PHYSICAL REVIEW B VOLUME 32, NUMBER 10 15 NOVEMBER 1985

Magnetic-field-induced localization in InSb and $Hg_{0.79}Cd_{0.21}Te$

M. Shayegan
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

V. J. Goldman and H. D. Drew
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

D. A. Nelson
Honeywell Electro-Optics Division, 2 Forbes Road, Lexington, Massachusetts 02173

P. M. Tedrow
Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 23 July 1985)

Transport measurements on *n*-type InSb are reported which display novel effects similar to those recently reported for $Hg_{0.79}Cd_{0.21}Te$ near the magnetic-field-induced metal-insulator transition. We observe anisotropic temperature dependence of the longitudinal and transverse resistances at low fields, followed by an anomalous behavior of the transverse and Hall resistances below the localization field. The data for the two systems are compared, and the universality of the effects is discussed.

Recent reports[1,2] on the high-field electrical transport phenomena in the narrow band-gap semiconductor *n*-type $Hg_{1-x}Cd_xTe$ ($x \simeq 0.2$) have stimulated interest regarding the nature of the magnetic-field-induced localization in this material. Rosenbaum, Field, Nelson, and Littlewood reported an abrupt rise in the Hall resistance at a characteristic field, and interpreted the linear dependence of this field on temperature T as the evidence for the melting transition of a Wigner crystal.[1] Similar observations were reported by Shayegan, Drew, Nelson, and Tedrow focusing on the anomalous behavior of the Hall resistance in the vicinity of the localization field.[2] It was pointed out that the transport properties just below the localization field were consistent with those of a viscous liquid.[2] Both of these papers therefore conclude that the localization in $Hg_{0.8}Cd_{0.2}Te$ is anomolous in comparison with the magnetic freeze-out picture which has been generally accepted for InSb. On the other hand, the electronic structures of $Hg_{0.8}Cd_{0.2}Te$ and InSb are very similar with regard to the parameters that govern the high-field state of the electrons. The electron effective mass m^*/m is equal to 0.014 (0.007) and the dielectric constant k is equal to 16 (17) for InSb ($Hg_{0.79}Cd_{0.21}Te$). It is surprising, therefore, that the localization transition in these two materials should be qualitatively different. In this Rapid Communication we address this question by reporting new magnetotransport measurements on InSb and $Hg_{0.79}Cd_{0.21}Te$ and conclude that the behavior of the two systems is essentially the same, except in fields much larger than the localization field. A possible explanation for this discrepancy at high fields is given.

We studied an *n*-type InSb sample[3] with a carrier concentration (determined from low-field Hall data) of $n_0 = 2.2\times10^{15}$ cm^{-3} and a Hall mobility of 24 $m^2/V\,s$ (at 77 K). This mobility is about four times higher than that for the sample with similar concentration studied by Ishida and Otsuka.[4] Comparing the mobility of our sample with those of Ref. 4, we estimate the compensation (the ratio of the density of acceptors to that of the donors) to be small (≤ 0.1). This is similar to the compensation estimated from the mobility data for our $Hg_{0.79}Cd_{0.21}Te$ samples.[2,5] The InSb and $Hg_{0.79}Cd_{0.2}Te$ samples were cut into rectangular plates and leads were soldered with indium. The samples were then etched in a bromine (5%)–methanol (95%) solution before mounting in the cryostat. The Hall and resistance measurements were made using the dc technique. The currents used were sufficiently small to ensure that nonlinear effects due to heating or large electric fields did not interfere with the measurement.

In Fig. 1 log-log plots of the longitudinal ρ_l, transverse ρ_t, and Hall ρ_H resistivities versus magnetic field are shown for InSb. For comparison, in Fig. 2 we show similar data on a $Hg_{0.79}Cd_{0.21}Te$ sample with $n_0 = 2.7\times10^{14}$ cm^{-3}. The InSb data in Fig. 1 show that, similar to $Hg_{0.79}Cd_{0.21}Te$ (Fig. 2, and also Figs. 1 and 2 of Ref. 2), ρ_l becomes temperature dependent at a field B_l which is considerably below B_t at which ρ_t shows any temperature dependence. The field B_l is of the same order as the extreme quantum-limit field above which only one magnetic subband is occupied.[2] The Hall data (ρ_H) in Fig. 1 show a "Hall dip" similar to that observed in $Hg_{0.79}Cd_{0.21}Te$ (Ref. 2 and Fig. 2). For temperatures below a characteristic temperature T_c ($T_c \simeq 1.6$ K for the InSb sample studied), ρ_H is independent of temperature up to the vicinity of a field B_H^0 above which ρ_H rises abruptly (the definition of B_H^0 is given below). As the temperature is raised above T_c, the "Hall dip" gradually disappears and the Hall resistivity rises to a high-temperature value consistent with the low-field carrier concentration. Above B_H^0, all three resistivities ρ_l, ρ_t, and ρ_H increase strongly with increasing field or decreasing temperature. This temperature dependence is discussed below.

In their study of $Hg_{0.76}Cd_{0.24}Te$, Rosenbaum *et al.*,[1] recently reported a linear dependence of ρ_H on field in the

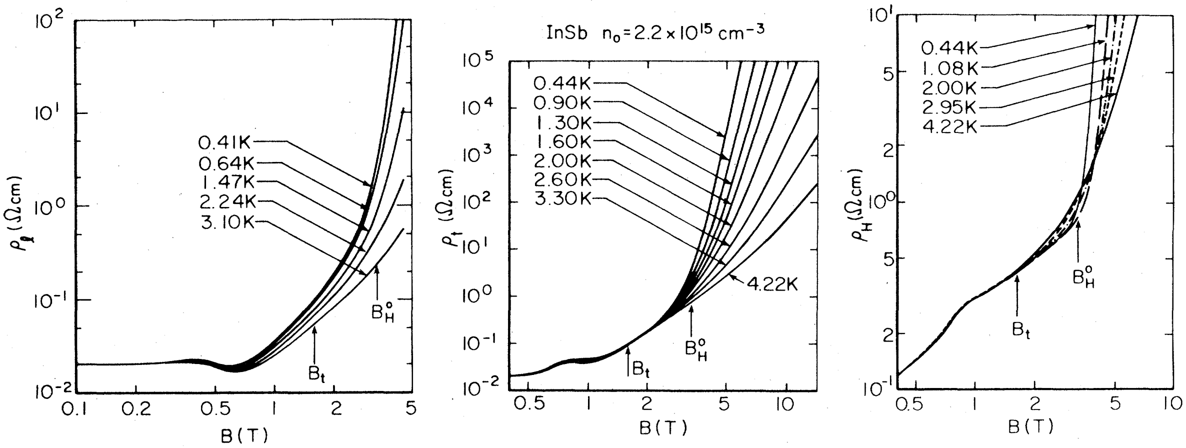

FIG. 1. The longitudinal ρ_l, transverse ρ_t, and Hall ρ_H resistivities of the *n*-type InSb sample are shown for the indicated temperatures as a function of the magnetic field *B*. The vertical arrows indicate the fields above which the different resistivities become temperature dependent (see text).

range $B > B_H^0$. In Fig. 3 we show plots of ρ_H vs B (linear scales) for two samples of $Hg_{0.79}Cd_{0.21}Te$ ($n_0 = 2.7\times10^{14}$ and 1.2×10^{15} cm^{-3}) and the InSb sample.[6] We note that in a limited field range above B_H^0, ρ_H does depend linearly on B. In Ref. 1, a temperature-dependent critical field was defined as the intercept of the linear extrapolation of ρ_H vs B with the field axis. A more suitable definition for the field $B_H(T)$ at given T is the intercept of the linear extrapolations of ρ_H below and above the abrupt rise in ρ_H. Plots of $B_H(T)$ vs T are shown in the insets to Fig. 3. We note a linear dependence of $B_H(T)$ on T similar to that reported in Ref. 1, where the linear $B_H(T)$ was observed down to very low temperatures ($T \simeq 10$ mK). The fields B_H^0 in Figs. 1 and 2 and also in Ref. 2 are the extrapolations of the $B_H(T)$ line to $T=0$ (see insets to Fig. 3).

It is evident from Figs. 1, 2, and 3 that InSb and $Hg_{0.79}Cd_{0.21}Te$ behave similarly. In order to make a quantitative comparison between the two systems, we consider the Mott metal-insulator transition criterion:[4,7,8]

$$n_0 a_\perp^2 a_\parallel = \delta^3 , \tag{1}$$

where $a_\perp$ and $a_\parallel$ approximate the values of the Bohr radius perpendicular and parallel to the applied field and δ is a con-

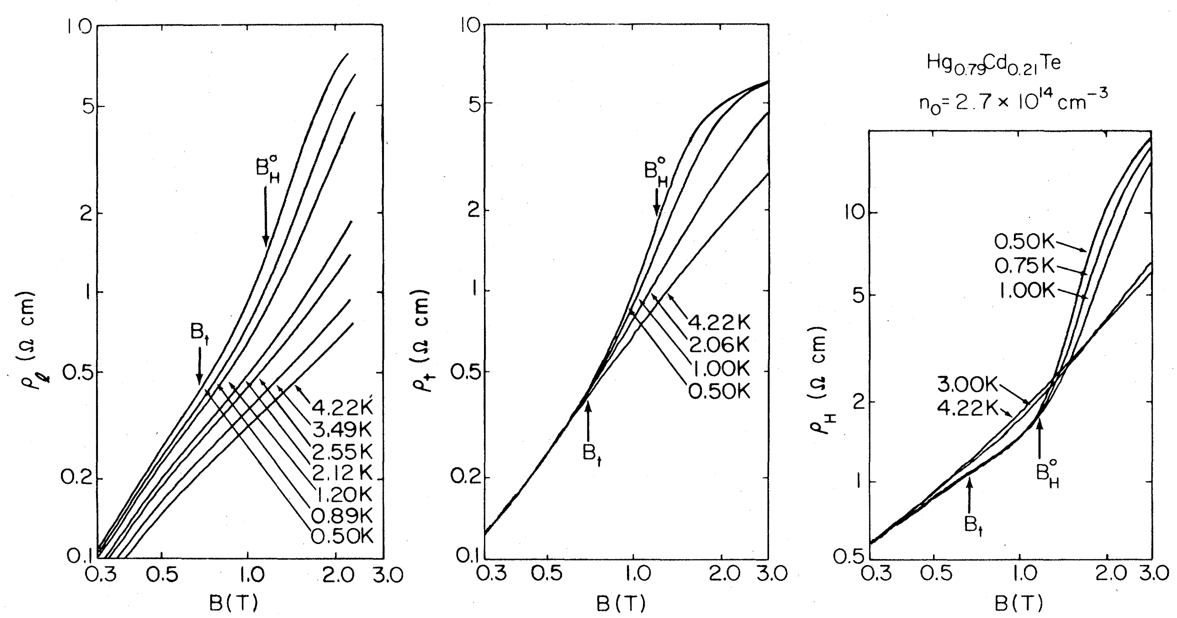

FIG. 2. The ρ_l, ρ_t, and ρ_H data are shown for an *n*-type $Hg_{0.79}Cd_{0.21}Te$ sample. The anisotropic temperature dependence of ρ_l and ρ_t and the "Hall dip" in ρ_H in the range $B < B_H^0$ are similar to the InSb data (Fig. 1). On the other hand, the weak field and temperature dependences of the resistivities at low temperatures and high fields (above B_H^0) observed in this figure are in contrast to the InSb data (Fig. 1).

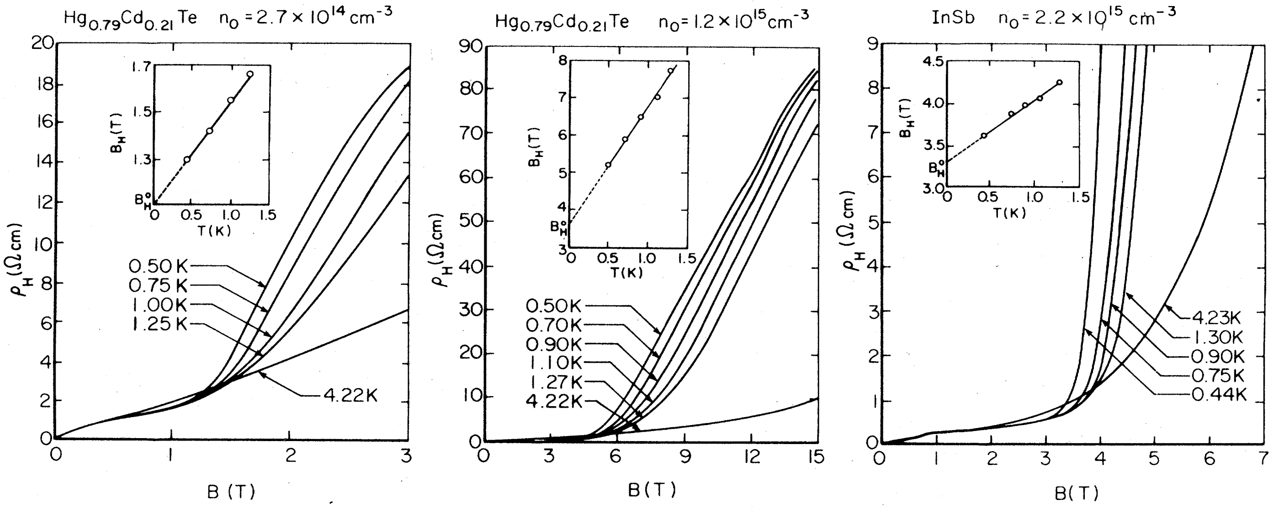

FIG. 3. The Hall resistivity ρ_H vs magnetic field is shown on linear scales for $Hg_{0.79}Cd_{0.21}Te$ and InSb. In both systems, at low temperatures and in the field range just above the localization field, ρ_H increases with field approximately linearly. The insets to the figures are plots of the fields B_H, defined as the intercepts of the linear extrapolations of ρ_H in the field range below and above the abrupt rise in ρ_H.

stant. Using the variational parameters of Yafet, Keyes, and Adams[9] for $a_\perp$ and $a_\parallel$, and our experimental fields B_H^0, we find that $\delta = 0.22$ for InSb and 0.21 ± 0.02 for the $Hg_{0.79}Cd_{0.21}Te$ samples that we have studied. These values of δ are in fair agreement with previously reported $\delta \simeq 0.26$ for the field-induced localization in InSb.[4,10]

For InSb, at fields greater than B_H^0, plots of $\ln\rho_l$ (or $\ln\rho_t$) vs T^{-1} show activated behavior for $1.6 \lesssim T \lesssim 4.2$ K with an activation energy E_A which increases with field. This is consistent with the well-known magnetic freeze-out effect in InSb.[4,11] For $T \lesssim 1.6$ K, ρ_l and ρ_t show a weaker dependence on $T (\ln\rho_l$ or $\ln\rho_t \sim T^{-m}$ with $m \simeq 0.3)$. These observations are consistent with previously reported results on InSb (Ref. 11), where the temperature dependences were interpreted in terms of variable range hopping conduction models. Below B_H^0, plots of $\ln\rho_l$ or $\ln\rho_t$ vs T^{-1} do not produce a straight line. Both ρ_l and ρ_t show increasingly weaker dependence on temperature as T is decreased. In the same field range, the Hall data exhibit a dip. We have associated this anomalous behavior to a highly correlated state of electron Fermi liquid[2] and will discuss the details of the temperature dependences of ρ_l, ρ_t, and ρ_H in this field range in a forthcoming publication. The anisotropic temperature dependence of ρ_l and ρ_t for $B < B_t$ is also a novel effect, and we have interpreted it in terms of pseudo-one-dimensional localization of the carriers in the extreme quantum limit.[2]

The observations described in the preceding paragraph are also valid for $Hg_{0.79}Cd_{0.21}Te$, except for the behavior of $\ln\rho_l$ (or $\ln\rho_t$) vs T^{-1} at fields well above B_H^0. In this high-field range, the temperature dependences are much weaker than expected from the magnetic freeze-out picture and an activated hopping model. This diverging behavior at high fields is especially surprising because in this field range it is expected that the electron's Coulomb interaction with the ionized impurities dominates, resulting in the magnetic freeze-out of the carriers as observed in InSb. We wish to emphasize in this Rapid Communication that one must be cautious when interpreting the high-field transport data in HgCdTe. Stadler, Nimtz, Schlicht, and Remenyi have discussed in a recent report,[12] that surfaces of n-type HgCdTe may be accumulated. Such surfaces can drastically alter and dominate the high-field transport measurements. For example, the data for the $Hg_{0.79}Cd_{0.21}Te$ sample in Fig. 2 show that the dependence of ρ on B becomes anomalously weak at large fields and low temperatures. Also, in Fig. 3, the Hall data for the $Hg_{0.79}Cd_{0.21}Te$ sample with $n_0 = 1.2 \times 10^{15}$ cm^{-3} (center figure) show weak oscillations (periodic in B^{-1}) at large fields and low temperatures. From our measurements, we have found that careful preparation and etching of the samples prior to the measurements is important. However, in our study of over a dozen samples, we have not yet been able to entirely eliminate the surface problem at high fields. We will discuss our results more fully in a future publication.

In summary, the magnetotransport data presented here for InSb and $Hg_{0.79}Cd_{0.21}Te$ indicate that the two systems behave similarly. Anisotropic temperature dependence of the longitudinal and transverse resistivities is observed at low fields, followed by an intermediate field range where the transport properties are dominated by correlation effects. An anomalous "Hall dip" is observed in this range. Finally, above a temperature-dependent field $B_H(T)$, localization of the carriers is observed. The temperature dependence of B_H was interpreted by Rosenbaum *et al.*[1] as the melting of a Wigner crystal. A temperature-dependent field B_H, however, may be explained by considering the screening effects on the magnetic-field-induced metal-insulator transition.[2,13] At fields well above $B_H(T)$ and at low temperatures, the InSb data can be understood in terms of the magnetic freeze-out and hopping conduction model, while the HgCdTe data show an anomalously weak dependence on temperature and field which, we believe, is due to the shorting by a surface layer. We are presently looking for spectroscopic evidence for donor levels in $Hg_{0.8}Cd_{0.2}Te$ at high fields which, to our knowledge, have never been reported.

Note added in proof. We have observed impurity cyclotron resonance[14] in $Hg_{1-x}Cd_xTe$ ($x \simeq 0.2$) samples with carrier density $n_0 \sim 5\times10^{13}$ cm^{-3}. This experiment gives direct evidence for a shallow donor-bound ground state in this material at magnetic fields above the metal-insulator transition.[15]

Part of this work was performed while some of the authors (M.S., V.J.G., and H.D.D.) were guest scientists at the Francis Bitter National Magnet Laboratory, which is supported at MIT by the National Science Foundation. We thank L. Rubin and B. Brandt and the Staff of the National Magnet Laboratory for technical assistance. Work supported in part by the National Science Foundation under Grant No. DMR-80-25617 and the U.S. Department of Energy under Contract No. DE-FG05-84ER45071.

[1]T. F. Rosenbaum, S. B. Field, D. A. Nelson, and P. B. Littlewood, Phys. Rev. Lett. **54**, 241 (1985).

[2]M. Shayegan, H. D. Drew, D. A. Nelson, and P. M. Tedrow, Phys. Rev. B **31**, 6123 (1985).

[3]Purchased from Cominco Ltd., Trail, British Columbia, Canada.

[4]S. Ishida and E. Otsuka, J. Phys. Soc. Jpn. **42**, 542 (1977); **43**, 124 (1977); **46**, 1207 (1979).

[5]M. Shayegan, V. J. Goldman, H. D. Drew, D. A. Nelson, and P. M. Tedrow (unpublished).

[6]Log-log plots of ρ_l, ρ_t, and ρ_H up to $B = 8$ T for the sample with $n_0 = 1.2\times10^{15}$ cm^{-3} were reported in Ref. 2.

[7]M. Pepper, J. Non-Cryst. Solids **32**, 161 (1979).

[8]B. I. Shklovskii and A. L. Efros, *Electronic Properties of Doped Semiconductors* (Springer-Verlag, Berlin, 1984).

[9]Y. Yafet, R. W. Keyes, and E. N. Adams, J. Phys. Chem. Solids **1**, 137 (1956).

[10]In comparing our results with those of Ishida and Otsuka (Ref. 4), we note that although they also use the parameters $a_\perp$ and $a_\parallel$ as given by Yafet *et al.* (Ref. 9), their definition of the localization field is different from ours. Using our definition for B_H and their Hall data (Fig. 3 of the second report in Ref. 4), we obtain essentially the same value for $\delta(\simeq 0.22)$ as in our sample.

[11]H. Tokumoto, R. Mansfield, and M. J. Lea, Philos. Mag. B **46**, 93 (1982).

[12]J. P. Stadler, G. Nimtz, B. Schlicht, and G. Remenyi, Solid State Commun. **52**, 67 (1984).

[13]E. W. Fenton and R. R. Haering, Phys. Rev. **159**, 593 (1967).

[14]V. J. Goldman, H. D. Drew, M. Shayegan, and D. A. Nelson (unpublished).

[15]Impurity cyclotron resonance has been studied extensively in InSb. See, for example, T. Murotani and Y. Nisida, J. Phys. Soc. Jpn. **32**, 986 (1972).