# SMALL-SIZE SILICON ACCELEROMETER WITH A THERMALLY COMPENSATED SIGNAL IN THE TEMPERATURE RANGE OF 0-200°C

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We describe an integrated single-component inertial accelerometer with an input signal resistance strain gauge converter (IRC). The operation principle of the device and its design (the inertial element, which performs double differentiation of the [elastic] displacement and the resistance strain gauge element built as monolithic silicon single-crystals) are well known [1-3]. We propose a new version of the design, which improves certain metrological and performance characteristics of the instrument.

The accelerometer consists of (Fig. 1) the measurement module (MM) mounted on an extender of the carrier H coordinated by the thermal expansion coefficient; it is made of 29NK Kovar alloy. The electric connection with the next device of the information-measurement system is provided by a tape cable (TC) with a polyamide base and an RPS1-7 electric coupler. All the constructive elements (ELs) of the MM are made of single-crystal silicon plates, with orientation in plane (100). The elastic element (EE) (see Fig. 1) of the MM consists of 28 cantilever beams of length L, width $D_i$, and thickness $H_{EE}$, mounted rigidly on a ring support. The resistive elements of a bridge strain gauge circuit (BSC) are mounted on each of the two beams ($B_1$) and have a width $D_1$. The remaining beams ($B_2$), each of width $D_2$ (total number of beams n = 26), serve to regulate the conversion amplitude characteristics. The silicon caps (CAs) function as thermal compensation circuits and dampers of vibrations of the inertial and elastic elements.

New technological versions of the device seek to expand the working temperature range, compensating the variation in accelerometer sensitivity caused by temperature variations, achieve the desired damping level and maximum mechanical strength, develop a method for regulating the conversion amplitude characteristics sufficient for correcting the scatter of mass-produced instrument parameters, and reduce instrument size and weight.

The first part in the effort to expand the working temperature range is concerned with electric insulation of BSC by a p–n-junction from the elastic element in the temperature interval of up to 200°C, while preserving a satisfactory conversion characteristic in the input mechanical variable. In this statement, the criterion for failure of BSC insulation is set as a 1% change in the IRC gain factor ($K_{IRC}$) due to shunting of its output resistance by the base. This criterion can be satisfied by designing the BSC with a sufficiently small insulation junction area [4].

Figure 2 plots the temperature behavior of the inverse current of the insulating p–n-junction vs the ratio of the perimeter to the area of the junction surface: A) $K_{p-n}$ =

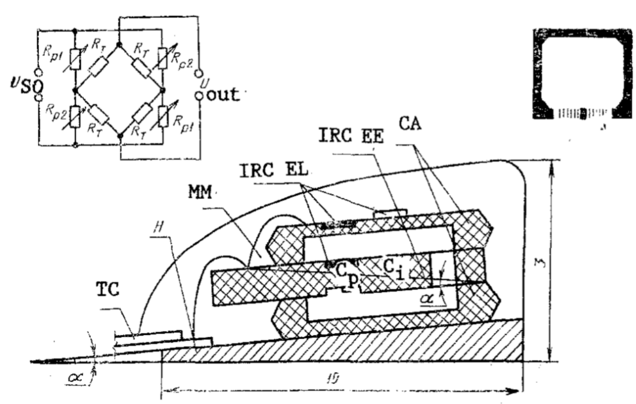


Fig. 1

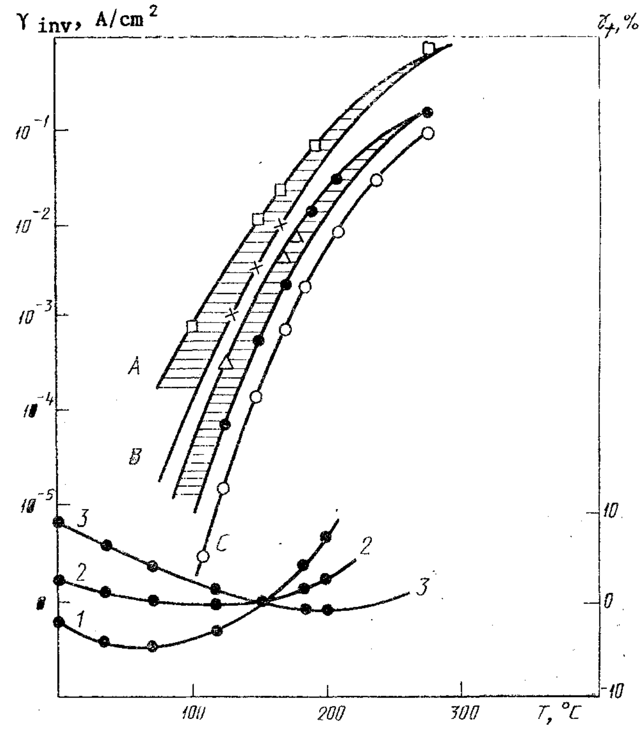


Fig. 2

800-1400 cm; B) $K_{p-n}$ = 500-700 cm; C) $K_{p-n}$ = 500 cm (it does not contain angles; the BSC configuration is formed of circles). The regions A, B, and C are constructed for ion-doped layers with a surface concentration of $5 \times 10^{18}$ $cm^{-3}$ and a concentration in a layer of the mean projected path length of $1.2 \times 10^{20}$ $cm^{-3}$. These layer concentrations in the alloy dose range from $8 \times 10^{15}$ to $4 \times 10^{14}$ $cm^{-2}$ are optimal with respect to insulation quality, scatter of BSC electric resistivities on the substrate, and nonlinearity of the behavior of resistance as a function of temperature in the interval of −60 to +200°C.

At positive temperatures, layers doped by diffusion with surface concentrations of $1\text{-}5 \times 10^{18}$ $cm^{-3}$ are also satisfactory in terms of insulation properties and the temperature behavior of the resistivity. Above 150°C, where the resistance of the p–n-junction insulation is determined by the diffusional component of the reverse current, and the temperature behavior of the reverse current density in layers doped by ions or by diffusion is more or less the same.

The second stage of the effort is to compensate for the strong temperature influence on the strain sensitivity coefficient without worsening the BSC insulation. At temperatures up to +200°C, two forms of compensation are available. One is compensation by planar resistance on dielectric insulation (in particular, resistance with negative temperature resistivity of a material based on PC-1004 alloy). The second alternative is compensating for the working gain factor by current, often referred to as autocompensation.

The BSC layers doped by ions considered in the present study are characterized in the range of 0-200°C by the relations

$$K^{u}_{IRC} = \frac{U^{bc}_{out}}{U_{SO}} = \left[ 10+60\,\frac{T_0}{T} - 14\left(\frac{T_0}{T}\right)^2 \right] \varepsilon_x;$$

$$R_{in} = R_{in0}\,[1+1.14\cdot 10^{-3}\,(T-T_0)+1.5\cdot 10^{-6}\,(T-T_0)^2],$$

those doped by diffusion are described by

$$K^{u}_{IRC} = \left[ 4+80\,\frac{T_0}{T} - 12\left(\frac{T_0}{T}\right)^2 \right] \varepsilon_x;$$

$$R_{in} = R_{in0}[1+2.3\cdot 10^{-3}\,(T-T_0+4\cdot 10^{-6}\,(T-T_0)^2],$$

where $\varepsilon_{in}$ is the uniaxial BSC deformation; $R_{in}$ is the input resistivity of the BSC; $R_{in0}$ is the input resistivity at the temperature $T_0$ = 423 K.

The coefficients at the linear term of the polynomial indicate that the diffusion-doped layers require thermally resistant material with a large temperature resistivity (TR) for compensation. Otherwise, the circuit sensitivity will be reduced considerably. To compensate for the accelerometer sensitivity change, we adopted a IRC circuit (see Fig. 1) constructed as a thermally sensitive bridge with two arms having positive TR and two arms having negative TR, with a BSC connected into the diagonal. The arms of the thermally sensitive circuit are characterized by the following relations: diffusion doped $R_p(T) = R_{p10}[1 + 3.4 \cdot 10^{-3}(T - T_0) + 2.3 \cdot 10^{-6}(T - T_0)^2]$; thin-film $R_{p2}(T) = R_{p20}[1 - 2.7 \cdot 10^{-3}(T - T_0) + 7.3 \cdot 10^{-6}(T - T_0)^2]$. (The surface resistivity of diffusion-doped layers is 300 Ω per square, so that they can be made with a small area of p–n-junctions.)

A circuit of resistors with such characteristics reduces the working gain factor compared to $K_{IRC}^u$ of an uncompensated circuit by a factor of 1.5 for a BSC with ion-doped resistors, and by a factor of 1.8 for diffusion-doped resistors. The error of the accelerometers with a BSC for both types of resistors between 0 and 200°C is 0.015%/°C.

Self-compensation with a BSC powered by a stabilized current is achieved at temperatures of 0-200°C. Figure 2 shows the temperature behavior of the working gain factor (T) with compensation by a bridge of thermal resistors (curve 2), self-compensation by an ion-doped BSC (curve 3), and by a diffusion-doped BSC (curve 1). As can be seen from Fig. 2, with self-compensation the accelerometer error for BSCs of both types does not exceed 0.04%/°C.

In a wide temperature range, air damping is preferable. For small-size sensors, damping should be provided in the narrow gaps between the planes of the inertial element and the inner surfaces of body components (lids). Silicon lids with inner cavities were used in this accelerometer. For the specific design, the attenuation factor $\theta^*$ that characterizes the damping level is linked with the geometric size of the gap $w = (20\text{-}80) \times 10^{-6}$ m by the empiric relation

$$\theta^* = \frac{2 \cdot 10^{-11}}{(H_{ee} - 11 \cdot 10^{-6})(w - 16 \cdot 10^{-6})},$$

where $H_{ee} = (15\text{-}25) \times 10^{-6}$ m is the thickness of the elastic element.

The mechanical strength of the deformable component of the sensor element is determined by three factors. The first factor is the reduction in the geometric dimensions to values corresponding to [5]. As a result, the strength of the deformable regions of the elastic element becomes greater than the strength of monolithic silicon single-crystals. The second factor is the processing of the silicon surface by chemical etching in the course of fabrication of the elastic element. The third factor is associated with the choice of adjustment method: the separation of the deformable part of the plate (the elastic element) into several strips. If one of the strips is destroyed because of a random structural defect, the neighboring strips remain unaffected. The strength of the elastic element of this configuration and with this surface treatment is higher by an average factor of 25 than the working deformation level ($\varepsilon_x = 4 \times 10^{-4}$).

Sensitivity adjustment is accomplished by breaking the strips with a laser. With this method the sensitivity to mechanical variables and the sensitivity to temperature variations can be adjusted independently. The technique is also convenient, because after the adjustment the elastic elements of the entire series of accelerometers for a certain input rating are characterized by similar amplitude–frequency responses. The sensitivity variation is hyperbolic and can be calculated by using the method of [2].

The sensitivity to the acceleration components acting in the plane normal to the component being measured is due to the displacement of the center of mass of the inertial element of the MM relative to the median planes of the plates of the elastic element (see Fig. 1). This sensitivity may be as high as 15% relative to the component being measured. A partial compensation for this error is obtained by mounting the MM on a wedge-shaped carrier, with the angle $\alpha$ between the upper and lower surfaces being equal to the angle between the surface of the elastic element and the plane passing through the centers of the inertial element $C_i$ and the plates $C_p$.

The error due to these components of acceleration is reduced to 3%.

The carrier also functions as the mechanical separator of the silicon MM protecting it from stresses caused by attachment of the accelerometer and the strain of the object.

The specifications for a small-sized silicon accelerometer are the following: dimensions = 10 × 8 × 3 mm; weight = 1.5 g; acceleration ranges = 0 ± 15g, 0 ± 30g; sensitivity = 3.3 and 6.6 mV/g; transverse sensitivity ≥ 3%; working frequency range = 0-150 and 0-300 Hz; main error ≥ 3%; working temperature range = −60 to +200°C; temperature range of thermal compensation = 0-200°C; components of additional temperature error: temperature drift of initial output signal < 0.04%/°C, temperature drift of sensitivity < 0.04%/°C; power voltage = 10 and 15 V; input resistivity of circuit = 800-1000 Ω.

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