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Possibility of a metal-insulator transition at the Mott critical field in InSb and $Hg_{1-x}Cd_xTe$

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The rapid increase in the magnetoresistance that occurs near the Mott critical field in $Hg_{1-x}Cd_xTe$ and InSb has been reexamined using a simple picture of magnetic freeze-out on shallow, hydrogenic donors. The results indicate that the Mott critical field, as defined in the literature, does not mark the boundary between a metallic state and an insulating state.

Low-temperature, high-magnetic-field transport studies of the narrow-gap semiconductors $Hg_{1-x}Cd_xTe$ and InSb show a dramatic and rather abrupt increase in the resistivities ρ_{xx}, ρ_{xy}, and ρ_{zz} with increasing magnetic field. This effect, which is generally called *field-induced localization* or a *metal-insulator transition* (MIT), has received much recent attention,[1,2] especially in $Hg_{1-x}Cd_xTe$ since it has been attributed to Wigner crystallization[2-4] of the conduction electrons. Goldman *et al.*[5] have observed cyclotron resonance of impurity bound electrons in $Hg_{1-x}Cd_xTe$ and they have suggested that the MIT cannot be due to Wigner crystallization since the electron-impurity interaction is significant at high magnetic fields. The group of Shayegan, Goldman, and Drew[1,5-9] (SGD) have stressed the similarities in the transport and optical properties of InSb and $Hg_{1-x}Cd_xTe$, and they have proposed a Mott-Anderson type MIT in the impurity band of these narrow-gap semiconductor systems. On the other hand, Rosenbaum and co-workers[2,4] have argued that the electron-electron (e^--e^-) interaction is comparable in strength to the electron-impurity (e^--i) interaction so that strong correlation effects would be expected in these systems. Rosenbaum *et al.* account for these competing forces by proposing a Wigner "polycrystal" as the high-magnetic-field ground state for the electronic system in $Hg_{1-x}Cd_xTe$.[2,4]

These previous studies of field-induced localization have examined the behavior of the critical magnetic field, B_{MI}, which separates a metallic state from an insulating state.[1,2,4,5-11] As Rosenbaum *et al.* assume a finite-temperature, field-induced, liquid-solid phase transition, they plot the temperature dependence of the critical field or the *melting curve* for the phase transition.[2,4] On the other hand, SGD expect a zero-temperature Mott-Anderson phase transition in a *metallic impurity band.* Thus, they extrapolate the finite-temperature B_{MI} to $T=0$ K and show that the resulting critical field $B_{MI}(T=0)$ satisfies the Mott criterion, implying a Mott-Anderson transition.[1,5-9,11] Both these groups define B_{MI} as the value of B above which ρ_{xy} "abruptly" increases.

We have been puzzled by these contradictory claims[1,2] especially since these groups have similar samples and data. Thus, we have investigated low-temperature ($T > 0.5$ K), high-field ($B < 7$ T) transport in high quality $Hg_{1-x}Cd_xTe$ and InSb crystals. We have found that our experimental results can be adequately described by magnetic freezeout. We have also reexamined some previously published data[1,2] for these systems using our picture and we have found no evidence for critical behavior in the vicinity of the critical field specified in those works. Thus, we suggest that there is no evidence for a low-temperature ($T<2$ K), high-field, solid electronic phase as suggested by Rosenbaum *et al.*[2] Also, we see no evidence for a Mott-Anderson transition in a *metallic impurity band* as proposed by SGD (Ref. 1) for these narrow-gap systems.

These transport studies were carried out on standard Hall bars oriented in the transverse configuration ($I \perp B$). Four terminal resistance R and the Hall effect were measured with a constant dc current I applied to the sample and ohmic behavior was verified at the highest field for the applied current. The samples were mounted on the cold finger of a He^3 refrigerator and the data were collected with a computer. Our $Hg_{1-x}Cd_xTe$ ($x=0.206$) sample is comparable in quality to the samples used by SGD (Ref. 1) and Rosenbaum *et al.*[2] in their studies. The high quality of the $Hg_{1-x}Cd_xTe$ is reflected in our observation of magnetophonon oscillations to $T \sim 250$ K.[12] Hall-effect and low-temperature Shubnikov–de Haas measurements indicated that the electron density n and the Hall mobility μ were roughly temperature independent for $T<77$ K: $n=1.1\times10^{15}$ cm^{-3} and $\mu=300000$ cm^2/Vs. The neutron activated InSb sample used in our study was grown at Cominco. At $T=4.2$ K, the electron density $n=5\times10^{14}$ cm^{-3} obtained from the Shubnikov–de Haas period agreed with Hall-effect measurements to within 10%. The Hall mobility $\mu=125000$ cm^2/Vs at $T=4.2$ K. The observation of Shubnikov–de Haas oscillations in these samples indicates a degenerate electron gas in the absence of a field at the lowest temperatures.

In Fig. 1, we have plotted the resistivity ρ_{xx} vs B for our InSb sample. We have evaluated the critical field, B_{MI}, from the Mott criterion, $n(a_\perp^*)^2 a_\parallel = \delta^3$, using $\delta=0.34$ as specified by SGD.[1] Here, $a_\perp=(\hbar/eB)^{1/2}$ ($a_\parallel = a_B/[2\ln(a_\perp/a_B)]$) are approximately the transverse (longitudinal) extension of the donor bound electronic wave function in the presence of magnetic field and $a_B=\hbar/m^*e^2$ is the zero-field Bohr radius. From the criterion, we obtain $B_{MI}\sim 11$ kOe, which appears to be consistent with the dramatic enhancement of the positive magnetoresistance with decreasing temperatures around $B\sim 11$ kOe. Thus, the transport properties of our sample are similar to the results reported by SGD.[1]

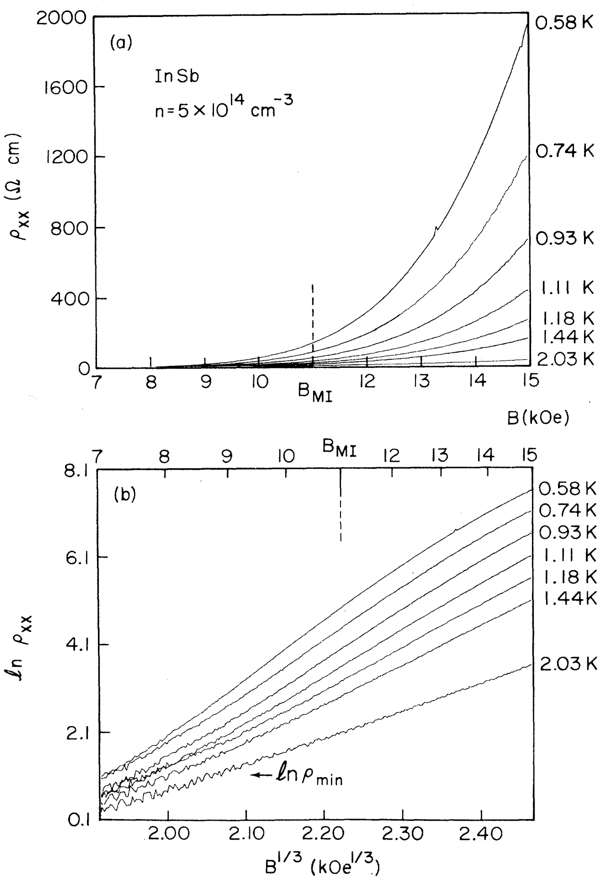

FIG. 1. (a) The magnetoresistivity ρ_{xx} is plotted vs the field B for InSb. $B_{\rm MI}$ denotes the Mott critical field as defined in Ref. 1. (b) The data is replotted in terms of the natural variables, $\ln(\rho_{xx})$ vs $B^{1/3}$. The resulting figure shows no hint of critical behavior at $B_{\rm MI}$. The figure also shows $\rho_{\rm min}=\sigma_{\rm min}^{-1}$, where $\sigma_{\rm min}$ is the minimum metallic conductivity.

Now, we reinterpret these data using a simple picture of magnetic freezeout of conduction-band electrons onto shallow hydrogenic donors.[13] Thus, the magnetoresistivity $\rho_{xx}(B)$ is approximately given by $\rho_{xx}(B)\cong[\sigma_0(B)]^{-1}$ where $\sigma_0(B)=n(B)e\mu$. Here, $n(B)$ is the field-dependent, free-electron density which varies smoothly with the magnetic field. Over the range of fields where magnetic freezeout occurs, we expect the density to vary as $n(B)=n_0(B)\exp(-E_A/2k_BT)$ where $n_0(B)$ is a weakly increasing function of the magnetic field which reflects the increasing degeneracy of the conduction-band Landau-level. The activation energy E_A is the hydrogenic binding energy of the shallow donor in the presence of a magnetic field which for $B=0$ reduces to $E_A=-e^2/2a_B$. As a variational solution for the hydrogen atom in the strong magnetic field limit requires a numerical solution of a set of coupled, nonlinear equations,[14] we approximate the binding energy by $E_A(B)=-e^2/2a_B(B)$ where $a_B(B)$ is the effective Bohr radius in the presence of a magnetic field. For magnetic fields such that $a_B(B=0)>\lambda$, $\lambda=(\hbar/eB)^{1/2}$, we use the approximation $a_B(B)=(a_\perp^2 a_B)^{1/3}$ with $a_\perp=\lambda$ and $a_B=\hbar^2/m^*e^2$. Then, the field dependence of the binding energy is $|E_A|=(e^2/2a_B)\gamma^{1/3}$ where $\gamma=\hbar\omega/2E_A(0)\sim B$. For comparison, we note that our approximation for the field dependence of the binding energy, $|E_A(B)|=e^2/2a_B\gamma^{1/3}$, agrees within 30% with the variational solution of Yafet, Keyes, and Adams[14] which also shows linear variation versus $\gamma^{1/3}$ and can be described by our empirical expression $|E_A(B)|=1.5(e^2/2a_B)\gamma^{1/3}$ for $1<\gamma<350$. Thus, magnetic freezeout predicts that the resistance would increase with the magnetic field as $R\sim\rho_{xx}=\rho_{xx}(B)\exp[(aB^{1/3}/k_BT)]$. To test this prediction, we replot the data in terms of the approximate natural variables, i.e., $\ln(\rho_{xx})$ vs $B^{1/3}$, in Fig. 1(b). We point out that the abrupt increase of ρ_{xx} seen in Fig. 1(a) has vanished in this new picture and the curves show smooth behavior in the vicinity of the critical field, $B_{\rm MI}=11$ kOe, even at the lowest temperatures, $T=0.58$ K. A plot of $d(\ln\rho_{xx})/dB^{1/3}$, evaluated at $B=B_{\rm MI}$, vs $1/T$ showed linear behavior as predicted by this picture and the zero-field Rydberg extracted from these curves, $E_A(B=0)=0.3\pm0.1$ meV, is consistent with results reported in the literature.[13] For comparison, Fig. 1(b) also indicates $\ln(\rho_{\rm min})$, where $\rho_{\rm min}=(\sigma_{\rm min})^{-1}$ and $\sigma_{\rm min}$ is the minimum metallic conductivity.

We have also reexamined the data of SGD (Ref. 1) in order to determine if critical behavior associated with a metal-insulator transition at the Mott critical field is observable only at lower temperatures which are inaccessible in our laboratory. Thus, in Fig. 2, we reproduce the results of Ref. 1 for an InSb sample, $n=2.2\times10^{15}$ cm^{-3}, which shows a dramatic increase in ρ_{xx} near $B=30$ kOe. Using two methods, SGD have measured the critical field to be $B_{\rm MI}=33$ kOe ($\pm10\%$) and obtained good agreement with the Mott criterion for $\delta=0.34$.[1] In Fig. 2(b), we have replotted their data in terms of the natural variables, i.e., $\ln(\rho_{xx})$ vs $B^{1/3}$. Again the dramatic increase of ρ_{xx} seen in the vicinity of $B_{\rm MI}$ in Fig. 2(a) has disappeared in this new plot and the data show no hint of critical behavior in the vicinity of $B_{\rm MI}=33\pm3$ kOe. The linearity of these curves indicates that magnetic freezeout adequately describes the data to $T=0.08$ K.

We now turn our attention to the $Hg_{1-x}Cd_xTe$ system where there have been reports of Wigner crystallization.[2-4] Our $Hg_{1-x}Cd_xTe$ sample $x=0.206$ originated from the same wafer as sample "B" in Ref. 1 of SGD. We point out that sample "B" in Ref. 1 was characterized by $n(T=77\text{ K})=1.2\times10^{15}$ cm^{-3} which is comparable to the carrier density of our sample, $n(77\text{ K})=1.1\times10^{15}$ cm^{-3}. We also note that SGD have measured $B_{\rm MI}$ for their sample "B" to be $B_{\rm MI}=36$ kOe. We obtain similar values for $B_{\rm MI}$ using the Mott criterion, $B_{\rm MI}=36$ kOe, with $\delta=0.31$ for $Hg_{1-x}Cd_xTe$ as specified in Ref. 1. In Fig. 3, we plot ρ_{xx} vs B for our sample. Note the dramatic increase in the resistance that occurs around $B\sim36$ kOe in agreement with the reported values for $B_{\rm MI}$ by SGD.[1] In Fig. 3(b), we have replotted the data in terms of the natural variables, i.e., $\ln(\rho_{xx})$ vs $B^{1/3}$. Again, these curves show smooth variation in the vicinity of the Mott critical field $B_{\rm MI}$ with no indication of critical behavior. The slopes of these curves, $d\ln\rho_{xx}/dB^{1/3}$, evaluated at $B=B_{\rm MI}$, also showed linear variation versus $1/T$ as predicted by our

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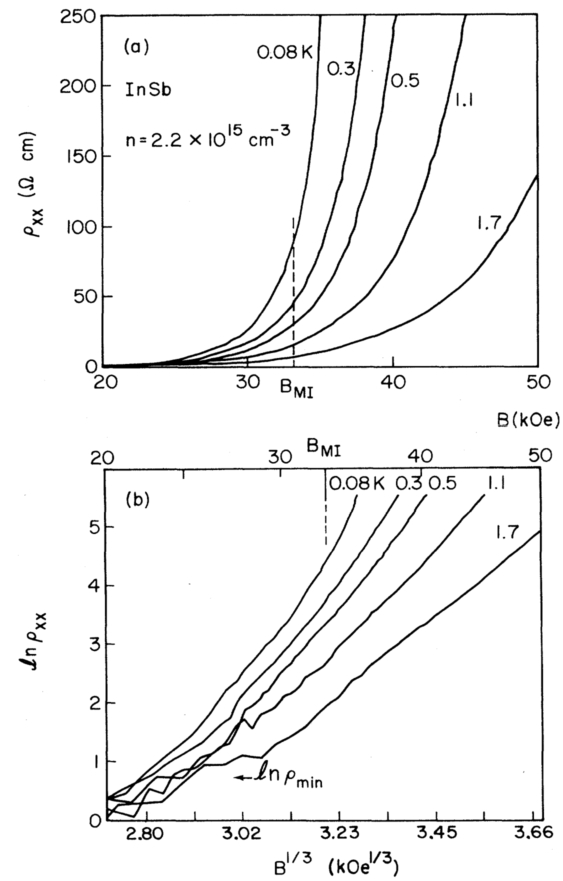

FIG. 2. (a) The data of Ref. 1 for InSb (2.2×10^{15} cm^{-3}) is reexamined as in Fig. 1. (b) The linearity of the curves indicates that magnetic freezeout adequately describes the data to $T=0.08$ K.

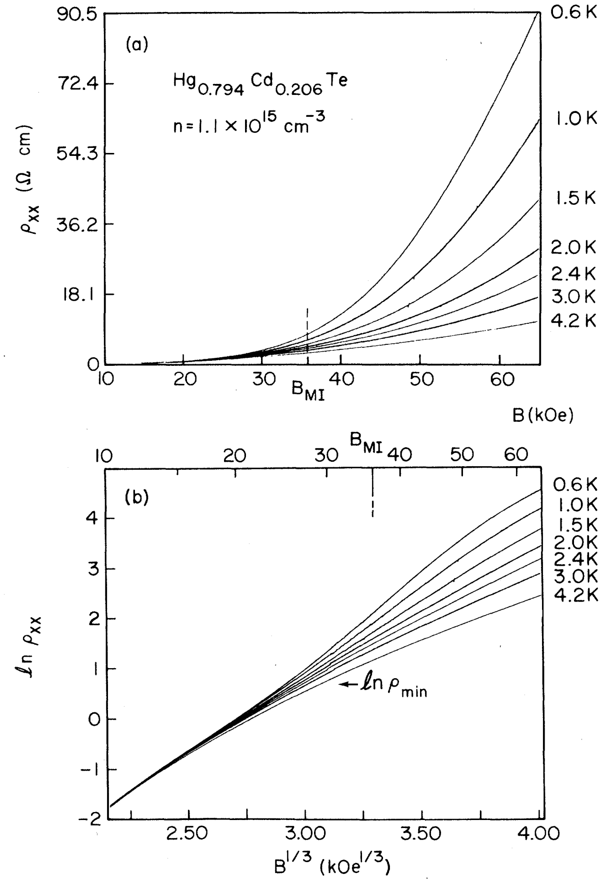

FIG. 3. (a) A standard plot of ρ_{xx} vs B for $Hg_{1-x}Cd_xTe$. (b) When the data is replotted as $\ln(\rho_{xx})$ vs $B^{1/3}$, the apparent critical field B_{MI} for the metal-insulator transition loses its significance.

picture and we have found that $E_A(B=0)=0.08\pm0.03$ meV for $Hg_{1-x}Cd_xTe$.

Although these results indicate that magnetic freezeout adequately describes the data over a wide range of fields including the Mott critical field,[1] the observation of low-field Shubnikov–de Haas oscillations in these samples implies a degenerate electron gas at fields below the quantum limit which cannot be understood in the simple freezeout picture. In the simple freezeout picture, free electrons are thermally activated into the conduction band from a discrete, sharp donor level. The application of a field enhances the donor binding energy and results in a decrease of the free-electron density, i.e., magnetic freezeout. This picture predicts a nondegenerate electron gas with $\sigma\rightarrow0$ as $T\rightarrow0$ even in the absence of a magnetic field.

The relatively small donor binding energy in InSb and $Hg_{1-x}Cd_xTe$ suggests that spatial fluctuations of the conduction-band edge and the donor level due to doping, defect, and alloy inhomogeneities can result in donor levels lying above the conduction-band edge in spatially separated regions, i.e., the disorder broadened impurity band overlaps the conduction band. Then, it is possible to obtain degeneracy as electrons abandon high-energy donor states in a given region in favor of lower-energy conduction-band states elsewhere. The application of a magnetic field results in a uniform increase of the donor binding energy throughout the sample and electrons return to the donors as the donor states become energetically favorable compared to the conduction-band states. At sufficiently high fields such that the disorder broadened donor band falls below the conduction band mobility edge, we expect these samples to be nondegenerate and the transport results to be well described by classical freezeout. In this picture, a $T=0$ K field induced MIT occurs at the value of field for which the donor band separates from the conduction band. However, the critical field for this freezeout induced MIT depends upon the broadening of the donor band which is a complicated function of the doping, defect, and alloy inhomogeneities and also the compensation. As these effects are difficult to predict from simple considerations, we do not expect the Mott criterion[1] to correctly predict the critical field in real samples. Finally, our picture implies a nonmetallic impurity band, in contrast to the model of SGD,[1] since the donor states would tend to be Anderson localized by the disorder.

In summary, we have shown that the experimental data for InSb and $Hg_{1-x}Cd_xTe$ can be adequately described within a simple picture of magnetic freezeout of conduction-band electrons throughout the field range in the vicinity of the reported critical fields for the MIT. As there is no hint of a phase boundary in our plots of the data in terms of the natural variables, we suggest that there is no finite temperature phase transition between a liquid and a solid electronic phase as proposed by Rosenbaum and co-workers.[2,4] Rosenbaum *et al.* have argued that e^--e^- interaction effects cannot be neglected in $Hg_{1-x}Cd_xTe$ since it is comparable in magnitude to the e^--i interaction. We point out, however, that the application of a magnetic field results in a progressive strengthening of the e^--i interaction relative to the e^--e^- interaction so that freezeout effects dominate at high fields. SGD have argued that the observation of impurity cyclotron resonance (ICR) at fields *below the Mott critical field,* along with their successful modeling of the "Hall dip" in terms of percolating metallic states in the impurity band implies a Mott-Anderson-type MIT in a *metallic impurity band.*[1] However, our analysis shows that their transport data are consistent with magnetic freezeout, which implies metallic conduction in the conduction band. Finally, the Mott criterion, as defined by SGD,[1] overestimates the critical field in these narrow-gap systems.

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