Drift of the electron–hole liquid in germanium in crossed electric and magnetic fields

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A drift of the electron–hole liquid in crossed electric and magnetic fields was observed under conditions of dc conductivity in an electron–hole drop system, proving the flow mechanism of conductivity.

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An abrupt jump in conductivity as a result of photoexcitation of germanium[1,2] can be observed when electron–hole drops (EHD) occupy a large fraction of the volume of the crystal.[2,3] Therefore, the suggestion first made by Guillaume and Voos[4] that conductivity is determined by the EHD mechanism seems reasonable. A sharp increase of conductivity in the flow model should be determined by the increased fraction of the crystal volume occupied by the EHD, and may be attributed to the appearance of conducting channels in the electron–hole liquid (EHL) that closes the contacts.[5] A drift displacement of the EHL in crossed electric and magnetic fields has been observed by us, thereby demonstrating the existence of such channels.

Let us estimate the characteristic Ampere force acting on the EHL current channels and the drift velocity corresponding to it. If $B = B_z$ and $E = E_y$, then for a single electron–hole pair

$$F = F_x = \frac{\sigma_\perp(B)}{c\,n_0}\,EB, \tag{1}$$

where $\sigma_\perp(B)$ is the transverse conductivity of the EHL in a magnetic field and n_0 is the density of the EHL. To determine $\sigma_\perp(B)$ we use the conductivity tensor obtained[6] for an electron–hole system. If we assume the existence of drift of the EHL and take $\tau_{l1} \approx \tau_{l2}$, $\tau_l/\tau \gg 1$, $(\omega_1 - \omega_2)/\omega_2 \simeq 1$ for the components of the $\sigma(B)$ tensor, we can obtain the approximate expressions[6]

$$\sigma_{xx} = \frac{e^2 \tau n_0}{\mu}\,(1 + \omega_1 \omega_2 \tau_p \tau)^{-1}, \quad |\sigma_{xy}| << \sigma_{xx}. \tag{2}$$

Here subscripts 1 and 2 refer to electrons and holes, respectively; τ_l and τ are the

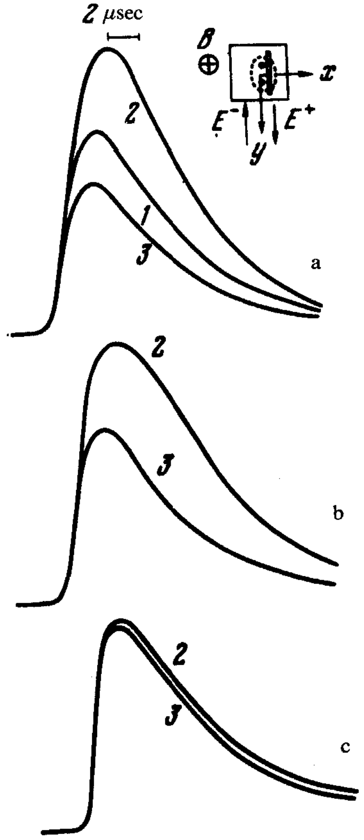

FIG. 1. Kinetics of the modulation signal of the probing light for $B=0.08$ T and various electric fields E, V·cm^{-1}: 1) $E=0$; 2a) $E=0.5$; 2b) $E=0.16$; 2c) $E=0.02$; 3a) $E=-0.5$; 3b) $E=-0.16$; 3c) $E=-0.02$. The geometry of the experiment is shown at top right; the dotted curve represents the excitation region of the sample and the vertical line denotes the location of the probing slit. The excitation level corresponds to a mean concentration of the electron–hole pairs $n \approx 5\times10^{16}$ cm^{-3}, a lifetime of the current carriers $\tau_0 \approx 10$ μsec, and $T=1.8$ K.

lattice and electron–hole relaxation times with respect to a pulse of the current carriers, $\omega_{1,2}$ are the cyclotron frequencies of the current carriers, and $\mu=(1/m_1+1/m_2)^{-1}$. It follows from Eq. (2) that $\sigma_\perp \approx \sigma_{xx}$; thus we have for the drift velocity

$$v = \frac{F\tau_l}{m_1+m_2} = \frac{e^2}{c\,m_1m_2}\,EB\,\frac{\tau_l\tau}{1+\omega_1\omega_2\tau_l\tau}\,. \tag{3}$$

Setting $\tau_l \approx 10^{-9}$ sec,[7] $\tau \approx 6\times10^{-11}$ sec ($T=1.8$ K),[8] $E=0.1$ V·cm^{-1}, and $B=0.1$ T, Eqs. (1)–(3) yield $F \approx 10^{-14}$ dyn and $v \approx 10^4$ cm/sec. Drifting at this velocity, the conducting EHL channels will move a distance $l \approx 0.1$ cm during a time $t \approx 10^{-5}$ sec.

To detect this effect, we used the method of recording EHD's thin germanium samples, as developed by Asnin *et al.*[9,10] This method is based on the fact that the absorption coefficient decreases sharply inside an EHD in the vicinity of direct interband transitions because of the Burshteĭn effect in the valence band and shielding of the electron–hole Coulomb interaction. Therefore, if a crystal is illuminated by light

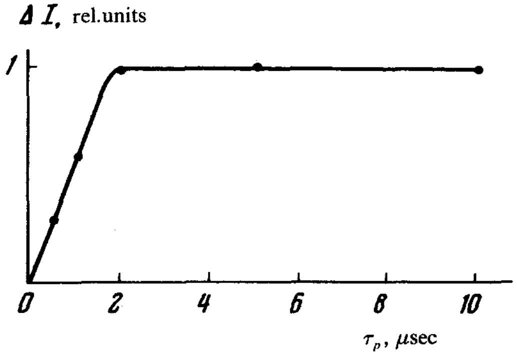

FIG. 2. Modulation signal of the probing light as a function of the electric-field pulse length. $B = 0.16$ T, $E = 0.3$ V·cm^{-1}, $T = 1.8$ K.

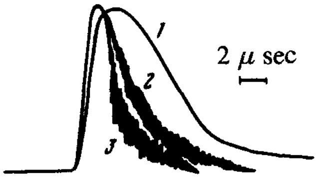

FIG. 3. Kinetics of the photocurrent in various magnetic fields for $E = 0.3$ V·cm^{-1} and $T = 1.8$ K: 1) $B = 0$; 2) $B = 0.08$ T; 3) $B = 0.8$ T. An electric field was applied in the form of square 20-μsec pulses immediately after the excitation pulse.

whose wavelength corresponds to the edge of the direct transitions ($\lambda \approx 1.4$ μm), then the appearance of an EHD in the crystal will increase the intensity (modulation) of the light transmitted through it. In thin samples, where $\alpha d \approx 1$ (α is the absorption coefficient and d is the thickness of the sample), the signal for the modulation of light is approximately proportional to the volume of the EHL. At the same time the shape of the modulation spectra is constant, since it is determined only by the local density of the current carriers in the EHL.[9,10]

In our experiments we used $0.5 \times 0.5 \times (1.5 \times 10^{-3})$ cm pure germanium samples, to which contacts ≈ 0.5 mm in diameter made from In + As alloy were fused in, ≈ 0.3 cm apart. After the samples were placed inside a superconducting solenoid, they were excited by 2-μsec pulses of light from a GaAs laser, so that the excitation level exceeded the threshold of the conductivity in the EHD system.[1] The area of the excitation region was 0.4×0.3 cm. The sample was probed by a vertical light slit ≈ 0.05 cm wide at a wavelength of $\lambda \approx 1.4$ μm, isolated by a monochromator (Fig. 1). The light-modulation signal produced by excitation of the EHD's in the sample was received by a photodiode receiver with $\tau \approx 2$ μsec and recorded by an S7–8 stroboscopic oscillograph using an X-Y recorder.

To determine the drift of the EHL, the slit was focused on the periphery of the excitation region, where the sample was filled less densely with the EHL than at the center. The experiment geometry (Fig. 1) shows that when the electric field is directed along the y axis ($E = E^+$), the current channels should drift along the x axis, and the filling of the sample with the EHL under the slit will increase. As a result the modulation signal will strengthen. It is clear that at $E = E^-$ we can expect the modulation amplitude to decrease. Figure 1 indicates that the modulation signal of the probing light does indeed rise at $E=E^+$ and fall at $E=E^-$. This effect, which can be observed whenever $B \gtrsim 8\times10^{-3}$ T and $E \gtrsim 2\times10^{-2}$ V·cm^{-1}, increases according to Eq. (3), with a growing electric field (Fig. 1) and decreases in strong magnetic fields. A change in direction of the magnetic field changes the sign of the effect.

Upon scanning the sample by the slit we found that an increase of the modulation signal on one side of the contact is accompanied by a decrease on the other side. Spectral measurements showed that the modulation signal changes if the shape of the modulation spectra is preserved. This means that the effects observed are attributable to a drift displacement of conducting regions with a constant concentration of current carriers.

To estimate the EHL drift velocity we conducted experiments in which an electric field was applied to the sample in the form of square pulses whose leading edge coincided with the trailing edge of the excitation pulse. Figure 2 shows how the modulation signal ΔI of the probing light depends on the duration of the field pulse (the experiment geometry is the same as in Fig. 1). The effect becomes saturated when $\tau_{\text{pulse}} = 2$ μsec. ΔI apparently stops increasing when during the transmission of current the conducting regions are displaced a distance of the order of the slit width. We therefore obtain an EHL drift velocity $v \approx 3\times10^4$ cm/sec for $E=0.3$ V·cm^{-1} and $B=0.16$ T, a value of the same order as the estimates obtained above.

We can expect that a displacement of the EHL by a distance comparable to the size of the excitation region can sharply decrease the number of channels and hence the current flowing through the sample. As Fig. 3 shows, the kinetics of the photocurrent is in fact greatly reduced in the magnetic field. It is accompanied by irregular current fluctuations in the form of high-frequency noise (≈ 10 MHz), which apparently reflect fluctuations in the number of conduction channels as they break up during the drift.

We believe, then, that the EHL drift observed by us in crossed electric and magnetic fields proves that the EHD model can describe conduction in the EHD system in germanium.

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