



**HAL**  
open science

# Temperature Dependence of Sensitivity of Silicon Integrated Mechanical Transducer in The Temperature Range from $-60^{\circ}\text{C}$ to $+200^{\circ}\text{C}$

M. Yu. Tikhomirov, Yu. M. Spalek, V. N. Borshchev

► **To cite this version:**

M. Yu. Tikhomirov, Yu. M. Spalek, V. N. Borshchev. Temperature Dependence of Sensitivity of Silicon Integrated Mechanical Transducer in The Temperature Range from  $-60^{\circ}\text{C}$  to  $+200^{\circ}\text{C}$ . Technology. Technology of Instrument Making: Scientific and Technical Collection, 1988, 13 (2), pp.80-100. 10.13140/RG.2.2.35275.67362/3 . hal-04163200

**HAL Id: hal-04163200**

**<https://hal.science/hal-04163200v1>**

Submitted on 20 Jul 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

# Temperature Dependence of Sensitivity of Silicon Integrated Mechanical Transducer in The Temperature Range from -60°C to +200°C

Michael Y. Tikhomirov; Yuriy M. Spalek; Viacheslav N. Borshchev.

Published in 1988: Technology. Technology of Instrument Making: CSTI 'Poisk' (Volume: 13, Issue: 2, p.80-100, 1988), USSR

## Abstract

This article presents an investigation of the temperature dependence in integrated silicon resistive transducers (IRTs) used in mechanical sensors. IRTs employ a DC bridge measurement circuit with four piezoresistors to convert strain in an elastic element. The circuit transfer function determines the conversion characteristic, which is dependent on both temperature and strain. Two requirements are discussed in the manufacturing and design of IRTs to achieve a null normalized output ( $K_0(T) = 0$ ). The article explores the impact of various factors, such as contact dimensions, resistivity, and impurity concentration distribution, on the temperature instability coefficient and the strain sensitivity coefficients. Experimental results and theoretical calculations are provided to illustrate the temperature dependence of the transducer gauge factor and the resistance. The findings contribute to a better understanding of the temperature behavior of IRTs, which is essential for designing accurate and reliable mechanical sensors.

In integrated silicon resistive transducers (IRT) used in mechanical sensors, a DC bridge measurement circuit consisting of four piezoresistors<sup>1 2</sup> is used to convert the strain of an elastic element. The conversion characteristic of this circuit is determined by the transfer function, denoted as  $k$ , which depends both on the temperature and the strain:

$$k = K_0(T) + K(\varepsilon_x, T) \quad (1)$$

Here,  $K_0(T)$  represents the null normalized output of the transfer function in the absence of an input mechanical quantity, and  $K(\varepsilon_x, T)$  denotes the conversion coefficient for the deformation (or the difference in principal deformations) of the elastic element due to the influence of the input mechanical quantity.

When the circuit is supplied from a stabilized voltage source  $U_{in}$ , where  $U_{in}$  is constant, the output signal of the circuit is given by:

$$U_{out} = U_{in} \cdot k = U_{in} [K_0(T) + K(\varepsilon_x, T) \cdot \varepsilon_x] \quad (2)$$

Similarly, when supplied from a stabilized current source  $I_{in}$ , where  $I_{in}$  is constant, the output signal is defined as:

$$U_{out} = I_{in} \cdot R_{in} [K_0(T) + K(\varepsilon_x, T) \cdot \varepsilon_x] \quad (3)$$

Here,  $R_{in}$  represents the input resistance of the measuring circuit.

In expression (2), the term  $K(\varepsilon_x, T)$  completely determines the temperature dependence of the transducer Gauge Factor (GF) when the second component  $K_0(T) = 0$ . The latter condition can be achieved by meeting specific requirements in the manufacturing technology and design of the IRT, which include:

- Minimizing the variation of electrical resistance in silicon p-type resistors around their average values and ensuring the temperature characteristics of the resistors are identical.

- Minimizing the magnitudes and spreads of the initial n-type silicon elastic element (EE) deformations in the regions where the piezoresistors are located.

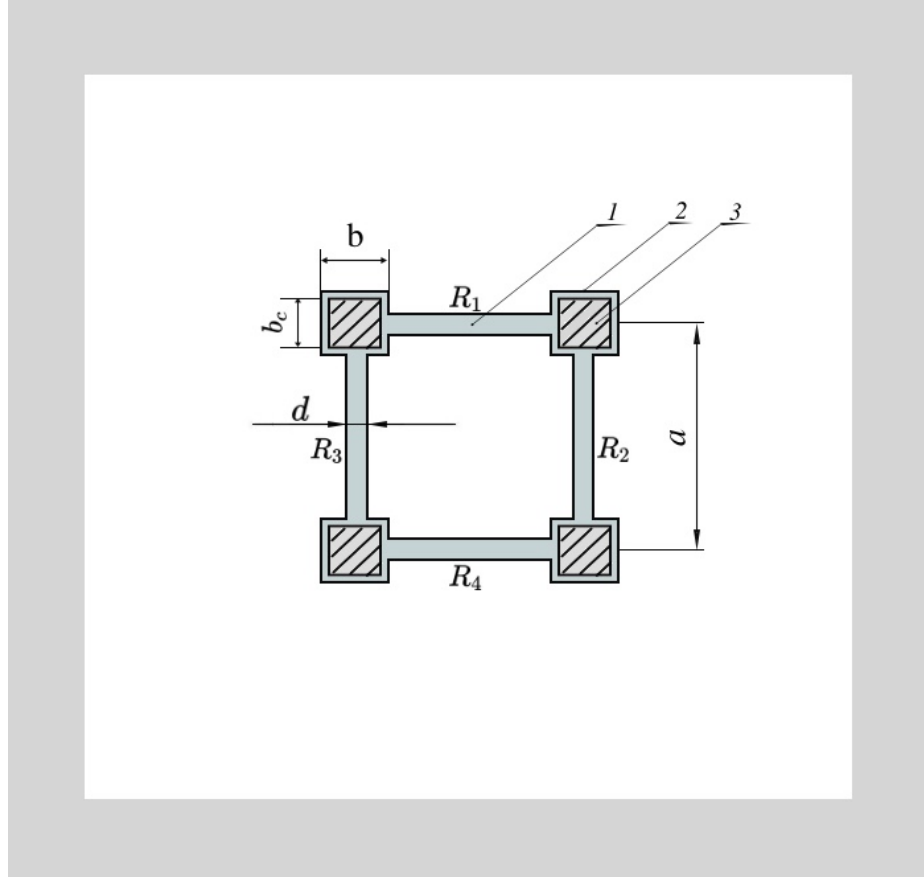


Figure 1: Topological structure of a symmetric four-branch bridge circuit. 1-piezoresistive channel; 2-diffusion contact pad of p-type; 3-contact "Al-Si (p-type)".

In domestic practice, the highest precision in reproducing the dimensions of elastic elements (EEs) is achieved through local anisotropic etching of weakly and medium-alloyed silicon wafers oriented in the (100) plane<sup>3</sup>. This method is suitable for shaping the most commonly used types of EE<sup>4</sup>. In such integrated resistive transducers (IRTs), piezoresistors, which are doped with acceptor impurity, are aligned parallel to the faceted EE along the crystallographic directions [110]. Due to the identical stress states of the regions where the longitudinal and transverse piezoresistors are located, small deformations cause proportional changes in the resistances of the piezoresistors, with magnitudes close to each other and opposite in sign.

To achieve the condition  $K_0(T) = 0$ , a measuring circuit with a symmetric four-arm bridge circuit (BC) is often used, as depicted in Figure 1. BC consists of equal square contact areas of size  $b$  located at the vertices of a square of size  $a$ . These contact areas are interconnected by four single-band piezoresistive channels, with longitudinal piezoresistors ( $R_1$  and  $R_3$ ) and transverse piezoresistors ( $R_2$  and  $R_4$ ) having a width of  $d$ .

Assuming  $K_0(T) = 0$ , the transfer function  $k$  of the conversion characteristic of such a BC is determined by the following equation:

$$k = 2 \cdot K_{\parallel} \cdot \varepsilon_{x_0} \cdot \left[ \frac{1 - \frac{K_{\perp}}{K_{\parallel}} \cdot \frac{(\varepsilon_{x_4} + \varepsilon_{x_2})}{2\varepsilon_{x_0}}}{\left[ 2 + K_{\parallel} \cdot \varepsilon_{x_0} \cdot \left( 1 + \frac{K_{\perp}}{K_{\parallel}} \cdot \frac{\varepsilon_{x_2}}{\varepsilon_{x_0}} \right) \right] \cdot \left[ 2 + K_{\parallel} \cdot \varepsilon_{x_0} \cdot \left( 1 + \frac{K_{\perp}}{K_{\parallel}} \cdot \frac{\varepsilon_{x_4}}{\varepsilon_{x_0}} \right) \right]} \right] \quad (4)$$

Here,  $K_{\parallel}$  and  $K_{\perp}$  represent the longitudinal and transverse GFs of the silicon channel layer, respectively.  $\varepsilon_{x_0}$  denotes the strain value of the EE in the geometric centers of the piezoresistor channels  $R_1$  and  $R_3$ , while  $\varepsilon_{x_2}$  and  $\varepsilon_{x_4}$  correspond to the strain values in the geometric centers of the piezoresistor channels  $R_2$  and  $R_4$ , respectively.

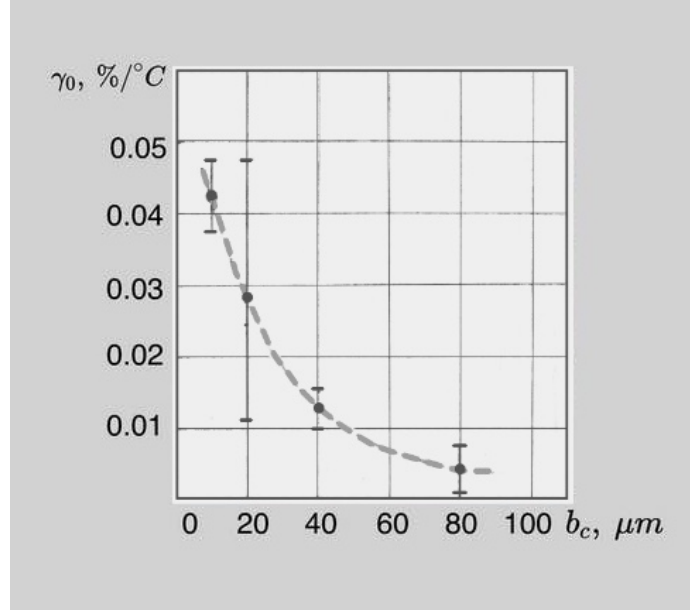


Figure 2: Graph of the temperature instability coefficient versus contact size.

To ensure sensor operation at temperatures up to  $+200^{\circ}\text{C}$ , the total area of the insulating p-n junction, denoted by  $S$ , should not exceed  $5 \times 10^{-4} \text{ cm}^2$ . This area can be calculated using the formula  $S = 4b^2 + 4d(a - b)$ .

In our experiment, we investigated BC tests with different contact dimensions ( $b_k$ ) using Al-pSi structures formed by boron ion implantation at a doping dose of  $1 \times 10^{15} \text{ cm}^{-2}$  ( $80 \text{ } \Omega/\square$ ). Contact diffusion regions of  $p^+$  type had a surface resistance of  $8 \div 10 \text{ } \Omega/\square$ . Figure 2 graphically shows the dependence of the temperature instability coefficient,  $\gamma_0$ , defined as  $\gamma_0 = \frac{K_{0\text{max}} - K_{0\text{min}}}{K_{0(T=0^{\circ}\text{C})}} \cdot 100\%$ , on the contact size  $b_k$  when BC is supplied from a stabilized DC voltage source.

By setting the lower limit of  $\gamma_0$  to  $0.02\%/\text{°C}$ , we choose the minimum contact dimensions as  $b_c = 50 \text{ } \mu\text{m}$  and the corresponding diffusion alloyed contact areas as  $b = 60 \text{ } \mu\text{m}$ . Typical values of  $R_{in}$  for BC range from  $500$  to  $800 \text{ } \Omega$ . For a channel width of  $d = 20 \text{ } \mu\text{m}$  and a surface resistance of the ion-doped layer of  $80 \text{ } \Omega/\square$ , the channel length ( $a - b$ ) falls within the range of  $(180 \div 250) \text{ } \mu\text{m}$ , resulting in a total junction area of p-n of  $(2 \div 3) \times 10^{-4} \text{ cm}^2$ .

BCs with such dimensions can be assembled on miniature membrane and beam EEs. When the size of the elastically deformable part of the EE is greater than  $2 \times 2 \text{ mm}$ , the assumption  $\varepsilon_{x_2} \approx \varepsilon_{x_4} \approx \varepsilon_{x_0}$  holds. In this case, Equation (4) simplifies to:

$$k = 0.5 \cdot K_{\parallel} \cdot \varepsilon_{x_0} \left( 1 - \frac{K_{\perp}}{K_{\parallel}} \right). \quad (5)$$

The electrical resistance function of the piezoresistor  $R$  (or  $R_{in}$  for BC) as a function of temperature, at  $\varepsilon_x = 0$ , exhibits two extremes. The first (minimum) is attributed to a change in the mechanism of scattering of free charge carriers at  $T_{\text{min}} < 273 \text{ K}$ . The second (maximum) is caused by the appearance of intrinsic conductivity at  $T_{\text{max}} > 400 \text{ K}$  <sup>5</sup>.

The temperature range ( $T_{\text{min}}, T_{\text{max}}$ ) can be considered as the natural operating range and the thermal compensation range.

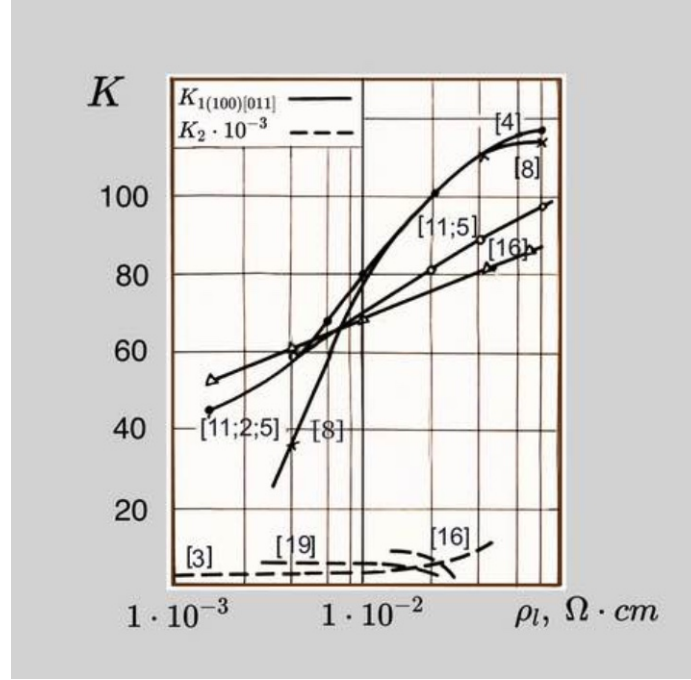


Figure 3: GFs dependence plot on resistivity of uniformly doped p-type silicon layers

Within the range  $T \in (T_{\min}, T_{\max})$ , the resistance of the semiconductor material increases monotonically with increasing temperature and is described by the following dependence<sup>6</sup>:

$$R(T) = R_0 [1 + A_1(T - T_0) + A_2(T - T_0)^2] \quad (6)$$

Here,  $T_0$  represents the temperature in the middle of the selected operating range,  $R_0$  is the resistance of the layer at  $T = T_0$ , and  $A_1$  and  $A_2$  are the coefficients of linear and quadratic resistivity temperature.

The relative change in the resistance of the piezoresistor due to deformation, denoted as  $\frac{\Delta R}{R}$ , can be expressed using the article's notation<sup>7</sup>:

$$\frac{\Delta R}{R} = K_1 \cdot \varepsilon + K_2 \varepsilon^2 + \dots \quad (7)$$

Here,  $K = \frac{\Delta R}{R \cdot \varepsilon}$  represents the GF, which can be decomposed as  $K = K_1 + K_2 \varepsilon + \dots$ .  $K_1$  corresponds to the linear coefficient of GF,  $K_2$  represents the quadratic coefficient of GF and  $\varepsilon$  denotes the relative strain of the piezoresistive channel.

The temperature dependence of the coefficients  $K_1$  and  $K_2$  exhibits a complex character<sup>8, 9</sup>, and the understanding of this relationship is not yet complete<sup>10</sup>.

To ensure comparability between the results of previous studies and the results obtained in this work, we present the relationship<sup>7</sup> in the following form:

$$\frac{\Delta R}{R} = \left[ K_{A_1} + K_{B_1} \frac{T_0}{T} + K_{C_1} \left( \frac{T_0}{T} \right)^2 \right] \varepsilon + \left[ K_{A_2} + K_{B_2} \frac{T_0}{T} + K_{C_2} \left( \frac{T_0}{T} \right)^2 \right] \varepsilon^2, \quad (8)$$

or for GF:

$$\frac{\Delta R}{R \cdot \varepsilon} = (K_{A_1} + K_{A_2} \cdot \varepsilon) + (K_{B_1} + K_{B_2} \cdot \varepsilon) \frac{T_0}{T} + (K_{C_1} + K_{C_2} \cdot \varepsilon) \left( \frac{T_0}{T} \right)^2. \quad (9)$$

Now, taking into account expressions (2) and (3), the BC output signals (reduced to the parameter of the power supply) will be determined by the following relations:

$$\frac{U_{\text{out}}}{U_{\text{in}}} = K_0(T) + (K_{A_1} + K_{A_2} \cdot \varepsilon) \cdot \varepsilon + (K_{B_1} + K_{B_2} \cdot \varepsilon) \frac{T_0}{T} \cdot \varepsilon + (K_{C_1} + K_{C_2} \cdot \varepsilon) \left(\frac{T_0}{T}\right)^2 \cdot \varepsilon \quad (10)$$

$$\begin{aligned} \frac{U_{\text{out}}}{I_{\text{in}}} &= R_{\text{in}0} \cdot \left[ K_0(T) + (K_{A_1} + K_{A_2} \cdot \varepsilon) \cdot \varepsilon + (K_{B_1} + K_{B_2} \cdot \varepsilon) \frac{T_0}{T} \cdot \varepsilon + (K_{C_1} + K_{C_2} \cdot \varepsilon) \left(\frac{T_0}{T}\right)^2 \cdot \varepsilon \right] \times \\ &\times \left[ 1 + A_1 (T - T_0) + A_2 (T - T_0)^2 \right] \end{aligned} \quad (11)$$

where  $R_{\text{in}0}$  is the resistance to the BC input at  $T = T_0$ .

To proceed with the analysis, let us assume that at  $\varepsilon = 0$ , the resistances of the piezoresistors ( $R_1, R_2, R_3, R_4$ ) are equal to  $R$ , and thus  $K_0 = 0$ .

The electrophysical characteristics (EPhCh) of a piezoresistor are integral functions of the impurity concentration distribution  $N$  in its channel along the direction  $Z$ , perpendicular to the planar surface of the integrated resistive transducer (IRT). In previous studies<sup>11 12</sup>, the EPhCh is related to the surface concentration  $N_s$ , which is calculated using the known value of  $N$  at a depth  $x_j$  from the p-n junction isolating the channel, as well as the resistance value of the channel surface ( $R_s$ ). This relationship assumes that the distribution of  $N$  follows a Gaussian function or a complementary error function (erfc).

However, in certain cases, such as when  $N \approx 10^{20} \text{ cm}^{-3}$ , this assumption can lead to an error of half an order of magnitude in determining  $N_s$ , as discussed in the referenced work<sup>11</sup>. Therefore, it is proposed to integrate the known erfc for uniformly doped silicon using the actual impurity distribution. Studies on the piezoresistive coefficient ( $\pi$ ) in uniformly doped silicon have been conducted<sup>13 7 14</sup>.

In the established technological process of forming the p-type piezoresistor channel on the n-type substrate, where the usual ratio is  $N_a/N_d \gg 1$ , the characteristics of the piezoresistor are well reproducible when the parameter  $\bar{\rho}_l = R_s \cdot \bar{x}_j$  of the piezoresistive layer is reproducible. Within a small interval of variation of  $\bar{\rho}$ , the relationship between the EPhCh and this value is equivalent, in terms of informativeness, to a similar relationship in homogeneously doped silicon. This is due to the weak dependence of  $\left[\left(\frac{dz}{d\rho(x_j)}\right)\right]^{-1}$  on changes in the upper integration limit, limited by the scatter from the nominal ( $N_{d_{\text{nom}}}$ ) impurity concentration in the substrate, when  $N_a/N_d \gg 1$ . Therefore, in a well-established process, we can consider  $\frac{dR_s}{R_s} \approx -\frac{dx_j}{x_j}$ . In the subsequent analysis, the study of the piezoresistive layers will be related to the parameter  $\bar{\rho}_l$ .

In IRTs with a planar surface aligned with the plane (001) and piezoresistors oriented along the crystallographic direction [110], the strain coefficients  $K_{(100)[011]}$ , as described in<sup>15</sup>, can be expressed by the following relationship:

$$\frac{\Delta R}{R \cdot \varepsilon_{x_0}} = \pm 0.5 (1 - \nu_{12}) \cdot E_{12} \left[ \pi_{44} \pm (\pi_{11} + \pi_{12}) \frac{1 + \nu_{12}}{1 - \nu_{12}} \right] = \pm 7.9 [\pi_{44} \pm 1.13 \cdot (\pi_{11} + \pi_{12})] \quad (12)$$

Here, the positive sign corresponds to the longitudinal strain coefficient  $K_{\parallel}$ , and the negative sign corresponds to the transverse strain coefficient  $K_{\perp}$ .  $E_{12}$  and  $\nu_{12}$  represent Young's modulus and Poisson's coefficient, respectively, in silicon along the crystallographic direction [011].  $\pi_{44}$  represents the main shear piezoresistive coefficient in  $Pa^{-1}$ .

Limited information is available on the concentration and temperature dependencies of the main longitudinal ( $\pi_{\parallel}$ ) and transverse ( $\pi_{\perp}$ ) piezoresistive coefficients. It is known that  $\pi_{11}$  decreases with increasing impurity concentration from  $2 \times 10^{-11} Pa^{-1}$  in  $N = 3 \times 10^{18} \text{ cm}^{-3}$  to  $1 \times 10^{-11} Pa^{-1}$  at  $N = 1 \times 10^{21} \text{ cm}^{-3}$ <sup>16 17</sup> (which is above the limit of boron solubility in silicon). The compressibility coefficient of volume ( $\pi_{11} + \pi_{12}$ ) has a positive sign and is approximately equal to  $(1-2) \times 10^{-11} Pa^{-1}$  for the mentioned concentrations<sup>17</sup>. However, some authors<sup>18 4</sup> argue that due to the small values compared to  $\pi_{44}$ , the coefficients  $\pi_{11}$  and  $\pi_{12}$  can be neglected, indicating that  $|K_{\parallel}| = |K_{\perp}|$ .

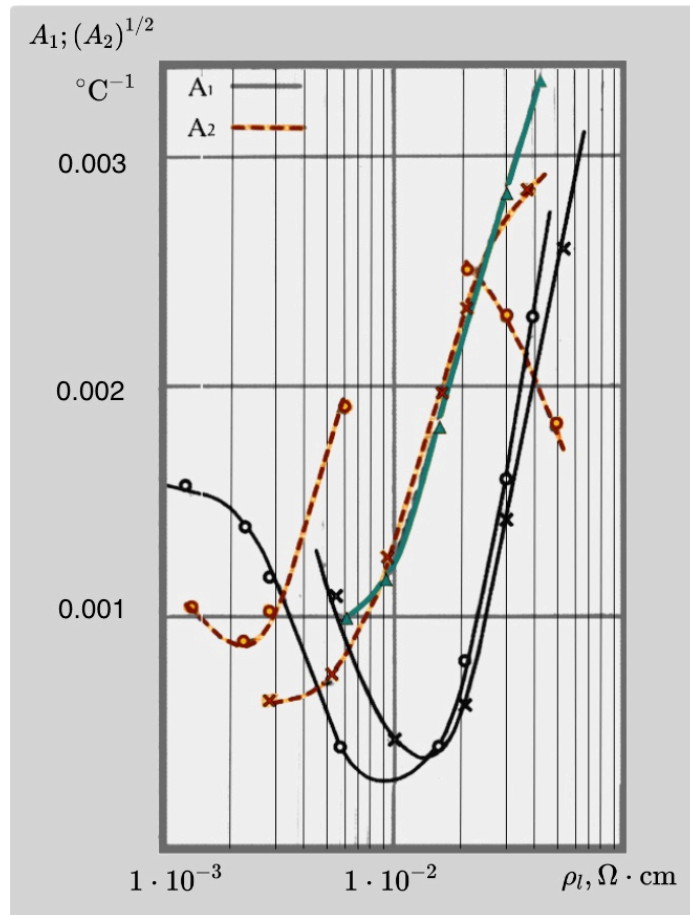


Figure 4: Dependence of the approximation coefficients of the temperature dependences of resistance on the resistivity ( $\rho_l$ ) for silicon p-type:  $\times$ -diffusion-doped layers <sup>22</sup> (experimental data);  $\circ$ -diffusion-doped layers <sup>11</sup> (experimental data);  $\text{—}$  - uniformly doped layers <sup>23</sup> (calculated data)

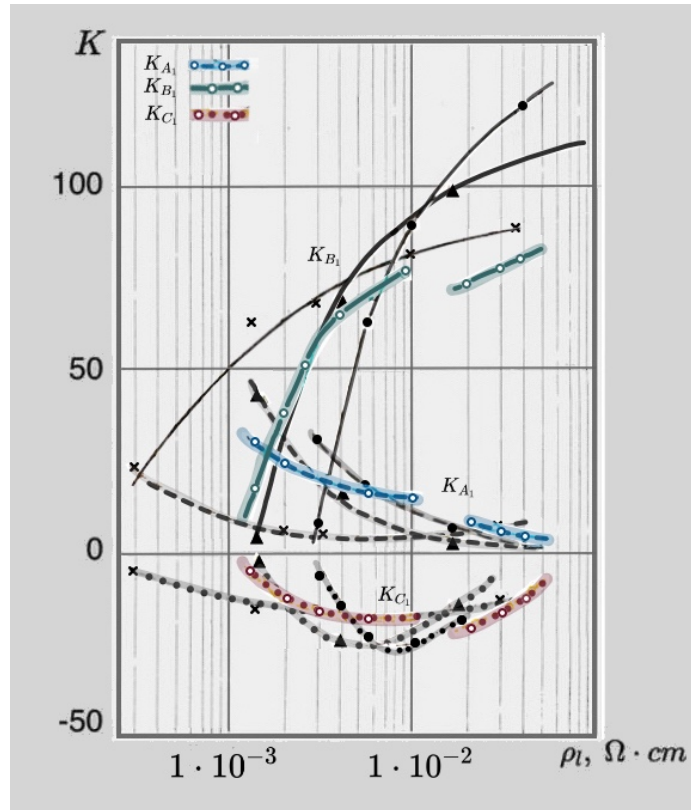


Figure 5: Graph of approximation coefficients of temperature dependences of GF for silicon p-type layers;  $\blacktriangle$  - uniformly doped layers [2] (experimental data);  $\bullet$  - uniformly doped layers [8] (calculated data);  $\times$  - diffusion layers [6] (experimental data);  $\circ$  - dependences obtained from studies of diffusion piezoresistive channels



Figure 3 illustrates the dependencies of the linear coefficient  $K_1$  and the quadratic coefficient  $K_2$  on the doping level, based on data from various sources<sup>4 7 8 9 14 13 16</sup>. For convenience of comparison, the dependences  $K_2$  are presented as products of their values by the relative strain of silicon equal to  $1 \times 10^{-3}$  (the limit of use). From the graph, it can be seen that the value of  $K_2 \times 10^{-3}$  does not exceed 10

Assuming the nominal output signal of the bridge circuit (BC) is 100 mV with  $U_{in} = 10$  mV, and using Equation (2) with (5) for the minimum value of  $K_{1(100)[011]} = 33$  (as shown in Figure 3), the strain  $\varepsilon_{x_0}$  would be equal to  $3 \times 10^{-4}$ .

In the subsequent analysis, we consider that  $K_2 \times \varepsilon$  is negligible compared to  $K_1$  in Equation (7), and Equations (10) and (11) are simplified as follows:

$$K_u(T) = \frac{U_{out}(T)}{U_{in} \cdot \varepsilon_{x_0}} = K_{A_1} + K_{B_1} \cdot \frac{T_0}{T} + K_{C_1} \cdot \left(\frac{T_0}{T}\right)^2 \quad (13)$$

$$K_i(T) = \frac{U_{out}(T)}{I_{in} \cdot \varepsilon_{x_0}} = R_{in_0} \cdot [1 + A_1 \cdot (T - T_0) + A_2 \cdot (T - T_0)^2] \left[ K_{A_1} + K_{B_1} \cdot \frac{T_0}{T} + K_{C_1} \cdot \left(\frac{T_0}{T}\right)^2 \right] \quad (14)$$

Here,  $K_u(T)$  represents the sensitivity coefficient of the BC when powered from a stabilized voltage source, and  $K_i(T)$  represents the sensitivity coefficient of the BC when powered from a stabilized current source.

Figures 4 and Figure 5 show the dependencies of the approximation coefficients for the resistance temperature variations ( $A_1, A_2$ ) and the sensitivity coefficients ( $K_{A_1}, K_{B_1}, K_{C_1}$ ) on the resistivity of the piezoresistive layer. Experimental research on the sensitivity coefficients covers a temperature range of 200 - 480 K. To ensure comparability within the same range, the temperature dependencies of the approximation coefficients for the resistivities of the silicon layer are considered. However, it should be noted that the results from different research sources exhibit significant discrepancies. The differences in the approximation coefficients can be attributed to the mismatch between the actual distribution and the idealized distribution used in the models.

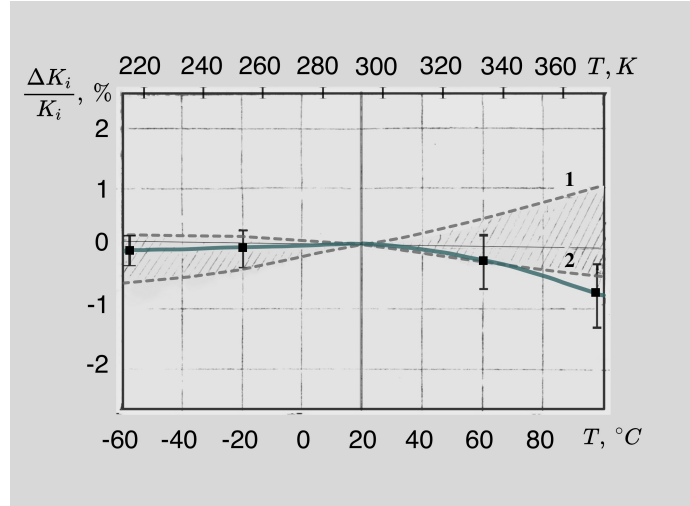


Figure 6: Temperature Dependence Graph of IRT Strain-Sensitivity Coefficient for BC with Low-Resistance Diffusion Piezoresistive Channels ( $0.0022 \dots 0.0086 \Omega \cdot cm$ ). The circuit is powered by a stabilized current source. Calculation Dependencies: 1-  $\rho_{l_1} = 2.2 \cdot 10^{-3}$  2-  $\rho_{l_2} = 2.6 \cdot 10^{-3}$  —■— Experimental Dependencies for Pressure Sensor Samples

It is crucial to base the calculations for IRT on data obtained within a stable technology. In our experimental investigation, we examined the dependencies  $K_{A_1}(\rho_l)$ ,  $K_{B_1}(\rho_l)$ ,  $K_{C_1}(\rho_l)$ ,  $A_1(\rho_l)$ , and

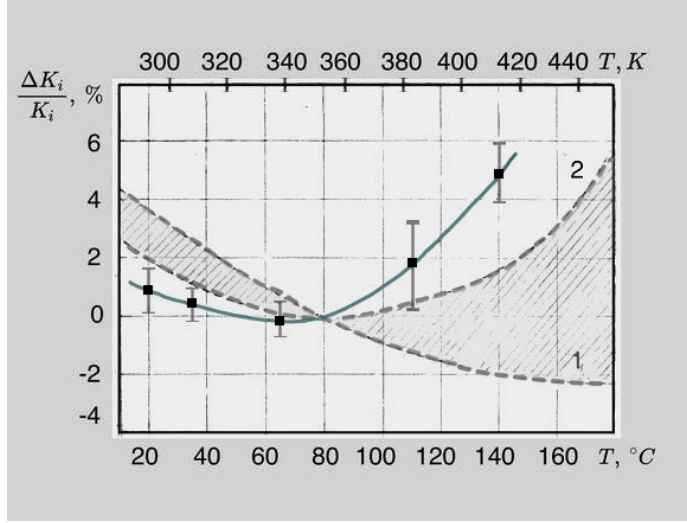


Figure 7: Temperature dependence graph of IRT strain-sensitivity coefficient for BC with high-resistance diffusion piezoresistive channels  $0.03 \dots 0.04 \Omega \cdot \text{cm}$ . The circuit is powered from a stabilized current source. --- calculation dependencies ( $1 - \rho_{l_1} = 3.0 \cdot 10^{-2}$ ;  $2 - \rho_{l_2} = 4.0 \cdot 10^{-2}$ ); —■— experimental dependences for samples of pressure sensors

$A_2(\rho_l)$  in the doping regions of  $(1 \times 10^{19}, \text{ to } 1 \times 10^{20}), \text{ cm}^{-3}$  and  $(1 \times 10^{18}, \text{ to } 5 \times 10^{18}), \text{ cm}^{-3}$ . These areas correspond to the levels of doping at which one can expect a "autocompensation" of additional temperature error when BC is powered from a stabilized current source<sup>19</sup>. The range of higher values of  $\rho_l$  aligns with the alloying level commonly used by many foreign firms in the production of IRT. Furthermore, considering that BC isolated by the p-n junction can operate at significantly higher positive temperatures<sup>20</sup> than predicted in widely available scientific and technical information<sup>15</sup>, our research extends to temperatures up to  $+200^\circ\text{C}$ .

For BCs with diffusion layers having  $\rho_l = (1.5 \div 8) \times 10^{-3}, \Omega \cdot \text{cm}$ , the upper limit of operating temperatures is restricted to  $(+130 \div +150)^\circ\text{C}$  due to the real values of the p-n junction area. In this case, the temperature investigation range is chosen as  $(200 \div 400), \text{ K}$ .

For BCs with diffusion layers  $\rho_l = (2 \div 4) \times 10^{-2}, \Omega \cdot \text{cm}$ , increasing  $R_s$  allows the insulating area of the p-n junction to be reduced to  $1 \times 10^{-4}, \text{ cm}^2$ , thus increasing the upper limit of stable properties of the insulating p-n junction to  $+200^\circ\text{C}$ . In this scenario,  $T_{min}$  is defined by values within the range  $(-20 \div -70)^\circ\text{C}$ . The research range for this case was chosen as  $(273 \div 473), \text{ K}$ .

Ion implantation technology enables an extended temperature range of  $+200^\circ\text{C}$  while maintaining a sufficiently high concentration of alloying impurities. The investigation of ion-implanted layers is limited to a single value, a doping dose of  $2 \times 10^{15}, \text{ cm}^{-2}$ , which allows for optimal p-n junction isolation and minimal scattering of electrical resistivity when other process parameters are fixed<sup>21</sup>.

Figures 4 and 5 and Table 1 present the experimentally obtained dependencies of the approximation coefficients for the temperature variations of resistances and GF in terms of  $\rho_l$  for diffusion channels. The values of the coefficients for the ion-alloyed channels are provided in Table 2.

To estimate the temperature error of the IRT using equations (13) and (14), the temperature sensitivity coefficients of the bridge circuit (BC) are determined.

$$\Gamma_{K_u} = \frac{1}{K_{u_0}} \frac{dK_u(T)}{dT} = \Gamma_{u_2} \cdot \left(\frac{T_0}{T}\right)^2 + \Gamma_{u_3} \cdot \left(\frac{T_0}{T}\right)^3; \quad (15)$$

$$\Gamma_{K_i} = \frac{1}{K_{i_0}} \frac{dK_i(T)}{dT} = \Gamma_{i_0} + \Gamma_{i_1} \cdot T + \Gamma_{i_2} \cdot \left(\frac{T_0}{T}\right)^2 + \Gamma_{i_3} \cdot \left(\frac{T_0}{T}\right)^3, \quad (16)$$

where  $K_{u_0} = K_{A_1} + K_{B_1} + K_{C_1}$  represents the BC sensitivity coefficient when a stabilized voltage is applied at  $T = T_0$ , and  $K_{i_0} = R_{i_{n_0}} \cdot K_{u_0}$  represents the BC sensitivity coefficient when a stabilized

current is supplied at  $T = T_0$ .

Table 1: Values of The Parameters for The "Autocompensation" Condition.

$\rho_l, \Omega \cdot cm$	Temperature range, K	$T_0, K$	$A_1, K^{-1}$	$A_2, K^{-2}$	$K_{A_1}$	$K_{B_1}$	$K_{C_1}$
0.0022	200 ÷ 400	293	$1.43 \cdot 10^{-3}$	$7.6 \cdot 10^{-7}$	23.4	44	-11
0.0026	200 ÷ 400	293	$1.3 \cdot 10^{-3}$	$8.7 \cdot 10^{-7}$	20.6	52	-13
0.03	273 ÷ 473	353	$1.6 \cdot 10^{-3}$	$5.3 \cdot 10^{-6}$	5.8	78.5	-13.4
0.04	273 ÷ 473	353	$2.3 \cdot 10^{-3}$	$1.1 \cdot 10^{-5}$	4.1	81	-9.6

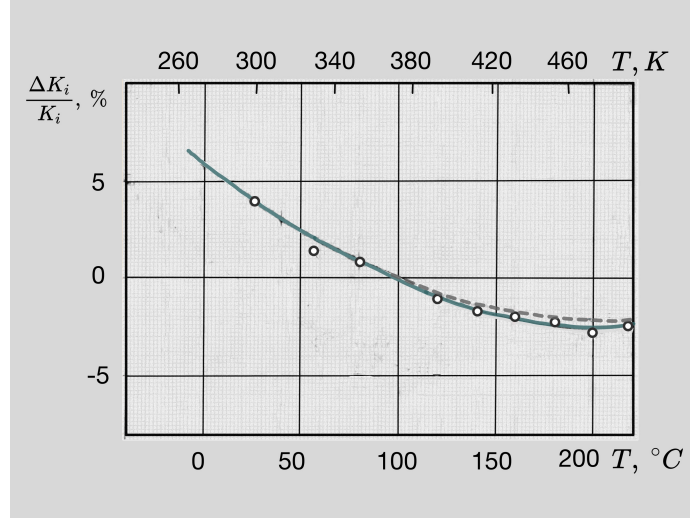


Figure 8: Temperature dependence graph of IRT strain-sensitivity coefficient for BC with ion-alloyed piezoresistive channels,  $N_d = 5 \cdot 10^{15} cm^{-2}$ . --- calculation dependencies; — experimental dependences for samples of pressure sensors

The temperature coefficients  $\Gamma_{K_u}$  and  $\Gamma_{K_i}$  are calculated using the following expressions:

$$\begin{aligned}
 \Gamma_{u_2} &= -\frac{K_{B_1}}{T_0 \cdot K_{u_0}}; & \Gamma_{u_3} &= -\frac{2 \cdot K_{C_1}}{T_0 \cdot K_{u_0}}; \\
 \Gamma_{i_0} &= \frac{K_{A_1} \cdot (A_1 - 2A_2 \cdot T_0) + K_{B_1} \cdot A_2 \cdot T_0}{K_{u_0}}; \\
 \Gamma_{i_1} &= 2 \cdot \frac{K_{A_1} \cdot A_2}{K_{u_0}}; \\
 \Gamma_{i_2} &= \frac{K_{B_1} \cdot \left( A_1 - A_2 \cdot T_0 - \frac{T}{T_0} \right) - K_{C_1} \cdot (A_1 - 2 \cdot A_2 \cdot T_0)}{K_{u_0}}; \\
 \Gamma_{i_3} &= 2 \cdot \frac{K_{C_1} \left( A_1 - A_2 \cdot T_0 - \frac{1}{T_0} \right)}{K_{u_0}}.
 \end{aligned} \tag{17}$$

In this study, the temperature coefficients  $\Gamma_{K_u}$  and  $\Gamma_{K_i}$  are determined by Equations (15), which are used to analyze the "autocompensation" of sensitivity to temperature variations when the BC is powered by a stabilized voltage or current. The results suggest that conditions  $K_{B_1} = K_{C_1} = 0$  and  $K_{B_1} = -2 \cdot K_{C_1}$  for "autocompensation" in the case of stabilized voltage supply are not feasible

Table 2: Values of Approximation Coefficients for Channels Doped with Boron Ions

Approximation coefficients	Temperature range	
	$(213 \div 373)K$	$(293 \div 473)K$
$A_1, K^{-1}$	$1 \cdot 10^{-3}$	$1.14 \cdot 10^{-3}$
$A_2, K^{-2}$	$1.1 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$
$K_{A_1}$	21	10
$K_{B_1}$	52	60
$K_{C_1}$	-10	-14

due to physical limitations such as boron solubility in silicon and the observed relationships in the graph.

For the case of stabilized current supply, the dependence of the temperature coefficient of BC sensitivity on the parameters is more complex. The optimal values of  $\rho_l$  should be chosen for "autocompensation" ( $\Gamma_{K_i} = 0$  at  $T = T_0$ ). Table 1 presents the calculated values of  $\rho_l$  and the approximation coefficients for this condition. The temperature dependencies of the relative change in the output signal of the BC at stabilized current supply are illustrated in Figures 6, 7, and 8.

Based on these findings, IRT designs have been developed, appropriate technological processes have been selected, and experimental samples of pressure, force, and LF-accelerometers have been manufactured. Temperature dependences of the sensitivity of the output signal for these samples are shown in Figures 6, 7, and 8. These results can be valuable for the development of IRTs with enhanced temperature compensation and improved performance in various applications.

2225

## References

- <sup>1</sup>Erler, W., Walter, L. (1974). Ehlektricheskie izmereniya neelektricheskikh velichin poluprovodnikovymi tenzorezistorami. [Electrical measurements of nonelectrical quantities by semiconductor strain gauges]: Vol. (in Russian) (Y. v. Malkov, Ed.). MIR.
- <sup>2</sup>Osadchii, E. P. (1979). Proektirovanie datchikov dlya izmereniya mekhanicheskikh velichin [Designing sensors for measuring mechanical quantities]: Vol. (in Russian). Mashinostroenie
- <sup>3</sup>Kanischeva G.A., Kilmetov R.S., Kobayakova L.P., et al. (1978). Poluchenie vypuklykh i vognutykh ploskosti anizotropnym travleniem Si (100). [Obtaining convex and concave planes by anisotropic etching of Si (100)]. Ehlektronnaya Tekhnika. [Electronic Engineering.], Seriya 3 (5), 77–81 (in Russian).
- <sup>4</sup>Stuchebnikov, V. M. (1983). Poluprovodnikovye integral'nye tenzorezistornye preobrazovateli mekhanicheskikh velichin. [Semiconductor integral strain gauge transducers of mechanical quantities.]. Izmereniya, Kontrol', Avtomatizatsiya, 1 (in Russian).
- <sup>5</sup>Sze, S. M. (1984). Fizika poluprovodnikovyykh priborov [Physics of semiconductor devices]: Vol. (in Russian). Mir.
- <sup>6</sup>Levshina, E. S., & Novitsky, P. v. (1983). Ehlektricheskie izmereniya fizicheskikh velichin: (Izmeritel'nye preobrazovateli) [Electrical measurements of physical quantities: (Measuring transducers)]: Vol. (in Russian). Energoatomizdat.
- <sup>7</sup>Lenk, A. (1975). Electromechanische system (VEB Verlag Technik). Bd 3 Systeme mit Hilisenergie
- <sup>8</sup>Kanda, Y. (1982). A Graphical Representation of the Piezoresistance Coefficients in Silicon. IEEE Trans. Electron Devices, ED-29, 64–70.
- <sup>9</sup>Yamada, K., Nishihara, M., Shimada, S., Tanabe, M., Shimazoe, M., Matsuoka, Y. (1982). Nonlinearity of the piezoresistance effect of p-type silicon diffused layers. IEEE Transactions on Electron Devices, 29(1), 71–77. <https://doi.org/10.1109/T-ED.1982.20660>
- <sup>10</sup>Gridchin, V. A. (1981). Teoriya proektirovaniya i tekhnologicheskije osnovy razrabotki kremnievykh integral'nykh tenzopreobrazovatelei s temperaturno-stabilizirovannyimi kharakteristikami: Diss. dok. tekhn. nauk. [Design Theory and Technology Basis for the Development of Silicon Integral Stress Gauge Transducers with Temperature-Stable Characteristics: D. Sci.]
- <sup>11</sup>Granveand M., & Malsan P. (1967). Piezoresistivite de 'lemrnts diffuses in silicium. L'Onde Electr, 47(480–481), 392–392.
- <sup>12</sup>Tufte, O. N., Long, D. (1963). Recent developments in semiconductor piezoresistive devices. Solid-State Electronics, 6(4), 323–338. [https://doi.org/10.1016/0038-1101\(63\)90097-2](https://doi.org/10.1016/0038-1101(63)90097-2)
- <sup>13</sup>BRETSCHI, J. (1976). Linearisierung von Meßumformern, demonstriert am Beispiel von Halbleiter-Dehnungsmeißstreifen / Linearization of measurement transducers shown at the example of semiconducting strain gages. Tm - Technisches Messen, 480–491(JG). <https://doi.org/10.1524/teme.1976.480491.jg.431>
- <sup>14</sup>Mezon V.P., Forst D.J., & Tornillo L.M. (1965). Sovremennoe razvitie poluprovodnikovyykh datchikov. Poluprovodnikovye tenzodatchiki. [Modern Development of Semiconductor Sensors. Semiconductor strain gauges.]: Vol. (in Russian) (M. Dean, Ed.; Energy). Energy (in Russian).
- <sup>15</sup>Vaganov, V. I. (1983). Integral'nye tenzopreobrazovateli [Integral strain gauges]: Vol. (in Russian). Energoatomizdat.
- <sup>16</sup>Kerr, D. R., Milnes, A. G. (1963). Piezoresistance of diffuse layers in cubic semiconductors. Journal of Applied Physics, 34(4), 727–731. <https://doi.org/10.1063/1.1729524>
- <sup>17</sup>Tufte, O. N., Stelzer, E. L. (1963). Piezoresistive Properties of Silicon Diffused Layers. Journal of Applied Physics, 34 (2), 313–318. <https://doi.org/10.1063/1.1702605>
- <sup>18</sup>Gridchin, V. A. (1980). Sovremennoe sostoyanie teorii i praktiki proek- tirovaniya integral'nykh preobrazovatelelei. - V kn.: Izmeritel'nye preobrazovateli mekhanicheskikh i teplovykh velichin na baze mikroelektroniki. [The current state of theory and practice of integrated transducer design.- In book: Measurement of mechanical and thermal quantities on the basis of microelectronics]: Vol. (in Russian) (MDNTP). Moscow House of Scientific and Technical Propaganda
- <sup>19</sup>Tikhomirov, M. Y., Spalek, Y. M., Kharenko, K. Y., Giletsky, N. P., Bogatov, P. N., Yazovtsev, V. I., Borshchev, V. N. (1977). Integrated strain-sensitive element of mechanical transducer with low temperature instability. Technology. Technology of Instrument Making: Collection of scientific-technical documents / TsNTI Poisk (in Russian), 3 (14) 19, 19 to 27. <doi:10.5281/ZENODO.7261945>
- <sup>20</sup>Tikhomirov, M. Y. (1984). Study of the Characteristics of the Measuring Circuit of the Silicon Integrated Mechanical Transducer at Temperatures Above +100 ° C. Works of the Moscow Forestry Engineering Institute, 158, 53. <doi:10.5281/ZENODO.8061553> <hal-04131081v2>
- <sup>21</sup>Borshchev, V. N., Demidova, V. A., Spalek, Y. M., Kharenko, K. Y. (1983). Ehlektrofizicheskie kharakteristiki tenzorezistivnykh struktur, legirovannykh implantirovannyim borom. [Electrophysical characteristics of tensoresistive structures alloyed with implanted boron.]. Tekhnologiya. Tekhnologiya Priborostroeniya: Nauch.-Tekhn.Sb. TSNTI 'Poisk' 2, 8 (in Russian), 71-80.
- <sup>22</sup>Tufte, O. N., Stelzer, E. L. (1963). Piezoresistive Properties of Silicon Diffused Layers. Journal of Applied Physics, 34(2), 313–318. <https://doi.org/10.1063/1.1702605>
- <sup>23</sup>Marchenko Aleksandr N. (1978). Upravlyaemye poluprovodnikovye rezertory. [Controlled Semiconductor Resis-

