Metal–Hall insulator transition

S. S. Murzin
Institute of Solid State Physics, Academy of Sciences of the USSR

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The possible existence of a Hall insulator in the three-dimensional case—a state with zero diagonal components of the conductivity tensor and a nonvanishing Hall conductivity—is explored. Experiments show that a Hall insulator can conceivably be formed in *n*-InAs.

In the absence of a magnetic field, strongly doped semiconductors have a metallic conductivity. In strong magnetic fields H, there is a metal-insulator transition (magnetic freezing-in). In the final stage of this transition, the current carriers are trapped in the impurities and the static conductivity at zero temperature, $T=0$, is $\sigma_{ij}=0$. In the present letter we raise the question of the existence of an intermediate phase (a Hall insulator) in the 3D systems. We will consider a phase in which the diagonal components of the conductivity tensor are $\sigma_{ij}=0$ at $T=0$ and the Hall conductivity $\sigma_{xy}\neq 0$. It would be possible for such a phase to occur if σ_{ii} would vanish in magnetic fields smaller than σ_{xy}. This phase would be an intermediate phase between the metallic phase and the insulator phase (Fig. 1).

A Hall insulator occurs in 2D metallic systems under conditions corresponding to quantum Hall effect, in which the Fermi level lies in the region of localized states at the edge of a broadened Landau level.[1] The existence of a Hall insulator in a 2D system is due to the discrete nature of the electronic spectrum in a magnetic field.

In the 3D case, the electronic spectrum in a system of noninteracting electrons is continuous in a magnetic field. The electron-electron interaction can, in our view, physically account for appearance of a Hall insulator in a three-dimensional system. Under the condition $kT \ll (\hbar/\tau) \ll \epsilon_F$ (τ is the momentum relaxation time and ϵ_F is the Fermi energy) the electron-electron interaction in a metal leads to a correction to the conductivity[2,3]:

$$\frac{\Delta\sigma}{\sigma} \sim -\lambda \frac{\tau^{-1/2}}{\nu_F (D_1 D_2 D_3)^{1/2}\hbar} \qquad (1)$$

where ν_F is the state density at the Fermi level, D_1, D_2, and D_3 are the principal values of the diffusion tensor, and $|\lambda|\sim 1$. [The temperature-dependent part of the correction, which is given in Ref. 2 and which is $(kT\tau/\hbar)^{1/2}$ times smaller, is not included in (1).] In the absence of a magnetic field we would have $|\Delta\sigma/\sigma| \sim (\hbar/\tau \sim \epsilon_F) \ll 1$. In a strong magnetic field $\omega_c\tau \gg 1$ (ω_c is the cyclotron frequency) the relative correction to the diagonal components of the conductivity tensor $\Delta\sigma_{ii}/\sigma_{ii}$ increases by a factor of $(\omega_c\tau)$ due to a decrease in the diffusion coefficients across the field.[2] This correction is on the order of $(\hbar\omega_c/\epsilon_F)^2$. The electron-electron interaction has no effect on the Hall conductivity: $\Delta\sigma_{xy}/\sigma_{xy}=0$ (Ref. 4). In the ultraquantum limit, in which only one Landau level, with one spin direction, is filled, we have $\lambda>0$ (see Ref. 3). Substitution

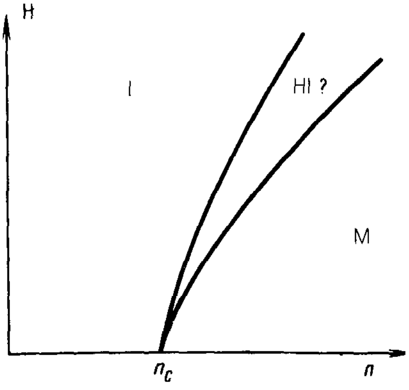

FIG. 1. Schematic representation of the metal–insulator phase diagram. I—insulator; M—metal, HI—Hall insulator; n—impurity density.

into (1) of v_F, D_1, D_2, D_3 and τ (here τ is the relaxation time of the momentum along the magnetic field) found in Ref. 5 leads to $\Delta\sigma_{ii}/\sigma_{ii} \gtrsim 1$, $\Delta\sigma_{ii} < 0$ in the case of scattering by impurities. Although Eq. (1) does not apply in this case, an estimate shows, nevertheless, that a decrease in the diagonal components of the conductivity tensor due to electron-electron interaction is of the same order of magnitude as the initial values of $\sigma_{ii}(H)$. Since the electron-electron interaction has no effect on the Hall conductivity σ_{xy}, it is conceivable that σ_{ii} vanishes when σ_{xy} is still nonvanishing; i.e.,

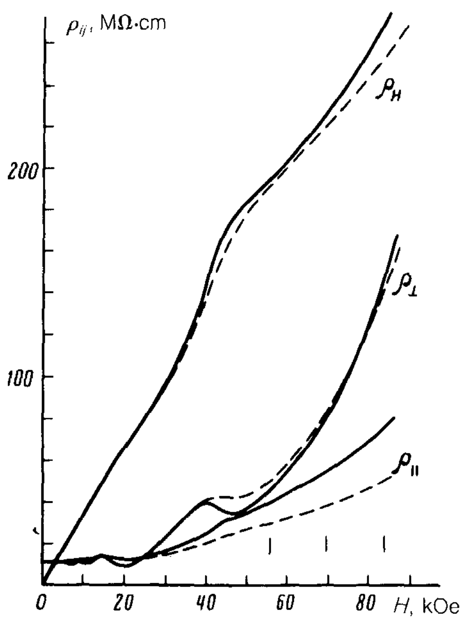

FIG. 2. $\rho_\parallel$, $\rho_\perp$, and ρ_H versus the magnetic field. Solid curve—$T = 0.35$ K; dashed curve—$T = 4.2$ K.

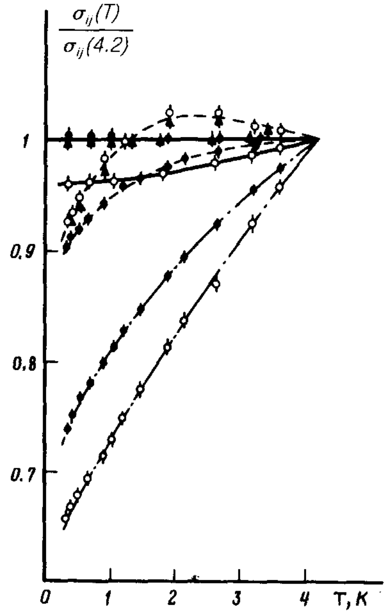

FIG. 3. The temperature dependences of σ_{xy}, σ_{xx}, and σ_{zz} in various magnetic fields: — σ_{xy}; - - - σ_{xx}; -·- σ_{zz}; ●—$H = 56$ kOe; ▲—70 kOe; ○—84 kOe. The temperature dependences are shown only for 56- and 84-kOe fields.

a Hall insulator forms. The electron-electron interaction decreases not only the conductivity but also the single-particle state density $\nu(\epsilon)$ near the Fermi level,[2] so that $\nu(\epsilon_F)$ apparently vanishes in the metal–Hall insulator transition. We cannot assume, however, that transition to the Hall insulator is the direct result of the reduction of $\nu(\epsilon_F)$ to zero, since Einstein's relation $\sigma_{ij} = e^2(\partial n/\partial \mu) D_{ij}$ does not contain $\nu(\epsilon_F)$ but rather the derivative of the electron density n in the chemical potential[3] μ. The diagonal components of the conductivity tensor decrease because of the decrease of the diagonal components of the electron-diffusion tensor near the Fermi level.

To determine the validity of the arguments given above, we have measured the transverse resistivity $\rho_{\perp} \equiv \rho_{zz}$, longitudinal resistivity $\rho_{\parallel} \equiv \rho_{zz}$ of a degenerate n-InAs as functions of temperature and magnetic field. In our samples the electron concentration is $n = 1.8 \times 10^{16}$ cm^{-3} and the electron mobility is 3×10^4 cm^2/(s·V). In the absence of a magnetic field $\epsilon_F = 90$ K, $\hbar/\tau \sim 14$ K, and the resistivity is essentially independent of temperature over the temperature interval 0.35–4.2 K. The ultraquantum limit with a single occupied Landau level $0\downarrow$ is reached in a nearly 50-kOe field (see Fig. 2). At these magnetic fields the components of the resistivity tensor change markedly as the temperature is lowered. The most strongly temperature-dependent resistivity is the longitudinal magnetoresistivity. The temperature dependences of the components of the resistivity tensor were measured thoroughly in fields represented by dashed curves in Fig. 2. From these measurements we determined the temperature dependences of the conductivity-tensor components $\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2)$, $\sigma_{zz} = \rho_{zz}^{-1}$, and σ_{xy}

$= \rho_{xy}/(\rho_{xx}^2 + \rho_{xy}^2)$ (see Fig. 3). The nonmonotonic temperature dependence of σ_{xx} in 70- and 84-kOe fields suggests that the temperature dependence of the conductivity $\hat{\sigma}$ is affected by several factors. At temperatures below 2 K, the diagonal components of the conductivity tensor σ_{xx} and σ_{zz} decrease with decreasing temperature and σ_{xy} is nearly independent of T. This behavior can be used as the experimental basis for raising the question as to whether a Hall insulator can exist in the 3D case.

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