Giant photogalvanopiezomagnetic effect in germanium under exciton-metallization conditions

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(Submitted 18 March 1982)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 9, 367–369 (5 May 1982)

A sharp jump in the photocurrent has been observed at high excitation densities in germanium crystals in a magnetic field crossed with an inhomogeneous strain field at 2 K. The jump in the photocurrent results from an insulator-metal transition in a dense system of drifting excitons. The transition is accompanied by the appearance, above a threshold, of a new spectral line, which corresponds to the recombination emission of an e-h plasma with a density 7×10^{15} cm^{-3} ($r_s \approx 2$).

PACS numbers: 72.40. + w, 72.80.Cw, 71.35. + z, 71.30. + h

Galvanomagnetic effects occur in semiconductors because the carriers moving perpendicular to the magnetic field **H** are deflected from their initial direction by the Lorentz force. This deflection gives rise to a transverse voltage. The carrier motion perpendicular to **H** may be caused by a variety of physical factors: an electric field (the Hall effect), a temperature gradient (the Nernst effect), or a carrier density gradient (the Kikoin–Noskov photoelectromagnetic effect). We have previously pointed out that a gradient of a strain field could also give rise to such a carrier motion. In this case the transverse voltage $V_\perp$ and the short-circuit current j_s can be much larger than in these other effects. In this case, for example, the electron and hole contributions to $V_\perp$ and j_s add up, rather than subtract as they do in the case of the Hall effect, and the average carrier velocity across the magnetic field, which can be adjusted by adjusting the inhomogeneous compression of the crystal, can be much higher than the corresponding velocities in the cases of the Nernst and Kikoin–Noskov effects.

We will not go into detail here on the photogalvanopiezomagnetic effect, which will be the subject of a separate paper, but we do wish to emphasize that this effect presents us with a very effective tool for studying the insulator-metal transition in a dense system of excitons. The idea underlying the method is quite simple: Until the electron and hole combine into an exciton they are moving in an inhomogeneous strain field. They experience essentially no deflection from their original direction in the magnetic field, and they do not contribute to the short-circuit current in the photogalvanopiezomagnetic effect.

According to Mott's hypothesis,[1] the screening of the Coulomb interaction which sets in when a certain critical exciton concentration (n_c) is reached should cause an abrupt ionizational destruction of the excitons, accompanied by an abrupt increase in the photoconductivity of the crystal. A sharp increase in the photoconductivity at 2 K has been reported in undeformed pure germanium crystals[2] at $H = 0$ and in doped germanium

crystals[3] (with an impurity concentration of 10^{15} cm^{-3}) at $H \lesssim 5$ T. This jump was caused, however, not by an ionizational destruction of excitons but by a percolation conductivity along metallic electron-hole droplets. As the temperature is raised above the critical value for condensation into these droplets, the exciton-plasma transition becomes diffuse because of the thermal ionization of excitons.

The photogalvanopiezomagnetic effect has certain advantages for studying a Mott transition in germanium which is compressed along the ⟨100⟩ axis: First, there is a pronounced decrease, to 2-3 K, in the critical temperature for electron-hole condensaton (because of the lifting of the band degeneracy[4,5] and also because of the magneto-Stark effect for the electron-hole droplets moving in the magnetic field). Second, there is a sharp decrease in the relative number of nonequilibrium free carriers in the exciton flux with distance from the excitation surface (because of the low drift velocity of the electrons and holes, which are put into revolution by the magnetic field).

In the present experiments we studied germanium crystals with a shallow-impurity concentration of 10^{12}-10^{14} cm^{-3}. The samples were cut in the form of rectangular parallelepipeds 3 × 3 × 10 mm in size. Before being placed in the cryostat, they were etched in SR-4a polishing etchant. An inhomogeneous strain was produced by a trihedral prism (Fig. 1) nearly along the ⟨100⟩ direction. The potential well in this case was axisymmetric, and its bottom was a distance 1.5 mm in the crystal below the excitation surface. Contacts were applied to the sample (Fig. 1) by soldering with indium and were punctured by an rf discharge.

Figure 2 shows a double logarithmic plot of the short-circuit photocurrent against the excitation power W. At high temperatures, where the excitons undergo a rapid thermal ionization, the short-circuit current in the photogalvanopiezomagnetic effect increases gradually with increasing excitation density (curve c^+, $T = 20$ K). At $T < 5$ K (curves a and b), the curves of $j_s(W)$ exhibit a sharp jump in the photocurrent at a certain critical excitation density W_c. The photocurrent jumps by as much as three orders of magnitude at $T = 2$ K. As expected, j_s changes sign when the magnetic field is reversed. The difference between the $j_s(W)$ curves for opposite field directions (curves a^+ and a^-) is a consequence of contacts which are not perfectly ohmic; it can be seen from Fig. 2 that this difference is not important. As the magnetic field is increased, the threshold shifts toward a higher excitation density (Fig. 2).

In addition to measuring the photocurrent, we also studied the photoluminescence spectra at 2 K (Fig. 3). At the lowest excitation densities (spectrum 1 in Fig. 3 corres-

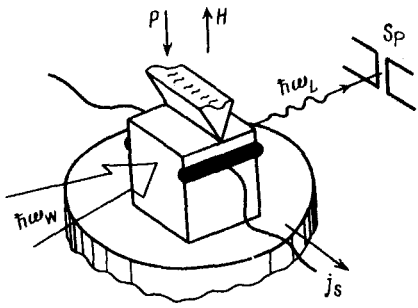

FIG. 1. The experimental arrangement.

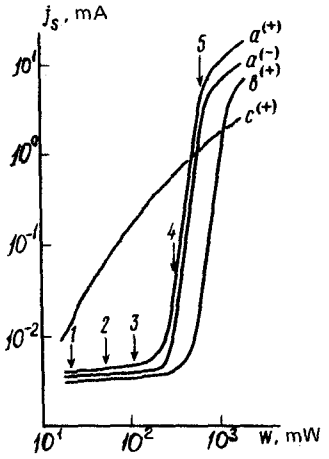

FIG. 2. Dependence of the short-circuit current j_s, in milliamperes, on the power W, in milliwatts, of the exciting light in the photogalvanopiezomagnetic effect. a, b–At 2 K; c–at 20 K; a, c–in a magnetic field $H = 0.7$ T; b–4 T. Curves a^+ and a^- correspond to opposite magnetic field directions.

ponds to point 1 in Fig. 2, etc.), the spectrum reveals an emission by excitons in a potential well, whose depth is 6 meV in the case of Fig. 3. As W is increased, the exciton density in the potential well increases, and the excitons form an *e-h* liquid at the bottom of the well (line L, spectrum 2). With a further increase in the excitation density, a new line, P, appears in the emission spectrum when a threshold is reached, at the same time as the discontinuity in the photocurrent (spectra 4 and 5). This new line can be distinguished particularly well in the spectra recorded with a 15% modulation of the exciting light (differential spectrum 5′).

The experimentally observed increase in the photocurrent after a threshold is reached and the appearance of a new line in the emission spectrum are naturally attributed to an insulator-metal transition in the drifting exciton gas when a critical density is reached. The density of the *e-h* plasma which arises can be determined by analyzing the shape of line P by means of the expression[4]

$$I(h\nu) = \int_0^{h\nu} D_e(E) f_e(E)\, D_h(h\nu - E) f_h(h\nu - E)\, dE,$$

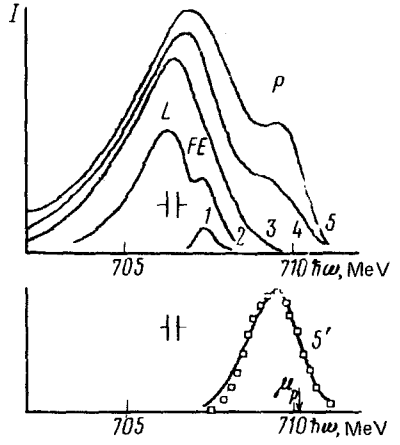

FIG. 3. The LA emission spectra of germanium compressed along the ⟨1.1.16⟩ axis in a magnetic field $H = 0.7$ T at 2 K and at the various excitation densities indicated by the arrows in Fig. 2. Spectrum 5′ was recorded at point 5 with a 15% intensity modulation of the exciting light.

where $D_{e(h)}$ and $f_{e(h)}$ are the state density and distribution function of the electrons (or holes). It follows from this approximation (Fig. 3) that the density of the *e-h* plasma is $(7 \pm 0.5) \times 10^{15}$ cm^{-3}, or $r_s = (3/4\pi n a_{ex}^3)^{1/3} \approx 2$. This value agrees well with some previous estimates,[5] $r_s^c \simeq 2.5$-2, found from an analysis of the emission spectra of homogeneously compressed germanium crystals. The shift of the threshold toward higher excitation densities with increasing magnetic field results from a transverse compression of the exciton wave function (at $H = 4$ T, the magnetic length is $a_H = 0.8 a_{ex}$). We wish to emphasize that the chemical potential (μ) of the *e-h* plasma which is found from the violet edge of the *P* line is considerably higher than the chemical potential of the *e-h* system at the bottom of the potential well. Accordingly, the metallization of excitons which we have detected occurs at a significant distance from the bottom of the well. Nevertheless, judging from the width of the emission line of the resulting *e-h* plasma, this plasma occupies only a small spatial region Δx. This result is not surprising in view of the sharp decrease in the drift velocity of the *e-h* pairs after the destruction of the exciton states.

In summary, by studying the photogalvanopiezomagnetic effect we have been able to observe a sharp change in the photoconductivity characteristics under conditions corresponding to the metallization of excitons. These changes have not been observed previously.

We wish to thank V. N. Zverev for assistance in fabricating the contacts and for a discussion. We also thank V. F. Gantmakher, É. I. Rashba, and V. M. Édel'shteĭn for a discussion of these results.

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Translated by Dave Parsons
Edited by S. J. Amoretty