

## Microsensors of Temperature, Magnetic Field, and Strain

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The microsensors of temperature, magnetic field and strain to be used in the temperature range from 1.5 to 400 K and in magnetic fields up to 10 T were designing on the base of thin films of Ge on GaAs substrates.

### INTRODUCTION

In different fields of engineering and in experimental physics, it becomes more and more often necessary to measure locally temperature, magnetic field, and strain in the temperature range from liquid helium to room temperatures. In some instances, temperature, magnetic field, and deformation should be measured under the conditions of the simultaneous action of all these factors - for example, when testing large superconducting magnetic systems for various applications. Thus, it is necessary to develop sensors capable of operating under extreme conditions of low temperatures, high magnetic fields, high strain, in other words, under the action of destabilizing factors.

This paper presents our results on designing microsensors of temperature, magnetic field, and deformation to be used in the temperature range from 1.5 to 400 K and in magnetic fields up to 10 T. The technology developed by us is an all-purpose one, allowing fabrication of various high-performance microsensors in a unified technological process. As a sensitive material of sensors, heteroepitaxial films of Ge on GaAs are used, produced by an unconventional technology and possessing electrical properties required for the development of the above-listed sensors.

### RESULTS AND DISCUSSION

#### Features of technology

The choice of Ge-GaAs heterostructures for development of the sensors was dictated by the following reason. During the process of Ge epitaxial deposition in vacuum onto GaAs substrates, Ga and As atoms are diffusing intensively from the substrate to the growing film. Solubility limits and diffusion coefficients of these impurities in the film turn out to be significantly higher (by  $10^2$  -  $10^3$  times) than those in bulk germanium. Diffusion in Ge-GaAs heterostructures disobeys the classical laws of diffusion and, in this respect, is anomalous. Such an anomalous diffusion takes place during film growth only and is not observed at thermal treatment of the heterojunctions.

The GaAs substrate supplies donors and acceptors to the Ge films, thus controlling its impurity composition. Interdiffusion of the two materials is an adverse factor for preparation of superlattices and heterojunctions. However, in case of sensors, diffusion processes in Ge-GaAs heterostructures may be useful for controllable autodoping of Ge films and for achieving required electrical properties.

It was found that the diffusion processes at the interface essentially depend on the technological conditions of epitaxy, such as the substrate temperature, deposition rate, and state of the GaAs surface before the deposition. The structure of the GaAs surface can be transformed by various methods, such as thermal, chemical, ion-beam treatment, and the like. Changing the conditions of epitaxy and using various physico-chemical treatments of GaAs, it is possible to obtain single-crystal Ge films of both p- and n-

types of conductivity with different levels of doping and compensation degree. We have shown [1] the possibility of obtaining thin Ge films with the compensation degree  $K = N_D/N_A$  close to 1.

Technological control of self-doping allows fabrication of epitaxial Ge films with resistivity ranging from  $10^{-3}$  to  $140 \Omega \cdot \text{cm}$  and carrier concentration from  $10^{14}$  to  $3 \cdot 10^{20} \text{ cm}^{-3}$ . This makes possible the realization of a wide variety of electrical properties of the films, required to develop sensors of temperature, magnetic field, and strain.

Sensors of different physical parameters should meet different requirements. These sensors each must have a high sensitivity to the influence of a certain parameter, being practically insensitive to the other parameters. In case of Ge films on GaAs substrates, it can be achieved by varying the levels of doping and compensation. The technology of making such sensors is an all-purpose one.

Today for manufacturing sensors for different physical parameters various materials (and, accordingly, different technologies) are used. This is a shortcoming by complex serial manufacturing because it demands organization of several technological sections having their own equipment and technical personnel. The all-purpose technology of sensors is economically more expedient. It allows fabrication of various sensors in a unified technological process, and it allows also to make integral multifunctional sensors for simultaneous measurements of different physical parameters. Besides, the thin films technology is compatible with the integral technology in manufacturing semiconductor devices. Use of the group methods of microelectronics allows to diminish both sizes and costs of sensors, to improve their technical characteristics, to expand the area of use, and to manufacture sensors both as discrete devices and integral circuits.

#### Temperature sensors

Let us consider characteristics of a temperature-sensitive resistor (thermistor) based on Ge films grown on semiinsulating GaAs substrates. To manufacture a wide-range thermistor, it is necessary to realize in a semiconducting material several different mechanisms of conductivity, each providing thermosensitivity in a certain temperature range. This is commonly achieved through multi-component doping and compensation of a semiconductor. Therefore, heavily doped and compensated Ge films are used for thermistors. The thermometric characteristic of a thermistor depends on the choice of a doping level and compensation degree of germanium.

The temperature dependences of the resistance  $R$  of Ge films fabricated under different technological conditions are shown in Fig.1. Temperature sensitivity of the sensors depends on the technological conditions of epitaxy, whereas the magnitude of resistance is controlled by the sensor topology, which is formed by photolithography and is variable over a wide range. The sensors studied displayed resistances between 50 to  $300 \Omega$  at room temperature.

It is known that the temperature measurements made with the magnetic field present result in an error, therefore it is necessary to correct for this error the thermometric characteristic of the sensor under the magnetic field.

The characteristic of cryogenic thermistors were studied under the magnetic field up to 6.5 T. It is shown that the correction to the thermometric characteristic under the magnetic field essentially depends on the conditions of film manufacturing, i.e. on the mechanism of conductivity responsible for the temperature sensitivity. For various thermistors the temperature measurements in the magnetic field of 6.5 T at 4.2 K are in error by 0.05 - 1.5 K. Low magnetic field-induced errors of the thin ( $0.1 \mu\text{m}$ ) films thermistors were observed. A low mobility in thin films is caused, probably, by the additional scattering of the carriers on the surface and structural defects at the film-substrate interface. In case of thin films the magnetoresistance is positive and increases with the magnetic field. It was shown that the temperature measurements in the magnetic field of 6.5 T at 4.2 K are in error by 0.05 - 0.1 K.

Thermistors based on epitaxial Ge films grown on GaAs substrates have been fabricated by the microelectronic technology and measurement  $1.0 \cdot 1.0 \cdot 0.5 \text{ mm}$  for the over all dimensions and  $0.5 \cdot 0.5 \cdot 0.15 \text{ mm}$  for the sensitive elements.

#### Strain sensors

Films of heavily doped n- and p-germanium are useful for strain sensors making. The n-type films display higher values of strain sensitivity, but they also have a strong temperature dependence of the resistance  $R$  and strain sensitivity coefficient  $S = (R_X - R) / R \cdot X$ , where  $R$  is the sensor resistance without the strain,  $R_X$  is the resistance of the strained sample,  $X$  is the relative strain. In the low temperature range, the

temperature dependences of R and S are weak, because charge carriers are heavily degenerated. This allows the use of such strain sensors for cryogenic engineering. In the temperature range from 4.2 to 25 K the temperature coefficients R and S are close to each other and equal  $3 \cdot 10^{-4} \text{ K}^{-1}$ . In this case, the strain sensitivity coefficient  $S = 150$ . The p-Ge films have lower values of strain sensitivity and temperature coefficients R and S in a wide temperature range. In the range from 4.2 to 350 K the temperature coefficients R and S can reach  $4 \cdot 10^{-4} \text{ K}^{-1}$  at most. The strain sensitivity coefficient for such strain sensors is about 20.

The temperature dependences of R and S for the n- and p-films in the temperature range from 4.2 K to 400 K are shown in Fig.2a. For the purposes of cryogenic and thermonuclear power-engineering (large-size superconductive magnetic systems) it is necessary to control the deformation with strong magnetic fields present. Investigations of the strain sensors in the magnetic fields up to 8.0 T and the temperature of 4.2 K have shown that magnetoresistance  $\Delta\rho/\rho$  is typically negative for n-Ge based sensors and positive for p-Ge ones. In case of heavily doped p-Ge,  $T=4.2 \text{ K}$  and magnetic fields above 1.0 T, the magnetoresistance increases linearly with the magnetic field. With temperature decreasing down to 1.5 K, the value of magnetoresistance increases and the dependence ( $\Delta\rho/\rho$ ) = f(B) becomes sublinear.

The correction term  $\Delta X$  for the strain sensor characteristic as a function of the magnetic field is shown in Fig.2b. Strain sensors based on n-Ge films have a lower value of correction term because they feature a high coefficient of strain sensitivity. However, for the strain sensors based on p-Ge taking account of the correction term is simplified due to the linear magnetic field dependence of the magnetoresistance.

#### Hall sensors

When choosing germanium films suitable for Hall sensors, we took into consideration the two principal parameters, namely, the maximum magnetic sensitivity and the minimum temperature coefficient of the magnetic sensitivity. The most suitable characteristics were observed for Hall sensors based on n-germanium films 0.1  $\mu\text{m}$  thick with carrier concentration of  $(2-3) \cdot 10^{18} \text{ cm}^{-3}$ . The basic characteristics of such Hall sensors are listed in Table 1. These Hall sensors were 0.5\*0.5\*0.15 mm in size.

Table 1 The basic characteristics of Hall sensors

Field range	from 0 to 10 T
Temperature range	from 1.5 to 400 K
Magnetic sensitivity	(20 - 50) mV/T
Coefficient of nonlinearity	1.0 %
Temperature coefficient of sensitivity	$10^{-4} \text{ K}^{-1}$
Temperature coefficient of resistance	$5 \cdot 10^{-4} \text{ K}^{-1}$
Resistance	$(1.0-2.0) \cdot 10^3 \Omega$
Current	1.0 mA

#### CONCLUSION

It was demonstrated that Ge films grown on GaAs are suitable for fabrication of thermistors with a wide temperature range from 1.5 to 400 K, strain sensors with the same temperature range from 1.5 to 400 K, and Hall sensors for magnetic fields up to 10 T and the same temperature range from 1.5 to 400 K. The technology of manufacturing such microsensors is an all-purpose one.

#### REFERENCES

- 1 Garbar N.P., Matveeva L.A., Mitin V.F., Tkhonik Yu.A., Harman R., Shvarts Yu.M., and Stroubek Z., Heavily doped and strongly compensated heteroepitaxial germanium films Fiz. Tekh. Poluprovodn. (1987) 21 393-399 [Sov. Phys. Semicond. (1987) 21 245-249]

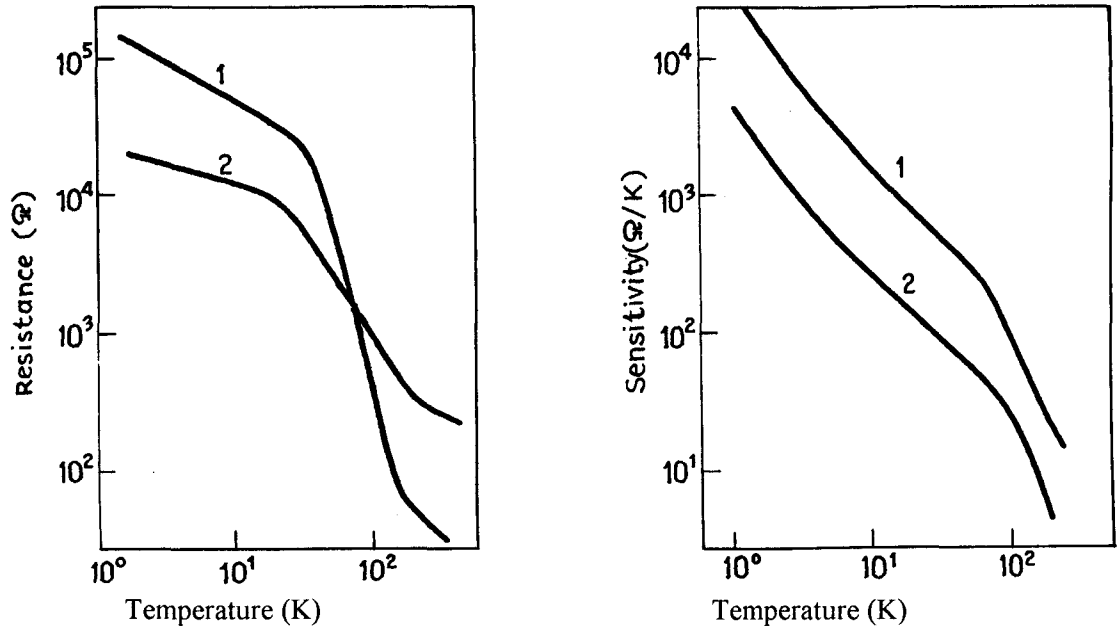


Figure 1 The characteristics of thermistors.

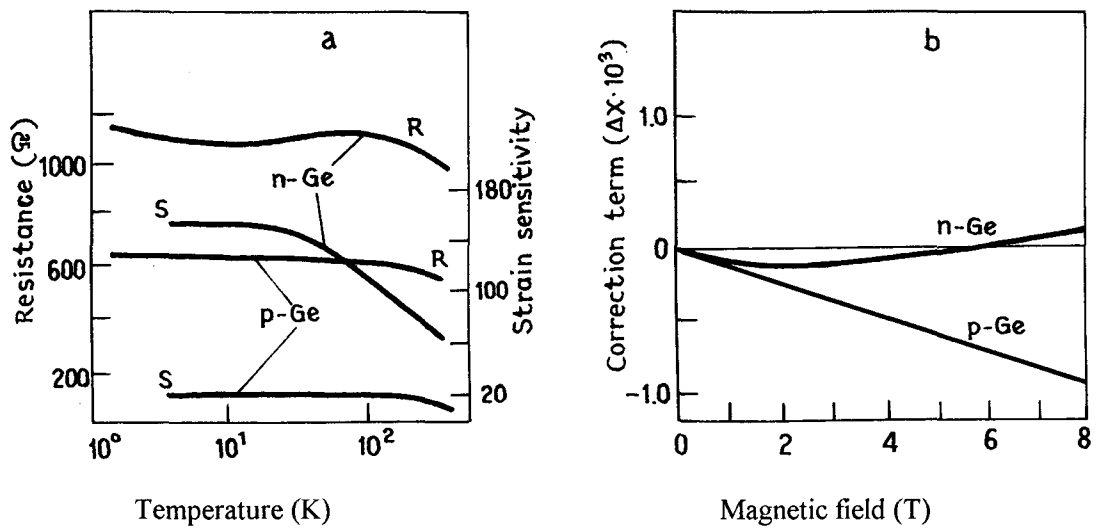


Figure 2 The characteristics of strain tensor resistive sensor.