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The question of a Hall-insulator state in the resistivity of a bulk semiconductor in very high magnetic fields

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Abstract. For single crystals of n-InSb and n-InAs in the extreme quantum limit of the applied magnetic field, the transverse resistivity ρ_{xx} decreases and the longitudinal resistivity ρ_{zz} increases with a logarithmic temperature dependence from 1 K to 50 mK. Since the Hall resistivity ρ_{xy} and conductivity $\sigma_{xy} \simeq 1/\rho_{xy}(\rho_{xx} \ll \rho_{xy})$ are constant in this temperature region, the origin of this effect could lie in the electron–electron interaction in a disordered system. Extrapolation of the data to zero temperature points to a Hall-insulating state.

1. Introduction

In the absence of a magnetic field, strongly doped semiconductors have a metallic conductivity. For strong magnetic fields where the extension of the electronic wavefunction at the impurity becomes comparable to the distance between impurity sites, a metal–insulator transition occurs [1–3]. In the final stage of this transition the current carriers are trapped at the impurities (magnetic freezing out), and both the diagonal and off-diagonal elements of the conductivity tensor vanish at zero temperature ($T = 0$). Under quantum-Hall-effect conditions of a two-dimensional (2D) electron system, the diagonal components of the conductivity tensor vanish for $T \to 0$, whereas the Hall conductivity does not. The existence of this so-called Hall-insulator state is related to the discrete electron spectrum with forbidden gaps between the Landau levels of a 2D electron system in a magnetic field. In the fractional quantum Hall effect the Hall-insulator state is caused by the opening of an energy gap in the electron spectrum as a result of electron–electron correlations [4].

According to the theory for a pure three-dimensional (3D) system in the extreme quantum limit of the applied magnetic field with only one Landau level occupied, the electron–electron correlations can induce a charge-density-wave state or a Wigner crystal with an energy gap at the Fermi level [5]. One may expect that the charge-density-wave (or spin-density-wave) state shows the Hall-insulator properties [6, 7]. However, in semiconductors the number of charged impurities is comparable to the number of electrons. As the impurities are distributed randomly, it is difficult to expect that electrons can form some regular state in this disordered potential distribution.

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The diffusive transport in a disordered metallic system influences the single-particle density of states around the Fermi level via the electron–electron interaction [8]. In view of this electron–electron interaction in disordered metallic systems, the possible existence of a Hall insulator—a novel state for a 3D system with zero diagonal elements σ_{xx} and σ_{zz} of the conductivity tensor and a non-vanishing Hall conductivity σ_{xy} at $T = 0$—was discussed for a metallic semiconductor in a strong magnetic field (parallel to the z-axis) [9]. In the first experiments to explore the hypothesis for the existence of a Hall insulator in 3D systems, a decrease in ρ_{xx} and an increase in ρ_{zz} were observed in a n-InAs single crystal going from 2 to 0.3 K in an applied magnetic field of 8 T, ρ_{xy} staying constant [9]. The observed changes in the diagonal tensor components were small ($< 10\%$) and the temperature range not sufficiently large to determine any functional temperature dependence of the effect. Therefore we investigated the resistivity tensor in n-InAs and n-InSb for applied magnetic fields in the extreme quantum limit up to 20 T and temperatures down to 50 mK. The experimental data show a remarkable decrease of the transverse resistivity and an increase of the longitudinal resistivity for decreasing temperatures below 1 K, which could point to a Hall-insulating state.

2. Samples and experimental details

In order to have a system with free electrons in a sufficiently large magnetic field range above the extreme quantum limit, we investigated InAs and InSb samples with high concentrations of electrons as summarized in table 1. The samples (Te-doped InSb supplied by MCP Wafer Technology Ltd, UK) have mobilities typical for this kind of crystals. In the table we have listed the magnetic field values where the samples enter the extreme quantum limit (H_{EQL}) and where the field-induced metal–insulator transition occurs (H_{MI}). The values for H_{EQL} have been obtained from the experimental magnetoresistance data and for H_{MI} from the magnetic-freezing-out condition $n a_{\parallel} a_{\perp}^2 = \delta^3$ with $\delta \simeq 0.3$, where n is the electron concentration, $a_{\parallel} = a_{\mathrm{B}}/\ln(a_{\mathrm{B}}/\Lambda)^2$ and $a_{\perp} = 2\Lambda = 2(\hbar/eH_{\mathrm{MI}})^{1/2}$ (a_{B} is the effective Bohr radius and Λ is the magnetic length) [10]. The given values for H_{MI} have been corrected for the non-parabolicity of the conduction band in the two-band model [11], with a magnetic-field-dependent effective mass $m^*(H) = m^*(H = 0)(1 + 4E/E_{\mathrm{g}})^{1/2}$ for the electron energy $E = \hbar\omega_{\mathrm{c}}/2 - |g^*|\mu_{\mathrm{B}}H/2$ at the lowest Landau level ($\omega_{\mathrm{c}} = eH/m^*$ cyclotron frequency, g^* effective g-factor, E_{g} band gap).

Table 1. Electron concentration n_{77} and mobility μ_{77} at 77 K for the investigated samples together with the field values for the extreme quantum limit (H_{EQL}) and for the metal–insulator transition (H_{MI}).

	Sample number	$n_{77}(10^{16}\ \mathrm{cm}^{-3})$	$\mu_{77}(10^3\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1})$	H_{EQL}(T)	H_{MI}(T)
n-InAs		2.7	40	5.3	23
n-InSb	1	1.4	123	3.5	16.3
n-InSb	2	5.6	80	8.2	44
n-InSb	3	5.4	82	7.8	43

The samples were spark cut from single-crystalline material in a geometry including the legs for (Hall-)voltage measurements. The sizes of the samples were of the order of 1 mm^2 in cross section and 10 mm in length. In applied magnetic fields up to 20 T, the transverse (ρ_{xx}), longitudinal (ρ_{zz}) and Hall (ρ_{xy}) resistivities were measured as a function of temperature in a $^3He/^4He$-dilution refrigerator using phase-sensitive detection. The observed experimental results are independent of the chosen contact configuration on the Hall bar or on the polarity of the field. At low fields both ρ_{xx} and ρ_{zz} (measured on the same part of the sample by rotating the sample with respect to the field) are nearly constant, indicating the uniformity of the samples. For the temperature measurements in a magnetic field a thick-film resistor consisting of a RuO_2-composite was used [12]. Corrections (few %) on the temperature scale for the magnetoresistance of the sensor were made. Below 100 mK these corrections increased above 10%, therefore increasing the error in the temperature measurement as indicated in the data presented for the lowest temperatures.

3. Results

In figure 1 we have plotted the transverse (ρ_{xx}) and Hall (ρ_{xy}) resistivities as a function of the magnetic field at $\simeq$ 1 K and $\simeq$ 80 mK for sample InSb number 2. After the appearance of the Shubnikov–de Haas oscillations the extreme quantum limit starts at fields above 8 T with strongly increasing ρ_{xx}. The Hall resistivity varies practically linearly with the magnetic field. The observed plateau-like feature in the Hall voltage around 8 T has been explained recently in terms of the existence of localized states at the bottom of the 0 $\downarrow$ Landau level crossing the Fermi level [13]. In a strong magnetic field, the transverse resistivity ρ_{xx} decreases with decreasing temperature, but the Hall resistivity ρ_{xy} is independent of the temperature within the measuring accuracy (1%).

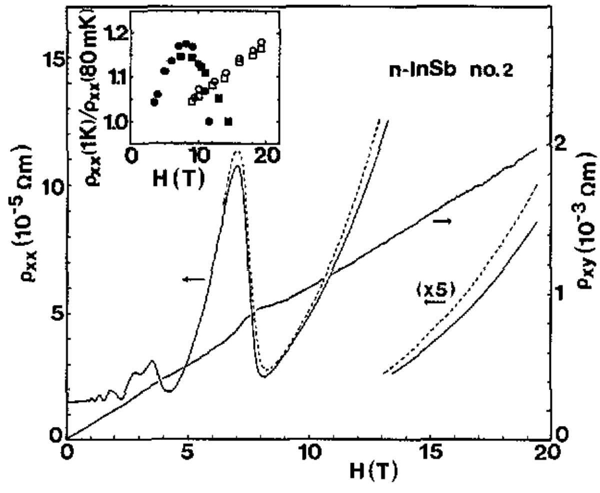

Figure 1. Magnetic dependence of the transverse resistivity ρ_{xx} and Hall resistivity ρ_{xy} for the n-InSb sample 2 at $\simeq$ 1 K (broken curve) and at $\simeq$ 0.08 K (full curve). The Hall resistivity was independent of temperature. The inset shows ρ_{xx}(1 K)/ρ_{xx} (0.08 K) as a function of the magnetic field for the investigated samples (for a definition of the symbols see figure 2).

In the inset of figure 1 we have plotted the ratio $\rho_{xx}(\simeq 1\ \mathrm{K})/\rho_{xx}(\simeq 0.08\ \mathrm{K})$ as a function of the magnetic field for the investigated samples. For the InSb samples numbers 2 and 3, the temperature dependence in ρ_{xx} becomes stronger with increasing magnetic field. For the InSb sample with the smallest electron density, $\rho_{xx}(1\ \mathrm{K})/\rho_{xx}(0.08\ \mathrm{K})$ at first increases and then decreases with increasing magnetic field. Also for InAs this decrease is observed at higher magnetic fields. The decrease in $\rho_{xx}(1\ \mathrm{K})/\rho_{xx}(0.08\ \mathrm{K})$ is accompanied by a temperature dependence in the Hall component ρ_{xy} (increasing ρ_{xy} with decreasing temperature). The effect of temperature dependences of ρ_{xy} are indications for the starting influence of magnetic freezing out.

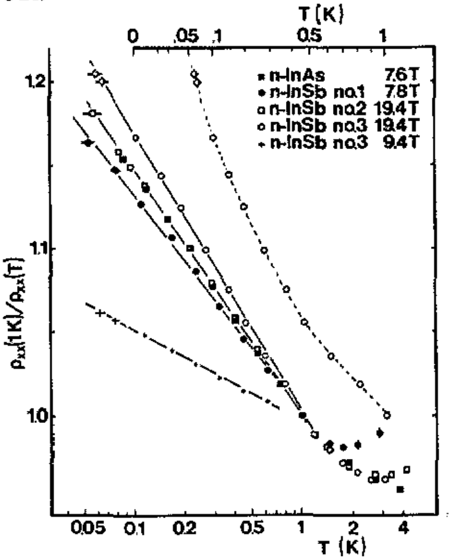

Figure 2. Inverse of the transverse resistivity $1/\rho_{xx}(T) \simeq \sigma_{xy}^2/\sigma_{xx}$ normalized at $T = 1$ K as a function of the temperature on a logarithmic scale (bottom scale) for the different samples in the indicated magnetic fields. One set of data points (open dots) has been plotted on a $T^{1/2}$ scale (top scale).

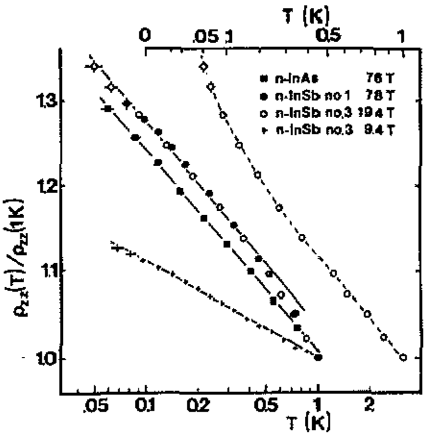

Figure 3. Longitudinal resistivity $\rho_{zz}(T) \simeq 1/\sigma_{zz}$ normalized at $T = 1$ K as a function of the temperature on a logarithmic scale (bottom scale) for the different samples in the indicated magnetic fields. One set of data points (open dots) has been plotted on a $T^{1/2}$ scale (top scale).

The temperature-dependent resistivity measurements were done at such magnetic field values when the Hall resistivity $\rho_{xy} \gg \rho_{xx}$ was independent of temperature, indicating a metallic behaviour with a constant electron density. Figures 2 and 3 show the temperature dependences of $1/\rho_{xx}$ and ρ_{zz} for the investigated samples in a constant applied magnetic field. In these fields $\rho_{xy} \gg \rho_{xx} \geqslant \rho_{zz}$ for the measured resistivity components, and therefore $\sigma_{zz} \gg \sigma_{xy} \gg \sigma_{xx}$ with $\sigma_{zz} = 1/\rho_{zz}$, $\sigma_{xy} \simeq 1/\rho_{xy}$ and $\sigma_{xx} \simeq \rho_{xx}/\rho_{xy}^2$. The experimental data in figures 2 and 3 show a logarithmic temperature dependence corresponding to a decrease in σ_{xx} and σ_{zz} with decreasing temperature. For comparison, we have plotted in figures 2 and 3 one set of data points on a $T^{1/2}$ scale which gives no satisfactory description of the temperature dependence of the data. Other power-law dependences (like $\sigma_{ii} \simeq AT^{1/x} + B$) can be fitted to the data below 1 K, with a reasonable agreement compared with the accuracy of the data only for $x \geqslant 4$.

4. Discussion

Related experimental work on transport measurements of semiconductors at low temperatures and high magnetic fields is mostly done near the metal–insulator transition where different types of temperature dependences have been observed for the resistivity tensor (see reviews [2, 3] and [14–18]). Moreover, the criterion $\rho_{xy} > \rho_{xx}$, which is valid for a 'good' metal where $\rho_{xy}/\rho_{xx} = \omega_c\tau$, is not fulfilled in these experimental data (τ is the scattering time). In some of these experiments [3, 16], ρ_{xx} and ρ_{zz} increase strongly when lowering the temperature while ρ_{xy} increases only weakly. In other experiments [18], σ_{xx} decreases for decreasing temperatures followed by a rise for temperatures below $\simeq 100$ mK.

For our experiments the 'metallic' condition $\rho_{xy}/\rho_{xx} \gg 1$ holds and the Hall constant does not depend on the temperature and the magnetic field. Moreover, the experimental results differ from others.

The behaviour of the conductivity tensor—a decrease of the diagonal elements, whereas the Hall conductivity is constant for decreasing temperatures—is in agreement with a picture taking account of the electron–electron interaction in a disordered system. In a system with finite mean free path the interaction between electrons leads to a correction in the single-particle density of states around the Fermi level and in the conductivity, with, respectively, energy and temperature dependences given by the dimensionality of the system [8, 19]. In the 3D case, this correction $\delta\sigma$ can be written for $T = 0$ as [8]

$$\delta\sigma_{ii}/\sigma_{ii} = \lambda\tau^{-1/2}/N(D_1D_2D_3)^{1/2}\hbar \qquad \text{with } i = x, y, z \tag{1}$$

where N is the electron density of states and D_i are the anisotropic diffusion coefficients. λ is a parameter of order unity depending on the evaluation of the Hartree and exchange terms for the electron–electron interaction, and taking a negative value in a high magnetic field for a band with only one spin orientation due to dominating exchange terms [20]. In zero magnetic field (1) leads to small corrections of the order $(\hbar/\tau)^2/E_F^2$ with E_F the Fermi energy in zero magnetic field. In classically strong magnetic fields ($\omega_c\tau > 1$) the corrections increase by a factor $(\omega_c\tau)^2$, since the transverse diffusion coefficients decrease, and become of the order of

$$|\delta\sigma_{ii}/\sigma_{ii}| \sim (\hbar\omega_c/E_F)^2. \tag{2}$$

Off-diagonal elements σ_{xy} are not influenced by electron–electron interaction effects. In a strong quantizing magnetic field, no detailed theory exists for the electron–electron interaction in a disordered system. To give an order of magnitude for $\delta\sigma/\sigma$ due to interaction effects, (1) can be used with the magnetic-field-dependent quantities in the extreme quantum limit [21] yielding $|\delta\sigma_{ii}/\sigma_{ii}| \simeq 1$ in the case of electron scattering on point defects. In a crude way, this result can be achieved from (2) by applying $E_F \simeq \hbar\omega_c$. The estimation $|\delta\sigma_{ii}/\sigma_{ii}| \simeq 1$ gives the maximum value of the effect for zero temperature. For increasing temperatures $|\delta\sigma_{ii}|$ decreases with a $T^{1/2}$ temperature dependence in a 3D system. The above estimation has been made for scattering on point defects, but in doped semiconductors the scattering takes place at ionized impurities. By evaluating (1) for this case in the extreme quantum limit [22, 23], $|\delta\sigma_{ii}/\sigma_{ii}|$ approaches one when the electronic wavelength ($\propto H$) is of the order of the screening length ($\propto 1/H$) and is smaller in lower fields. This fact could explain the increase of $\rho_{xx}(1\ \mathrm{K})/\rho_{xx}(\simeq 0.08\ \mathrm{K})$ with increasing fields above H_{EQL} (see inset of figure 1). The decrease of this ratio in higher magnetic fields is caused by the approach of the insulating state.

The observed logarithmic temperature dependences in the transverse and longitudinal resistivity are not clear so far. The dimensionality of the diffusional transport determines the specific temperature dependences for the corrections in the conductivity due to weak localization and electron–electron interaction: $\log T$ for 2D systems and $T^{1/2}$ for 3D systems [19]. The criterion for the relevant dimensionality depends on the sample size L with respect to the diffusion length $(D\hbar/k_{\mathrm{B}}T)^{1/2}$ for the electrons in a time $\hbar/k_{\mathrm{B}}T$. For $L < (D\hbar/k_{\mathrm{B}}T)^{1/2}$, the considered dimension is not of importance. Our samples are certainly 3D, but we observe a 2D-type logarithmic temperature dependence rather than a $T^{1/2}$ dependence.

From a scaling theory, the temperature dependence of the conductivity near the critical region of the mobility edge is found to be $T^{1/3}$ [24]. Such a temperature dependence does not give a good description of the experimental data below 1 K. Moreover, for such an effect close to the mobility edge, the temperature-dependent part of the conductivity will be much larger than the temperature-independent part.

For large variations in the conductivity (up to 30% in our experiment) the electron–electron-interaction theories [19] based on first-order corrections are no longer valid. However, even for the small variations in the conductivity at lower fields the temperature dependences are logarithmic as well. The $\log T$ extrapolation of $1/\rho_{xx} \propto 1/\sigma_{xx}$ would yield $\sigma_{xx}(T \to 0)$ tending to zero at zero temperature. In the same way, $\sigma_{zz}(T \to 0)$ extrapolates to zero. With the Hall effect staying constant, the low-temperature extrapolations would correspond to a Hall-insulating state for a 3D system. With this $\log T$ extrapolation not firmly supported by a theoretical model, a direct proof for the existence of such a Hall-insulating state is not given.

5. Conclusions

For bulk InAs and InSb in the extreme quantum limit, a decrease is observed in the transverse magnetoresistance for decreasing temperatures below 2 K together with a temperature-independent Hall resistance. Such a behaviour is totally different from the metal–insulator transition usually observed in doped semiconductors induced by a magnetic field. Extrapolating the $\log T$ dependence in the conductivity for $T \to 0$, would yield a conductivity tensor in 3D with zeros on the diagonal like the tensor in 2D for the quantum Hall effect. A phenomenological estimate shows the importance of electron–electron interaction effects in a disordered system for a possible explanation of the presented data. Experiments at still lower temperatures would be of interest to clear up the possible existence of a Hall-insulator state in metallically doped semiconductors.

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