Observation of the regions of a 2D electron gas in a layered indium selenide

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Quantum oscillations of the resistance of layered *n*-InSe crystals have been observed at liquid-helium temperature in a magnetic field. These oscillations occur because of the presence in the samples of regions with a 2D electron conductivity.

It has now been established that electronic states which form the fundamental-absorption edge of indium selenide are slightly anisotropic. Strong anisotropy of the conductivity of indium selenide and of its analogs cannot be accounted for in terms of the available information about the band structure and the effective mass of the current carriers in these crystals.[1] The recently published experimental studies[2,3] of the cyclotron resonance in InSe, which were interpreted on the basis of the assumption that there are regions of 2D electron gas in this crystal, also cannot be explained in terms of the existing band scheme. The circumstances mentioned above have provided the incentive to carry out an experimental study of the low-temperature magnetoresistance of indium selenide.

The experiments were carried out with *n*-InSe samples prepared from single crystals grown by the Bridgman method. The resistivity of the samples was $(0.1 - 10^3)\Omega \cdot \text{cm}$ at room temperature. The low-resistance indium contacts were fabricated on a freshly cleaved surface. The resistance was measured by the four-contact method in the plane of the cleaved surface normal to the *c* axis. The sample was immersed directly into liquid helium at the center of a superconducting solenoid

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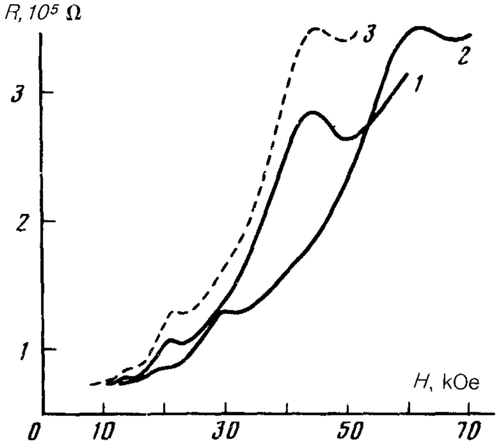

FIG. 1. Oscillations of the magnetoresistance of a n-InSe sample at various angles α between the vectors **H** and **c**. 1—$\alpha = 0$; 2,3—$\alpha = 43°$. For curve 3 the scale along the abscissa is compressed $(\cos\alpha)^{-1}$ times. $T = 1.3$ K.

which produced a 70-kOe field. The magnetoresistance was measured in the $\mathbf{H}\|c$ geometry and in a tilted field.

In most samples the resistance R increased with decreasing temperature from 4.2 to 1.3 K, and a positive magnetoresistance was observed in fields higher than several kilo-oersteds as a result of application of a magnetic field. In several samples the $R(H)$ dependence was oscillating. These oscillations are shown in Fig. 1 for different directions of the vector **H** relative to the c axis. A deviation of H from the normal to the plane of the layers causes the extrema to shift toward the high fields, as can be seen from a comparison of curves 1 and 2. The position of the extrema is inversely proportional to the cosines of the angle between the vectors **H** and **c**, as demonstrated by curve 3 which was obtained by compressing curve 2 along the abscissa with the coefficient equal to $(\cos\alpha)^{-1}$ $(\alpha = 43°)$. The observable magnetoresistance oscillations are thus determined solely by the component of the vector **H** normal to the c axis, showing that the behavior of the electrons in these samples is two-dimensional in nature. The oscillation period changes along the inverse magnetic field scale from one sample to the next within the limits $(1.4\text{–}3.4)\times 10^{-5}$ Oe^{-1}.

The most interesting results were obtained in a sample whose $R(H)$ dependence is shown in Fig. 2. At $H = 0$ the resistance of this sample is essentially independent of the temperature (1.3 K$\leqslant T \leqslant$4.2 K); i.e., the conductivity is metallic in nature. The $R(H)$ curve, which has no monotonic behavior corresponding to positive magnetoresistance, exhibits large-amplitude oscillations. At $T = 1.3$ K the resistance in the minimum situated in a field $H \cong 37$ kOe is approximately two orders of magnitude lower than that in the neighboring maximum situated in large fields. As the temperature is raised, the resistance in the minimum increases exponentially (Fig. 3).

The Shubnikov-de Haas oscillations in Fig. 2 are typical of 2D electron gas. The presence of deep minima and the activation temperature dependence of the resistance in them show that electrons become localized under these conditions and that the detected conductivity is caused by the thermal activation of the carriers to the mobile states in two Landau levels between which the Fermi level is situated. According to

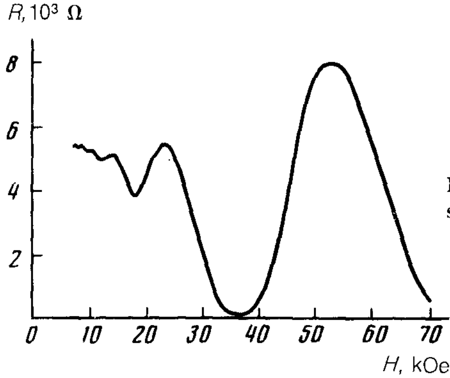

FIG. 2. Oscillations of the magnetoresistance of a *n*-InSe sample with a "metallic" conductivity. $T = 1.3$ K.

the calculations of Nicholas *et al.*,[4] the conductivity of 2D electrons in the quantum-oscillation minima can be described by the following relation in the temperature interval studied by us:

$$\sigma_{xx}^{min}(T) \sim T\exp[(\hbar\Omega - 2\Gamma)/2kT], \qquad (1)$$

where $\Omega = eH/mc$ is the cyclotron frequency of the electrons, $\Gamma = \hbar\Omega/\sqrt{2c/\pi\mu H}$ is a quantity which characterizes the broadening of the Landau levels, and μ is the electron mobility. Since under conditions corresponding to the quantum Hall effect the transverse component of the magnetoresistance tensor $\rho_{xx} \propto \sigma_{xx}$, relation (1) must also be valid for the transverse magnetoresistance. The experimental points which describe the $R(T)$ dependence in the minimum are well interpolated by Eq. (1) (Fig. 3). Using the value of the cyclotron mass of electrons[2] $m = 0.13m_0$, we thus determine from the slope of the plot in Fig. 3 the valules $\Gamma \approx 1.3$ meV and $\mu \approx 10^4$ cm^2/(V·s). From the oscillation period in Fig. 2 we find the 2D electron density $n \approx 10^{11}$ cm^{-2}.

The 2D effects that have been observed experimentally, and the anisotropy of the conductivity of the crystals such as indium selenide, are attributable, in our view, to the particular features of the actual structure of layered semiconductors. The polymor-

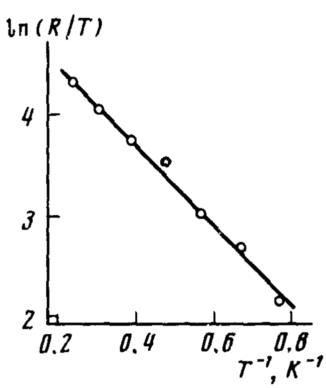

FIG. 3. The temperature dependence of the resistance in the minimum at $H \approx 37$ kOe.

phic nature of these crystals and the presence of azimuthal disorder in the stacking of the layers are responsible for the two-dimensional defects in the basal plane of the crystals such as GaSe. These defects account for the characteristic potential relief along the c axis.[5] The explanation of the results of the experiments[2,3] on the cyclotron resonance of InSe was based on the assumption that the electrons are trapped by defects of this sort, resulting in the formation of regions with a 2D conductivity.

The presence of regions with a 2D conductivity can also be deduced from our data. The resistivity of the sample, whose $R(H)$ dependence is shown in Fig. 2, is approximately 10 kΩ, on the order of the maximum resistivity of a 2D metallic layer, $h/e^2 \approx 26$ kΩ. This means that we are recording the resistivity of the 2D-conductivity region closest to the surface and that the other similar regions, if they exist, are separated by regions with a small conductivity.

This circumstance does not rule out the possible existence of a region of 2D electron gas at the sample's surface.

If the longitudinal dimensions of the regions of 2D metallic conductivity are smaller than the spacing between the contacts, the oscillations will occur against the background of a positive magnetoresistance (Fig. 1) which is produced as a result of the gradual engagement of the regions of the sample which exhibit a hopping conductivity.

The various pieces of evidence found in the literature and those presented in this letter thus suggest that at liquid-helium temperature indium selenide crystals have regions of 2D electron gas. In a quantizing magnetic field the kinetic properties of such samples exhibit phenomena characteristic of the quantum Hall effect.

[1]G. L. Belen'kiĭ and V. V. Stopachinskiĭ, Usp. Fiz. Nauk **140**, 233 (1983) [Sov. Phys. Usp. **26**, 497 (1983)].
[2]E. Kress-Rogers, R. J. Nicholas, J. C. Portal, and A. Chevy, Solid State Commun. **44**, 379 (1982).
[3]E. Kress-Rogers, R. J. Nicholas, and A. Chevy, J. Phys. C: Solid State Phys. **16**, 2439 (1983).
[4]R. J. Nicholas, R. A. Stradling, and R. J. Tidey, Solid State Commun. **23**, 341 (1977).
[5]K. Maschke and H. Overhof, Phys. Rev. B **15**, 2058 (1977).

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