Magnetoresistive determination of localization effects in InSb

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(Received 5 November 1982)

We have made magnetoresistance measurements in samples of n-InSb in the temperature range 0.05–1.5 K. The carrier densities of the samples studied were $\sim 3.1\times10^{14}$ and $2.7\times10^{13}/\text{cm}^3$. At low fields ($<50$ G) the negative magnetoresistance is interpreted as being due to orbital effects, and a detailed comparison with theory is made. The strength of the observed effects with applied field H is 0.55 of that expected from theory. Interaction effects could explain the discrepancy. The inelastic scattering localization rate is determined to vary as T^3.

Stimulated by the scaling theory of localization by Abrahams, Anderson, Licciardello, and Ramakrishnan,[1] electron transport in many experimental systems of different dimensionality have been studied.[2] Parallel to this single-particle description of localization, Altshuler and Aronov[3] have shown that many-body Coulomb effects cannot be ignored and give rise to unexpected temperature and magnetic field dependences at low temperatures. In two dimensions, it has been demonstrated[2,4] that the localization and correlation effects can be differentiated by low-temperature magnetoresistance measurements in fields parallel and perpendicular to the sheet. It was argued that, because the localization effects are orbital in nature, they depend on field orientation while the correlation effects are isotropic in H.

Both effects have been shown to contribute to the transport properties at low temperatures and a combination of tunneling as well as magneto- and temperature-dependent resistance measurements have demonstrated[2] the various contributions. In addition, two-dimensional (2D) magnetoresistance measurements have yielded determinations of the inelastic scattering rate τ_i^{-1} and allowed critical comparisons[4–6] with theory.[7]

In three dimensions the separation of the various contributions to the transport is not so straightforward. The anisotropy utilized in the magnetoresistance in two dimensions to distinguish the effects does not carry over. Several groups[8–16] have investigated different systems via transport and tunneling and there is clear evidence that near the critical point for the metal-insulator transition the behavior is strongly modified by Coulomb interaction effects. It has been demonstrated that in the semiconductor systems Si:P, Ge:Sb, and InSb, as well as the disordered Au-Ge, granular Al and Si:Nb, that both localization and Coulomb interaction effects are present. In this paper, we report high-sensitivity magnetoresistance measurements on high-mobility samples of InSb at rather low temperatures and fields. These measurements show that orbital effects attributed to localization are also present in an analogous way to those seen in two-dimensional systems.[4–6] From careful H and T dependences below 1 K of the magnetoresistance and a quantitative fit to the theory of Kawabata,[17] it is shown that the strength of these localization effects is of the correct order of magnitude (but smaller by about a factor of 2) as predicted. The discrepancy is probably due to correlation effects. In addition, the measurements show that the inelastic scattering rate $(\tau_i^{-1})\propto T^3$.

Following the 2D work of Hikami *et al.*,[18] Kawabata[17] extended these ideas to three dimensions and showed that a negative magnetoresistance is also expected in this case. He showed that, independent of field direction, the correction to the conductivity is given by

$$\Delta\sigma(H,T)=\sigma(H,T)-\sigma(O,T)=\frac{\alpha e^2}{2\pi^2\hbar l}\sum_{N=0}^{\infty}\left[2[(N+1+\delta)^{1/2}-(N+\delta)^{1/2}]-\frac{1}{(N+1/2+\delta)^{1/2}}\right], \quad (1)$$

where $l=(c\hbar/eH)^{1/2}$ and $\delta=3l^2/4\lambda_e\lambda_i$.

λ_e is the mean free path for elastic collisions and λ_i that for inelastic processes. At low temperatures, generally $\lambda_i \gg \lambda_e$, and it is the elastic processes which determine the resistivity. The field dependence is observed when the lowest Landau orbit becomes comparable in size to the distance an electron diffuses before an inelastic scattering process. We have added the parameter α to Kawabata's original expression as we have found it necessary to adjust the amplitude of the correction as will be discussed later.

This expression is valid in the limit where $\lambda_e \ll l$ and $k_F\lambda_e>1$ (the weak localization regime). Because it is an orbital effect with influence when the orbit size becomes comparable to $\sqrt{\lambda_i\lambda_e}$, it is expected that these effects will be observed at very low fields in analogy with those results in two dimensions.[4–6] The expected temperature dependence comes about from the temperature dependence of λ_i. With increasing T, λ_i is expected to decrease and so a higher field is necessary to achieve the case where $l \sim \sqrt{\lambda_i \lambda_e}$.

Two samples of n-type InSb were studied. The Hall coefficients of the samples at 10 K yielded a net electron density for sample 1 of $N_D - N_A = 3.1 \times 10^{14}/\text{cm}^3$, and for sample 2 a density of $N_D - N_A = 2.7 \times 10^{13}/\text{cm}^3$. Mobilities were also temperature dependent[19] and at $T = 10$ K both had mobilities $\sim 2 \times 10^5$ $\text{cm}^2/\text{V sec}$. Two other samples of higher electron density (9.0×10^{14} and 2.0×10^{15}) were also surveyed. Studies of $\rho(H,T)$ on these samples showed results that were consistent with the results reported here in more detail and earlier measurements.[15] The two samples (1 and 2) closer to the metal-insulator transition where these effects are more prominent were studied more extensively. The samples were cut in a bar geometry with current leads at the ends and voltage and Hall probes along the sides. In all, there were six contacts on each sample and from the various configurations of the leads it was determined that the current density was very uniform in the bar. The samples were etched before mounting. The experiments were performed in a dilution refrigerator and the measurements were made down to temperatures of 50 mK. Measurements were made both in fields perpendicular and parallel to the current and the independence of field orientation was demonstrated. At the lowest temperatures (50 mK) heating effects became serious and so power dissipations were kept at a minimum. A typical power dissipation in a sample of 10^{-2} cm^3 is $\sim 10^{-10}$ W. Even with these low powers there is potentially a fundamental problem in cooling the electron gas much below this temperature. As will be seen later, it is determined that the inelastic scattering time becomes longer than 10^{-8} sec below 0.2 K. At this temperature the inelastic diffusion length $L = (\lambda_i \lambda_e)^{1/2}$ begins to be a measurable fraction of the dimensions of the sample. If L becomes larger than the sample, the carriers simply do not cool down in the distance of the sample length and the actual measuring process drives the carriers out of equilibrium. We do not believe we are in this regime for the samples and geometry chosen here but extrapolation of our results below 50 mK suggests potential problems below this temperature.

For the two samples chosen for this study, we determine at low temperatures that for sample 1, the product $k_F \lambda_e = 3.89$, while for sample 2, the corresponding number for $k_F \lambda_e = 0.065$. These two samples span the $k_F \lambda_e = 1$ regime and, in view of the limitations of Kawabata's expression, we quantitatively analyze only sample 1.

Before illustrating the detailed analysis it is instructive to show the gross features of the magnetoresistance in order to make contact with previous magnetic field studies on InSb. In Fig. 1 we show the magnetoresistance of samples for select temperatures of sample 2. Here it is seen that for different field ranges various effects are observed. At the lowest fields a negative magnetoresistance is observed which is due to localization effects and is the main subject of this work. This will be discussed in more detail shortly. At intermediate fields (50–1000 G), a positive magnetoresistance dominates and the functional form is approximately $H^{1/2}$. It is this term which is the Zeeman term associated with electron correlation effects and has been studied in Si:P by Rosenbaum *et al.*[8] and in InSb recently by Morita *et al.*[15] This term has also been seen in metal-oxide-semiconductor field-effect transistors (MOSFET's) in the 2D case.[2] At even higher fields (> 1 kG) it is observed that the magnetoresistance varies exponentially with H. This effect has been observed previously[20] and is due to magnetic-field-induced reduced overlap of the wave function of adjacent donors in this regime delicately close to the metal-insulator transition. With modest fields (25 kG) the sample resistivity is seen to change more than ten orders of magnitude in this

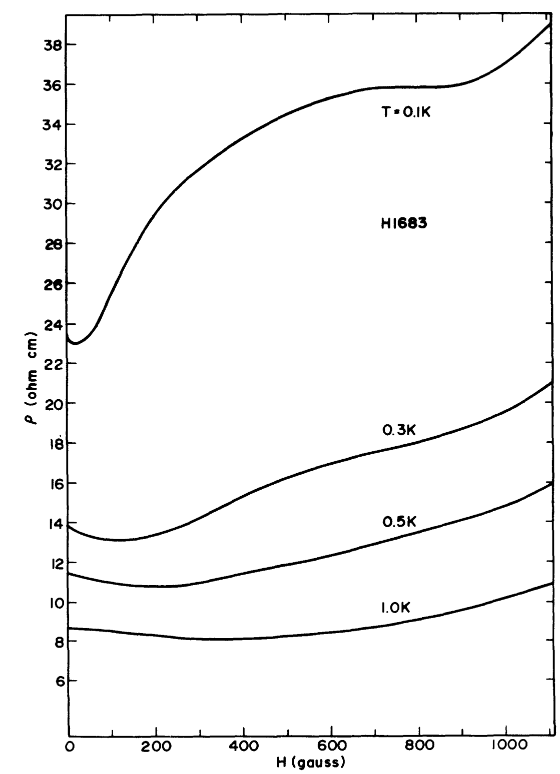

FIG. 1. Magnetoresistance of InSb sample 2 in the intermediate-field range for various selected temperatures. The negative magnetoresistance at low fields is due to the delocalizing effects of the applied field.

exponential regime.

A similar set of data for the higher-density sample 1 was taken. This sample was in the regime ($k_F\lambda > 1$) where we can make contact with theory. Again at low fields a negative magnetoresistance was observed due to delocalizing effects. At higher fields (above 100 G) a positive magnetoresistance was observed which again finally showed an exponential dependence above 5 kG. In this case there was no obvious intermediate $H^{1/2}$ region. As a function of temperature it was seen that the positive component of the magnetoresistance was suppressed at higher temperature, presumably as the donors show less tendency to freeze out at higher T. Close inspection of the low-field data revealed a temperature dependence which allowed a determination of the temperature dependence of the inelastic scattering rate through an analysis of Eq. (1).

We have studied these localization effects below 50 G in this sample as a function of temperature and imposed a fit to Eq. (1) (this is shown in Fig. 2). The two adjustable parameters in this fit are the strength of the localization effects (α) and the inelastic scattering rate $\tau_i^{-1} = v_F/\lambda_i$. The results of these measurements are shown for several temperatures and the fits to Eq. (1) are shown as the solid lines. It is seen that Eq. (1) adequately describes the data over the temperature range studied. The parameters τ_i and α are uniquely determined in that α determines the absolute strength of the negative magnetoresistance while τ_i the shape of the curve. It is found that over the temperature range studied ($0.05 \rightarrow 1.2$ K) a best fit is obtained with the parameter $\alpha = 0.55$. In the original theory[17] it was anticipated that $\alpha = 1$. It has been observed in 2D systems, however, that the strength of this parameter does indeed deviate from unity, and Fukuyama[21] has shown that in that case additional terms due to correlation effects could be responsible. Recently, Isawa, Hoshimo, and Fukuyama[22] have suggested that the interaction effects in 3D could also result in apparent reduced strength. It was shown that certain correlation effects are orbital in nature and so can alter the resistance in these low fields. In the limit where $\delta << 1$, the amplitude of the localization corrections will be reduced by $F/2$ where F is a screening parameter. This parameter can take on values $0 \rightarrow 1$. The value $\alpha = 0.55$ obtained from these measurements implies, from this calculation, a value of $F = 0.45$, in reasonable agreement with estimates.[22]

The inelastic scattering times determined from this data are shown in Fig. 3. At the lowest temperatures (below 0.2 K), τ_i is determined to be sufficiently long so that it has no influence on the magnetoresistance in the field range studied. One would have to look at substantially lower fields below this tempera-

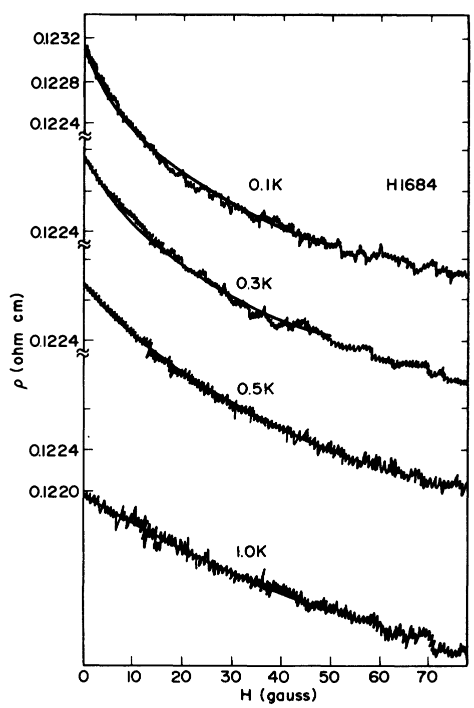

FIG. 2. Magnetoresistance of InSb sample 1 for various temperatures at low fields. The negative magnetoresistance is due to the delocalizing effects of the applied field. The vertical axis has been displaced for each trace. The solid line through the data is a fit to Eq. (1) in the text with $\alpha = 0.55$. The resultant inelastic scattering rates ($1/\tau_i$) are shown in Fig. 3.

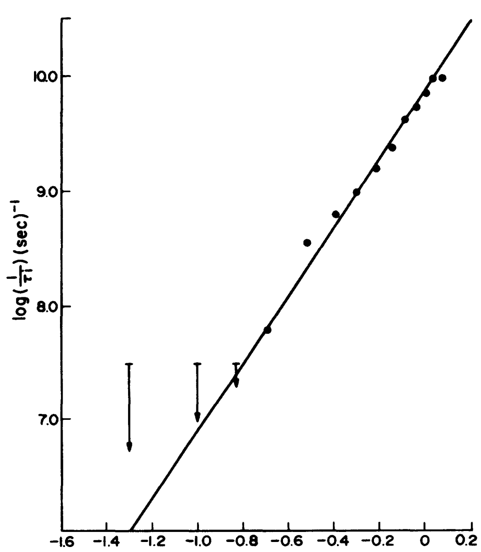

FIG. 3. Inelastic scattering rate ($1/\tau_i$) as a function of temperature derived from fits to the data of Fig. 3. The solid line through the data has as slope $=3$. Below 0.2 K, τ_i is sufficiently long so that the data are insensitive to the choice of this parameter.

ture to obtain meaningful estimates of τ_i. The line drawn through the data is a line of slope 3 implying $(\tau_i)^{-1} \propto T^3$. This dependence is what would be expected for electron-phonon coupling in the clean limit in three dimensions. These results are in contrast to the results obtained in the 2D case of Si MOSFET's where it is observed[4–6] that the inelastic scattering rate varies approximately as T with a surprisingly strong-coupling strength. This was interpreted in this case as due to strong electron-electron scattering in the dirty limit and electron-phonon scattering was negligible in this same temperature range. In this case we are apparently dominated by electron-phonon scattering.

In zero magnetic field the sample studied most extensively (1) shows essentially no temperature dependence to the resistivity below 0.5 K. This is in agreement with calculations[22] which estimate that the resistivity varies as $C\sqrt{T}$, where $C \gtrless 0$ for $(\frac{2}{3} - \frac{3}{2}F) \lessgtr 0$. For our estimate of $F = 0.45$, $C \approx 0$. The temperature dependences of the various samples studied in zero magnetic field and in finite field are in agreement with the earlier measurements of Morita *et al.*[15]

In summary, we have presented measurements on the temperature and magnetic field dependence of the resistivity of n-type InSb with carrier densities in the region 10^{13}–$10^{14}/\text{cm}^3$. Magnetoresistance measurements show clearly the effects of electron localization, Coulomb correlation effects, and finally at the higher fields, freeze-out. At the lowest fields, the data are dominated by orbital effects, and we have analyzed the data using localization theory and an expression for the magnetoresistance derived by Kawabata. The results of this analysis suggest that the strength of these effects is 0.55 of that expected from localization effects alone. The reduction appears due to correlation effects. In addition, from detailed fits of $\rho(H)$, we were able to extract an inelastic scattering rate $(\tau_i)^{-1}$ over a particular temperature range, and the results indicate that the inelastic scattering is dominated by electron-phonon processes.

These results clearly show that localization effects as well as many-body correlation effects are operative in the critical regime near the metal-insulator transition.

ACKNOWLEDGMENTS

We acknowledge valuable discussions with P. W. Anderson, W. F. Brinkman, D. J. Bishop, P. A. Lee, and E. Abrahams. We thank D. C. Tsui for supplying the samples.

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