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All-purpose technology of physical sensors on the base of Ge/GaAs heterostructures

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This work is devoted to development of the basic principles of designing sensors on the base of Ge/GaAs heterostructures. The Ge films grown on semi-insulating GaAs substrates may be used as a universal sensitive material for manufacturing various physical sensors. The possibility of manufacturing photodetectors and temperature, strain and Hall sensors was demonstrated. In the case of Ge films on GaAs, realization of a wide variety of electrical properties needed for sensor design can be achieved by controllable autodoping of Ge films. This is caused by high diffusion of Ga and As atoms from the substrate into a growing film. The technology of sensor manufacturing developed by us is an all-purpose one. It allows one to produce various sensors in a unified technological process. © 1997 Elsevier Science Ltd.

1. Introduction

At present various semiconductor materials are used in manufacturing a wide range of semiconductor sensors that are required by both industry and experimental physics. These materials possess properties which enable the needed

sensor sensitivity to be provided when measuring temperature, strain, magnetic field, etc. Different materials, as well as one-off technological procedures, are used to produce sensors of different types. This fact substantially increases the manufacturing costs and hampers potentialities for quick response to market demands.

We have reported [1, 2] the possibility of developing an all-purpose technology for manufacturing various semiconductor sensors. In this technology one and the same semiconductor material is used, whose physical properties can be varied over a wide range by a rather simple control over the technological procedure. Heteroepitaxial Ge-on-GaAs films are such a material. In this paper we present how the temperature sensors for a wide (1.5–450 K) temperature range, as well as strain and magnetic field sensors and photodetectors, can

be produced on the base of the above material using a single technology.

2. Basic principles for designing sensors on the base of Ge/GaAs heterostructures

The choice of Ge/GaAs heterostructures as a sensitive material for sensors is based on the following principal reasons. Firstly, for Ge films on GaAs it is possible to realize a wide variety of electrical properties needed for development of the above sensors. Secondly, Ge–GaAs is an ideal heteropair, because lattice constants of its components, as well as their thermal expansion coefficients, are very close. The lack of thermal strains in a sensitive element is of particular value for device operation in a wide temperature range. Besides, thin-film technology is compatible with the integration technology in semiconductor device manufacturing. Use of microelectronic technology in fabrication of sensors makes it possible to improve their technical parameters, to reduce both size and costs, and to widen the fields of their application. It also opens opportunities for manufacturing sensors either as discrete devices, or as parts of integrated systems.

In the case of Ge films grown on GaAs substrates realization of electrical properties needed for sensor design can be achieved by autodoping. It is caused by high interdiffusion of the two materials. During the process of epitaxial deposition of the Ge onto GaAs substrates, Ga and As atoms strongly diffuse from the substrate into the growing film. Solubility limits and diffusion coefficients of these impurities in the film turn out to be significantly higher 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 during thermal treatment of the heterostructures. Diffusion processes at the film–substrate interface depend primarily on the process conditions of the epitaxy, such as the

substrate temperature, deposition rate and state of the GaAs surface before deposition. By changing the conditions of epitaxy, one is able to obtain single-crystal Ge films of both p- and n-type with different doping levels and compensation degrees.

3. Preparation of Ge films and their properties

The films were prepared by thermal evaporation of Ge in a vacuum (2×10^{-4} Pa) onto the semi-insulating GaAs (100) substrates characterized by a room-temperature resistivity $\rho = 10^5 \Omega \text{ m}$. The substrate temperature during deposition of the films may range from 300 to 650°C. The electron diffraction patterns of the films investigated indicated the structure to be that of a perfect single crystal when substrate temperature varied between 450 and 550°C. At $T \cong 350^\circ \text{C}$ the investigated films were polycrystalline.

Figure 1 shows the dependencies of resistivity ρ , Hall coefficient R_H , and Hall mobility μ_H on the temperature for films deposited at different substrate temperatures T_s . The film thickness was about 5×10^{-6} m. The dependencies of the electrical properties on the substrate temperature are clearly associated with the structural perfection of the films. Substrate temperature determines the perfection degree of films.

Figure 2 shows the dependencies of resistivity, Hall coefficient and activation energy of electrical conductivity ε on the thickness of films deposited at different rates V . The substrate temperature during film deposition was $T_s = 450^\circ \text{C}$. The temperature dependence of the film resistivity for $T > 250 \text{ K}$ was $\rho = \rho_0 \exp(\varepsilon/kT)$, where ε is the activation energy of the conduction process and k is the Boltzmann constant. The curves have maxima at a certain critical film thickness d_c . The sign of the thermoelectric power corresponds to n-type conduction for thicknesses $d < d_c$ and to p-type conduction for $d > d_c$. The film resistivity may range from 10^{-4}

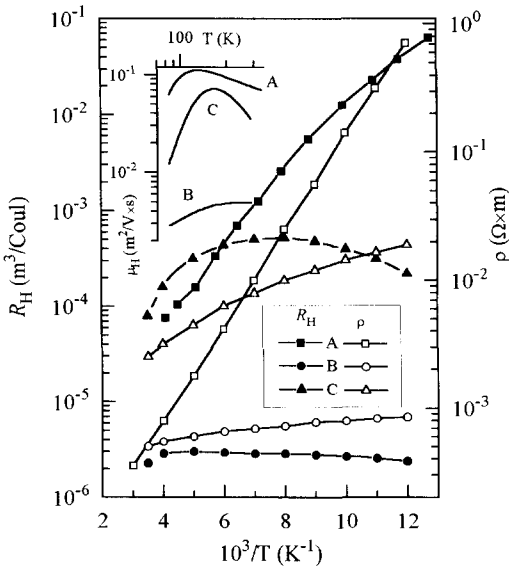


Fig. 1. Dependencies of resistivity ρ , Hall coefficient R_H and Hall mobility μ_H on the temperature for Ge films deposited at different substrate temperatures T_s : (A) $T_s=450^\circ\text{C}$; (B) 350°C ; and (C) 600°C .

to $1.4\ \Omega\ \text{m}$, carrier density from 10^{20} to $10^{25}\ \text{m}^{-3}$ and activation energy of conduction can rise up to half the band gap of germanium, i.e. to $0.4\ \text{eV}$. These dependencies of the electrical properties on the technological conditions of epitaxy are clearly associated with the characteristic features of Ga and As diffusion into Ge film during its growth. Such a diffusion determines the doping level and compensation degree in the films.

The films with resistivity of about $1.0\ \Omega\ \text{m}$ and activation energy close to half the gap of Ge are of great interest. Figure 3 shows the temperature dependencies of resistivity ρ , Hall coefficient R_H and Hall mobility μ_H . The film thickness was about $10^{-7}\ \text{m}$. For the temperatures $T > 250\text{--}290\ \text{K}$ the dependencies $\rho(T)$ and $R_H(T)$ are exponential, the ρ and R_H activation energies being equal. For temperatures $T < 250\text{--}290\ \text{K}$ a lowering of the ρ and R_H activation energies was observed.

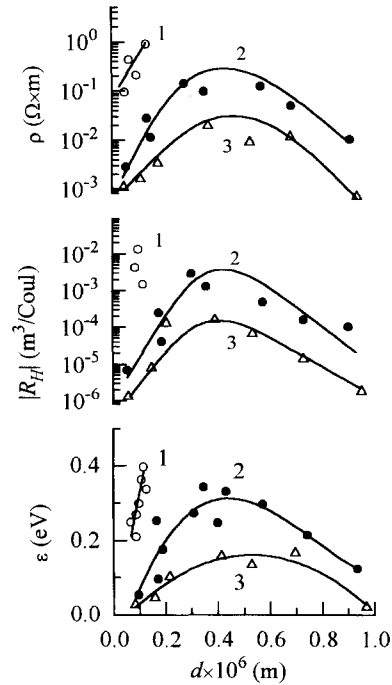


Fig. 2. Dependencies of resistivity ρ , Hall coefficient R_H and activation energy ε of Ge films on their thicknesses d at room temperature. The rates during films deposition were $V=0.3 \times 10^{-10}$, 2×10^{-10} and $12 \times 10^{-10}\ \text{m/sec}$ for curves 1, 2 and 3, respectively.

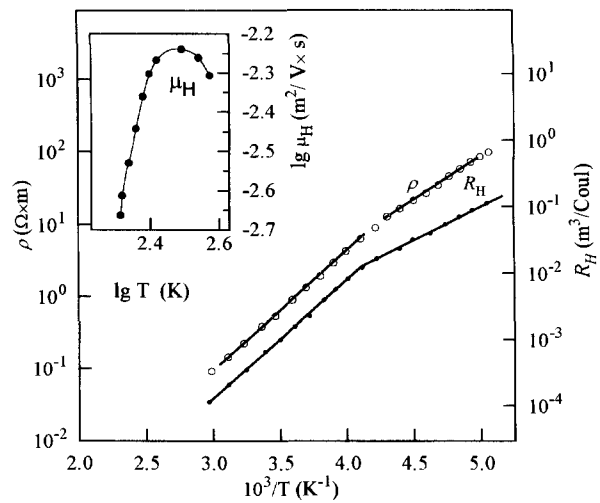


Fig. 3. Dependencies of resistivity ρ , Hall coefficient R_H and Hall mobility μ_H of heavily doped and strongly compensated Ge films on the temperature.

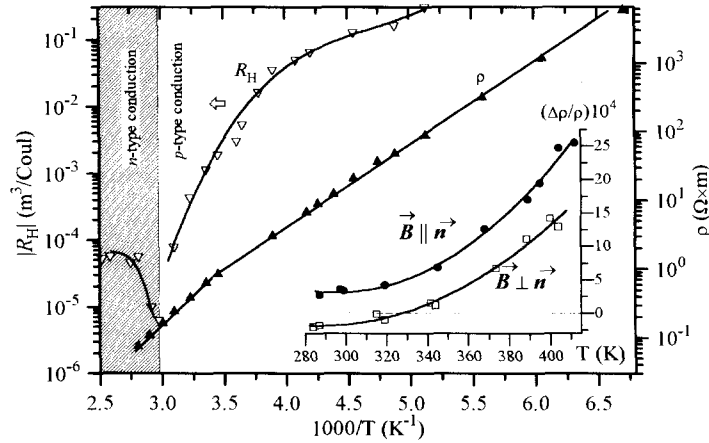


Fig. 4. Dependencies of resistivity ρ , Hall coefficient R_H and transverse magnetoresistance $\Delta\rho/\rho$ on the temperature for two orientations of magnetic induction, $\mathbf{B}\parallel\mathbf{n}$ and $\mathbf{B}\perp\mathbf{n}$, in a magnetic field $B=2$ T.

Inversion of the sign of Hall coefficient has been observed in some films. Figure 4 shows the temperature dependencies of R_H and transverse magnetoresistance $\Delta\rho/\rho$ for two orientations of magnetic induction ($\mathbf{B}\parallel\mathbf{n}$ and $\mathbf{B}\perp\mathbf{n}$, where \mathbf{n} is a vector along the normal to the film surface) in a magnetic field $B=2$ T. The film thickness was about 1.5×10^{-7} m. The magnetoresistance of these films was anisotropic in relation to the magnetic field. Besides, the negative magnetoresistance was observed in some films at room temperature.

The electrical properties of the films studied have no explanation in the frames of the theory of homogeneous semiconductors. The properties of such films are similar to those of amorphous semiconductors [3]. However, the electron diffraction and Raman spectra studies of the films show their high structural perfection degree. Unlike Raman spectra, the electroreflectance spectra of films (which strongly depend on perturbation of band structure) differ essentially from the spectra of bulk Ge with the same resistivity [4].

The consistent explanation for the whole range of properties of the Ge films investigated can be provided if we assume that the material of the

films is the heavily doped and strongly compensated Ge, with compositional disorder but with high degree of structural perfection [4].

4. Electrical conduction mechanisms in films

Let us consider the conduction mechanisms of heavily doped and strongly compensated Ge thin films. There are electric potential fluctuations in heavily doped and compensated semiconductors. Their properties are determined by potential fluctuations caused by random inhomogeneous distribution of impurities. Potential fluctuations modulate the energy bands of a semiconductor (Fig. 5). The amplitudes and sizes of fluctuations depend on the doping level and compensation degree of a semiconductor [5]. A random electrostatic field changes the energy spectrum of charge carriers, thus leading to the manifestation of the state density tails in the band gap and to changes in kinetic coefficients. According to [5] the value of optimal potential fluctuation is

$$\gamma = \frac{q^2(N_a + N_d)^{1/3}}{\chi(n_e + p_e)^{1/3}} \quad (1)$$

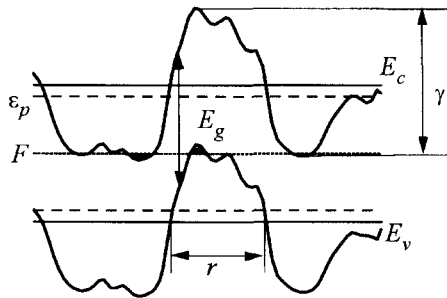


Fig. 5. Energy diagram of a heavily doped and strongly compensated semiconductor. r is the size of a typical fluctuation of the potential, ϵ_p is the percolation level (dotted line) and F is the Fermi level.

where q is electron charge, χ is dielectric susceptibility of semiconductor, N_a and N_d are concentrations of acceptor and donor impurities, and n_e and p_e are total concentrations of non-localized electrons and holes, respectively. These are determined as

$$n_e = N_c F_{1/2}^c(\gamma, F), p_e = N_v F_{1/2}^c(\gamma, E_g - F) \quad (2)$$

where N_c and N_v are effective densities of states in the nonperturbed conduction and valence band, respectively, and

$$F_{1/2}^c(\gamma, F) = \frac{2}{\sqrt{\pi kT}} \int_{-\infty}^{\infty} f_0(E, F) g(E) dE \quad (3)$$

is the modified Fermi integral corresponding to the density of states for disordered bands:

$$g(E) = \frac{1}{\sqrt{\pi kT}} \int_{-\infty}^{E/\gamma} (E, \gamma u)^{1/2} e^{-u^2} du \quad (4)$$

f_0 is the Fermi-Dirac distribution function.

The electrical conductivity of a semiconductor of this kind is characterized by the percolation level, i.e. by the minimum energy at which charge carriers can still migrate freely through the crystal with some potential pattern by passing the potential barriers. Both percolation and Fermi levels depend on random field characteristics, i.e. on the impurity concentration and

compensation degree. Besides, the position of percolation level depends on the space dimensionality. In a three-dimensional (3D) potential relief the percolation level for the electrons lies below the non-perturbed bottom of the conduction band. A 2D potential relief corresponds to the case when $r \geq d$, where r is the size of a typical fluctuation of the potential and d is the conducting layer or film thickness. The 2D percolation level for electrons coincides with the non-perturbed bottom of the conduction band.

At sufficiently high temperatures, the conduction in a semiconductor of this kind is controlled by thermal emission of carriers from the Fermi level F to the percolation level ϵ_p . The activation energy of conduction, ϵ , in such systems is governed by the separation between the percolation and Fermi levels. Only the carriers with energies above the percolation level can take part in the conduction and other transport phenomena. The concentration of such carriers, p_f , depends essentially on the compensation degree. Thus, variation of compensation degree controls conduction in a wide range. At low temperatures the conduction through the localized states in the vicinity of the Fermi level prevails. The temperature of the transition from the conduction due to percolation to that through the localized states is determined by the competition between the processes of thermal transition of carriers to the percolation level and their tunnelling to the neighbouring potential wells.

Figure 6 demonstrates the calculated temperature dependencies of the hole density in Ge with $N_A = 2 \times 10^{24} \text{ m}^{-3}$ and different values of compensation degree K . Here p_e is the total concentration of free holes and p_f is the concentration of holes with energies higher than the percolation level. (2D) and (3D) mean that the calculations relate to two- and three-dimensional films, respectively. For these calculations we have solved a set of equations (1), (2) in

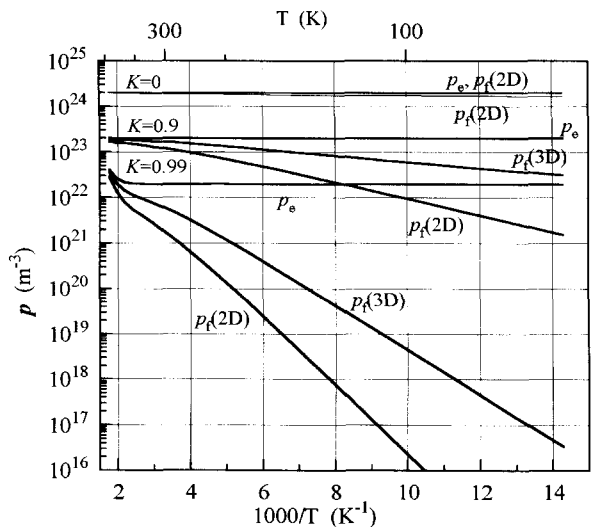


Fig. 6. Temperature dependencies of hole densities in Ge with $N_A=2 \times 10^{24} \text{ m}^{-3}$ and different values of compensation degree K .

combination with the neutrality condition. This allows us to determine p_e , n_e , F and γ for any temperature from the known N_a and N_d values.

For the films studied the activation energy of conduction depends strongly on technological conditions during the preparation of films and can reach half the band gap of Ge. Such an effect is possible in the 2D percolation systems only [3]. Indeed, in the 3D potential relief the activation energy of the electrical conduction

$\epsilon = |F - \epsilon_p|$ must be essentially less than $E_g/2$, and the Hall effect is not determined by the carriers at the percolation level. The estimation of typical potential fluctuation values (supposing that the films represent the heavily doped and strongly compensated Ge with a non-correlated impurity distribution) gave r values lying within $(2.0 - 20) \times 10^{-8} \text{ m}$. This is comparable to (or larger than) the film thickness. This fact confirms the presence of a 2D potential relief in the Ge films. As a result, the activation energy reached the value of $E_g/2$, ρ and R_H activation energies being equal, and the anisotropy of the transverse magnetoresistance was observed [4, 6].

Changing the doping level and compensation degree in Ge, it is possible to change the characteristics of the random field and thus to obtain the required thermal sensitivity in a certain temperature region.

5. Resistance temperature sensors

Figure 7 shows the characteristics for two series (TTR-1A and TTR-1B) of resistance temperature sensors with a wide (1.5–350 K) temperature range for operation. The heavily doped and compensated Ge thin films were used as a sensitive material for thermometers. Temperature sensitivity of resistance thermometers depends on the technological conditions of epitaxy, which define doping level and compensation

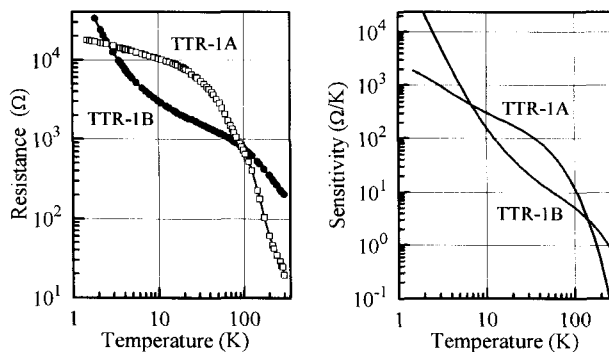


Fig. 7. Characteristics of cryogenic resistance thermometers.

degree of Ge. The resistance value is controlled by sensor topology, which is formed by photolithography and varies over a wide range. The sensor crystals for usual models were $(0.5 \times 0.5 \times 0.2) \times 10^{-9}$ and $(1.0 \times 1.0 \times 0.2) \times 10^{-9}$ m³ in size. Hermetic package sizes for various models were $(3.0 \times 1.5 \times 1.2) \times 10^{-9}$ and $(1.6 \times 15) \times 10^{-9}$ m³.

Ge bulk resistance thermometers have, for a long time, been used in low-temperature experiments and cryogenic engineering [7-9]. In the low-temperature range such thermometers have high temperature sensitivity. At $T > 100$ K the sensitivity and resistance are small ($R < 10 \Omega$). This fact retards the use of such thermometers in a relatively high temperature range. The thin-film Ge sensors studied displayed resistances of about 20 and 250 Ω at 300 K for the series TTR-1A and TTR-1B, respectively. This makes it possible to use thin-film sensors in a wide temperature range, up to 350 K.

Let us consider the thin-film Ge resistance thermometers (series TTR-3) with a temperature range for operation from 200 to 450 K. To make such thermometers, heavily doped and strongly compensated Ge thin films were used. The characteristics of thin-film resistance thermometers are shown in Fig. 8. The dependence of the resistance of such thermometers on temperature is exponential. The thermometers have high sensitivity and may be used in the range 200-450 K. Changing the technological conditions of Ge epitaxy, it is possible to obtain resistance thermometers with a temperature coefficient of sensitivity ranging from 0.4×10^{-2} to $6.0 \times 10^{-2} \text{ K}^{-1}$ at room temperature.

6. Strain tensor resistive sensors

Strain tensor resistive sensors need to provide a small temperature coefficient of tensosensitivity in a wide temperature range and a high sensitivity to the influence of strain. To satisfy these

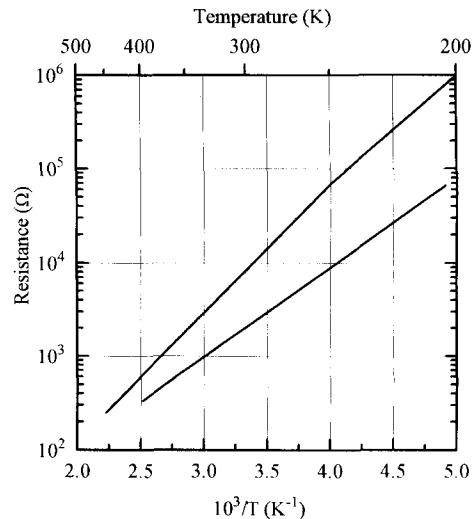


Fig. 8. Characteristics of resistance thermometers on the base of heavily doped and strongly compensated Ge films.

demands the heavily doped n- and p-Ge films were used. The dependencies of sensor resistance R and tensosensitivity $S = (R_x - R) / (R_x \times X)$ (where R is the sensor resistance without strain, R_x is the resistance of the strained sample, X is the relative strain) on temperature for the heavily doped n- and p-Ge films in the temperature range 4.2-400 K are shown in Fig. 9. The dependencies of resistance and tensosensitivity on the temperature for such films are weak, because charge carriers are degenerate. The n-Ge thin films with carrier concentration of about $3 \times 10^{24} \text{ m}^{-3}$ display higher values of strain sensitivity and small temperature coefficients of strain sensitivity and resistance in the low temperature range. In the temperature range from 4.2 to 25 K the R and S temperature coefficients are close and equal about $3 \times 10^{-4} \text{ K}^{-1}$. In this case, the strain sensitivity coefficient is about 150. This allows the use of such strain sensors for cryogenic engineering. The p-Ge films display lower values of strain sensitivity, but they also have smaller temperature coefficient of resistance and smaller strain sensitivity in a wide temperature range. In the range from 4.2 to 400 K the R and S tempera-

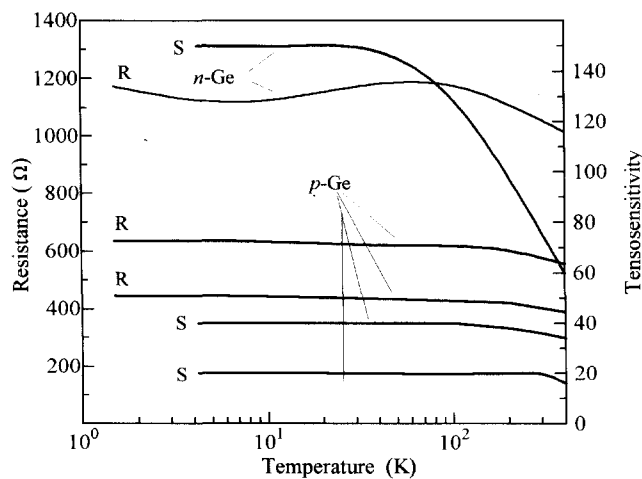


Fig. 9. Characteristics of strain tensor resistive sensors.

ture coefficients can reach $4 \times 10^{-4} \text{ K}^{-1}$ at most. The strain sensitivity coefficient is about 40 and 20 for such p-Ge films with carrier concentration of 2×10^{25} and $3 \times 10^{26} \text{ m}^{-3}$, respectively. The strain sensors for various models are $(1.5 \times 0.5 \times 0.2) \times 10^{-9}$ and $(8.0 \times 4.0 \times 2) \times 10^{-9} \text{ m}^3$ in size.

7. Hall sensors

When choosing Ge films suitable for Hall sensors, we took into consideration two principal parameters, namely, the maximum magnetic sensitivity and the minimum temperature coefficients of the magnetic sensitivity and resistivity. The most suitable characteristics were observed for the Hall sensors based on n-Ge films $0.1 \times 10^{-6} \text{ m}$ thick with carrier concentration of $(2-3) \times 10^{24} \text{ m}^{-3}$. The basic characteristics of such Hall sensors are listed in Table 1. These Hall sensors were $(0.5 \times 0.5 \times 0.2) \times 10^{-9}$ and $(1.0 \times 1.0 \times 0.2) \times 10^{-9} \text{ m}^3$ in size for various models.

8. Photodetectors

The Ge/GaAs heterojunction may be used for manufacturing a photodetector for the

$0.6 \times 10^{-6} - 1.5 \times 10^{-6} \text{ m}$ spectral range. Besides, the technology of epitaxial deposition of Ge onto semi-insulating GaAs allows the manufacture of photoresistors with fast characteristic radiation response times. In this case the semi-insulating GaAs serves as a photosensitive material for a photoresistor. Thin ($d \leq 0.15 \times 10^{-6} \text{ m}$) heavily doped Ge films were used as transparent electrodes. The detectors of laser radiation for the $0.25 \times 10^{-6} - 0.9 \times 10^{-6} \text{ m}$ spectral range were developed. The time of the photocurrent rise to its peak is $(2.4-3.9) \times 10^{-10} \text{ sec}$ and the time of photocurrent drop is $(2.8-4.3) \times 10^{-10} \text{ sec}$. Such a photodetector may be used in laser techniques for measuring characteristics of short radiation pulses.

TABLE 1 Basic characteristics of Hall sensors

Operating temperature range (K)	1.5-400
Magnetic sensitivity (V/(A×T))	20-50
Non-linearity error up to 10 T, not greater than (%)	1.0
Temperature coefficients of sensitivity and resistance, not greater than (1/K)	5×10^{-4}
Resistance (Ω)	$(1-2) \times 10^3$
Maximum input dc at 298 K (A)	5×10^{-3}

249. Conclusion

We have proved that Ge films on the semi-insulating GaAs substrates can serve as a general-purpose sensitive material for fabrication of high-performance sensors, suitable for measuring temperature, strain, magnetic field and electromagnetic radiation.

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