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Implement and Research on the Miniature Quartz Tuning Fork Temperature Sensor

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Abstract: Temperature sensor using piezoelectric quartz tuning fork resonators have attracted much interest due to their simple structure and potentially high sensitivity. In this paper, we present the fundamental limits of the use of quartz tuning fork (QTF) for temperature sensor. The QTF temperature sensors are tuning fork quartz crystal vibrating in flexural model and optimally designed with a thermal cut, which their frequency is both extremely sensitive to temperature and high linear. The QTF temperature sensor using frequency-based technique which resonance frequency is about 35.6 kHz at 25 °C has the advantage of being immune to amplitude noise in the measurement system and a thermo-sensitivity of roughly -77×10^{-6}/°C. This high thermal sensitivity offers the ability to detect fine changes in temperature. Based on the finite element method, the QTF vibratory modes are analyzed, the size of the QTF beam and the structure of the QTF temperature sensor have optimized and resigned. Experimental results show the QTF temperature sensor with an accuracy of 0.05 °C and a useable resolution of roughly 0.005 °C with a temperature range from 0 °C to 100 °C. This work presents a miniature QTF temperature sensor with a high thermo-sensitivity and small non-linearity. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Miniature temperature sensor, Quartz crystal, Tuning fork resonator, Thermal cut, Flexural model, Finite element method.

1. Introduction

Precise temperature measurement is an important part of modern metrology. High performance temperature sensor plays an essential role in designing high-precise temperature measuring and control systems [1-2]. Traditional thermocouples, platinum thermometers and semiconductor electron thermometers are getting more and more unsuitable for measurement and control of high technological processes parameters and productions. Quartz temperature sensor is inherently insensitive to noise because the output is a frequency shift caused by an external temperature and has a fast response, a high sensitivity and a high resolution [3].

Due to its high stability, precision and low power consumption, the QTF resonators have been utilized not only as a basic component for frequency measurements but also for different sensors to detect different quantities [4]. Those frequency-based techniques inherently insensitive to noise because the output is a frequency signal and can be easily converted into a digital signal that can directly be connected to a micro-controller without an AD converter [5]. QTFs have been proven to be extremely useful as sensors for temperature, humidity, mass, force, density and gyroscopes [6-13].

Recent advances in materials and micromachining technology have offered exciting new technologies for detection in high performance sensors [14]. 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 the capability of compatibility with the integrated circuit process and can be operated at an ultra low voltage while consuming only microwatts of power [15-17].

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. Experiments have been carried out on 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 simulation using FEM results are compared with the experimental results.

2. Sensor Design

2.1. Thermal cut of the QTF

The basic principle of the tuning fork is well known. A tuning fork is a simple metal 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 as shown in Fig. 1. The QTF packaged in a metallic cylinder 8 mm in height and 3 mm in diameter, holding a two-terminal electronic component and filled with helium of 90 Pa.

Fig. 1. SEM image of QTF.

The QTF temperature sensors are tuning fork quartz crystals using a new cut and vibrating in a flexural mode. 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. The temperature coefficients are highly dependent on the crystallographic orientation of the plate. 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 as shown in Fig. 2.

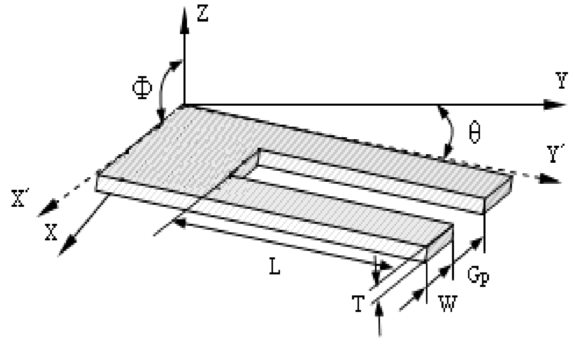


Fig. 2. Thermal-cut Crystallography of QTF.

The frequency temperature characteristic (FTC) of QTF is mainly dependent on the cutting angles θ and Φ, which is written mathematically as $f_T=F(\theta, \Phi)$. Although the frequency temperature characteristic of QTF temperature sensor is nearly linear, it is not exactly so. The temperature frequency characteristic of each resonator can be represented by a polynomial of nth order and has the form of different cuts [5]. While higher order polynomial models are possible, a second order model is usually sufficient. A better model is a second order polynomial in temperature:

$$\begin{gathered}\frac{f(T)}{f(T_0)} = 1+\alpha\Delta T+\beta\Delta T^2 \\ \alpha=\frac{1}{f}\frac{\partial f}{\partial T}, \beta=\frac{1}{2!f}\frac{\partial^2 f}{\partial T^2}\end{gathered} \tag{1}$$

where $\Delta T=T-T_0$, α and β are so called the 1st and 2nd 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 big 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 for sensor, the selection of the cutting angle of a QTF also needs to ensure the proper electromechanical coupling coefficient k (proportional to $D'/S'^{1/2}$). The piezoelectric constants of quartz ***D*** and the elastic compliance constants of quartz ***S*** are mainly dependent on $\boldsymbol{d}'_{12}$ and $\boldsymbol{s}'_{22}$, which are functions of the cutting angles $\boldsymbol{\theta}$ and $\boldsymbol{\Phi}$. The FTC relation of cut(θ, Φ) is as shown in Fig. 3.

For larger $\boldsymbol{\theta}$, 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 $\boldsymbol{\theta}$ can maintain a better piezoelectricity activity, and can improve the thermo- sensitivity of the sensor. Suitable changes of $\boldsymbol{\Phi}$ will improve the linear property of the sensor. According to the fundamental analysis, it has been experimentally determined the cutting angle θ must be in the range of 60°–90° and Φ must be in the range of 20°–40°.

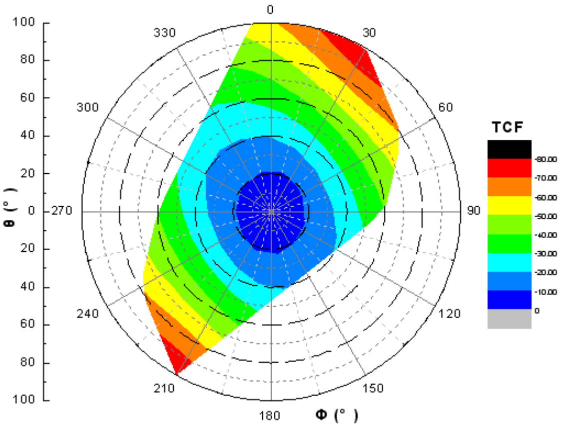


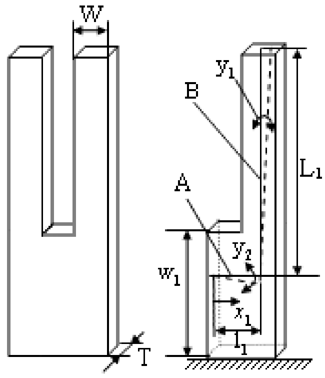
Fig. 3. The relationship of FTC vs. cutting angle (θ,Φ).

Micro-machined QTF resonators vibrating in a flexural mode are adopted, which have high sensitivity (60–80×10^{-6}/°C), satisfied equivalent series resistor and low power dissipation. Deeply study the FTC, When we chose the cutting angle of the quartz resonator, generally, it was the temperature sensitivity and linearity degree that always valued. According to fundamental analysis, we choice (62°/29°) thermal-cut. It is show that it is possible to construct a miniature quartz tuning fork temperature sensor with high sensitivity and small non-linearity.

2.2. Modeling of the QTF

Let us consider cantilever of thickness T, width W and length L in a rectangular system. 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 one end and one free boundary conditions as shown in Fig. 4. These assumptions are valid when the beam length is much larger than its width and thickness. In this study analyzed the frequency of a QTF, in consideration of the clamped position of the base of tuning fork, on the basis of Sezawa's approximation [18]. The electrodes are designed as shown in Fig. 5.

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.



(a) (b)

Fig. 4. (a) Over configuration and (b) configuration of the right half of a quartz crystal tuning fork resonator.

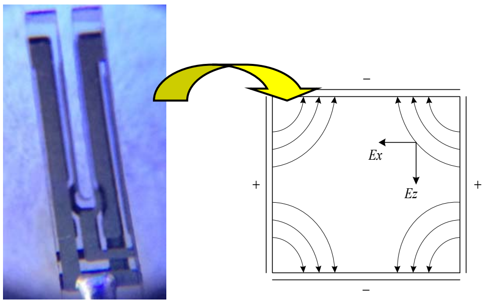


Fig. 5. Electrodes of QTF resonator.

The equations of motion of the beams A and B, undergoing flexural vibration, are expressed by

$$A_1\frac{\partial^2 y_1}{\partial t^2}+\frac{E_1 I_1}{\rho}\frac{\partial^4 y_1}{\partial x_1^4}=0\,, \qquad (2)$$

$$A_2\frac{\partial^2 y_2}{\partial t^2}+\frac{E_2 I_2}{\rho}\frac{\partial^4 y_2}{\partial x_2^4}=0 \qquad (3)$$

Thus, the equation of motion for this vibrating beam model is

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

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 35.6 kHz at 25 °C.

3. 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 method should be refined using FEM analysis to properly simulate part of the geometry, electro-mechanical, and other physical effects of the piezoelectric quartz crystal [15]. 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 e are expressed as

$$\boldsymbol{T} = \boldsymbol{c}^E \boldsymbol{S} - \boldsymbol{e}^{\mathrm{T}} \boldsymbol{E} \,, \tag{5}$$

$$\boldsymbol{D} = \boldsymbol{e}\boldsymbol{S} + [\boldsymbol{\varepsilon}^S]^T \boldsymbol{E} \,, \tag{6}$$

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, electromechanical 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 c^{E} among others is chosen to be effective [16, 19].

In FEM analysis, the resonance frequency and vibration mode analysis are carried out by harmonic analysis [20]. Considering solid material with losses, stress, electric potential distribution and equivalent circuit parameters as shown in Fig. 6.

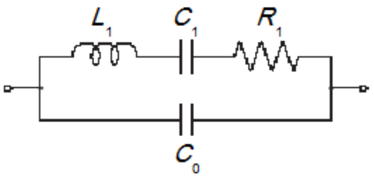


Fig. 6. Equivalent circuit of QTF resonator.

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. The analysis is based on the finite element modeling including the piezoelectric effect. 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: 528 elements in the bare quartz portion, of which 336 elements are in the arm portion and 192 elements are in the base portion, and 354 elements in the electrode portion as shown in Fig. 7.

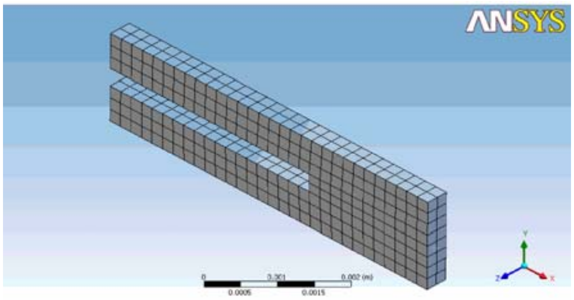


Fig. 7. Mesh generation geometric body of QTF resonator.

The simulation model for the tuning fork, 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 result of the simulation is given in Fig. 8.

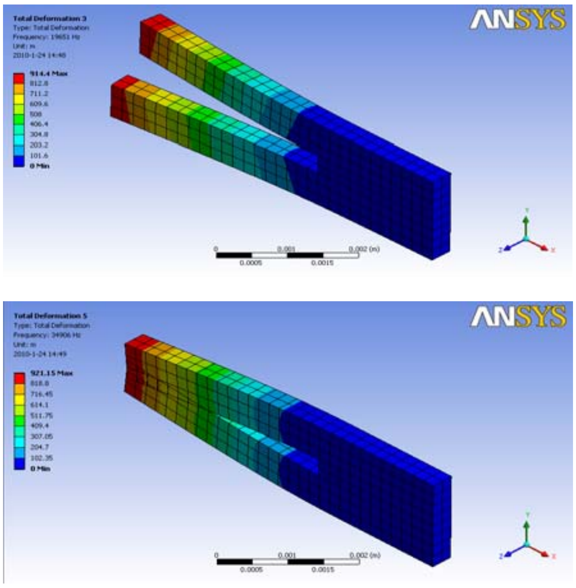


Fig. 8. Vibration mode of QTF resonator.

The resonance frequency with the fourth vibration mode (resonance frequency 36.906 kHz) is closed to the theoretical analysis mode (35.592 32 kHz), which is suitable for a sensor with low power consumption and fast 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 the 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 approximately 37.02 kHz). The design parameters of the QTF resonator are shown in Table 1 [15].

Table 1. Design parameters of quartz and the dimension of the tuning fork [12].

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 (°)	62
	Φ (°)	29

The flexural vibration tuning fork has Cr-Au electrodes. The quartz tuning fork temperature sensors are prepared of synthetic quartz with Q-factor over 6×10^4 on ZYtw-cut plates. The resonators are installed in standard capsules of package Φ3×8 holders and filled with Helium of 90 Pa is shown in Fig. 9. Before mounting into the holder the quartz crystal resonators were tempered for 48 hours at temperature of 140 °C. This work was done to make a pre-ageing to increase long-term stability of the temperature sensor and reduce ageing effects.

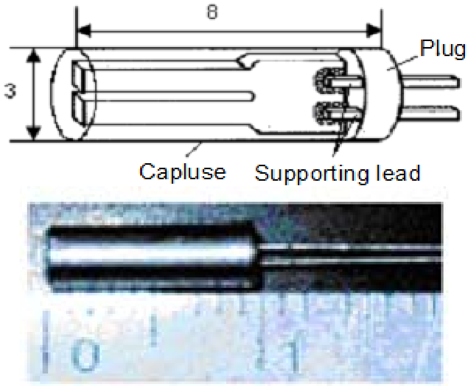


Fig. 9 Mounting structure of QTF resonator.

4. Experiment and Results

The survey of the electrical parameters of the quartz tuning fork resonators was flowed by precise temperature-frequency analyses. The test system for measuring temperature-frequency characteristic of the quartz crystal tuning-fork resonators is shown in Fig. 10.

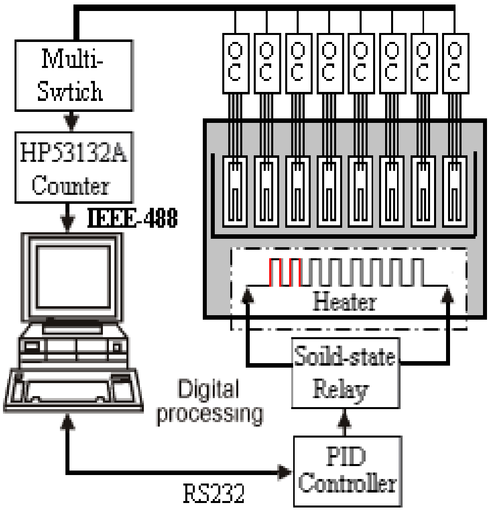


Fig. 10. Setup for the experiment.

It includes personal computer (PC) for digital processing and display, the quartz tuning fork temperature sensor array with eight samples, a multi-switch controlled by PC, a home-made oscillation circuit (OC) was used to drive the quartz crystal frequency, a high precise frequency counter (Agilent 34411A) with IEEE-488 interface and a temperature sensor (Pt1000 resistor) was mounted as heater and was driven by DC power supply. The temperature of the heater was controlled by a solid-state relay (SSR, Omron GSNA) and standard proportional-integral-derivative (PID) digital temperature controller with RS232C interface, the temperature of the chamber was controlled by standard PID algorithm with a gradient of the temperature field less than 0.05 °C. Temperature fluctuation as well as the gradient of temperature field was additionally diminished by putting the investigated sample in an aluminum block, which is placed in the working chamber.

QTF has high quality factor, which permits a precise measurement of the resonant frequency by placing in a tuned electrical circuit and exciting into self oscillation. The frequency of the QTF temperature sensor is connected to a frequency counter (Agilent 34411A). This information can be read out from high-precision frequency counter in terms of resonance frequency. Measurements are done from 0 to 100 °C by 5 °C steps. At each temperature, the device was allowed to equilibrate for 30 min before reading the frequency. For each point we had a minimum of 30 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. 11.

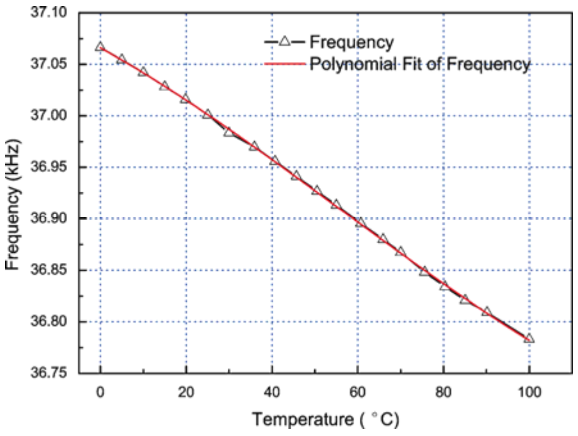


Fig. 11. FTC of QTF temperature sensor.

In Fig. 11, it indicates that our QTF temperature sensor has a linear temperature coefficient of frequency. From 0 °C 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 thermal-cut angles (θ=62°, Φ=29°) 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 for a new thermal-cut.

The deviation from the linearity of the sensor is as shown in Fig. 12. The largest deviation of the sensor does not exceed ±0.05 °C in a temperature interval from 0 °C 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 °C to 100 °C is possible with optimized quartz thermal-cut.

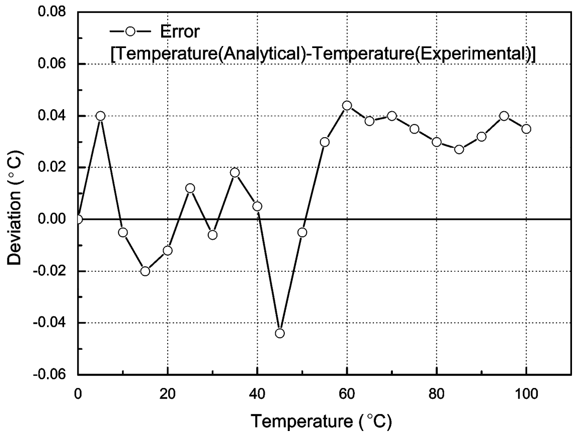


Fig. 12. Deviation analysis curve.

A significant advantage of the QTF temperature sensor is illustrated in Fig. 13. During a rapid temperature cycling from 0 °C to 100 °C 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 °C to 100 °C. The measurement temperature of 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. 14 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 °C to 100 °C.

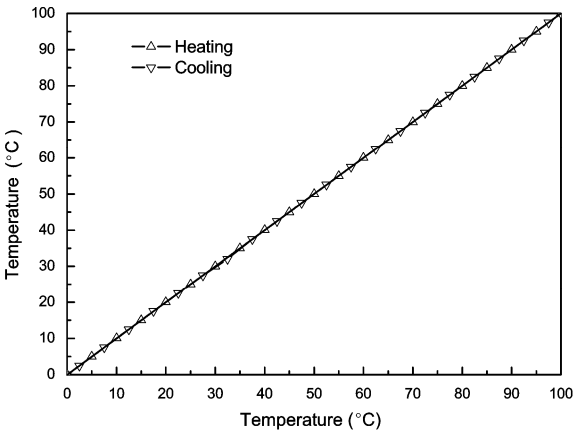


Fig. 13. Hysteresis characteristic of QTF temperature sensor.

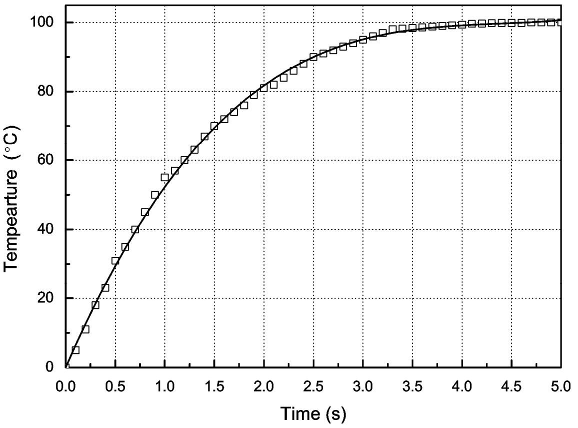


Fig. 14. Response time of QTF temperature sensor.

The stability of the QTF temperature sensor is tested in the measurement system. Setting the test temperature at 30 °C, 60 °C and 90 °C, the frequency of the QTF temperature sensor was read every 30 min for a total of 48 h (Fig. 15).

Fig. 15 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 °C 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 2.

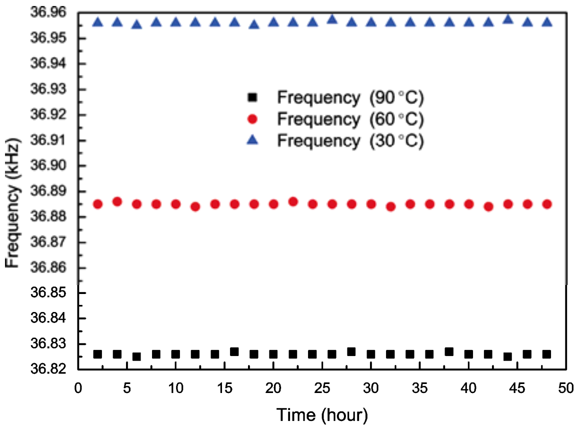


Fig. 15. Stability of QTF temperature sensor.

Table 2. Typical parameters of QTF temperature sensor.

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

5. Conclusions

The use of QTF resonators as temperature sensor has been demonstrated. The thermal cut of QTF was obtained by the theoretical analytical and experimental solution. The resonance frequencies of QTF were analyzed by the Sezawa's approximations method of the equation of motion with pertinent boundary conditions and the FEM method.

It was shown that the measurement of temperature in a thermal application is using self excitation of QTF. The QTF with a resonance frequency of 37.02 kHz at 25 °C parked in a sealed metal container was used. On a temperature transition from 0 °C 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 precision of the temperature sensor designed in this paper exhibits an accuracy of 0.05 °C. Experiments indicate that the QTF temperature sensor show a high thermal sensitivity and a shift infrequency that is steady, repeatable and reliable.

Acknowledgements

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