MAGNETOCOCONDUCTIVITY OF METALLIC InSb IN THE EXTREME QUANTUM LIMIT


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In the extreme quantum limit of the applied magnetic field, the resistivity tensor of n-type InSb has been measured in magnetic fields up to 20 T and temperatures down to 50 mK. For decreasing temperatures below 1 K, the transverse resistivity shows an anomalous decrease with a logarithmic temperature dependence, but the Hall effect is temperature independent. Because of the constant number of electrons, the observed phenomenon is totally different from the usually observed metal-insulator transition induced by a magnetic field.

For metallically doped semiconductors in strong magnetic fields, the extension of the electronic wavefunction at the impurity shrinks and a metal-insulator transition can be induced by the magnetic field (1). Experimentally this magnetic freeze-out of the electrons is observed in an applied magnetic field with a strong increase in all the elements of the resistivity tensor. This increase is more pronounced at lower temperatures. Ignoring the disorder which is inherently present in a doped semiconductor, correlated phenomena for the interacting electron system in a magnetic field (spin-density-wave, charge-density-wave, Wigner crystal) have been predicted (2) with similar effects on the transport properties. Well below the metal-insulator transition, we investigated the magnetoconductivity of doped InSb in magnetic fields in the extreme quantum limit with only one spin-splitted Landau level occupied by the electrons, and observed an anomalous behaviour in the magnetotransport data.

The studied InSb samples were single crystalline with electron concentrations n above $10^{18}$ cm$^{-3}$ (InSb 1: 1.4 $10^{18}$; InSb 2: 5.6 $10^{18}$; InSb 3: 5.4 $10^{18}$). The dimensions of the bulk samples were of the order of 1 mm$^3$ in cross section and 10 mm in length. The various components of the resistivity tensor were measured in a $^3$He/$^4$He dilution refrigerator in fields up to 20 T using phase-sensitive detection techniques.

In Figure 1 we have plotted the transverse ($\rho_{xx}$) and Hall ($\rho_{xy}$) resistivities for InSb 3 as a function of the magnetic field (parallel to the z-axis) at ~ 1 K and 100 mK. The Shubnikov-de Haas oscillations in $\rho_{xx}$ end up in a strong increase of the resistivity above 8 T as a manifestation of the extreme quantum limit. In the extreme quantum limit the measured transverse resistivity decreases with decreasing temperature. The amount of

![Magnetic field dependence of the transverse resistivity $\rho_{xx}$ (a) and Hall resistivity $\rho_{xy}$ (b) for the n-InSb 3 sample at ~ 1 K and ~ 100 mK. The Hall resistivity was independent of temperature.](image)

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temperature dependence in $\rho_{xx}$ increases with increasing magnetic field. The Hall resistivity $\rho_{xy}$ varies approximately linearly with the magnetic field. The structure in $\rho_{xy}$ around 8 T can be ascribed to magnetic quantum oscillations in the Hall effect. The Hall coefficient $R = \rho_{xy}/H$ reveals an oscillatory behaviour similar to the Shubnikov-de Haas effect in the transverse resistivity. The observed temperature dependence of $\rho_{xx}$ and $\rho_{xy}$ in the extreme quantum limit differs from related work on the metal-insulator transition, where both $\rho_{xx}$ and $\rho_{xy}$ increase for decreasing temperatures (3). The constant Hall coefficient can be interpreted as a constant number of electrons without any influence of magnetic freeze-out. The field for magnetic freeze-out to occur can be found from the Mott criterion by comparing the size of the electron wavefunction with the electron density, $n_{\text{e}}/a_{\text{Bohr}}^2 = \delta^3$ with $\delta = 0.3$, $a_{\text{Bohr}} = a_{\text{Bohr}}/n_{\text{e}}(a_{\text{Bohr}}/2)^2$ and $a_{\text{Bohr}} = 2$ (5). The magnetic fields are not sufficiently high to reach the Mott criterion for the investigated samples. In the presented experiments holds $\rho_{xy} > \rho_{xx}$, pointing to a good metallic system where $\rho_{xy}/\rho_{xx} = \omega_{c}/t$ ($\omega_{c}$ is the cyclotron frequency with $t_\text{m}$ the effective mass). However, this condition is not observed in experimental data near the known metal-insulator transition induced by a magnetic-field.

In Figure 2 we have plotted the temperature dependence of the transverse resistivities for the investigated samples at constant magnetic fields in the extreme quantum limit. The resistivity decreases with a logarithmic temperature dependence for temperatures below 2 K. At the magnetic fields indicated in Figure 2, the variation in the Hall resistivity $\rho_{xy}$ was much smaller ($\leq 1\%$). Because $\rho_{xy} \gg \rho_{xx} \gg \rho_{xx}$ in the applied magnetic fields, the conductivity components can be written as $\sigma_{xx} \simeq \rho_{xx}/\rho_{xx}^2$, $\sigma_{xy} \simeq 1/\rho_{xy}$ and $\sigma_{xx} = 1/\rho_{xx}$ with $\sigma_{xx} >> \sigma_{xy} >> \sigma_{xx}$. Hence, the conductivity $\sigma_{xx}$ decreases also with a logarithmic temperature dependence upon cooling down. In a measurement of $\sigma_{xx}$, a similar decrease with logarithmic temperature dependence has been observed.

The observed log-T dependence is difficult to explain with the dimensionality of our bulk samples. In disordered systems a log-T dependence is expected for two-dimensional systems in view of diffusion related quantum phenomena in the transport properties (electron-electron interaction and weak localization). In a three-dimensional system, diffusional transport yields rather a T$^{1/2}$-dependence.

![Figure 2](image_url)

The transverse resistivity $\rho_{xy}(T)$ normalized at $T = 1$ K as a function of the temperature on a logarithmic scale for the different samples in the indicated magnetic fields.

The observed log-T dependence in $\rho_{xx}$ yields $\sigma_{xx} \rightarrow 0$ in the limit $T \rightarrow 0$. This situation describes a Hall insulator in three dimensions, with a conductivity tensor analogously to that of the quantum Hall effect (zeros on the diagonal and constant $\sigma_{xy}$). For the possible occurrence of such a novel state, the importance of the electron-electron interaction in a disordered system (5) in the extreme quantum limit of the magnetic field has been put forward (6). Especially in the extreme quantum limit, electron-electron interaction effects could give a large correction to the conductivity.

REFERENCES