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# Temperature Dependence Estimation of the Vibration and Frequency Sensor Resonator Mechanical State

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**Abstract**

The complex of technological and metrological researches concerning development of filamentous monocrystals application and fixing methods on various materials of substrate (elastic elements) is considered. The ways of uncontrolled distortions avoiding of the initial monocrystal defect-free structure that can occur at the nodes of its mounting and reduce the Q-value of the resonator oscillations, which is the main characteristic of the tensotransducer quality, is shown. With this the monocrystal mechanical state should correspond to the stress at which its heating from the electric power supply current would not cause a noticeable monocrystal compression. The temperature dependence of deformation of a monocrystal resonator, which is a sensitive element of a vibration and frequency sensor in the operation temperature range, is studied. The factors that determine the temperature dependent deformation component of the resonant tensotransducer made of the semiconductor monocrystal are analyzed. The directions of vibration and frequency sensors characteristics optimization are indicated by purposeful control of the monocrystal deformation initial level, which is achieved by the choice of appropriate structural materials, as well as technological methods of their production.

**Keywords:** filamentous monocrystal; semiconductor; resonator; tensotransducer; frequency; sensor.

## 1. Introduction

The analysis of the current state of sensors development and production confirms that one of the most promising methods to improve their metrological and operational characteristics is the application of information processing algorithmic methods. However, this requires a sufficiently high stability of the characteristics in the time and reproducibility of the measurement results by the sensors themselves. The most acceptable for this are transducers of the input quantity into an electric signal that varies by frequency. The most widely used are transducers with mechanical resonators which are Q-value oscillatory systems [1–8].

Particular attention should be paid to resonance tensotransducers from filamentous monocrystals of silicon and silicon- germanium alloy [9, 10], which are grown by the method of chemical transport reactions, have a perfect crystal structure and have no defects. The monocrystals elastic properties exceed the properties of bulk crystals by a factor of hundreds, and their strength limit corresponds to a deformation of several percent. This set of properties permits the implementation of a monocrystals-based oscillatory system with the maximum possible Q-value, stability and reliability. A small value of the silicon density ($2.33 \cdot 10^3\ kg/m^3$) allows supporting the oscillations at minimum values of excitation energy. The breaking strength of monocrystals with diameter $5\ 10^{-6}\ m$ reaches up to $10^9\ N/m^2$, which ensures the maximum (as compared to any other known materials) value of its own frequency per unit length of the crystal. The oscillating element from the tenzosensitive monocrystal changes its electrical resistance at deformations due to its transverse oscillations, which allows removing from the element an alternating electric signal with tens of millivolts voltage.

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Such semiconductor vibration and frequency sensors with sensitive elements in the form of monocrystal electromechanical resonators showed high sensitivity, stability, linearity and reproducibility of the output signal characteristics [11].

The monocrystal initial mechanical state, that is its deformation at zero input signal, determines the basic output characteristics of the vibration and frequency sensor. Therefore, studies were conducted to improve output characteristics by purposeful regulation of this deformation.

The study of monocrystals deformation temperature dependence determines dilatometric properties of the resonators being developed and their production technology.

## 2. Principle of vibration and frequency sensor resonator operation

The principle of the resonator operation is illustrated in Fig. 1. Structurally it contains a lining 1 (elastic element) from silicon, sapphire, quartz, ceramics, on the surface of which a metal film 2, which serves as an exciting electrode, is preformed. The ends of the crystal 3 with current conductors 4 are fixed in the nodes 5 on the plate. When using the lining from a semiconductor material, the excitation electrode is the plate itself, on the surface of which an electrical contact 6 is formed.

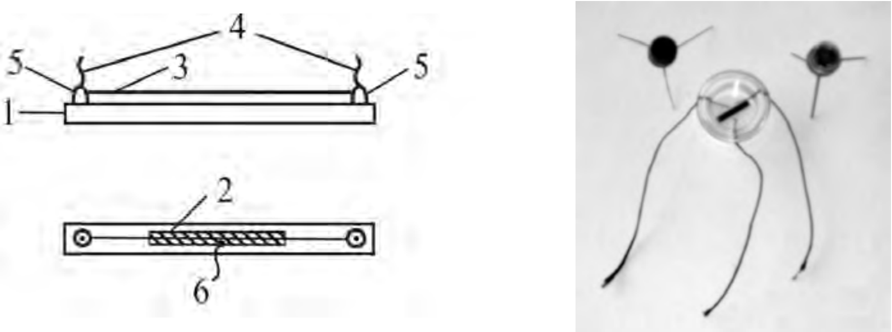

Fig. 1. Design scheme and general form of the electromechanical resonator

Under the effect of electrostatic excitatory force between the crystal and the lining, a transverse mechanical oscillations of own frequency arise in the monocrystal, which, as a result of the tensoeffect, are converted into electrical oscillations with a doubling frequency [11]. With the external mechanical effect on the lining, its deformation is transformed (transferred) to the monocrystal changing the frequency of its own mechanical oscillations, and hence the output signal frequency.

One of the research areas related to the improvement of sensors metrological characteristics was the development of monocrystals application and fixing methods with the help of glass crystal cements on different types of substrates.

## 3. Mathematical model of the resonator mechanical state

The initial deformation $\varepsilon_O$ of the monocrystal which is rigidly fixed on the lining can be represented as a sum of two components: temperature independent $\varepsilon_{ON}$ and temperature dependent $\varepsilon_{OT}$

$$e_O(T) = e_{ON} + e_{OT}(T)\ .$$

In the case of applying alternating voltage the electrostatic force of interaction between the monocrystal and the exciting electrode will lead to monocrystal dynamic deformation, which consists of the constant component of tension $\varepsilon_{OE}$ and the harmonic component of tension $\bar{e}_{OE}$. The components $\varepsilon_{OE}$ and $\varepsilon_O(T)$ determine the transducer resonant frequency. The constant component of monocrystal deformation can thus be presented as

$$e_O(T) = e_{ON} + e_{OE} + e_{OT}(T)\ .$$

If the monocrystal thickness is much lower than the thickness lining, then temperature dependent deformation component is determined by the temperature coefficients of linear expansion (TCLE) of the monocrystal material $\alpha_M$

and the lining material $\alpha_L$, as well as a technological parameter such as a temperature of monocrystal fixed nodes $T_O$ forming. It can be assumed that in the creation process of rigidly fixed nodes at the temperature $T=T_O$ the temperature dependent deformation component will be equal to zero, and when a rigid connection is already established, the change in temperature will lead to monocrystal deformation, which is proportional to the difference of the monocrystal and lining materials TCLE and temperature difference $T–T_O$.

The deformation that occurs from the TCLE inconsistency of two elements, which are connected together at a temperature $T$, can be estimated approximately

$$e_{OT} = (a_L - a_M)(T - T_O). \tag{1}$$

Here $\alpha_L$ and $\alpha_M$ are TCLE, which are averaged in some temperature interval.

Due to the fact that the TCLE are essentially a function of temperature, and their difference sometimes depends very much on the temperature, the estimation (1) can give a significant error in the calculations. Therefore, it is expedient in this case to apply an integral dependence

$$e_{OT}(T) = \int_{T_O}^{T} (a_L(T) - a_M(T))\, dt\ . \tag{2}$$

The feature of monocrystal resonator fixing is that in the presence of a gap between lining and monorystal, the monocrystal overheating may occur due to the allocation of Joule heat at the passage of electric current and internal friction in the oscillating crystal itself. This overheating will become stronger as the heat transfer conditions from the monorystal get worse, for example, if the monorystal is in the vacuumed part of the pressure transducer. As a result of overheating, the temperature of the monocrystal will exceed the elastic element temperature $T$ at a certain value $\Delta T$. For this case, formula (2) should be written in the modified form

$$e_{OT}(T) = \int_{T_O}^{T} (a_L(T) dt - \int_{T_O}^{T+\Delta T} a_M(T)\ dt. \tag{3}$$

Expression (3) shows an important feature of vibration and frequency sensor tensotransducer resonator work in monocrystal overheating. This feature consists in the fact that $\varepsilon_{OT}(\mathrm{T})\neq 0$, even if the monocrystal and lining are made of homogeneous materials, i.e. $\alpha_L=\alpha_M$.

In order to evaluate the dilatometric properties of monocrystal resonators, a package of applied programs was made and the temperature dependences of the temperature dependent deformation component for silicon monocrystals that are fixed on elastic elements from different nonmetallic structural materials were calculated. To do this, we use the TCLE temperature dependences [12]. The results of calculations are shown in Fig.2 – 5, which shows the temperature change of temperature dependent deformation component of the monocrystal, which is fixed on the lining from various materials. The calculations were made for $T_O=470\ °C$, which corresponds to the conditions of fixed nodes monocrystal production from a glass cement with a certain filler.

Optimization of the vibration and frequency sensors characteristics by crystal tension adjustment allows solving two problems:

1. To optimize the initial tension in the excited monocrystal $\varepsilon_{ON}+\varepsilon_{OE}$.

2. To achieve the minimum temperature dependence of the temperature dependent deformation component $\varepsilon_{OT}$ in the operating temperature range of the vibration and frequency sensor tensotransducer resonator.

The need to solve the first problem is dictated by the fact that a strongly tensioned monocrystal has a higher transverse rigidity, which reduces the amplitude of the frequency output signal at excessive monocrystal tension up to its practical termination. At the same time, the pre-compressed monocrystal is in an unstable mechanical state, which excludes the stable operation possibility of the vibration and frequency sensor resonator. The optimal variant will be a small (close to zero) initial tension, when $\varepsilon_O>0$, i.e. the monocrystal in the mechanical state is close to free. The fact of maintaining this condition when temperature changes (the solution of second problem) should ensure the vibration and frequency sensor output signal linearity and stability in the whole range of operating temperatures.

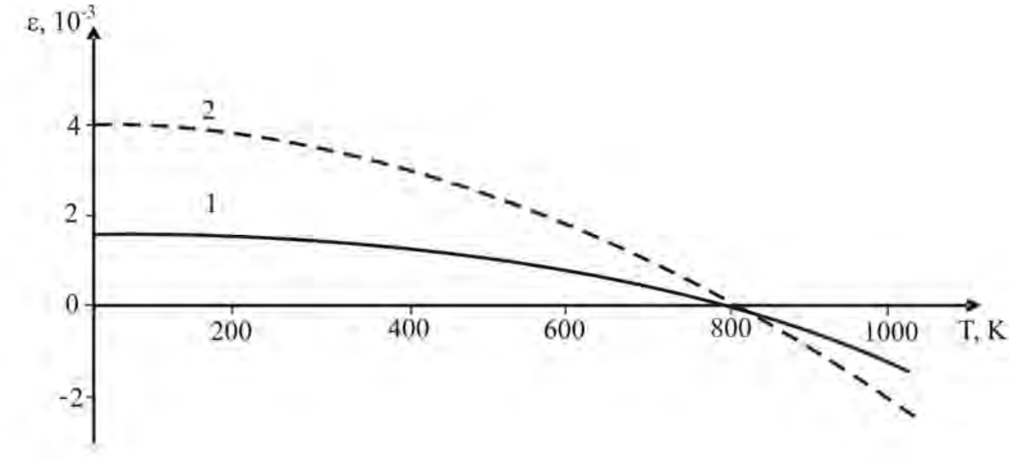

Fig. 2. Dependence $\varepsilon_{OT}(T)$ for silicon (1) and germanium (2)
monocrystals on the lining of fused quartz

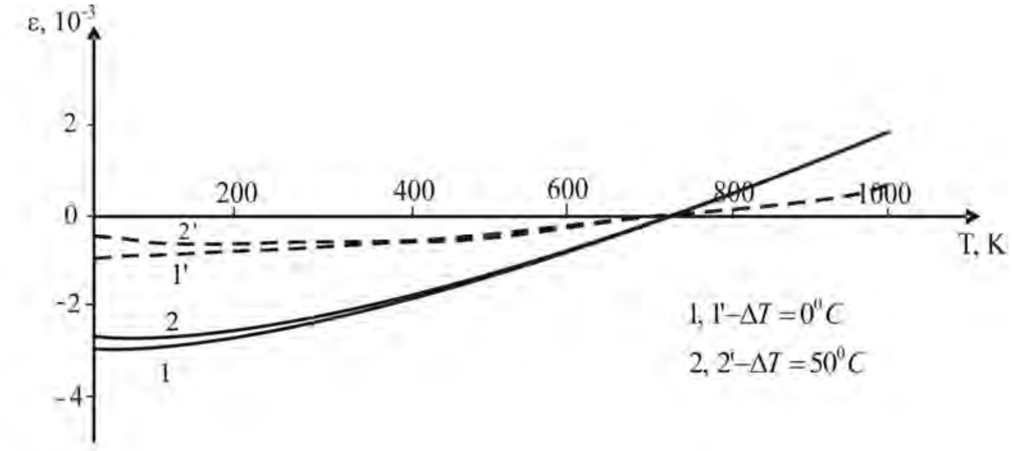

Fig. 3. Dependence $\varepsilon_{OT}(T)$ for silicon $(1,\ 2)$ and germanium $(1',\ 2')$
monocrystals on the lining of sapphire

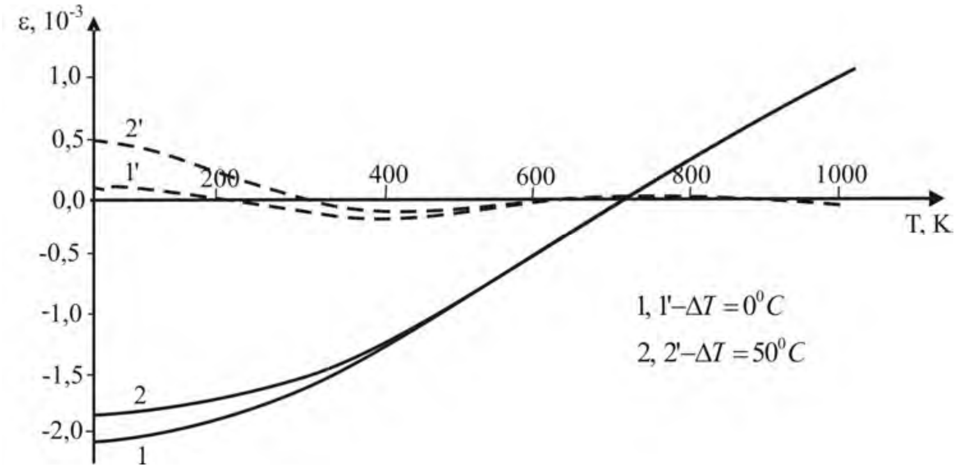

Fig. 4. Dependence $\varepsilon_{OT}(T)$ for silicon $(1,\ 2)$ and germanium $(1',\ 2')$
monocrystals on the lining of technical ceramics $(22XC)$

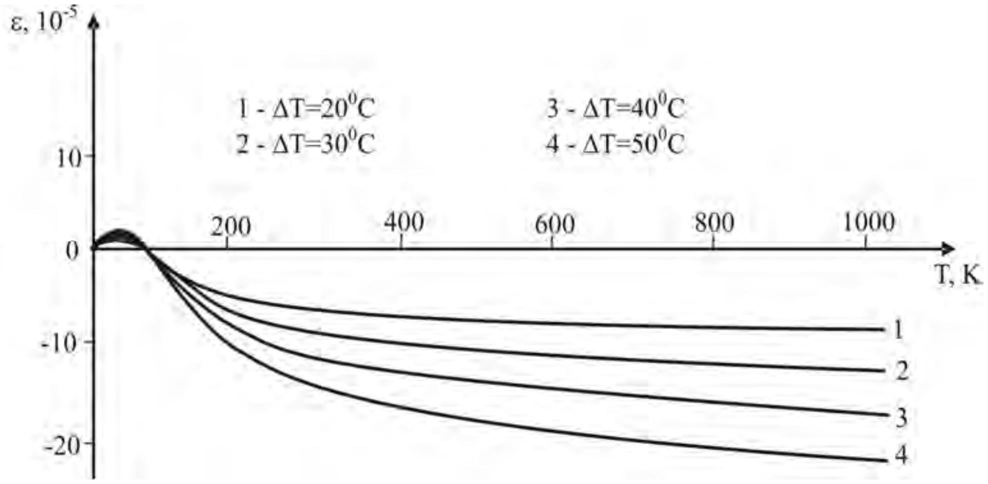

Fig. 5. Dependence $\varepsilon_{OT}(T)$ for silicon monocrystal on the lining of monocrystal silicon

The regulation of the temperature independent component of the initial monocrystal tension can be achieved by a number of technological methods when creating monocrystal fixing nodes. In particular, deformation component $e_{ON}$ can be changed by monocrystal fixing on a pre-deformed lining. Then, after the creation of rigid fixing nodes and after the load lifting from the lining, a certain monocrystal deformation level is created, which at a certain temperature $T$ can partially or completely compensate for the temperature dependent deformation component $\varepsilon_{OT}$.

The choice of the material for the creation of fixing nodes and the mode of thermal treatment allows regulating through the temperature change $T_O$ not only deformation component $\varepsilon_{ON}$, but also deformation component $\varepsilon_{OT}$.

Consequently, if the operating temperature range of the vibrating and frequency sensor resonator is sufficiently wide, then it is possible to achieve a critically minimum temperature dependence of deformation component $\varepsilon_{OT}$. Fig. 2–4 show that in temperature range *0–100*°C this condition is fulfilled for silicon monocrystals on the lining of fused quartz and for germanium monocrystals on the lining of ceramics and sapphire.

Good results can be obtained by using monocrystals of a silicon and germanium solid solution, since, by regulating the solid solution composition, it is possible to smoothly control its TCLE between the values $\alpha$ for silicon and germanium.

Important are the results shown in Fig. 5, for a silicon monocrystal on the monocrystal silicon lining. Overheating of the monocrystal in relation to lining ensures a slight monocrystal compression slightly dependent on the temperature practically throughout the all temperature range, which is compensated by the tension deformation component $\varepsilon_{ON}$,, that occurs when the excitation voltage is applied to the monocrystal. Consequently, the condition of a small initial monocrystal tension is carried out without any additional technological measures.

## 4. Conclusion

The results of the research prove the possibility of the characteristics optimization of the resonators which are sensitive elements of the vibration and frequency sensors by ensuring control of the monocrystal mechanical state. Such optimization can be achieved: by selecting of the monocrystal and lining materials to ensure the best adjustment of their TCLE in the range of operating temperatures; through the choice of material for the creation of monocrystal fixing nodes on the lining; by the mode of thermal treatment; through the special technological methods of monocrystal fixing on a pre-deformed lining; by using of homogeneous materials to ensure the consistent operation of the monocrystal and the lining in a wide range of temperatures.

Such studies are important in the design of sensors because they ensure the necessary level of their metrological quality.

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# Оцінювання температурної залежності механічного стану резонатора вібраційно-частотного сенсора

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**Анотація**

Розглянуто комплекс технолого-метрологічних досліджень щодо розроблення методів посадки і закріплення ниткоподібних монокристалів на різних матеріалах підкладок (пружних елементів). Показано шляхи уникнення неконтрольованих спотворень вихідної бездефектної структури монокристала, які можуть виникати у вузлах його кріплення і знижувати добротність коливань резонатора, яка є основною характеристикою якості тензоперетворювача. Механічний стан монокристала повинен відповідати напруженню, за якого його нагрівання від електричного струму живлення не спричинило би помітного стиску монокристала. Досліджено температурну залежність деформації монокристалічного резонатора – чутливого елемента вібраційно-частотного сенсора в робочому температурному діапазоні. Проаналізовано чинники, що визначають температурно-залежну складову деформації резонансного тензоперетворювача з напівпровідникового монокристала. Вказано напрями оптимізації характеристик вібраційно-частотних сенсорів шляхом цілеспрямованого контролю початкового рівня деформації монокристала, що досягається вибором відповідних конструкційних матеріалів, а також технологічними способами їх виготовлення.

**Ключові слова:** ниткоподібний монокристал; напівпровідник; резонатор; тензоперетворювач; частота; сенсор.