Electron Transport in the Magnetically Induced M-I Transition in InSb

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Measurements of the components of the resistivity tensor of n-InSb in the region of the magnetic field-induced M-I transition are described. On the metal side of the transition the magnetic dependence of $\rho_{xx}/\rho_0$ and $\rho_{zz}/\rho_0$ are in satisfactory agreement with the theory of Roth and Argyres providing the screening theory of Jog and Wallace is used. Measurements close to the transition which were reported in [1] showed that the critical magnetic field which induces the M-I transition is in good agreement with Mott's formula. On the insulator side the temperature dependence of $\rho_{xx}$ and $\rho_{zz}$ is of the form $\rho_0 \exp(\lambda T/T_0)$ with $x = 1/4$ for these heavily doped samples, in contrast to $x = 1/2$ previously observed for lightly doped samples. The possibility that the transition is due to a Wigner crystallisation is discussed but it is concluded that the transition is a Mott type followed on the insulator side by a magnetic freeze-out of the electrons.

1. Introduction

A magnetic field induces a metal-insulator transition in semiconductors with a small energy gap such as InSb and HgCdTe but it is difficult to determine the precise value of the magnetic field $H_{MI}$ which induces the transition. Initial attempts on InSb used Arrhenius plots of the resistivity for various magnetic fields and $H_{MI}$ was chosen as the field when activated behaviour was first observed. Following the lead of the Bell group who investigated the metal-insulator transition by conductivity measurements of a series of samples of varying doping levels and hence of varying donor separations. MANSFIELD, ABDUL-GADER and FOZOONI [1] studied the temperature variation of $\sigma(T)$ in InSb at closely spaced magnetic fields near the transition, which is equivalent to varying the size of donor centres. They found $\sigma(T)$ obeyed the relation used by the Bell group:

$$\sigma(T) = \sigma(0) + AT^\frac{1}{3} + BT. \quad (1)$$

Thus $\sigma(0)$ could be found and the field for which $\sigma(0) = 0$ was determined and identified with $H_{MI}$. The critical field obtained this way was in good agreement with Mott's formula $n^1/2a_B = 0.26$ for the M-I transition using $a_B = (a_1 a_2)^{1/3}$ where $a_1$ and $a_2$ are either the Yafet, Keyes and Adams parameters defining the donor wave function or $a_1 = (hc/\epsilon H)^{1/2} = \lambda$ the magnetic length and $a_2 = a_B/2ln(\pi a_B/\lambda)$ both evaluated at $H_{MI}$. These detailed measurements were made on the resistivity in a longitudinal magnetic field $\rho_{zz}$ since the conductivity can be calculated using the relation $\sigma_{zz} = \rho_{zz}^{-1}$. This is necessarily the case if measurements are made of $\rho_{xx}$ since $\sigma_{xx} = \rho_{xx}^{-1}$.

Finally ROSENBAUM et al. [2] estimated $H_{MI}$ for HgCdTe from measurements of the Hall resistance $\rho_{xy} = -HR$ ($R$ = Hall coefficient). They found a critical
magnetic field where a rapid increase in $p_{xy}$ with $H$ occurred. This critical field increased linearly with temperature and the extrapolated field at $T = 0$ was identified with $H_{Mf}$. The fact that the critical field varied with temperature was attributed to the formation of a Wigner crystal since the melting temperature of such a crystal is a function of the field. The critical field determined from these measurements was found to be a factor of two greater than the expected value for the field to induce a Wigner transition. These results have been criticized by several groups who have suggested that they are not characteristic of the bulk material but are governed by a low resistivity surface layer. An anomalous feature of Fig.1 of ROSENBAUM et al [2] which is not discussed is that $p_{xy}$ appears to be negative below $H_{Mf}$ which corresponds to a positive Hall coefficient.

SHAYEGAN et al [3] have measured $p_{xx}, p_{zz}$ and $p_{xy}$ on both HgCdTe and InSb pointing out that both materials have very low electron effective masses and similar dielectric constants and hence one would expect the localization transition should be similar. Their measurements were confined to temperatures greater than 0.4 K and they confirmed that for both materials there was a critical magnetic field where a rapid increase in $p_{xy}$ with $H$ occurs and that this critical field varies linearly with temperature. The extrapolated field at $T = 0$ was also identified with $H_{Mf}$ and they concluded that the two systems behaved similarly. Recently [4] Impurity cyclotron resonance (ICR) has been observed in HgCdTe where an optically induced transition of a donor bound electron occurs to an excited bound state. This energy separation is slightly greater than that of the related Landau levels which give rise to conduction-band cyclotron resonance (CCR). The ICR absorption is observed to increase and CCR to decrease as the temperature is reduced, showing freeze-out of the electron onto donor centres, and this is confirmed by altering the electron temperature by varying the power level of the far infra-red radiation. An anomalous feature of their results which does not fit any metal-insulator model is that ICR is observed at magnetic fields below that required for the M-I transition where the material should be metallic. It is suggested that even on the metallic side of the M-I transition the delocalized electrons are in donor-band states which are distinct from conduction band states. We suggest that an alternative explanation is that the value of $H_{Mf}$ which could not be determined on the low concentration sample and which had to be estimated by extrapolation of data on samples with a higher concentration might be too large. A check on our results on InSb using low concentration samples shows that there is a discrepancy between $H_{Mf}$ obtained from the rapid rise in $p_{xy}$ and by other methods based on $p_{xx}$ and $p_{zz}$ and this discrepancy increases as the concentration decreases. For example, a rapid rise in $p_{xy}$ in sample 1015 described in TOKUMOTO et al [5] does not occur until 30 kG whereas the M-I transition determined by the Mott formula and from measurements of the $p_{xx}$ and $p_{zz}$ is at 15 kG. This point is discussed in more detail later.

2. Results

The preliminary report in [1] only presented results on $p_{zz}$ on two fairly heavily doped samples of InSb. Measurements taken at the same time on the transverse resistivity $p_{xx}$ and Hall resistivity $p_{xy}$ [6] are presented here, together with a more detailed discussion of the results on either side of the transition.

Figures 1 and 2 show field dependencies of $p_{xx}$, $p_{zz}$ and $p_{xy}$ and Figure 3 gives the temperature dependence of the Hall coefficient of sample 6715. The theoretical field dependencies also shown in Figs. 1 and 2 are of $p_{xx}$ and $p_{zz}$ in the metallic region calculated using the theory of ROTH and ARGYRES [7] for a degenerate semiconductor in the extreme quantum limit in