Silicon IPT Operating Characteristics, -60 to 200°C

Michael Y. Tikhomirov;

1988

Abstract

For the output signal (U_{out}) of integrated transducers (IRT) with a bridge measuring circuit (BC) having a "square" topological structure, a comparative analysis of data from different studies of the electrophysical characteristics of the tensoresistive layers was performed. Because of the significant difference in the results obtained from these data within a stable technology, the characteristics of BC have been investigated depending on the average level of the doped layer (ρ). The boundaries of the thermocompensation ranges were determined, in which the temperature error of MC with different ρ does not exceed 0.02 $\%/^oC$

1 Rationale for The Choice of Solutions Used.

In silicon integrated resistive transducer (IRT) of a mechanical quantities sensor, a DC bridge measuring circuit of four piezoresistors [1][2] serves to transform the strain of an elastic element. The conversion characteristic of this circuit is determined by the transfer function k with the following dependence on temperature and strain changes

$$\mathrm{k} = K_0(T) + K\left(\varepsilon_x, T\right) \tag{1}$$

where $K_0(T)$ are the initial values of the transfer function (in the absence of the input mechanical quantity); $K\left(\varepsilon_x, T\right)$ is the conversion coefficient of the deformation (or difference of principal deformations) of the elastic element from the influence of the input mechanical quantity.

When supplied from a stabilized voltage source U_{in}, $U_{in} = const$, the output signal of the circuit is defined as

$$\mathrm{U}_{out} = U_{in} \cdot k = U_{in}\left[K_0(T) + K\left(\varepsilon_x, T\right) \cdot \varepsilon_x\right] \tag{2}$$

When supplied from a stabilized current source I_{in}, $I_{in} = const$, as

$$\mathrm{U}_{out} = I_{in} \cdot R_{in}\left[K_0(T) + K\left(\varepsilon_x, T\right) \cdot \varepsilon_x\right] \tag{3}$$

where R_{in} is the input resistance of the measuring circuit.

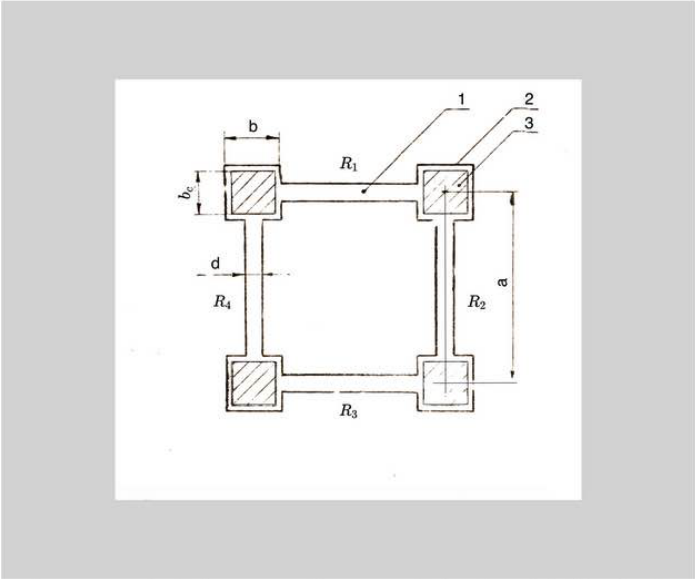

Figure 1. Topological structure of a symmetric four-branch bridge circuit. 1-piezoresistive channel; 2-diffusion contact pad of p-type; 3-contact "Al-Si (p-type)".

In expression (2) the component $K(\varepsilon_x, T)$ completely determines the temperature dependence of the transducer sensitivity coefficient in the case when its second component $K_0(T) = 0$. The latter is possible if certain requirements are met in the manufacturing technology and design of IRT, among which are:

- minimizing the variation of electrical resistance of silicon p-type resistors from the average values and the identity of the temperature characteristics of the resistors;
- minimization of magnitudes and spreads of the initial n-type silicon elastic element (EE) deformations in the areas where the piezoresistors are located and the identity of the temperature dependences of these quantities;
- equality of all thermal resistances in the PIESORESISTER-EE and IRT-SENSORBODY heat sink channels;
- minimizing the temperature gradient at the location of the piezoresistors.

In domestic practice, the greatest accuracy in reproducing the dimensions of EEs is achieved by local anisotropic etching of weakly and medium-alloyed silicon wafers with orientation in the plane [3]. This method can be used to shape most of the practically used types of EE [4]. In such ICs, the channels of piezoresistors doped with an acceptor impurity are arranged parallel to the

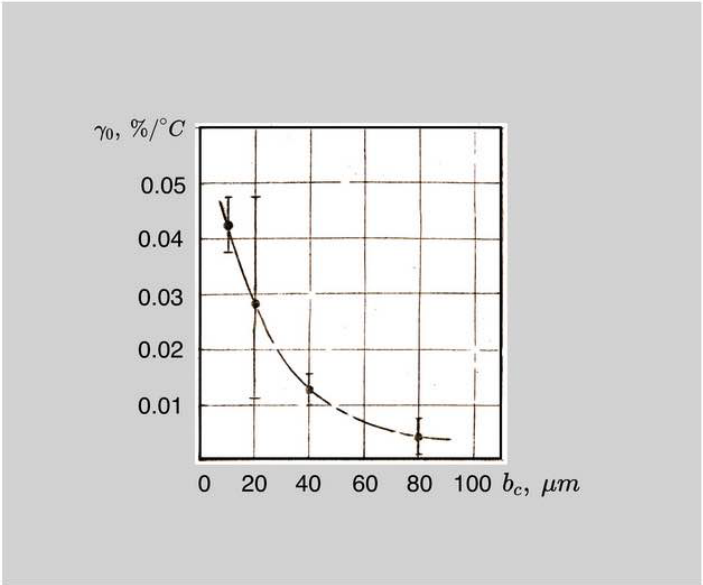

Figure 2. Graph of the temperature instability coefficient versus contact size.

faceting EE, i.e., along the crystallographic directions [110]. The identical stress states of the EE regions, in which the longitudinal and transverse piezoresistors are located, cause (at small deformations) proportional changes of piezoresistors resistances, which are close to each other in magnitude and opposite in sign.

The requirements for approaching the components $K_0(T)$ to zero in many cases can be fulfilled by a measuring circuit, which is a symmetrical four-arm bridge circuit (BC). The topological structure is shown in Fig. 1. Equal square contact areas of size b, centered at the vertices of a square of size a, are interconnected by four single-band piezoresistive channels of width d of longitudinal $(R1; R3)$ and transverse $(R2; R4)$ piezoresistors.

If we assume that $K_0(T) = 0$, the transfer function k of the conversion characteristic of such an MC is determined from the relation:

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

where $K_{\parallel}$, $K_{\perp}$, are, respectively, longitudinal and transverse strain gauge coefficients of the silicon channel layer; ε_{x_0} - value of strain of UE in geometric centers of the piezoresistors channels $R_1; R_3$; $\varepsilon_{x_2}, \varepsilon_{x_4}$ - strain values in the geometric centers of the piezoresistors channels $R_2; R_4$.

To operate the sensor at temperatures up to $+200°C$,
the total area of the insulating p-n junction, defined for the BC by the formula $S = 4b^2 + 4d(a-b)$, should not exceed $5 \cdot 10^{-4} cm^2$.

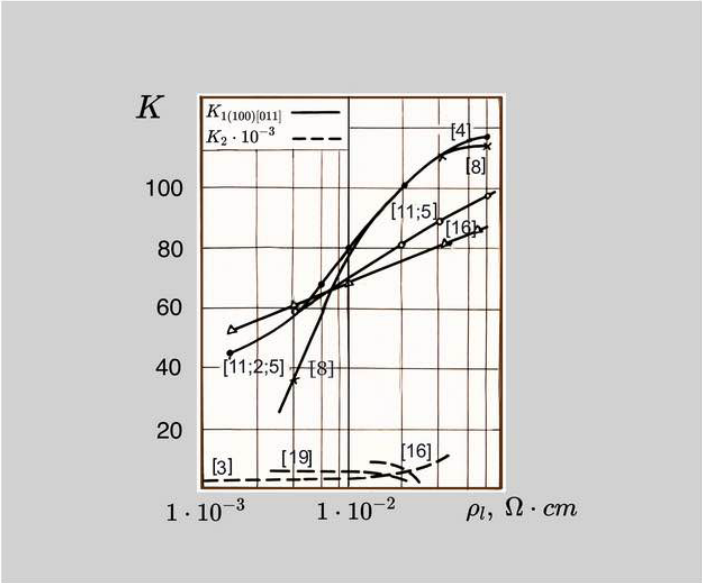

Figure 3. Strain-sensitivity coefficients dependence plot on resistivity of uniformly doped p-type silicon layers

In our experiment we investigated test MS with different contact dimensions (b_k) Al-pSi structures formed by boron ion implantation of doping dose $1 \cdot 10^{15} cm^{-2}$. The p-type contact diffusion regions had a surface resistance of 80 $\Omega/\square$. Figure 2 shows graphically the dependence of the temperature instability coefficient of γ_0, defined as $\gamma_0 = \frac{K_{0_{max}} - K_{0_{min}}}{K_{0_{(T=0^\circ C)}} \cdot \Delta T} \cdot 100\%$, on the contact size b_k when the MC is supplied from a stabilized DC voltage source.

Taking as the lower limit γ_0 a value equal to $0.02\%/^\circ C$, we choose the minimum contact dimensions $b_c = 50\mu m$, and the respective diffusion-alloyed contact areas $b = 60\mu m$. Quite common values of R_{in} value for BC lie in the range from 500 to 800 Ω; in this case, at channel width $d = 20\mu m$ and surface resistance of ion-doped layer 80 $\Omega/\square$, the channel length (a-b) lies in the range $(180 \div 250)\mu m$, and the total area of p-n junction - $(2 \div 3) \cdot 10^{-4} cm^2$.

BC with such dimensions can be assembled on miniature membrane and beam EEs; when the size of the elastically deformable EE part is more than $2 \times 2mm$, the equality $\varepsilon_{x_2} \approx \varepsilon_{x_4} \approx \varepsilon_{x_0}$ can be considered to be true. The relation (4), in this case, will take the form

$$\mathrm{k} = 0,5 \cdot K_{\parallel} \varepsilon_{x_0} \left(1 - \frac{K_{\perp}}{K_{\parallel}}\right). \tag{5}$$

The piezoresistor electrical resistance function R (R_{in} for BC) as a function of temperature (at $\varepsilon_x = 0$) has two extremes. The first (minimum) is due to a change in the scattering mechanism of free charge carriers at $T_{min} < 273K$. The

second (maximum) is caused by the appearance of the intrinsic conductivity at $T_{max} > 400K$ [5].

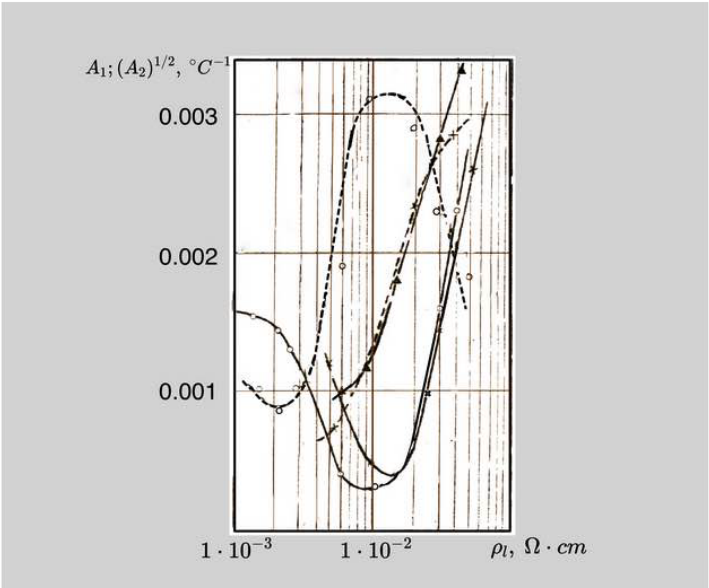

Figure 4: Graph of approximation coefficients of temperature dependences of resistances for silicon layers $-A_1$; $- -$ A_2; $\times$ - uniformly doped layers (experimental data); ▲ - uniformly doped layers (calculated data); ◯ - dependences obtained from studies of diffusion piezoresistive channels

The temperature range (T_{min}, T_{max}) can be thought of as the naturally formed operating range and thermal compensation range.

At $T \in (T_{\min}, T_{\max})$, the resistance of the semiconductor material increases monotonically with increasing temperature and is defined by the dependence [6]:

$$\mathrm{R}(T) = R_0 \left[1 + A_1 (T - T_0) + A_2 (T - T_0)^2\right] \tag{6}$$

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

The relative change in the strain resistance of the piezoresistor $\frac{\Delta R}{R}$ according to the article [7] can be represented as

$$\frac{\Delta R}{R} = K_1 \cdot \varepsilon + K_2 \varepsilon^2 + \ldots \tag{7}$$

$$K = \frac{\Delta R}{R \cdot \varepsilon} = K_1 + K_2 \varepsilon + \ldots$$

where K_1 is the linear coefficient of the strain-sensitivity ; K_2 is the quadratic coefficient of the strain-sensitivity; ε is the relative strain of the piezoresistive channel.

The dependence of the coefficients K_1 and K_2 on temperature has a complex character [8] [9], the study of which cannot be considered complete [10].

For comparability of the results of the studies and the results obtained in this work, we present relation [7] in the form:

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

or for strain sensitivity:

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

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 relations:

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

$$\frac{U_{\text{out}}}{I_{\text{in}}} = R_{\text{in}_0}\cdot\left[K_0(T) + (K_{A_1} + K_{A_{2\cdot\varepsilon}})\cdot\varepsilon + (K_{B_1} + K_{B_2}\cdot\varepsilon)\frac{T_0}{T}\cdot\varepsilon + (K_{C_1} + K_{C_2}\cdot\varepsilon)\left(\frac{T_0}{T}\right)^2\cdot\varepsilon\right]\times$$
$$\times\left[1 + A_1(T - T_0) + A_2(T - T_0)^2\right] \tag{11}$$

where R_{in_0} is the MC input resistance at $T = T_0$.

For further consideration, let us assume that at $\varepsilon = 0, R_{1,2,3,4} \equiv R$, then $K_0 = 0$.

2 Experimental Details And Results.

The electrophysical characteristics (EPhCh) of a piezoresistor are integral functions of the distribution of the impurity N concentration in its
channel in the Z direction normal to the planar surface of the IRT. In[1112], the EPhCh is related to the surface concentration N calculated from the known value of $N(z = x_j)$ at the depth x_j of the p-n junction isolating the channel and the value of the channel surface resistance R_s, assuming the distribution of N by a Gaussian function or an complementary error function (erfc).

In a number of cases, for example, at N=20 this assumption can lead to an error of determination No by half an order of magnitude, in connection with in [11] it is proposed to integrate the known EFC for uniformly doped silicon by real impurity distribution. Piezoresistive coefficient (π) studies in uniformly doped silicon are given in [13714].

In the established technological process of p-type piezoresistor channel formation in the n-type substrate at the usual $N_a/N_d \gg 1$ ratio the piezoresistor characteristics are well reproducible when the parameter $\overline{\rho}_l = R_s \cdot \overline{x_j}$ of the

piezoresistive layer is reproducible. In a small interval of variation $\overline{\rho}$, the relation of the EPhCh to this value, in contrast to the relation to R_s by informativeness is equivalent to a similar relationship in homogeneously doped silicon. The reason for this is simple and is explained by the fact that $\left[\left(\frac{dz}{d\rho(x_j)}\right)\right]^{-1}$ at $N_a/N_d \gg 1$ is weakly dependent on changes in the upper limit of integration, in the limits due to the scatter from the nominal ($N_{d_{nom}}$) of the impurity in the substrate. Then, in a well-established process, we consider that, $\frac{dR_s}{R_s} \approx -\frac{dx_j}{x_j}$. In what follows, the study of the piezoresistive layers will be related to $\overline{\rho_l}$.

In IRTs whose planar surface coincides with plane (001) and piezoresistors are oriented along crystallographic directions of type [110], the strain-sensitivity coefficients $K_{(100)[011]}$, according to [15], can be represented by the relation:

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

where, "+" sign corresponds to the longitudinal strain coefficient $K_{\parallel}$, "-" - to the transverse one, $K_{\perp}$; E_{12} , ν_{12} - Young's modulus and Poisson's coefficient, respectively, in silicon along the crystallographic direction [011]; π_{44} - main shear piezoresistive coefficient, Pa^{-1}.

There is little information about the concentration and temperature dependences of the main longitudinal ($\pi_{\parallel}$) and transverse ($\pi_{\perp}$) piezoresistive coefficients. It is known that π_{11} decreases with increasing impurity concentration from $2 \cdot 10^{-11} Pa^{-1}$ at $N = 3 \cdot 10^{18} cm^{-3}$ to $1 \cdot 10^{-11} Pa^{-1}$ at $N = 1 \cdot 10^{21} cm^{-3}$ [1617] (which is above the solubility limit of boron in silicon), and the volume compressibility coefficient $(\pi_{11}+\pi_{12})$ with + sign and is approximately equal to $(1 \div 2) \cdot 10^{-11} Pa^{-1}$ for the indicated concentrations [17]. The authors [184] believe that due to the small, relative to π_{44}, values, the coefficients π_{11} and π_{12} can be neglected, i.e. $|K_{\parallel}| = |K_{\perp}|$.

Figure 3 shows the dependences of linear K_1 and quadratic K_2 strain-sensitivity coefficients on the doping level, plotted from data in [4789141316]. For ease of comparison, the K_2 dependences are represented by the products of their values on the boundary, for use in piezometry, relative strain of silicon, equal to $1 \cdot 10^{-3}$. It can be seen from the graph that the value of $K_2 \cdot 10^{-3}$ does not exceed 10% of the smallest value of $K_{1_{(100)[011]}}$. If we take the nominal output signal of BC to be 100 mV at $U_{in} = 10mV$, then from (2) given (5) for the minimum value of $K_{1_{(100)[011]}} = 33$ (see Figure 3), the strain ε_{x_0} will be equal to $3 \cdot 10^{-4}$. In further consideration, consider that in (7) \$K_2\cdot \varepsilon \$ is negligible with respect to K_1, and relations (10) and (11) are converted to:

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

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

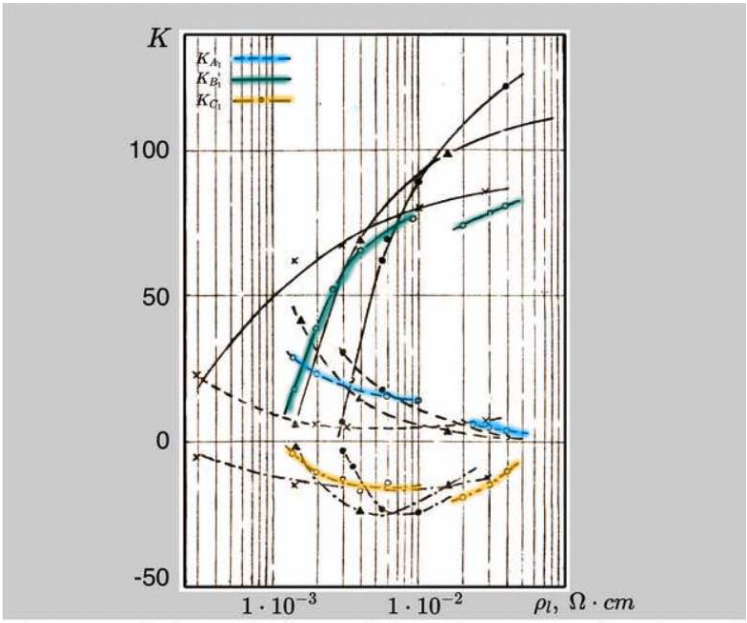

Figure 5. Graph of approximation coefficients of temperature dependences of strain-sensitivity for silicon p-type layers; ▲ - uniformly doped layers [2:1] (experimental data); ● - uniformly doped layers [8:1] (calculated data); × - diffusion layers [6:1] (experimental data); ○ - dependences obtained from studies of diffusion piezoresistive channels.

where, $K_u(T)$ - sensitivity coefficient of BC when powered from stabilized voltage source; $K_i(T)$ sensitivity coefficient of BC when powered from stabilized current source.

Figure 4 and Figure 5 show the dependences of the approximation coefficients for the temperature dependences of resistance (A_1, A_2) and strain-sensitivity $(K_{A_1}, K_{B_1}, K_{C_1})$ on the resistivity of the piezoresistive layer. The temperature range of experimental research of strain-sensitivity coefficients is 200 K - 480 K. For comparability, the temperature dependences of silicon layers resistances are considered in the same range. The results from different research sources differ significantly from each other. The difference in the approximation coefficients in all cases seems to be related to the discrepancy between the real distribution and the idealized one.

It is obvious that the IRT calculation should be based on data obtained within a sustainable technology. We experimentally investigated the $K_{A_1}(\rho_l), K_{B_1}(\rho_l), K_{C_1}(\rho_l), A_1(\rho_l), A_2(\rho$ dependences in the doping regions $\left(1 \cdot 10^{19} \div 1 \cdot 10^{20}\right) cm^{-3}$ and $\left(1 \cdot 10^{18} \div 5 \cdot 10^{18}\right) cm^{-3}$, where one would expect "autocompensation" sensitivity when the BC is powered from a stabilized current source. The range of higher ρ_l values corresponds to the level of alloying adopted in the manufacture of BC by many foreign firms. Taking into account that BCs isolated by p-n junction are operable at

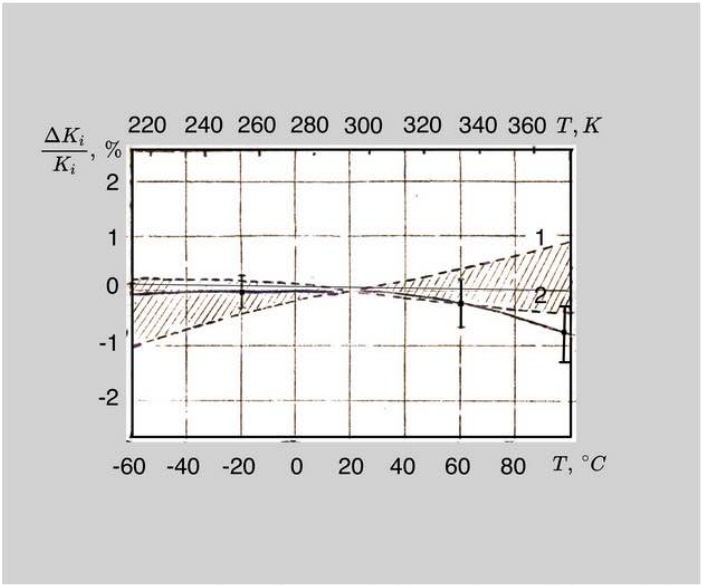

Figure 6. Temperature dependence graph of IRT strain-sensitivity coefficient for BC with low-resistance diffusion piezoresistive channels $0.0022 \ldots 0.0086\ \Omega \cdot cm$. The circuit is powered from a stabilized current source. – – – calculation dependencies ($1 - \rho_{l_1} = 2.2 \cdot 10^{-3}$; $2 - \rho_{l_2} = 2.6 \cdot 10^{-3}$); —— experimental dependences for samples of pressure sensors

much higher positive temperatures [19][20] than predicted in widely known scientific and technical information [15] , the research range is extended to $+200°C$. For BCs with diffusion layers having $\rho_l = (1.5 \div 8) \cdot 10^{-3} \Omega \cdot cm$, the real values of the p-n junction area limit the upper values of operating temperatures to $(+130 \div +150)^0 C$. The temperature investigation range in this case is chosen as $(200 \div 400) K$. For BCs with diffusion layers $\rho_l = (2 \div 4) \cdot 10^{-2} \Omega \cdot cm$, by increasing R_s, the insulating p-n junction area can be reduced to $1 \cdot 10^{-4} cm^2$, which increases the upper limit of stable insulating p-n junction properties to $+200°C$. T_{min} in this case is defined by values belonging to the interval $(-20 \div -70)^0 C$. The research range was chosen as $(273 \div 473) K$.

Extending the temperature range up to $+200°C$ while maintaining a largely convenient high concentration of the alloying impurity allows ion implantation [20]. The field of investigation of ion-alloyed layers here is limited to a single value, an doping dose of $2 \cdot 10^{15} cm^{-2}$, allowing the best p-n junction isolation and the smallest scattering of electrical resistivity at small deviations from the process parameters to be obtained at other fixed process parameters [21].

Figure 4 and Figure 5 show the experimentally obtained dependences of the approximation coefficients of temperature dependences of resistances and strain-sensitivity from ρ_l for diffusion channels. The values of the coefficients

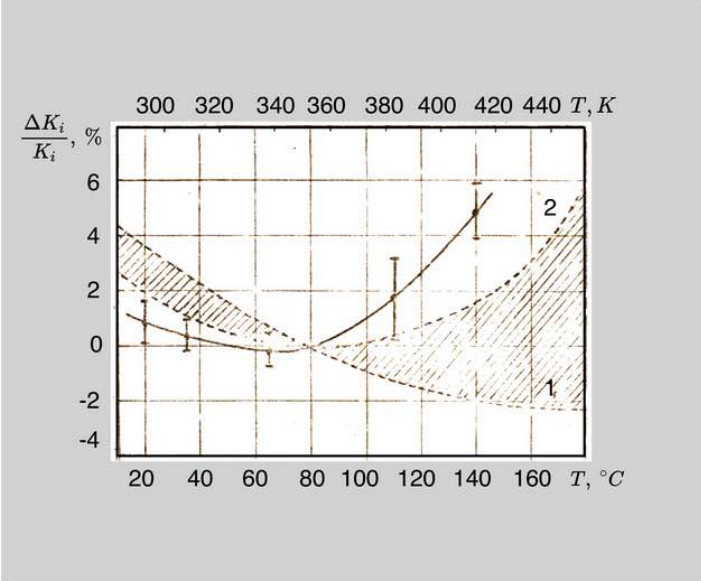

Figure 7. Temperature dependence graph of IRT strain-sensitivity coefficient for BC with high-resistance diffusion piezoresistive channels $0.03 \ldots 0.04\ \Omega \cdot cm$. The circuit is powered from a stabilized current source.
– – – calculation dependencies ($1 - \rho_{l_1} = 3.0 \cdot 10^{-2}$;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

for the ion-alloyed channels are given in Table 1.

To estimate the temperature error of the IRT from relations (13) and (14), the temperature sensitivity coefficients of the BC are determined:

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

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

where $K_{u_0} = K_{A_1} + K_{B_1} + K_{C_1}$ is the sensitivity coefficient of the BC when a stabilized voltage is applied, if $T = T_0$; $K_{i_0} = R_{in_0} \cdot K_{u_0}$ - sensitivity coefficient of BC when stabilized current is supplied, if $T = T_0$.

Table 1. Values of Approximation Coefflients for Chnnnels Doped with Boron lons

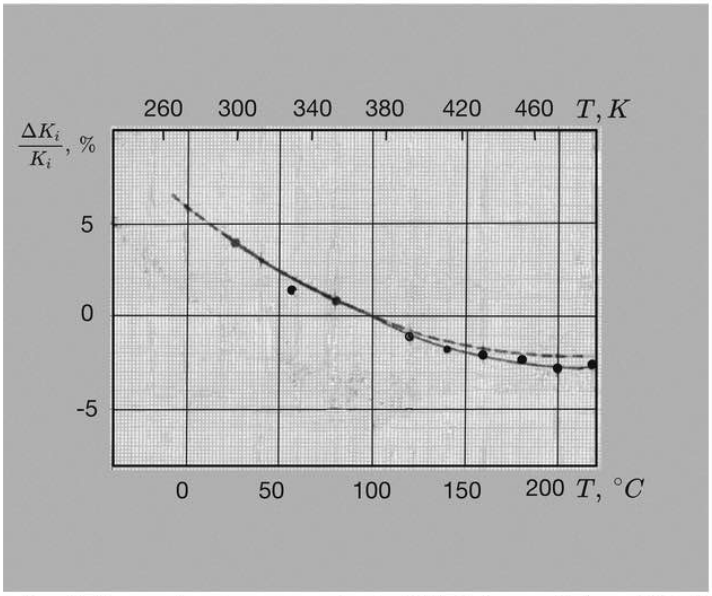

Figure 8. Temperature dependence graph of IRT strain-sensitivity coefficient for BC with ion-alloyed piezoresistive channels, $N_d = 5 \cdot 10^{15}\ cm^{-2}$. – – – calculation dependencies; —·— experimental dependences for samples of pressure sensors

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}	$1.1 - 10^{-6}$	$1.5 - 10^{-6}$
K_{A1}	21	10
K_{B_1}	52	60
K_{C_1}	-10	-14

The temperature coefficients Γ_{K_u} and Γ_{K_i} are defined by the following ex-

pressions:

$$\begin{aligned}
&\Gamma_{u_2} = -\frac{K_{B1}}{T_0 \cdot K_{u_0}}; \quad \Gamma_{u_3} = -\frac{2 \cdot K_{C_1}}{T_0 \cdot K_{u_0}};\\
&\Gamma_{i_0} = \frac{K_{A_1} \cdot (A_1 - 2A_2 \cdot T_0) + K_{B_1} \cdot A_2 \cdot T_0}{K_{u_0}};\\
&\Gamma_{i_1} = 2 \cdot \frac{K_{A_1} \cdot A_2}{K_{u_0}};\\
&\Gamma_{i_2} = \frac{K_{B_1} \cdot \left(A_1 - A_2 \cdot T_0 - \frac{T}{T_0}\right) - K_{C_1} \cdot (A_1 - 2 \cdot A_2 \cdot T_0)}{K_{u_0}};\\
&\Gamma_{i_3} = 2 \cdot \frac{K_{C_1} \left(A_1 - A_2 \cdot T_0 - \frac{1}{T_0}\right)}{K_{u_0}}.
\end{aligned} \tag{17}$$

Table 2. Values of The Parameters for The "Autocompensation" Condition.

$\rho_t, \Omega \cdot cm$	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	$200 \div 400$	293	$1.43 \cdot 10^{-3}$	$7.6 \cdot 10^{-7}$	23.4	44	-11
0.0026	$200 \div 400$	293	$1.3 \cdot 10^{-3}$	$8.7 \cdot 10^{-7}$	20.6	52	-13
0.03	$273 \div 473$	353	$1.6 \cdot 10^{-3}$	$5.3 \cdot 10^{-6}$	5.8	78.5	-13.4
0.04	$273 \div 473$	353	$2.3 \cdot 10^{-3}$	$1.1 \cdot 10^{-5}$	4.1	81	-9.6

From (15) it can be seen that when supplying BC with stabilized voltage, "autocompensation" of temperature changes in sensitivity is possible if $K_{B_1} = K_{C_1} = 0(a)$ or $K_{B_1} = -2 \cdot K_{C_1}(b)$). From Fig.5 condition (a) is expected to be realized at N values greater than $1 \cdot 10^{20} cm^{-2}$ $\left(\rho_l < 1 \cdot 10^{-3} \Omega \cdot cm\right)$, but due to physical limitations in the form of limiting boron solubility in silicon, it is not feasible. Condition (b), as can be seen from the graph, is also not feasible.

For the case of supplying with stabilized current supply there is a more complex dependence of the temperature coefficient of BC sensitivity on the parameters. It is necessary to choose the best possible values of ρ_l. Table 2 shows the calculated values of ρ_l and approximation coefficients for the implementation of the condition of "autocompensation", i.e. $\Gamma_{K_i} = 0$, if $T = T_0$. The graphs Figure 6, Figure 7, Figure 8 show the calculated temperature dependences of the relative change in the output signal of the MC at stabilized current supply.

On the basis of the obtained results the designs of IRTs are designed, the corresponding technological processes are selected and the experimental samples of pressure, force and LF-accelerometers are made. The graphs in Figure 6, Figure 7, Figure 8 show their temperature dependences of the sensitivity of the output signal.

References

[1]Erler, W., Walter, L. (1974). Ehlektricheskie izmereniya neehlektricheskikh velichin poluprovodnikovymi tenzorezistorami. [Electrical measurements of non-electrical quantities by semiconductor strain gauges.]: Vol. (In Russian) (Y. v. Malkov, Ed.). MIR.

[2]Osadchii, E. P. (1979). Proektirovanie datchikov dlya izmereniya mekhanicheskikh velichin [Designing sensors for measuring mechanical quantities]: Vol. (In Russian). Mashinostroenie.

[3]Kanischeva G.A., Kilmetov R.S., Kobyakova L.P., et al. (1978). Poluchenie vypuklykh i vognutykh ploskostei 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).

[4]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).

[5]Sze, S. M. (1984). Fizika poluprovodnikovykh priborov [Physics of semiconductor devices]: Vol. (In Russian). Mir.

[6]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.

[7]Lenk, A. (1975). Electromechanishe systeme (VEB Verlag Technik). Bd 3 Systeme mit Hilisenergie.

[8]Kanda, Y. (1982). A Graphical Representation of the Piezoresistance Coefficients in Silicon. IEEE Trans. Electron Devices, ED-29, 64–70.

[9]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

[10]Gridchin, V. A. (1981). Teoriya proektirovaniya i tekhnologicheskie osnovy razrabotki kremnievykh integral'nykh tenzopreobrazovatelei s temperaturno- stabilizirovannymi kharakteristikami: Diss. dok. tekhn. nauk. [Design theory and technological basis for the development of silicon integral strain-gauge transducers with temperature-stabilized characteristics: D. Sci.].

[11]Granveand M., & Malsan P. (1967). Piezoresisitivite de'lemrnts diffuses en silicium. L'Onde Electr, 47(480–481), 392–392.

[12]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

[13]BRETSCHI, J. (1976). Linearisierung von Meßumformern, demonstriert am Beispiel von Halbleiter-Dehnungsmeßstreifen / 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

[14]Mezon V.P., Forst D.J., & Tornillo L.M. (1965). Sovremennoe razvitie poluprovodnikovykh datchikov. Poluprovodnikovye tenzodatchiki. [Modern Development of Semiconductor Sensors. Semiconductor strain gauges.]: Vol. (In Russian) (M. Dean, Ed.; Energy). Energy (in Russian).

[15]Vaganov, V. I. (1983). Integral'nye tenzopreobrazovateli [Integral strain gauges]: Vol. (In Russian). Ehnergoatomizdat.

[16]Kerr, D. R., Milnes, A. G. (1963). Piezoresistance of Diffused Layers in Cubic Semiconductors. Journal of Applied Physics, 34(4), 727–731. https://doi.org/10.1063/1.1729524

[17]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

[18]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 mikroehlektroniki.[The current state of theory and practice of integrated transducers design.- In book: Measuring transducers of mechanical and thermal quantities on the basis of microelectronics.]: Vol. (In Russian) (MDNTP). Moscow House of Scientific and Technical Propaganda.

[19]Sea-Chung Kim, Wise, K. D. (1983). Temperature sensitivity in silicon piezore-

sistive pressure transducers. IEEE Transactions on Electron Devices, 30(7), 802–810. https://doi.org/10.1109/T-ED.1983.21213

[20]Tikhomirov, M. Y., Spalek, Y. M., Pivonenkov, B. I., Borshchev, V. N. (1985). Vozmozhnostni rasshireniya temperaturnogo diapazona ehkspluatatsii dlya poluprovodnikovykh akselerometrov. [Possibilities of extending the operating temperature range for semiconductor accelerometers.]. Tekhnologiya. Tekhnologiya Priborostroeniya: Nauch.-Tekhn.Sb. TSNTI "Poisk," 2, 8 (In Russian).

[21]Borshchev, V. N., Demidova, V. A., Spalek, Y. M., Kharenko, K. Y. (1983). Ehlektrofizicheskie kharakteristiki tenzorezistivnykh struktur, legirovannykh implantirovannym borom. [Electrophysical characteristics of tensoresistive structures alloyed with implanted boron.]. Tekhnologiya. Tekhnologiya Priborostroeniya: Nauch.-Tekhn.Sb. TSNTI "Poisk,"2, 8 (In Russian), 71–80.