\right),$$
$$\alpha=\frac{1}{f}\frac{\partial f}{\partial T},\quad \beta=\frac{1}{2!f}\frac{\partial^2 f}{\partial T^2},\quad \gamma=\frac{1}{3!f}\frac{\partial^3 f}{\partial T^3},\tag{1}$$

where α, β, and γ are called the 1st, 2nd, and 3rd order temperature coefficients, respectively, T_0 is the reference temperature, T is the environment temperature, and $f(T)$ and $f(T_0)$ are the output frequencies of the tuning fork resonator under the temperatures T and T_0, respectively. When choosing the cutting angles θ and ϕ of the quartz resonator, it is generally possible to make sure that the 1st order temperature coefficient is large enough, while the 2nd and 3rd temperature coefficients are very small. Thus, we can guarantee the linearity of the QTF temperature sensor.

On the other hand, the selection of the cutting angle of a QTF also needs to ensure the proper electromechanical coupling coefficient k (proportional to $D'/S'^{1/2}$). D' and S' are dependent mainly on d'_{12} and s'_{22}, which are functions of the cutting angles θ and ϕ, as

$$\begin{aligned}s'_{22}&=s_{11}\cos^4\phi+2s_{13}\cos^2\phi\sin^2\phi\\&\quad+2s_{14}\cos\theta\cos^3\varphi\sin\phi(3-4\cos^2\theta)\\&\quad+s_{33}\sin^4\phi+s_{44}\sin^2\phi\cos^2\phi,\end{aligned}\tag{2}$$

$$\begin{aligned}d'_{12}&=-\cos\phi(-d_{11}\sin^2\theta\cos\theta\cos\phi)\\&\quad-d_{12}\cos^3\theta\cos\phi-d_{14}\cos^2\theta\sin\phi\\&\quad+d_{25}\sin^2\theta\sin\phi+d_{26}\sin^2\theta\cos\phi\cos\theta,\end{aligned}\tag{3}$$

where s_{11}, s_{13}, s_{14}, s_{33}, and s_{44} are the elastic compliance constants of quartz, and d_{11}, d_{12}, d_{14}, d_{25}, and d_{26} are the piezoelectric constants of quartz. The relationship of s'_{22} vs. θ and ϕ is as shown in Fig. 2. The relationship of d'_{12} vs. θ and ϕ is as shown in Fig. 3.

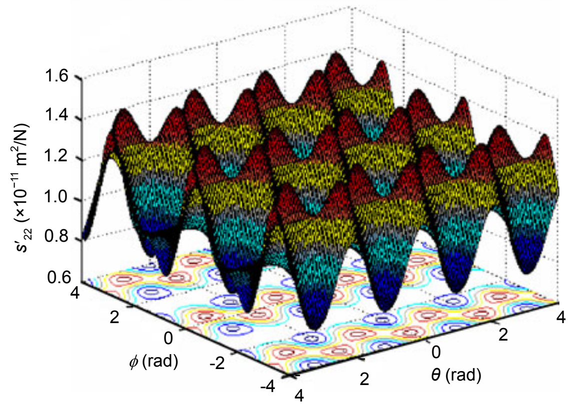

Fig. 2 Relational graph of s'_{22} vs. θ and ϕ

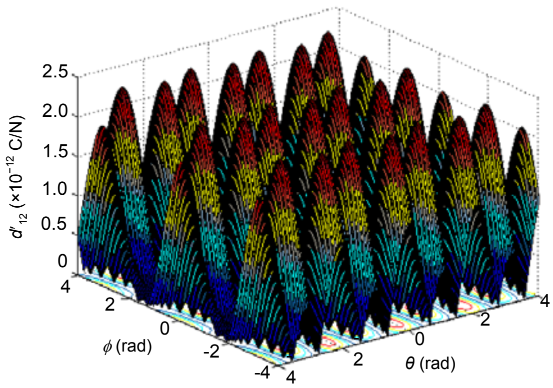

Fig. 3 Relational graph of d'_{12} vs. θ and ϕ

For larger θ, there is a reduction in the valid electric field in the X-axis direction, which worsens the piezoelectricity activity. As a result, coupling with the oscillation circuit will become more difficult. Appropriate adjustment of θ can maintain a better piezoelectricity activity, and can improve the thermo-sensitivity of the sensor. Suitable changes of ϕ will improve the linear property of the sensor. According to fundamental analysis, it has been experimentally determined that the cutting angle θ must be in the range of 117°–119° and that ϕ must be in the range of 17°–19°.

Micro-machined QTF resonators vibrating in a flexural mode are adopted. They have high sensitivity (60×10^{-6}–80×10^{-6}/°C), and satisfy equivalent series resistor and low power dissipation. The basic principle of the tuning fork is well known. 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. From the tuning fork cantilever cross-section, using the QTF as the center axis, the positive strain and negative strain are located separately in the two sides of the QTF. Then, the mirror method is applied to the other tuning fork cantilever, and the electrode is used to incant the QTF. Under normal operation, the tuning fork is excited at its natural frequency and closed-loop electronics keeps the device within resonance frequency. The electrodes are designed as shown in Fig. 4.

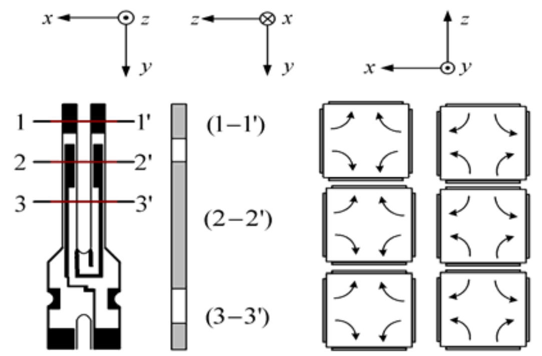

Fig. 4 Cross-section (right) and electrodes (left) of the quartz tuning fork (QTF) resonator

In theoretical analysis, each prong of the tuning fork is assumed to behave as a clamped beam. 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.

These assumptions are valid when the beam length is much larger than its width and thickness. For these assumptions and this vibrating mode, the equation of motion is classical:

$$Z^{(\mathrm{IV})} - \alpha^4 Z = 0, \tag{4}$$

where $\alpha^4=\rho S\omega/(EI)$, IV denotes the 4th order derivative with respect to the length of the beam, and Z is the displacement in the Z-direction of the beam. S is the cross-sectional area of the beam, E is Young's modulus, and $E=1/s_{22}$ for a beam oriented along the crystallographic Y-axis. s_{22} is the elastic constant, I is the inertia of the beam with $I=\omega t^3/12$, ρ is the mass density of material, and ω is the pulsation, $\omega=2\pi f$ where f is the flexural vibration frequency.

The derivation used in this model is based on the Bernoulli beam model where shear effects are neglected and without taking into account the piezoelectric effect. Thus, the equation of motion for this vibrating beam model is (Lee *et al.*, 2004)

$$f = \frac{m_n^2}{4\pi\sqrt{3}} \cdot \frac{W}{L^2} \cdot \sqrt{\frac{1}{\rho S'_{22}}}, \tag{5}$$

where L is the length of the tuning fork cantilever, W is the width of the tuning fork cantilever, m_n is the harmonic coefficient, ρ is the density of the quartz crystal, and S'_{22} is the flexible coefficient. The resonance frequency of the QTF is 35.592 32 kHz (m_n=4.73, W=0.60 mm, L=3.76 mm, ρ=2650 g/m^3, $S'_{22}=0.1413\times10^{-10}$ m^2/N).

Q value of any resonant system is commonly used to represent its frequency control ability. The ordinary tuning fork is packaged in a high vacuum to increase the Q value and to improve the long-term stability. But for the QTF temperature senor, the high Q value will increase the response time of the sensor. Therefore, the Q value needs to be reduced to shorten the response time by packaging the tuning fork using an inert gas (such as helium).

3 Finite element method (FEM) analysis and device fabrication

The theoretical analysis mode is simpler than the FEM to model the QTF. However, the results of the theoretical analysis should be refined using FEM analysis to properly simulate part of the geometrical, electro-mechanical, and other physical effects of the piezoelectric quartz crystal (Söderkvist, 1997). FEM enables a more versatile analysis as to the effects of tuning fork design parameters on the crystal performance. The FEM analysis is based on FEM modeling and takes into account the piezoelectric effect. The piezoelectric equations of $\boldsymbol{e}$ are expressed as

$$\boldsymbol{T} = \boldsymbol{c}^{\mathrm{E}}\boldsymbol{S} - \boldsymbol{e}^{\mathrm{T}}\boldsymbol{E}, \tag{6}$$

$$\boldsymbol{D} = \boldsymbol{e}\boldsymbol{S} + (\boldsymbol{\varepsilon}^{\mathrm{S}})^{\mathrm{T}}\boldsymbol{E}, \tag{7}$$

where $\boldsymbol{T}$, $\boldsymbol{D}$, $\boldsymbol{S}$, $\boldsymbol{E}$, $\boldsymbol{c}^{\mathrm{E}}$, $\boldsymbol{e}$, and $\boldsymbol{\varepsilon}^{\mathrm{S}}$ are the 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 $\boldsymbol{c}^{\mathrm{E}}$, $\boldsymbol{e}$, and $\boldsymbol{\varepsilon}^{\mathrm{S}}$ may change with temperature, only $\boldsymbol{c}^{\mathrm{E}}$ among others is chosen to be effective.

Finite element analysis software ANSYS was applied to analyze the resonance frequency and simulate the vibration mode of the QTF resonator using the ANSYS-code from first vibration mode to sixth vibration. The analysis is based on the finite element modeling including the piezoelectric effect. However, in the actual design of tuning fork crystals, important design parameters must also be considered, such as geometry of the tuning fork blanks and electrodes and other manufacturing requirements.

The dependence of the individual crystal parameters can be comprehensively analyzed using FEM and detailed information on the geometry of the tuning fork blanks and electrodes. For FEM analysis, considering the speed and the precision, the tuning fork was divided into 436 rectangular elements: 264 elements in the bare quartz portion, of which 168 elements are in the arm portion and 96 elements are in the base portion, and 172 elements in the electrode portion (Fig. 5).

The simulation model for the tuning fork is shown in Fig. 5, where all node points on the base side are fixed. The element type used in the simulation is the 3D coupled-field solid element, which has eight nodes with up to six degrees of freedom at each node consisting of three translations, temperature, voltage, and magnetic potential. The results of the simulation are given in Fig. 6.

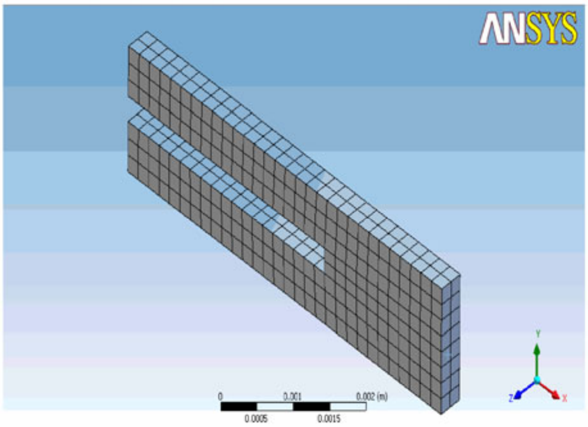

Fig. 5 Mesh generation geometric body of the quartz tuning fork (QTF)

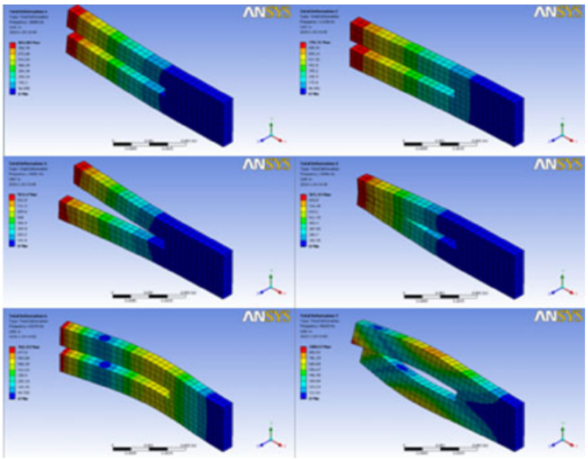

Fig. 6 Vibration mode of the quartz tuning fork (QTF) resonator

The resonance frequency with the fourth vibration mode (resonance frequency 36.906 kHz) is close to that with the theoretical analysis mode (35.592 32 kHz), which is suitable for a sensor with low power consumption and short response time. The value of resonance frequency of the QTF resonator from FEM analysis (36.906 kHz) is 3.7% higher than the value of 35.592 32 kHz from the theoretical model. The discrepancy from the theoretical expression is most likely due to the additional weight of the electrodes, the dependence of the elasticity modulus, and the deviation in geometry.

In the theoretical analysis method, the resonance frequency of the QTF was calculated from the tine width and length. However, in FEM analysis, the tuning fork shape and the electrode configuration are also considered. Therefore, the resonant frequency calculated by FEM is more accurate and close to the actual experimental results (the resonance frequency of the QTF was tested by experiment to be approximatelly 37.02 kHz).

Tuning fork resonators were fabricated from single crystalline ZY-cut quartz wafers by lithography followed by wet etching according to the scheme of Fig. 7. The devices were prepared from synthetic quartz with a *Q*-factor over 6×10^4 on ZY-cut quartz crystal wafers. The ZY-cut quartz wafers were purchased from LongCheng Intelligent Instrument Co., China. The design parameters of the QTF resonator are shown in Table 2 (Lee *et al.*, 2004).

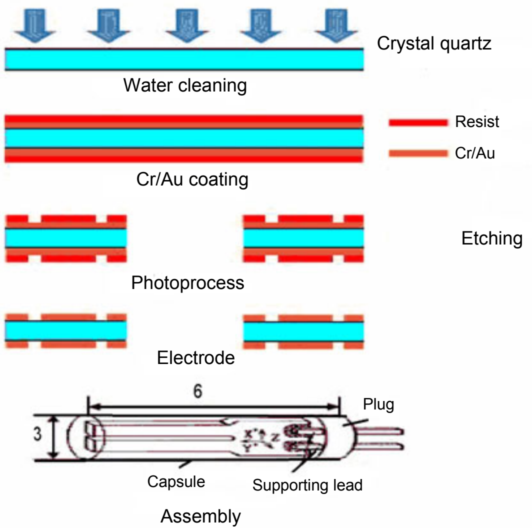

Fig. 7 Fabrication process of the quartz tuning fork (QTF) resonator

Table 2 Design parameters of quartz and the dimensions of the tuning fork (Lee *et al.*, 2004)

Part	Design parameter	Eigenvalue
Quartz bank	Arm length (mm)	3.76
	Width (mm)	0.6
	Thickness (mm)	0.16
	Gap (mm)	0.10
	Base length (mm)	1.00
Face electrode	Thickness (μm)	3
	Width (mm)	0.178
Side electrode	Thickness (μm)	2
Tine tip electrode	Thickness (μm)	5
Cutting angle	θ (°)	118
	ϕ (°)	18

The wafers were initially cleaned using piranha solution (H_2SO_4:H_2O_2=1:1, volume ratio) for 15 min, which was used to remove particles, debris, organic and metallic residues in a class 1000 clean room environment. Cr and Au were evaporated. The quartz was etched in an Alcatel AMS 100 inductively coupled plasma reactive ion etcher using SF6+Ar chemistry. Any remaining nickel mask is etched away using an HNO_3-based wet etching solution. The top and bottom electrodes are defined using lift-off thermally evaporated Cr/Au film on both sides of the wafer (Ren *et al.*, 2010). The etched side with individual bond pads is wire bonded using gold wires and packaged in a metallic cylinder 6 mm in height and 2 mm in diameter, holding a two-terminal electronic component and filled with helium of 90 Pa. Before mounting into the holder the quartz crystal resonators were tempered for 24 h at temperature of 140 °C. This work was done to increase the long-term stability of the temperature sensor and reduce ageing effects.

4 Experiment and results

The QTF temperature sensor can be electrically excited through the tuning fork resonant electrodes. The self-driving mode circuit is shown in Fig. 8. To eliminate the mutual interference and decrease the power consumption, an optimized integrated circuit with low-power shot (CMOS CD4069) was chosen for the oscillator measurement. This circuit offers advantages such as simple configuration, stable performance, as well as its wide adjustment range for parameters of electronic components.

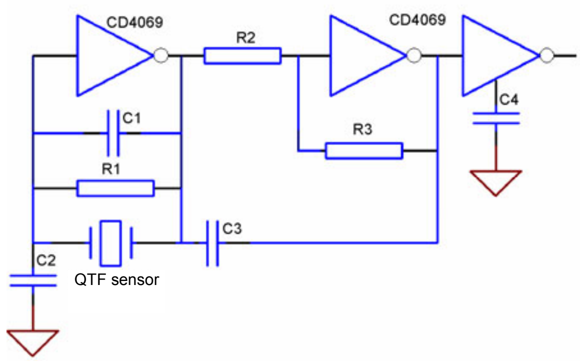

Fig. 8 Oscillation circuit of the quartz tuning fork (QTF) temperature sensor

The parameters of the electronic components of the circuit were optimized in this work. Results showed that a circuit with parameters C1=33 pF, C2=30 pF, C3=20 pF, R1=R2=500 Ω, and R3=200 kΩ could give stable oscillation. To eliminate the mutual interference, a capacitance C4=10 μF was added between each circuit power input terminal and ground to insulate the interfering oscillation wave from other circuits.

The temperature sensitivity of the resonators was measured in the range of 0 to 100 °C. The analysis of the thermo behavior of the QTF resonator has been performed using the experimental setup shown schematically in Fig. 9. The QTF temperature sensor was placed into a temperature oven, which is heated using a hot controller, providing the temperature range from 0 to 100 ºC. The temperature cloud is maintained at a steady value within 0.05 ºC.

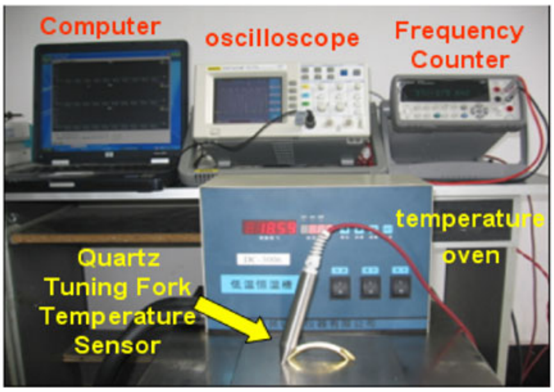

Fig. 9 Setup for the experiment

The frequency of the QTF temperature sensor is connected to an oscilloscope (RIGOL DS5102ACE) and frequency counter (Agilent 34411A). This information can be read out from the oscilloscope and high-precision frequency counter in terms of resonance frequency. Measurements are done from 0 to 100 °C by a 5 °C step. At each temperature, the device was allowed to equilibrate for 20 min before reading the frequency. For each point we had a minimum of 20 separately measured values, the averages of which were used in further analyses of experimental results. The experimental frequency vs. temperature characteristic of the quartz tuning temperature sensor is as shown in Fig. 10.

Fig. 10 indicates that our QTF temperature sensor has a linear temperature coefficient of frequency. From 0 to 100 °C, the resonance frequency shift is about 283 Hz. The thermo-sensitivity of the QTF temperature sensor of approximately -77×10^{-6}/°C is observed. The thermal analysis of our design and ZY-cut angles (θ=118°, ϕ=18°) predict a linear frequency shift near room temperature of -70×10^{-6}/°C. The thermal sensitivity of the QTF temperature sensor closely matches the theoretical analysis result for a new ZY-cut.

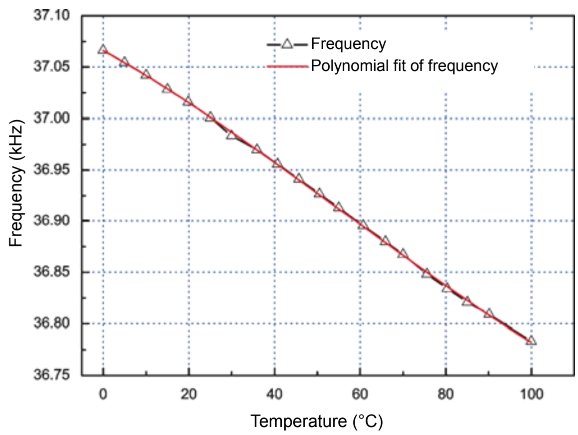

Fig. 10 Frequency-temperature characteristic of the quartz tuning fork (QTF) temperature sensor

The deviation from the linearity of the sensor is as shown in Fig. 11. The largest deviation of the sensor does not exceed ±0.05 °C in a temperature interval from 0 to 100 °C, which is close to the theoretically calculated value. Experimental data for ZY-cut resonators indicate that a maximum frequency deviation of $\pm4\times10^{-6}$ from 0 to 100 °C is possible with optimized quartz ZY-cut.

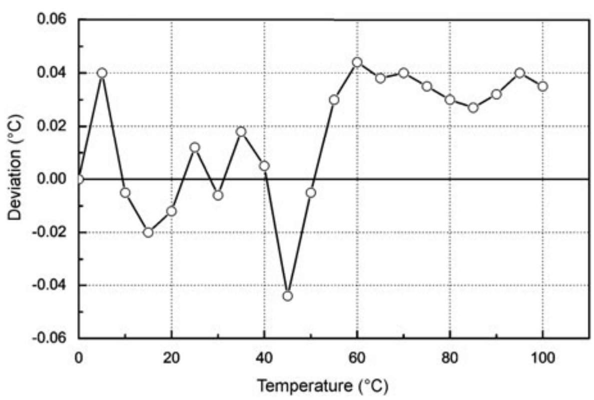

Fig. 11 Deviation analysis results

Deviation=Analytical temp.−Experimental temp.

A significant advantage of the QTF temperature sensor is illustrated in Fig. 12. During a rapid temperature cycling from 0 to 100 to 0 °C (5 °C/min), the increasing and the decreasing temperature processes are plotted. The maximum hysteresis error of the QTF temperature sensor is approximately ±0.005 °C from 0 to 100 °C. The measurement temperature of the QTF temperature sensor vs. the setup temperature of the temperature oven shows almost no hysteresis errors, because there is no physical separation between the thermometer and the QTF resonator.

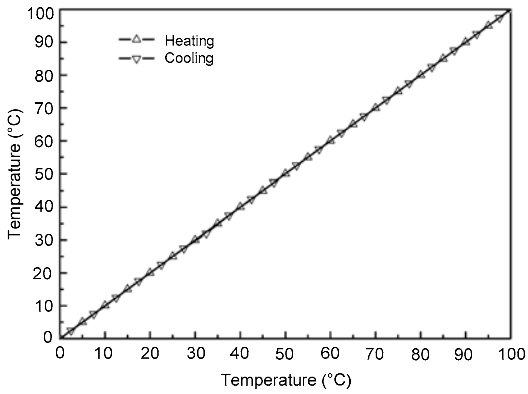

Fig. 12 Hysteresis charactertics of the quartz tuning fork (QTF) temperature sensor

Fig. 13 presents the response time of the QTF temperature sensor. The response time of the proposed micro QTF temperature sensor is determined to be 4.5 s to recover from 0 to 100 °C. The stability of the QTF temperature sensor is tested in the measurement system. Setting the test temperature at 30, 60, and 90 °C, the frequency of the QTF temperature sensor was read every 30 min for a total of 48 h (Fig. 14). Fig. 14 shows very nice stability of the QTF temperature sensor. The maximum fluctuation of resonance frequency of the QTF temperature sensor values was in the range ±0.06 Hz or 2×10^{-6} (the worst case). The reliability test for the QTF temperature sensors was done for temperature ranging from 0 to 100 °C. The quartz crystal tuning fork temperature sensors all worked normally over 1000 times during the test. The typical parameters of QTF temperature sensors are shown in Table 3.

From early research results (Wade and Slutsky, 1962; Smith and Spencer, 1963; Hammond *et al.*, 1964; Dinger, 1982; Spassov, 1992; Spassov *et al.*, 1997), temperature sensors based on quartz

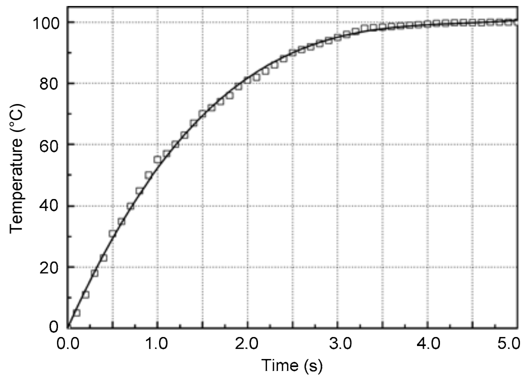

Fig. 13 Response time of the quartz tuning fork (QTF) temperature sensor

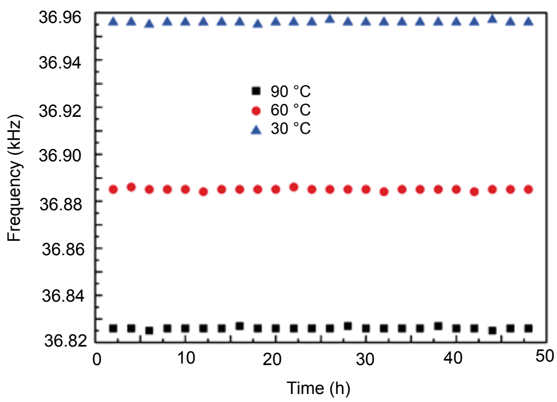

Fig. 14 Stability of the quartz tuning fork (QTF)

Table 3 Design parameters of quartz and the dimensions of the tuning fork

Parameter	Value
Standard frequency, *f* (kHz)	37
Load capacitance (pF)	8
Quality factor, *Q*	60 000
Motional capacitance, C1 (fF)	0.5
Motional resistance, R1 (kΩ)	40
Shunt capacitance, C0 (pF)	2
Drive level (μW)	0.3
Aging	2×10^{-6}

resonators that vibrate using the thickness shear modes (TSMs) present a high resonance frequency up to 10–28 MHz, which is more higher than the resoance frequency of the QTF resonator of our design (37.02 kHz). This will lead to larger power consumption of sensors and high frequency output signals are easily affected by electromagnetic interference. For the QTF temperature sensor working at tensional vibration mode (Dinger, 1982) and flexural vibration mode (Ueda *et al.*, 1986; He *et al.*, 2003), the former has a worse linearity and the latter has lower thermal sensitivity of $(55\times10^{-6}–65\times10^{-6})$/°C.

5 Conclusions

In summary, the study successfully demonstrated a new micro thermo-sensitive QTF resonator based temperature sensor. The design, fabrication, and experimental characterization of a QTF temperature sensor based on ZY-cut quartz bulk acoustic wave resonators have been presented. Using micromachining techniques, a high thermal sensitivity of the QTF temperature sensor vibrating in flexural mode was realized. The flexural vibration mode is analyzed by the theoretical analytical model and FEM method.

The QTF with a resonance frequency of 37.02 kHz and a typical load capacitance of 8 pF parked in a sealed metal container was used. Experiments indicate that the QTF temperature sensor shows a high thermal sensitivity and a shift infrequency that is steady, repeatable, and reliable. On a temperature transition from 0 to 100 °C, the QTF registered a drop in frequency of 283 Hz with a response time of 4.5 s. A very small change in frequency due to change in temperature can be detected. The temperature test results show that the temperature sensor designed in this paper exhibits an accuracy of 0.1 °C.

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