Lower limit on the mobility of charge carriers forming a two-dimensional gas

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Transport of the holes of a two-dimensional (2*D*) gas on germanium surfaces cleaved in helium has been studied experimentally. During scattering by Coulomb centers the mobility of the 2*D* holes approaches a lower limit as the temperature is lowered. This limit is independent of the sample temperature and of the density of scattering centers.

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The possible formation of a two-dimensional (2D) gas of charge carriers in surface channels on semiconductors[1,2] has stimulated study of the physical consequences of the 2D nature of such a gas. In this letter we are reporting a study of the transport of a 2D hole gas during scattering of the holes by charged centers.

A Hall-current method was used to study the temperature (T) dependence of the mobility μ and the concentration Γ of holes in channels on cleaved germanium surfaces. The samples are described in Ref. 3. A sample was cleaved in helium vapor and heated several times at $T \approx 60$ K. Curves of $\mu(T)$ and $\Gamma(T)$ were recorded after each heating; some typical measurements are shown in Fig. 1. The first heating was required for the appearance of the hole channels at the cleaved surfaces.[4,5] The duration of this heating was chosen to maximize the surface conductivity σ_s. During the subsequent heatings, σ_s decreased. Comparison of curves 1-3 in Fig. 1a shows that the decrease in σ_s is caused by a decrease in Γ. According to the condition of electrical neutrality, the concentration Γ is equal to N_{ss}, the concentration of electrons in surface states.[6] The decrease in N_{ss} during the repeated heatings results from changes in the characteristics of the surface states, which are apparently caused by an interaction of the freshly cleaved surface with impurities in the helium. The repeated heating was thus used to change N_{ss}. Curves of $\mu(T)$ (curves 1-3 in Fig. 3) were obtained at various concentrations N_{ss} of the charged centers localized at the surface (curves 1-3 in Fig. 1a). From Fig. 1b we see that μ increases with increasing T at $T > 20$ K. This increase is evidence that the scattering of holes by charged centers is the most important of the surface-scattering mechanisms.

To calculate the function $\mu(N_{ss})$, we proceed as follows: Estimates of the energies of the quantum levels from the experimental values of μ and Γ show that the holes form a 2D gas in these surface channels. In a 2D gas of holes we would have[6]

$$\Gamma = \frac{m_d}{\pi\hbar^2} kT \ln\left(1 + \exp\frac{E_{FS} - E_0}{kT}\right), \tag{1}$$

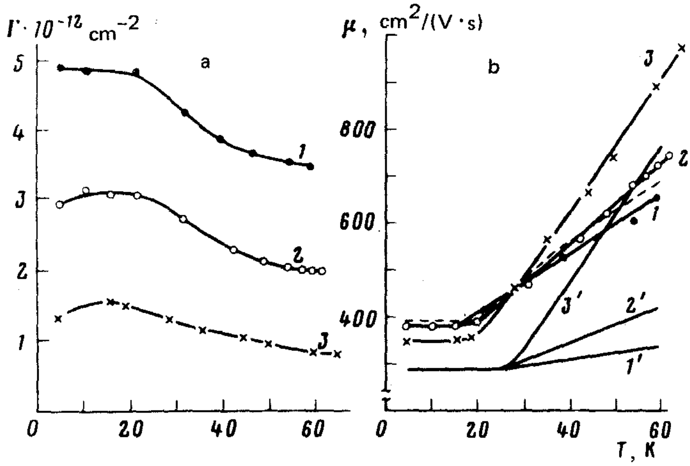

FIG. 1. Temperature dependence of the hole concentration (a) and the hole mobility (b) near cleaved surfaces of germanium after three successive heating cycles. Each curve is labeled with the order of the heating immediately preceding the given measurements. 1′-3′ and dashed curve—Theoretical.

where m_d is the effective mass of the state density, E_{FS} is the energy of the Fermi level at the surface, and E_0 is the energy of the first quantum level for hole motion perpendicular to the surface.

Substitution of the values of Γ from Fig. 1a in expression (1) reveals $E_{FS} - E_0/kT \gg 1$, so that the 2D gas of holes is degenerate. We can thus use the Born approximation to describe the scattering of holes by Coulomb centers.[7] Working from the Born cross section for the scattering of the carriers of a 2D gas by Coulomb centers,[1,7] and taking the average of the relaxation time over the energy, we find

$$\mu = \frac{2\epsilon^2 \hbar k T}{\pi^2 q^3 m_c N_{ss}} \, \frac{\mathcal{F}_1(E_{FS} - E_0)}{\mathcal{F}_0(E_{FS} - E_0)}\,, \tag{2}$$

where m_c is the effective mass for the electrical conductivity, q is the charge of the electron, ϵ is the dielectric constant, and $\mathcal{F}_1(E_{FS} - E_0)$ and $\mathcal{F}_0(E_{FS} - E_0)$ are Fermi–Dirac integrals.

Curves 1′-3′ in Fig. 1b are curves of $\mu(T)$ calculated from (1) and (2). The values $\Gamma = N_{ss}$ used in these expressions were taken from the experimental curves of $\Gamma(T)$ with the same labels in Fig. 1a. We assumed $m_d = m_c = 0.34 m_0$, where m_0 is the mass of the electron. For convenience in comparison with the experimental results on $\mu(T)$, the calculated values of μ in Fig. 1b have been multiplied by a factor of 10. The experimental (1-3) and theoretical (1′-3′) curves of $\mu(T)$ are in good qualitative agreement. The slope of the μ curves increases from curve 1′ to curve 3′ with increasing $T > 20$ K, in agreement with the tendency observed experimentally (curves 1-3 in Fig. 1b). A particularly interesting result is that as the temperature is lowered ($T < 20$ K) the mobility μ drops to a certain minimum μ_{min}, which is independent of both T and N_{ss}. It can be seen from this figure that the values of μ_{min}

for experimental curves 1-3 differ by ~10%, while the values of $\Gamma = N_{ss}$ corresponding to these values of $\mu_{\min}$ change by a factor of about 5.

To derive an analytic expression for $\mu_{\min}$, we note that Eq. (1) describes an increase in the degeneracy of a 2D hole gas as T is lowered. In the case of strong degeneracy, expression (2) becomes

$$\mu = \frac{\epsilon^2 \hbar (E_{FS} - E_0)}{\pi^2 q^3 m_c N_{ss}}\,, \tag{3}$$

Using $\Gamma = N_{ss}$ and $\exp E_{FS} - E_0/kT \gg 1$, and substituting $E_{FS} - E_0$ from expression (1) into (3), we find

$$\mu_{min} = \frac{\epsilon^2 \hbar^3}{\pi q^3 m_c m_d}\,. \tag{4}$$

We see that $\mu_{\min}$ depends on only a few characteristics of the semiconductor (ϵ, m_c, and m_d), and on this basis it may be assumed that $\mu_{\min}$ is a fundamental characteristic of a two-dimensional gas in channels of this type. Substitution of the value $\epsilon = 16$ and the values of $\mu_{\min}$ from experimental curves 1-3 in Fig. 1b in (4) leads to $m_c m_d = 8.8 \times 10^{-3}\ m_0^2$. We can distinguish between m_c and m_d by choosing values for them such that the condition $m_c m_d = 8.8 \times 10^{-3}\ m_0^2$ is satisfied, on the one hand, while the theoretical curve of $\mu(T)$ plotted from (1) and (2) approaches the experimental curve, on the other. The dashed curve in Fig. 1b was calculated from the values of $\Gamma(T)$ from curve 2 in Fig. 1a and from the values m_c $2.3 \times 10^{-2}\ m_0$ and $m_d = 0.38 m_0$. The result $m_c \neq m_d \neq 0.34 m_0$ (this is the effective hole mass in the interior of germanium) may be a consequence of the distortion of the constant-energy surfaces for the holes near the surface of the semiconductor.[6]

In conclusion, we should point out that expression (4) follows from expression (1) and (2), which apply only to a 2D gas of free carriers. The existence of a lower limit $\mu_{\min}$ in the case of scattering by Coulomb centers distinguishes a 2D gas from a 3D gas of charge carriers. The observation of a minimum mobility in this study constitutes an experimental confirmation that it is possible to form a two-dimensional gas of free charge carriers. This confirmation is independent of the confirmation reported by Stern and Howard and by Fowler *et al.*[2]

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