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Small-Size Silicon Accelerometer with a Thermally Compensated Signal in the Temperature Range Of $0 \div +200^{\circ}\text{C}$

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Abstract

We describe an integrated single-component inertial accelerometer for low-frequency ($0 \div 300$ Hz) accelerations ($0 \pm 100 \dots 0 \pm 300$) M/c^2 with overall dimensions less than $10 \text{ mm} \times 8 \text{ mm} \times 3 \text{ mm}$ with piezoresistive mechanical transducer. The principle of operation of the device and its design are well known. We propose a new version of the design, which improves some metrological and operational characteristics of the device. The obtained technical characteristics meet the requirements for the elements of control systems, control, regulation of research and design-improvement tests of mechanical engineering products. Accelerometers are characterized by the basic error less than 5 % and the additional temperature error from $0.06 \text{ \%}/^{\circ}\text{C}$ to $0.13 \text{ \%}/^{\circ}\text{C}$. Temperature operating range ($0 \div 200$) $^{\circ}\text{C}$.

The principle of operation of the device and its design (inertial element performing double differentiation [elastic] displacement and strain gauge resistance element made in the form of monolithic silicon monocrystal) are well known ^{1 2 3}. The new version of the design, improves the metrological and operational characteristics of the well-known devices.

The accelerometer consists of (Fig. 1) a measurement module (*IPTM*) mounted on a thermal expansion matched body extension BP^{α} made of Kovar alloy 29NK. Electrical connection to the subsequent device of information-measuring system is provided by ribbon cable (FC) on the basis of polyamide or by high-temperature heat-resistant anti-vibration cable of AVKTS type TU 16-785.130-80. Structural elements (*DE*) are made of monocrystalline silicon wafers with orientation in plane (100). The elastic element (*EE*) (see Fig. 1) consists of 28 cantilever beams of length L , width d_i and thickness H_{ee} , rigidly mounted on a ring support. The resistive elements R_{ch} (or *PCH*) of the bridge strain gauge circuit (*MC*) are mounted on each of the two beams D_1 . The remaining beams D_i , the total number of beams $n = 26$, serve to adjust the amplitude characteristics of the conversion (Fig. 1). The silicon covers (*SC*)

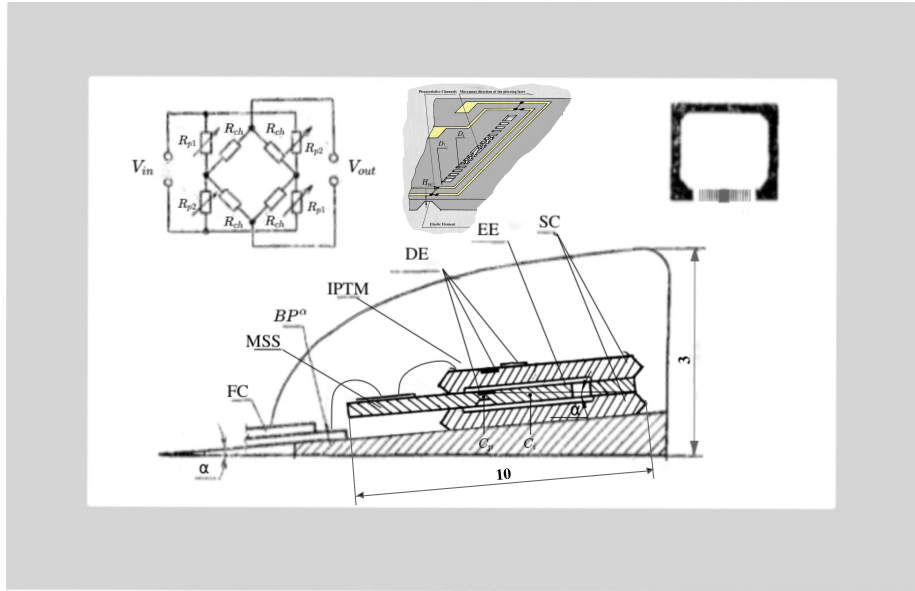


Fig. 1

act as thermocompensation circuits TCC and dampers of vibrations of inertial and elastic elements.

New technological versions of the device seek to expand the operating temperature range, compensate for changes in the sensitivity of the accelerometer caused by temperature changes, achieve the required level of attenuation and maximum mechanical strength, develop a method for adjusting the amplitude conversion characteristics sufficient to correct for the scattering parameters of mass-produced devices, and reduce the size and weight of the device.

The first part of the design, on extending the operating temperature range, relates to the electrical isolation of MC using a $p-n$ junction from an elastic element in the temperature range up to $+200^{\circ}\text{C}$, while maintaining a satisfactory conversion characteristic. In this formulation, the MC isolation failure criterion is given as a 1% change in sensitivity K_{mc} due to shunting of the output resistance by the elastic element ⁴.

The MC regions are plotted for 2 options:

- diffusion boron-alloyed layers with average resistivities PCH (where one would expect in the range $(0 \div +200)^{\circ}\text{C}$ "autocompensation" for temperature changes in sensitivity when feeding MC with stabilized current) $0.035 \Omega \cdot \text{cm}$
- for ion-alloyed layers with $2 \cdot 10^{15} \text{ cm}^{-2}$ ligation dose ($R_s = 80 \Omega/\square$)

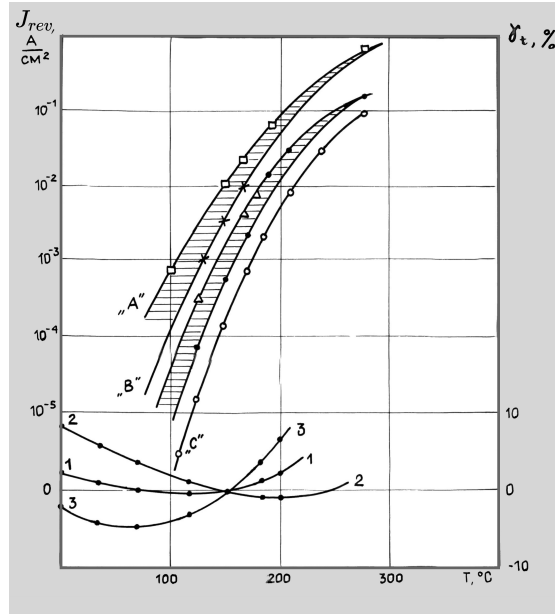


Fig. 2

Fig. 2 shows the behavior of $p-n$ junction reverse current temperature as a function of the ratio of perimeter to transition surface area: A) $K_{p-n} = (800 \div 1400) \text{ cm}$; B) $K_{p-n} = (500 \div 700) \text{ cm}$; C) $K_{p-n} = 500 \text{ cm}$ (the MC configuration is represented as a circle with inscribed channels). Regions A, B and C are constant impurity concentration layers with a surface concentration value of $5 \cdot 10^{18} \text{ cm}^{-3}$. The impurity concentration in these layers is optimal in terms of charge carrier dissipation and resistance nonlinearity as a function of temperature in the range of -60 to $+200^\circ\text{C}$.

At positive temperatures, diffusion doped layers with surface concentrations $(1 \div 5) \cdot 10^{18} \text{ cm}^{-3}$ are also satisfactory in terms of insulating properties and temperature behavior of resistivity. Above 150°C , when the isolation resistance $p-n$ -transition is determined by the diffusion component of the reverse current, the temperature behavior of the reverse current density in ion-doped or diffusion-doped layers is more or less the same.

The second part is to compensate for the strong influence of temperature on the bridge sensitivity without degrading the MC isolation. At temperatures up to $+200^\circ\text{C}$, two forms of compensation are chosen. One is compensation by a TCC circuit in the power supply circuit located on the separate DE . The second option is to compensate for the temperature drift of the current sensitivity of the bridge by the so-called "autocompensation".

The MC ion-doped layers considered in this study are characterized in the range from 0 to $+200^\circ\text{C}$ by the following relations:

$$K_{mc}^{ion} = \frac{V_{out}^{mc}}{V_{in}^{mc}} = \left[10 + 60 \frac{T_0}{T} - 14 \left(\frac{T_0}{T} \right)^2 \right] \varepsilon_x; \quad (1)$$

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

those doped by diffusion are described as follows:

$$K_{mc}^{dif} = \left[4 + 80 \frac{T_0}{T} - 12 \left(\frac{T_0}{T} \right)^2 \right] \varepsilon_x; \quad (3)$$

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

where ε_x is the uniaxial deformation *MC*; R_{in} is the input resistance *MC*; R_{in0} is the input resistance at temperature $T_0 = 423$ K.

To compensate for the change in the sensitivity of the accelerometer, we used a circuit (see Fig. 1) built as a thermosensitive bridge (with two arms with positive *TCR* and two arms with negative *TCR*) connected to *MC* in the diagonal. The shoulders of the thermosensitive circuit are characterized by the following relationships:

- diffusion doping

$$R_{p1}(T) = R_{p10} \left[1 + 3.4 \cdot 10^{-3} (T - T_0) + 2.3 \cdot 10^{-6} (T - T_0)^2 \right] \quad (5)$$

- thin-film from *RS1004*

$$R_{p2}(T) = R_{p20} \left[1 - 2.7 \cdot 10^{-3} (T - T_0) + 7.3 \cdot 10^{-6} (T - T_0)^2 \right] \quad (6)$$

The surface resistance of diffusion-alloyed layers is $300 \Omega/\square$, so they can be made with a small p-n junction area.

A resistor circuit with these characteristics reduces the bridge sensitivity K_{mc} compared to an uncompensated circuit by a factor of 1.5 for *MC* with ion-doped resistors and 1.8 for diffusion-doped resistors. The error of the *TCC* accelerometers for both types of resistors between 0 and $+200^\circ\text{C}$ is $0.015\%/^\circ\text{C}$.

Self-compensation of the *IPTM* powered with stabilized current is achieved at temperatures $(0 \div +200)^\circ\text{C}$. Figure 2 shows the temperature behavior of the error parameter γ when compensated by the bridge thermoresistors *TCC* (curve 2), self-compensation with ion-doped piezo-cut channels (*PCH*) (curve 3) and diffusion channels (curve 1). As can be seen from Fig. 2, with self-compensation, the accelerometer error for *IPTM* of both types does not exceed $0.04\%/^\circ\text{C}$.

Over a wide temperature range, air damping is preferred. For small gauges, damping must be provided in the narrow gaps between the planes of the inertial element and the inner surfaces of the *SC* (cover) housing parts. In this accelerometer, silicon caps with internal cavities were used. For a particular design, the damping coefficient θ^* , which characterizes the level of damping, is related to the geometric size of the gap $w = (20 \div 80) \cdot 10^{-6}$ m by the empirical relationship

$$\theta^* = \frac{2 \cdot 10^{-11}}{(H_{ee} - 11 \cdot 10^{-6})(w - 16 \cdot 10^{-6})} \quad (7)$$

Where $H_{ee} = (15 \div 25) \cdot 10^{-6}$ m is the thickness of the elastic element.

The mechanical strength of the deformable component of the *MSS* sensor element is determined by two factors. The first factor is the reduction of the geometric dimensions to values corresponding to ⁵. The second factor is the treatment of the silicon surface by chemical etching during fabrication of the elastic element. The strength of an elastic element of this configuration and with this surface treatment is on average 25 times higher than the working strain level ($\varepsilon_x = 4 \cdot 10^{-4}$).

The sensitivity is adjusted by fracturing the bands with the laser. With this method, the sensitivity to the mechanical input parameter and the sensitivity to temperature changes can be adjusted independently. The method is also convenient in that, after adjustment, the elastic elements of the entire series of accelerometers for a certain input nominal are characterized by the same amplitude-frequency responses.

The sensitivity to acceleration components acting in a plane normal to the measured component is due to the *MSS* shift in the center of mass of the inertial element relative to the median plate planes of the elastic element (see Fig. 1). This sensitivity can be as high as 15% relative to the measured component. A partial compensation for this error is obtained by mounting the MM on a wedge-shaped carrier, with the angle α 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 acceleration components is reduced to 3%.

The carrier also acts as a mechanical separator for the silicon *IPTM*, protecting it from stresses caused by mounting the accelerometer and deformation of the object.

Specifications for the small silicon accelerometer are as follows: dimensions = $10 \times 8 \times 3$ mm; weight = 1.5 gram; acceleration ranges = 0 ± 15 g, 0 ± 30 g; sensitivity = 6.6 mV/g and 3.3 mV/g; transverse sensitivity 3%; operating frequency range = $0 \div 150$ and $0 \div 300$ Hz; basic error $\leq 3\%$; operating temperature range = -60 to $+200^\circ C$; temperature compensation range = $0 \div +200^\circ C$; additional temperature error components: temperature drift of initial output signal $< 0.04\%/^\circ C$, temperature sensitivity drift $< 0.04\%/^\circ C$; supply voltage = 10 V; circuit input resistance = $800 \div 1000\Omega$.

The obtained technical characteristics meet the requirements for the ele-

ments of control systems, control, regulation of research and design-improvement tests of mechanical engineering products.

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