Influence of mechanical stresses on galvanomagnetic effects in heteroepitaxial *p*-type germanium films

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An investigation was made of the electrical resistivity, Hall effect, and transverse magnetoresistance (in weak magnetic fields H) of single-crystal p-type Ge films. These films were deposited from a molecular beam in vacuum on high-resistivity GaAs substrates and their thickness d ranged from 1 to 40 μ. The measurements were carried out at temperatures T from 77 to 450°K. The field H was oriented at right-angles to the current and its inclination relative to the normal to the film **n** influenced the magnetoresistance of films for all values of d and T. The magnetoresistance anisotropy $K = [\Delta\rho(H \perp n)/\Delta\rho(H \parallel n)] - 1$ varied with d and T but had a constant sign ($K < 0$). The electrical resistivity, Hall coefficient, and magnetoresistance were independent of the film thickness in the range $d > 3$–$5\,\mu$. The magnetoresistance anisotropy of the investigated films was associated with the deformation of films thicker than $5\,\mu$.

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1. Films of p-type Ge deposited from a molecular beam in vacuum on gallium arsenide substrates suffer from mechanical stresses of the order of 10^9 dyn/cm^2 (Refs. 1 and 2). According to Refs. 3-6, stresses of this magnitude result in a strong piezoresistance and piezomagnetoresistance of bulk p-type Ge, for which the influence of stresses on the galvanomagnetic effects has been determined by comparing the characteristics of deformed and undeformed samples. Films of p-type Ge are deformed right from the beginning but it is difficult to allow for the influence of stresses because there is no way of comparing the properties of such films with those of undeformed films: on the one hand, there are no undeformed films, and, on the other, a comparison cannot be made with bulk p-type Ge. This is probably the reason for our insufficient knowledge of the influence of stresses on the galvanomagnetic effects in heteroepitaxial films although deformation is known to alter not only the properties of the film but also to give rise to a basically new effect, which is the transverse magnetoresistance anisotropy,[7] i.e., the dependence of the magnetoresistance on the orientation of the magnetic field H (perpendicular to the current) relative to the normal to the film **n**.

We investigated earlier the influence of stresses on the galvanomagnetic effects in stretched p-type Ge films on silicon.[8,9] In the present paper we shall analyze the influence of stresses on the same effects in compressed p-type Ge films on gallium arsenide.

2. We investigated the electrical resistivity, Hall effect, and magnetoresistance (in weak magnetic fields) of single-crystal p-type Ge films deposited from a molecular beam (in $\sim 10^{-6}$ torr vacuum) on high-resistivity gallium arsenide substrates. These substrates were 200-250 μ thick and they were oriented along the (001), $(\bar{1}10)$, and $(\bar{1}11)$ planes. In all our measurements the current was directed along the [110] axis. The film thickness ranged from 1 to 40 μ, and the measurements were carried out at temperatures from 77 to 450°K.

Figure 1 shows the dependences of the electrical resistivity ρ and of the Hall coefficient R_H on the film thickness d at 293°K. Figure 2 gives the dependence of the transverse magnetoresistance $\Delta\rho/\rho_0$ on d at 293°K, whereas Fig. 3 gives the dependence on temperature T for films of thickness d = 5.3 and d = 18.6 μ. It is clear from Figs. 2 and 3 that the magnetoresistance is different in the $H \perp n$ and $H \parallel n$ cases, and the magnetoresistance anisotropy

$$K = \frac{\Delta\rho\,(H \perp n)}{\Delta\rho\,(H \parallel n)} - 1 \tag{1}$$

varies with the film thickness and temperature but has a constant sign ($k < 0$).

3. The magnetoresistance anisotropy due to the inhomogeneity of p-type Ge films across the thickness and/or due to the size effect has been observed earlier by others.[10-12] The thickness dependences of ρ, R_H, and $\Delta\rho/\rho_0$ of the investigated films (Figs. 1 and 2) differ from those given in Refs. 10-12 and we shall show that the treatment of the results adopted in the earlier reports is inapplicable to our case. Let us consider a film of thickness d in which the density p of free holes with an isotropic energy spectrum and the relaxation time τ of these holes depend on y in a layer of thickness d_1 ($0 \le y \le d_1$) near the substrate, whereas the same quantities are constant in a layer $d_1 \le y \le d$ (if the latter layer does not exist, then $d_1 = d$). It then follows from Ref. 12 that the electrical conductivity σ in H = 0 depends on the film thickness as follows:

$$\sigma = ep^{\infty}\mu_1^{\infty}\left(1 + \frac{d_1}{d}\,a\right),\quad a = \frac{1}{d_1}\int\limits_0^{d_1}\left(\frac{p\,(y)\,\mu\,(y)}{p^{\infty}\mu_1^{\infty}} - 1\right). \tag{2}$$

Here, the symbol ∞ denotes the values of the parameters in the layer $d_1 < y \le d$,

$$\mu_l = \left(\frac{e}{c}\right)^{l-1}\frac{e}{\Gamma\,(5/2)}\int\limits_0^{\infty}\chi^{3/2}\left(\frac{\tau}{m}\right)^l e^{-\chi}d\chi, \tag{3}$$

l = 1 or 2, m is the effective mass, e is the absolute charge of an electron, c is the velocity of light, τ is the momentum relaxation time, $\chi = \varepsilon/k_0T$, ε is the energy,

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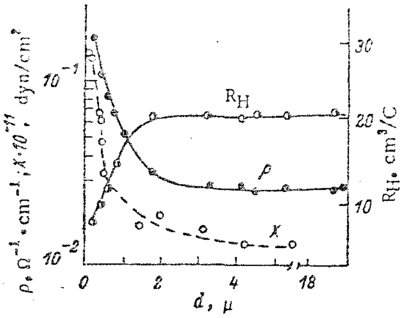

FIG. 1. Dependences of the electrical resistivity ρ, Hall coefficient R_H, and internal stresses X on the thickness of single-crystal germanium films on gallium arsenide, recorded at 293°K.

and k_0 is the Boltzmann constant.

On increase in d (in the range $d > d_1$) the value of σ tends to $\sigma^\infty = ep^\infty\mu_p^\infty$ as $1/d$.

It is clear from Fig. 1 that σ^∞ and R_H^∞ are attained in a thickness of $d \sim 3\ \mu$. This means that $d_1 \ll 3\ \mu$. The transverse magnetoresistance of such a two-layer film depends on the orientation of the magnetic field relative to the normal n (Ref. 12); if $d \gg d_1$, we then have

$$\frac{\Delta\rho(H\parallel n)}{\rho_0} = \frac{\Delta\rho(H\perp n)}{\rho_0} + \left(\frac{e\mu_2}{c\mu_1}H\right)^2 \frac{d_1}{d}\beta, \tag{4}$$

where

$$\beta = \frac{1}{d_1}\int_0^{d_1} \frac{p\mu_1}{p^\infty\mu^\infty}\left(\frac{e\mu_2\mu_1^\infty}{c\mu_1\mu_2^\infty}-1\right)^2 dy. \tag{5}$$

Clearly, we find that $K < 0$ but $|K|$ decreases on increase of d as $1/d$, whereas $\Delta\rho(H\perp n)/\rho_0$ and $\Delta\rho(H\parallel n)/\rho_0$ tend to the same saturation value as $1/d$. This dependence is not exhibited by our films of thickness $d > 5\ \mu$ (Fig. 2a). Therefore, there are no grounds for assuming that the magnetoresistance anisotropy of films with $d > 5\ \mu$ is associated with an inhomogeneous variation of their properties across the thickness.

In the case of the size effect the values of ρ, R_H, and $\Delta\rho(H\parallel n)/\rho_0$ are independent of d over distances equal to the cooling length, whereas $\Delta\rho(H\perp n)/\rho_0$ tends to $\Delta\rho(H\parallel n)/\rho_0$ as $1/d$ when the thickness exceeds a certain characteristic value.[13] Once again, the magnetoresistance anisotropy should decrease on increase in d as $1/d$. Thus, the magnetoresistance anisotropy of the investigated films of thickness exceeding 3-5 μ cannot be explained in the same way as in Refs. 10-12.

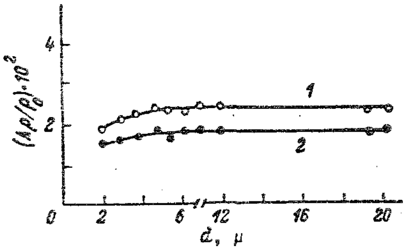

FIG. 2. Dependences of $(\Delta\rho/\rho_0)(H\parallel n)$ (1) and $(\Delta\rho/\rho_0)(H\perp n)$ (2) on the thickness of germanium films on gallium arsenide, recorded at 293°K.

We shall assume that the magnetoresistance anisotropy of thick films ($d > 3$-$5\ \mu$) is due to mechanical stresses (and we shall give additional experimental results confirming this effect). We can see from Fig. 1, which gives the thickness dependence of the mechanical stresses X in films of Ge on GaAs, that X is practically independent of the thickness in the range $d > 3\ \mu$ and, therefore, the magnetoresistance anisotropy of thick films does not vary with d. In the case of thin films, we have to allow not only for the stresses but also for an inhomogeneity of the properties of the film, which is clearly visible in Fig. 1. The magnetoresistance of deformed p-type Ge and the dependence of the magnetoresistance anisotropy should deformation $\bar\eta$ are considered in Ref. 7 for the case of scattering by acoustic lattice vibrations. In our samples the density of free holes is high (Fig. 1) so that at low temperatures the scattering is mainly on ionized impurities because in undeformed p-type Ge the relaxation times of the light and heavy holes are in the same ratio as the square roots of their effective masses[14] and the contribution of the light holes to the magnetoresistance is not important. A calculation of the magnetoresistance of deformed samples, carried out in the same way as in Ref. 7, shows that when carriers are scattered by ionized impurities, we find that $K < 0$ throughout the range where $\bar\eta < 0$ (and this is the range of interest to us because films of p-type Ge on GaAs are compressed and we have $\bar\eta < 0$ – Refs. 5 and 7), and the value of $|K|$ increases when $|\bar\eta|$ is made larger. In the case of strongly deformed samples ($|\bar\eta| \gg 1$), we find that $K = \tau_\parallel m_\perp/m_\parallel\tau_\perp - 1$ reaches the value -0.45 instead of -0.738 given in Ref. 7 [here $\tau_{\parallel,\perp}$ and $(m^{-1})_{\parallel,\perp}$ are the components of the tensors representing the relaxation times and reciprocal effective masses, which are close to the diagonal tensors when expressed in terms of the axes parallel to the film "edges" (Ref. 7)].

Cooling increases the relative deformation $|\bar\eta| = \Delta/2k_0T$ [here, Δ is the deformation-induced splitting of the energy bands,[7] which amounts to $(6$-$20)\cdot10^{-3}$ eV for stresses of $(1$-$3)\cdot10^9$ dyn/cm^2] and $|K|$ increases, approaching the value 0.45. In addition to an increase in the

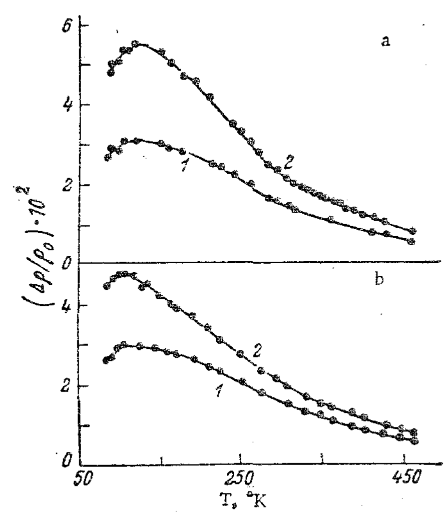

FIG. 3. Temperature dependences of $\Delta\rho(H\perp n)/\rho_0$ (1) and $\Delta\rho(H\parallel n)/\rho_0$ (2) for single-crystal germanium films of various thicknesses deposited on gallium arsenide. Thickness d (μ): a) 5.3; b) 18.6.

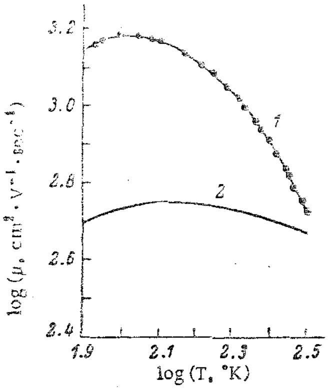

FIG. 4. Temperature dependences of the Hall mobility in a germanium film (d = 12 μ) on gallium arsenide (1) and qualitative nature of the dependence $\mu^*(T)$ for an undeformed film (2).

magnetoresistance anisotropy as a result of cooling (Fig. 3b), we found that this anisotropy rises on increase of Δ. Different values of Δ in films of the same thickness were established by selecting different orientations of the film plane [$\Delta_{(111)} > \Delta_{(110)} > \Delta_{(100)}$ – Ref. 1].

We shall conclude by noting that although a detailed comparison of the experimental results with the calculations of the galvanomagnetic effects is hardly possible for p-type Ge films, one must allow for the internal stresses in these films at least in a qualitative analysis of the results. This applies not only to the magnetoresistance anisotropy but to the magnetoresistance itself and also to the mobility. Figure 4 shows, by way of example, the experimental temperature dependence of the Hall mobility μ. It cannot be used to determine the scattering parameters because the temperature dependence of the mobility is not only due to the dependence of τ on ε and T, but also due to the temperature dependence of $|\bar{\eta}|$. The rise of $|\bar{\eta}|$ as a result of cooling has the effect of increasing μ compared with the undeformed material.[7] This effect is ignored in Ref. 15, where it is assumed that the dependence $\mu \propto T^{-\gamma}$ with $\gamma = 3/2$, characteristic of the predominant scattering by acoustic lattice vibrations, may be exhibited by deformed films when the degeneracy of the light- and heavy-hole bands is lifted. (It should be noted that this assumption is justified if the condition $|\bar{\eta}| \gg 1$ is satisfied at all temperatures. We can see that in the case of p-type Ge films on GaAs this can be true only at low temperatures.) Curve 2 in Fig. 4 represents qualitatively the temperature dependence of the mobility μ^* in an undeformed sample. Curve 2 is plotted assuming that the deformation does not alter the carrier density or scattering mechanisms and that at 77°K in the $|\bar{\eta}| \gg 1$ case the experimental value μ is "restored" to the mobility μ^* of an undeformed sample (in the case of scattering by ionized impurities and $|\bar{\eta}| \gg 1$ we can similarly obtain[7] the ratio $\mu/\mu^* = 2.18$). Knowing μ^* at 77°K and assuming that at 450°K the values of μ and μ^* differ only slightly [here, $|\bar{\eta}(450°K)| < 1$], we plot curve 2 using the dependence $\mu^*(T)$ obtained earlier for undeformed samples with the same values of R_H as the sample represented by curve 1. It should also be noted that a strong dependence of μ on $\bar{\eta}$ practically excludes the possibility of analyzing the temperature dependence of μ in order to determine the degree of compensation of deformed films.

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