Low-Frequency Accelerometer for Control Systems in LLRD Testing

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Abstract

The exponential growth in demand for compact and efficient accelerometers is driven by their diverse applications across industries such as automotive, aerospace, consumer electronics, and healthcare. This article presents two designs of small-size accelerometers: the ultra-compact "SRA_{micro}" and the slightly larger, higher-accuracy "SRA_{Hi-Pre}." Both accelerometers are designed to operate in frequency ranges of $(0 \div 200)\ Hz$ and temperatures $-50°C - +180°C$. The SRA_{micro} model is ideal for applications with limited space, while the SRA_{Hi-Pre} model offers higher accuracy for mission-critical applications. The article discusses the structures, materials, and methods used to create and optimize these accelerometers. Experimental results indicate that the SRA_{Hi-Pre} model, when combined with a thermal compensation circuit, significantly reduces the temperature sensitivity parameter (γ) and improves the overall performance of the device. These compact accelerometers have the potential to meet the increasing demands for diverse applications in various industries.

The demand for compact and efficient accelerometers is growing exponentially because of their diverse applications in industries such as automotive, aerospace, consumer electronics, and healthcare. These small devices measure the force of acceleration, allowing the detection of motion, orientation and vibration. As technology advances, manufacturers are constantly striving to create smaller, more accurate accelerometers that can meet a wide variety of requirements. One of the problems associated with managing research tests of reusable RD-170 (11D521) and RD-171 (11D520) LPRE units involves obtaining accurate information about vibration modes, dynamic stability parameters, and dynamic overloads on nodes and power elements. The range of measurable acceleration is from 0±1 g to 0±10 g, and the frequency spectrum is 0–300 Hz. The internal error of the accelerometers must not exceed ±5%.

Although piezoelectric accelerometers have significant advantages, such as a wide operating range, up to $(400 \div 600)°C$, and high sensitivity, their applications are limited to low frequencies $(5 \div 10)\ Hz$ [1]. The piezoresistive effect in semiconductor materials is used to measure linear and low-frequency (up to 200 Hz) vibration accelerations [2]. Produced silicon integral resistive low-frequency acceleration transducers (SRA) are designed for operation at temperatures below $100°C$ [3], but if the quality of insulation of strain gauges from the elastic element (EE) is improved, an extension of the operating range to temperatures close to the appearance of material intrinsic conductivity is possible [4].

In this article, we will look at two designs of small-size accelerometers. The first design, which we will call "SRA_{micro}"$6\,\mathrm{mm} \times 5\,\mathrm{mm} \times 2\,\mathrm{mm}$ size, is very small, making it ideal for applications with limited space. The second design, called "SRA_{Hi-Pre}",$14\,\mathrm{mm} \times 8\,\mathrm{mm} \times 3\,\mathrm{mm}$, is slightly larger, but offers higher accuracy.

The SRA (of both types) for frequency ranges of $(0 \div 200)\ Hz$ and temperatures $-50°C - +180°C$ is a design consisting of top and bottom silicon covers (SC) made of monocrystalline silicon and a mechanical silicon sensor (MSS_{micro};MSS_{Hi-Pre}) enclosed between them. Chemically etched cavities in the lids and the inner contour of the ring base of the MSS form a closed volume that protects the elastic element and the measuring circuitry from external influences; the amplitude of inertial mass vibrations during overloading is limited by the depth of the cavities in the lids.

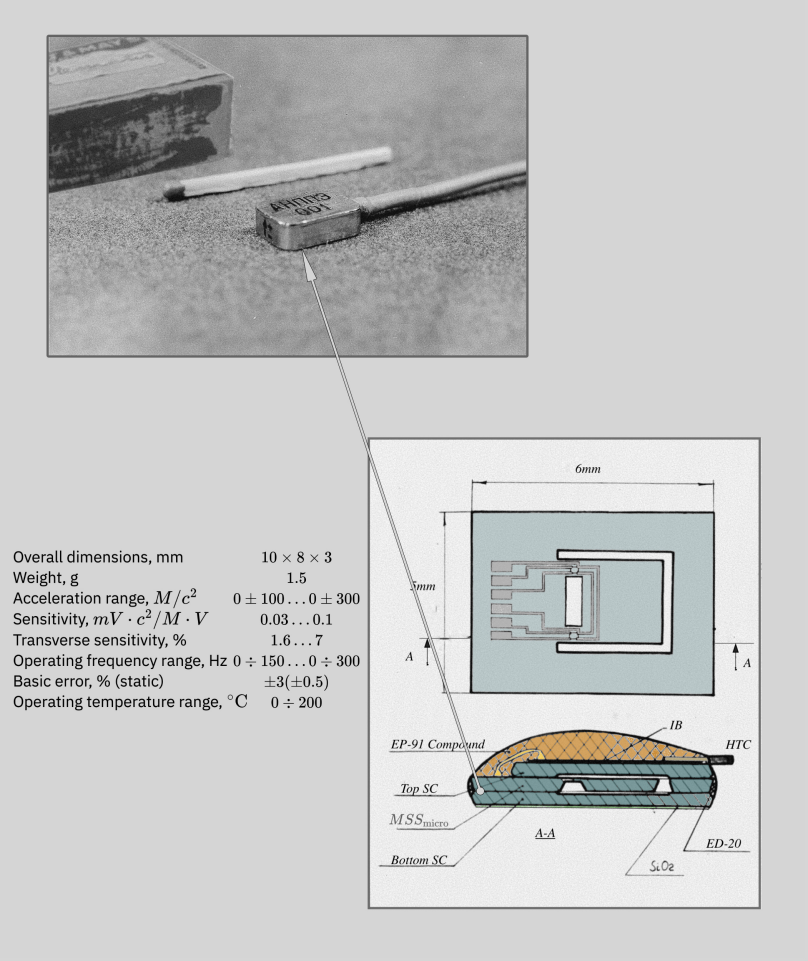

Figure 1: Micro Miniature Silicon Resistive LF Accelerometer SRA_{micro}

The MSS_{micro} is a monolithic structure in the form of two cantilever beams rigidly connected at the ends by a common inertial mass and an annular base side (see Figure 1). The inertial mass with dimensions $2\,\mathrm{mm} \times 2\,\mathrm{mm} \times 0.35\,\mathrm{mm}$, the cantilever beams and the annular base with a thickness of 0. 35 mm were formed by chemical etching from both surfaces of a silicon wafer (Silicon wafer, N-type, grown by the Czochralski method, 4.5 Ωcm) with orientation (100). This configuration of the elastic element (EE) ensures the conversion of a single acceleration component. The thickness of the cantilever beam determines the range of measured accelerations. The SRA_{micro} experimental samples are made in 2 versions : with $H_{ee} = 20\mu$ for accelerations $(0 \div 25)g$ and $H_{ee} = 30\mu$ for $(0 \div 75)g$.

The SRA_{micro} measuring circuit consists of parallel-connected piezo-bridges arranged on beams. Diffusion boron doping has been used to form piezoresistors with a channel width of $5\mu m$. The average resistivity

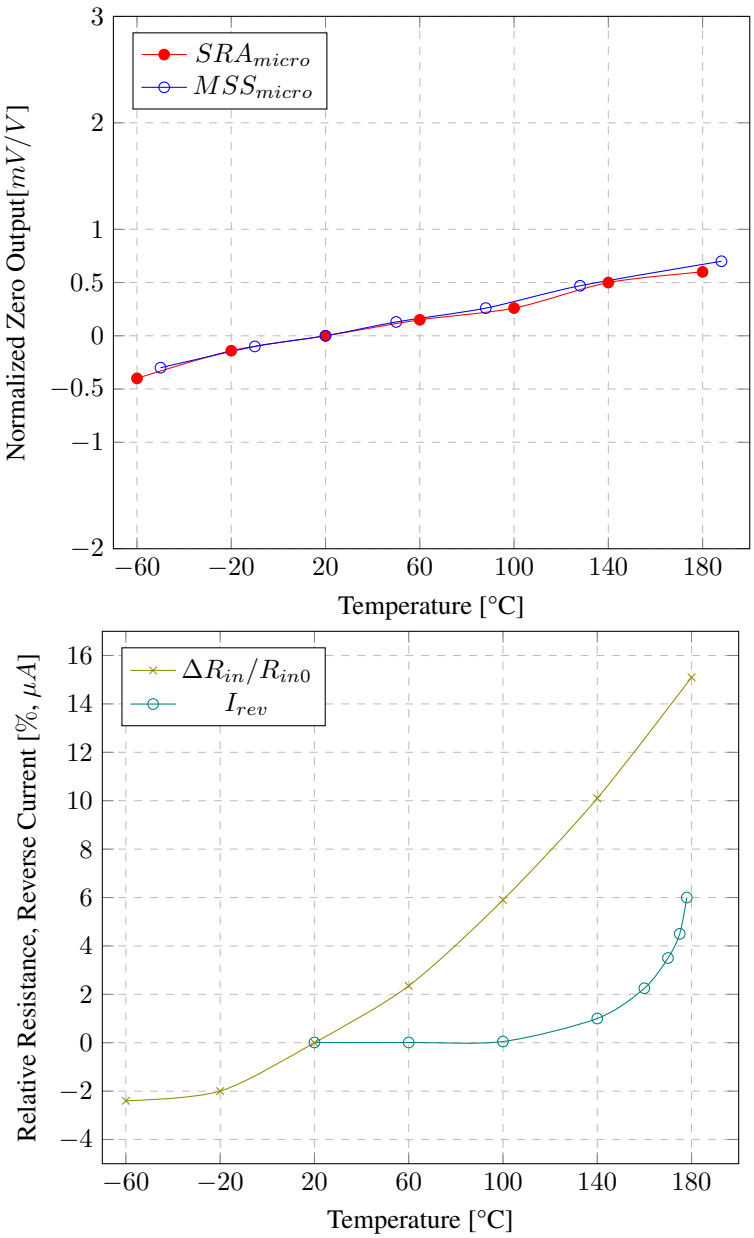

Figure 2: Graph of the dependence of the change in the normalized zero output $\Delta K_{mc0)}$, relative input resistance $\Delta R_{in}/R_{in0}$ and reverse current I_{rev} $p-n$ junction of the measuring circuit at $V_{rev} = 6\ V$ on temperature

is $0.02\ \Omega \cdot cm$. The topological structure of MSS_{micro} allows diffusion alloying to replace ion implantation. To electrically connect the MSS_{micro} aluminum contact pads (by a cable jumper), an intermediate board (IB) with thin-film three-layer (V - Cu - Ni) conductors allowing micro-welding and soldering is formed on the top silicon cap ($TopSC$). In the process of assembling the accelerometer, ED-20 based epoxy glue was used to glue the caps and MSS_{micro}. It is possible to replace the silicon covers with glass covers from

$$7740 PYREX\ (\mathrm{SiO_2} - 81\%; \mathrm{Al_2O_3} - 2\%; \mathrm{Na_2O} - 4\%; \mathrm{K_2O} - 0.5\%; B_2\mathrm{O_3} - 13\%)$$

and correspondingly applying electrostatic connection of the caps with MSS_{micro}.

EP-91 compound was used to protect the intermediate board, aluminum contact pads and gold leads.

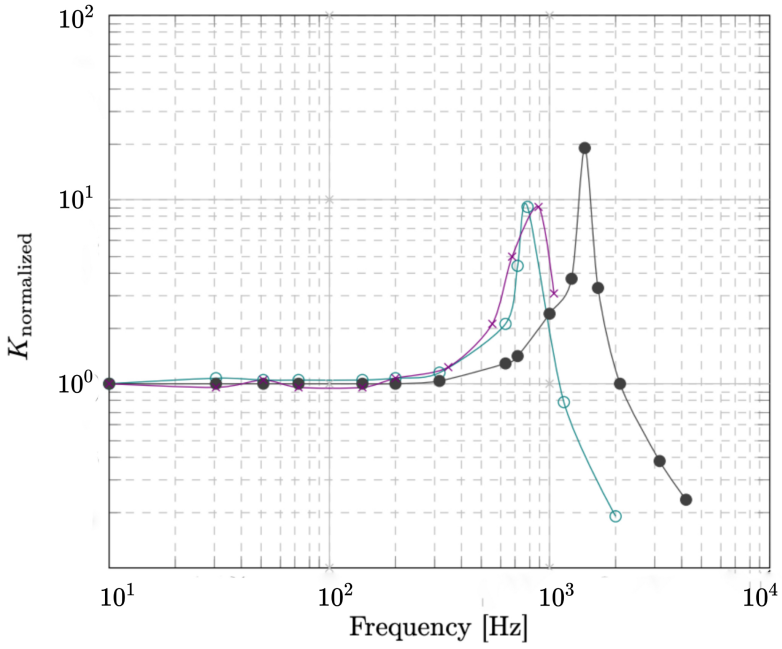

Figure 3: Graph of the amplitude-frequency response of the accelerometer SPA_{micro}

The temperature dependence of the input resistance change $\Delta R_{in}/R_{in_0}$ in Figure 2 shows a minimum below $-20°C$, which is a known fact for the doping level used $(1 \div 6) \cdot 10^{18}\ cm^{-3}$ [5]. However, the change $K_{mc0} = \frac{V_{out\,0}}{V_{in}}$ (normalized null output) with temperature change is monotonic throughout the analyzed range with a coefficient of $0.004\ mV/V°\mathrm{C}$. This indicates a high reproducibility of the characteristics of the piezoresistors of the measuring circuit. It should be noted that after joining the structural elements ($TopSC$-MSS_{micro}-$BattomSC$) by means of adhesive bonding, there were no noticeable changes in the temperature dependence of the normalized zero output.

Figure 3 shows a graph of the amplitude-frequency characteristics of the accelerometers. The calculated values of the resonant frequencies slightly differ from the experimental ones.

After exposure to sign-variable mechanical loads of 20 million cycles with a frequency of $(700 \div 900)$Hz and the amplitude value of the relative strain EE in the area of piezoresistors location $4 \cdot 10^{-4}$ the values of changes of zero, working output signals and reverse current of the insulating $p{-}n$ junction (at $V_{rev} = 0.8 \cdot V_{br}$) were within the laboratory error in measuring these quantities.

The problems of improving the accuracy of small-size sensors with silicon integrated resistor transducers

are mainly related to the non-reproducibility of geometrical dimensions EE and significant temperature variations of the electrical output signal [6] [7].

The standard systematic component of the basic error is set from $\pm 0.02\%$ to $\pm 10\%$, depending on the type and accuracy class of the sensor [8]. The absolute error of reproducing the thickness of the elastic element H_{ee} in the process of deep etching, when using silicon wafers of thickness $H_w = 350\ \mu$ as blanks, is given in [3] and is the value $\pm 7,5\ \mu$. The error of other geometrical dimensions, taking into account the etching angle of the plate with orientation (001), is $\pm 10\mu$. The marginal value of the relative error of the sensitivity coefficient of the beam MSS with inertial mass, $\delta_{k_{ee}}$ due to non-reproducibility of geometric dimensions is determined by the ratio:

$$\delta_{k_{ee}} = \frac{\Delta K_{ee}}{K_{ee}} = \frac{\Delta A}{A} + \frac{\Delta B}{B} + \frac{\Delta H_w}{H_w} + \frac{\Delta (A+L)}{A+L} + 2\frac{\Delta H_{ee}}{H_{ee}} \tag{1}$$

where A, B, H_w are the geometric dimensions of the inertial mass, L is the length EE, W is the width EE.

For an integral beam accelerometer in [2] with $\mathrm{H_{ee}} = 50\ \mu$; $A \times B \times C = 3\ mm \times 3\ mm \times 0.3\ mm$; $L = 0.3\ mm$ and $W = 0.4\ mm$, $\delta_{k_{ee}} = \pm 40\%$. For EE with smaller geometric dimensions, the error can be much larger.

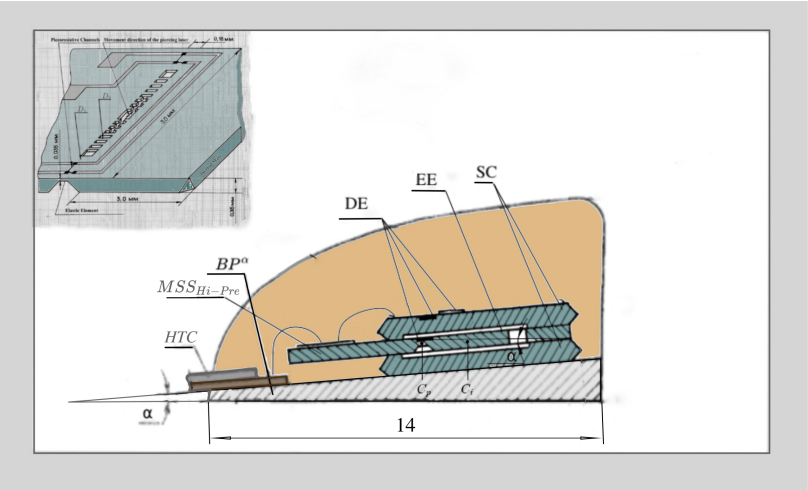

Figure 4: Small-Size Silicon Resistive LF-Accelerometer SRA_{Hi-Pre}

Developed and investigated a method for tuning beam transducers by changing the conversion coefficient of the input quantity (acceleration ϕ_{in}) through the inertial mass into the deformation of the elastic element

$$K_{ee} = \frac{\varepsilon_{ee} - \varepsilon_{ee0}}{\phi_{in}} = \frac{\Delta \varepsilon_{ee}}{\phi_{in}} \tag{2}$$

The tuning method is carried out as follows (see Figure 4): By anisotropic etching, elastic element and inertial mass regions are formed in the silicon wafer on the planar side. Using anisotropic etching of the wafer on the planar side, the EE regions are divided into groups of parallel D_1 bands with piezoresistors and adjusting n bands D_2 without piezoresistors. Monitoring the parameters MSS_{Hi-Pre}, determines the systematic component of the error $\delta_{k_{ee}}$, and the resonant frequency f_0. To adjust, the total value of the width of the adjustment bands $m \cdot D_2$ must be determined, which can be expressed by the ratio:

$$m \cdot D_2 = \delta_{k_{ee}} \cdot (2 \cdot D_1 + n \cdot D_2) \tag{3}$$

Then m of adjustment strips are broken without breaking the symmetry of the elastic element.

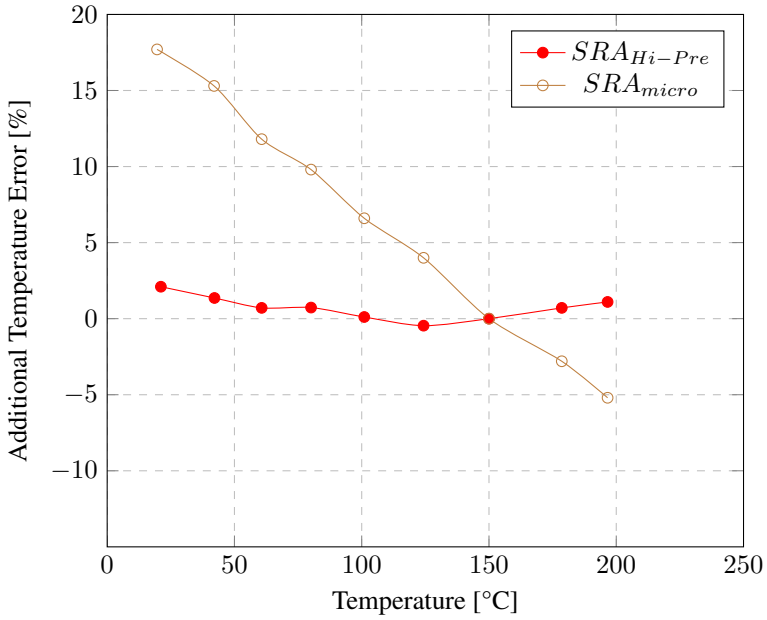

Figure 5: Temperature dependences of the coefficient γ_{mc} when powered from a stabilized voltage source: SRA_{micro} without compensation circuit; SRA_{Hi-Pre} with TCC containing regulating resistors with TCR of different sign.

For a SRA_{Hi-Pre} design where

$$D_1 = 400 \cdot 10^{-4}\ cm, \quad D_2 = 40 \cdot 10^{-4}\ cm, \quad n = 32,$$

the required number of break bands is determined by the ratio:

$$m = \delta_{k_{ee}} \frac{2 \cdot D_1 + n \cdot D_2}{D_2} = 52 \cdot \delta_{k_{ee}} \tag{4}$$

The SRA_{Hi-Pre} setup produced the following results:

Transducer Number	Sensitivity Before Tuning mV/g	Required Sensitivity mV/g	$\delta_{k_{ee}}$	m	Sensitivity After Adjustment mV/g	Error After Adjustment
1	10.2	15	33%	18	15.3	2%
2	7.9	10	21%	12	10.2	2%
3	13.2	15	12%	6	14.6	3%

The parameter of the additional temperature error γ for the range (T_1, T_2) is usually estimated by the change in the output signal as a percentage of its nominal value when the ambient temperature changes (temperature instability of the output signal) [8]:

$$\frac{V_{\text{out max}} - V_{\text{out min}}}{V_{\text{out}}\ (T_0)} \cdot \frac{1}{T_2 - T_1} \cdot 100\% \leq \gamma; \ \ \%/^\circ C \tag{5}$$

where $V_{out_{max}}$ and $V_{out_{min}}$ are, respectively, the maximum and minimum output values when the temperature changes.

To create sensors with low γ values, a thermal compensation circuit (TCC) must be used. [9]. In Figure 4, the SRA_{Hi-Pre} top cover contains regulating thin-film and silicon diffusion resistors . The choice of TCC resistive elements is due to the fact that the thin-film resistors and diffusion resistors retain their characteristics in the same temperature range as SRA, i.e. $(-50 \div +180)^0\, C$.

The accelerometer consists of (Figure 4) a measurement module 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 on the basis of polyamide or by high-temperature heat-resistant anti-vibration cable of AVKTS type TU 16-785.130-80 (HTC). Structural elements (DE) are made of monocrystalline silicon wafers with orientation in plane (100). The elastic element (EE) consists of 28 cantilever beams of length L, width d_i and thickness H_{ee}, rigidly mounted on a ring support. The resistive elements of the bridge strain gauge circuit (MC) are mounted on each of the two beams D_1. The remaining beams D_2, the total number of beams $\mathrm{n} = 26$, serve to adjust the amplitude characteristics of the conversion (Figure 4). The silicon covers (SC) act as thermocompensation circuits TCC and dampers of vibrations of inertial and elastic elements.

Figure 5 shows the experimentally obtained temperature dependences of the sensitivity changes for SRA_{micro} without compensation and SRA_{Hi-Pre} with compensation in the temperature range $(0 \div +230)^{\circ}C$. Connecting the TCC containing TCR adjusting resistors of different signs reduced the γ parameter from $0.13\ \%/^{\circ}C$ to $0.015\ \%/^{\circ}C$.

Low-frequency $(0 - 200$ Hz) accelerometers, such as SRA_{micro} and SRA_{Hi-Pre}, are designed to measure accelerations in the range of $0 \pm 10g$ to $0 \pm 75g$. They have certain performance characteristics, including an intrinsic error of less than $\pm 5\%$ and an additional temperature error that ranges from $0.02\ \%/^{\circ}\mathrm{C}$ to $0.13\ \%/^{\circ}\mathrm{C}$. These accelerometers are capable of operating within a wide temperature range, from $(-50 \div +180)^{\circ}C$.

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