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# Semiconductor Sensors for a Wide Temperature Range

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**Abstract:** Prototype sensors are described that are applicable for pressure, position, temperature, and field measurements in the temperature range of 4.2 to 300 K. The strain gauges utilize the silicon substrate and thin film technology. The tensosensitivity of strain sensors is 40 μV/mln$^{-1}$ or better depending on metrological characteristics of semiconductor films, orientation, and current. The temperature sensors (thermistors) make use of the germanium powder bulk. The temperature coefficient of resistance is within 50-100 % /K at 4.2 K. The magnetic field sensors use GaAs films that offer weak temperature dependence of parameters at high sensitivity (up to 300-400 mV/T). *Copyright © 2014 IFSA Publishing, S.L.*

**Keywords:** Semiconductor, Cryogenic, Hall sensors, Thermistors, Strain gauges.

## 1. Introduction

Design and implementation of semiconductor sensors for cryogenic temperatures involves selection or special fabrication of materials to provide required performance and durability. The sensor should survive thermally aggressive environment without deterioration of accuracy. Also, development of new measurement techniques is often required to accommodate for a variety of conditions [1, 2].

State-of-the-art microelectronic sensors commonly utilize semiconductor films that are suitable for integrated technologies and have advantages of reliable and reproducing characteristics and low cost.

## 2. Material and prototypes

Experimental prototypes of semiconductor sensors capable of measurement in a wide temperature range have been produced. The sensing elements utilize the GaAs film on the semi-insulating GaAs substrate, the polysilicon film on the silicon substrate, the Ge film on the GaAs, and also the doped Ge powder bulk [3]. In order to evaluate functionality of sensors, a series of measurements have been performed in the operating temperature range of 4.2-300 K

## 3. Results

### 3.1. Strain gauge

The strain gauges utilize the sensitive elements with n- or p-types polycrystalline Si films deposited on the $SiO_2$ substrate. The film thickness is 0.6 microns, the doping level is $10^{17}$ to $5 \cdot 10^{19}$ cm$^{-3}$.

Fig.1 shows a prototype strain gauge. The signal conditioning circuit is integrated on a silicon chip in a close contact with the sensing element. Such design provides temperature and field compensation and eliminates transverse sensitivity [4]. The overall dimensions of the package are 8.0×0.6×0.4 mm. The input/output resistance of the prototype strain gauges depends on the doping level and film thickness and varies within the range of 200÷3000 Ω, the nominal control current being in the range of 1÷10 mA. The resistance is reproducible within a test lot with fluctuations below 5%. The strain gauges can be supplied with nominal specifications that will vary slightly within batch. The gauge factor $\Delta U_B / \Delta\varepsilon$ is about 100 μV/mln$^{-1}$ at the supply voltage of 5 V (mln$^{-1}$ = 1/10$^6$ - a unit of relative deformation). Residual (null) output voltage $U_0$ is ~ 20 mV. The gauge factor variations with temperature is 0.02 %, the temperature dependence of residual voltage $U_0$ is ~ 20 μV/K.

**Fig. 1.** Prototype strain gauge.

The semiconductor strain gauge detects stress and strain from the change in resistance of the sensing element. Mechanical stress induces a strain state on the film along the sensor axis and, consequently, a resistance variation proportional to the strain. The integrated circuit converts it to voltage output $U_B$.

The measured strain is then defined as follows

$$\varepsilon = (U_B - U_0)/k, \quad (1)$$

where $U_B$ is the voltage output due to strain ε, $U_0$ is the residual output voltage, $k = \Delta U_B / \Delta\varepsilon$ is the gauge factor. Nominal residual voltage $U_0$ is specified for a strain gauge under free conditions, unbounded. Insignificant deviations of $U_0$ from the specifications can be indicated after mounting.

Glue bond is acceptable with conventional adhesives ensuring non-flexible mounting. During measurements, different coefficients of thermal expansion (TEC) for the sensor substrate and the specimen material can lead to a drift of the residual output voltage due to thermal stresses. To compensate the thermal output, the reference signal is applied from an identical strain gauge attached to a plate of the specimen material. The measured strain is then evaluated through the following relation

$$\varepsilon = [(U_B - U_0) - (U_B^1 - U_0^1)] / k, \quad (2)$$

where $U_B$ and $U_0$ are, respectively, the measured and residual voltage of the calibrated gauge at the given temperature T; $U_B^1$ and $U_0^1$ are the measured and residual voltage of the reference gauge at the same temperature; k is the gauge factor. If the difference between the residual voltages of both gauges is low enough to be neglected, Eq.2 can be simplified:

$$\varepsilon = (U_B - U_B^1)/k, \quad (3)$$

Note that the axial compression should be taken negative.

Fig. 2 illustrate temperature dependence for (1) the residual output voltage (relative strain ε =0), (2) gauge factor $k = \Delta U_B / \Delta\varepsilon$, and (3) thermal output of a reference gauge on a steel plate.

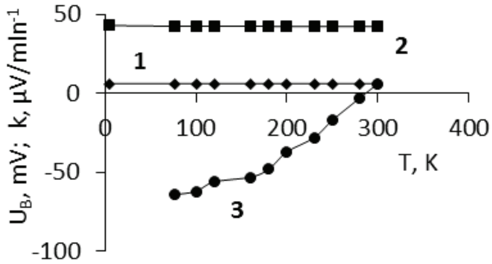


**Fig. 2.** Temperature dependence for
(1) residual voltage (deformation ε =0);
(2) gauge factor $k = \Delta U_B / \Delta\varepsilon$;
(3) thermal voltage of reference gauge.

Fig.3. presents the voltage output $U_B$ vs. strain. The plot demonstrates good linearity up to deformation of 2×10$^3$ mln$^{-1}$.

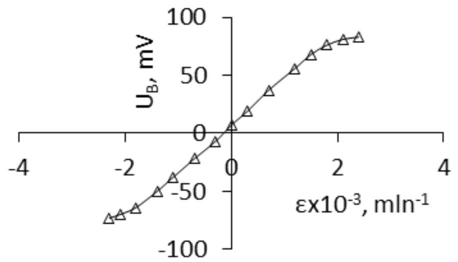


**Fig. 3.** Dependence of target voltage $U_B$ from the size of the enclosed deformation at 300 K.

Magnetic tests at 4.2 K have shown that the error introduced by a field up to 7 T does not exceed 3 %.

If TEC of the strain gauge and specimen materials are considerably different, then thermal overstress is possible at extended temperature ranges, making the strain gauge inapplicable. Care should be taken to ensure reliable measurements and data treatment. Further investigations are required in order to improve strain gauge capabilities.

### 3.2. Temperature sensors (thermistors)

Resistive temperature sensors covering the cryogenic range implement a variety of configurations and semiconductor materials [2, 5]. However, conventional semiconductors demonstrate low stability and are rather sensitive to ambient conditions (particularly, magnetic fields). The current trend is to utilize the thin-film technology offering more reliable operation.

Our prototype thermistor has a sensing element fabricated of a compacted powder Ge bulk (dispersed germanium). The Ge powder is produced of the n-type monocrystalline germanium with a resistivity of 15 Ω·cm. The dispersed germanium has the p-type conductivity with a high concentration of carriers at room temperature. Apparently, the p-type levels are created by structural defects [6.] The microstructure of the dispersed germanium provides low carrier mobility resulting in low magneto-resistance and, consequently, a low field response. This is crucial for measurements in the presence of magnetic fields.

The sizes of the sensitive element of the prototype Ge thermistor are 0.5 mm × 1.0 mm × × 1.0 mm. The resistance is 1÷10 Ω at 300 K, 50-100 Ω at 77 K, 50-100 kΩ at 4.2 K. The sensitivity at 4.2 K is 50÷100 %/K. The control current at 4.2 K is 1-10 μA.

Fig. 4 shows the temperature dependence for a dispersed Ge-bulk thermistor.

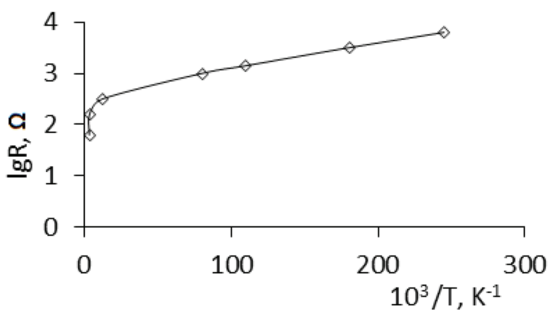


**Fig. 4.** Resistance of dispersed Ge-bulk thermistor vs. temperature.

In order to remove magnetic field-induced errors, a special configuration has been employed [11]. The scheme is presented in Fig. 5.

The measuring wires are attached to the sensing head so as the electrical contacts are at the distance

$$l = a \cdot R_H / \rho \cdot M, \quad (4)$$

where a is the width of the plate; $R_H$, is the Hall constant; ρ is the resistivity; M = Δρ/ρ·B is magneto-resistance at field B.

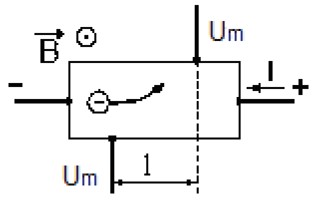


**Fig. 5.** Field-compensated temperature sensor: $U_m$ - the measured voltage; l - distance between the contacts.

As a result, the voltages generated on the contacts due to the Hall effect and magnetoresistance are mutually compensated so as to minimize the field effect on the measurement accuracy.

### 3.3. Magnetic field sensors (Hall sensors)

Characteristics of magnetic field sensors relying on the Hall effect depend on the materials used in fabrication, sizes, and shape of a sensitive element [7]. As the Hall effect is basically carrier mechanism, the high-mobility semiconductors such as InSb and GaAs, are utilized in Hall plates.

The prototype GaAs Hall sensors are made of the GaAs thin film deposited on a semiinsulating GaAs substrate. Such Hall sensor offer advantages of low noise, high linearity, low temperature sensitivity, and a miniaturized active area.

In our set of Hall sensors, the CaAs film thickness is varied within 0.1÷5 μm, the carrier concentration is$\cdot 10^{17} \div 5 \cdot 10^{18}$ $cm^3$. The size of the active zone is 100 × 30 μm. The input and output resistance is varied within 15÷1500 Ω depending on the film thickness films and carrier concentration. The control current is 3÷150 mA. The null output voltage $U_0$ is within the range of 0.01÷5 mV, the temperature dependence of $U_0$ is below 0.1 %/K. The temperature coefficient of resistance is ~0.08 %/K, magnetic sensitivity is 80–500 mV/T. The nonlinearity of the output voltage in a field up to 2 T is 0.1 % or better. The sensors are applicable in the temperature range of 4.2 - 400 K.

## 3. Conclusions

The working prototype of strain gauges and original measurement technique allow us to detect mechanical deformations in a range of operating temperatures of 4.2 to 400 K. The measurement error is conservatively estimated to be below 6 %.

In a field up to 7 T at a temperature of 4.2 K the sensor gives the error below 3 %.

The proposed Hall sensors are applicable in a wide range of temperatures, offering low temperature sensitivity and temperature dependence of the null output signal (less than 0.1 %). The nonlinearity of the output voltage does not exceed 0.1 % in a field up to 2 T, the magnetic sensitivity is as high as 500 mV/T.

The thermistors have diverse applications and can be used in magnetic fields. The sensors demonstrate high sensitivity and stability. They can be applied both in measurements and precision thermal stabilization for various devices.

As known from the literature [8, 9], neutron radiation affects drastically the physical properties of semiconductors causing structural defects and radioactive transformation. With an increase in a doping level, the influence of neutron radiation is weakened. Our study has shown that at 300 K the neutron radiation up to $10^{15}$ $cm^{-2}$ practically does not affect the basic characteristics of the prototype sensors proposed [10].

High sensitivity, resistance to ambient conditions and stability of operation make the proposed sensors attractive tools for precision measurements, development of position/ displacement/acceleration transducers and other instrumentation.

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