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Magnetic-Field-Induced Metal-Insulator Transition in Degenerately-Doped n-type Ge

R. M. Westervelt, M. J. Burns, P. F. Hopkins, and A. J. Rimberg
Division of Applied Sciences and Department of Physics
Harvard University, Cambridge, MA 02138

G. A. Thomas
AT&T Bell Laboratories, Murray Hill, NJ 07974

An experimental study is presented of the metal-insulator transition induced by strong magnetic fields at low temperatures in Ge degenerately doped with Sb donors to concentrations N_D up to twice the transition n_c in zero field. For unstressed samples with both the magnetic field and the electronic transport along <100> directions, the longitudinal and transverse resistivity increase strongly, by several orders of magnitude, above a characteristic field $H_c \sim 5$ Tesla for $N_D \sim 2n_c$ at temperatures $T < 1$ K. Below this field the conductivity changes slowly with temperature as $\Delta\sigma \propto T^{1/2}$, whereas above H_c the conductivity is thermally activated. The measured Hall coefficient changes relatively little through the transition, so that the apparent mobility is thermally activated in strong fields, while the apparent carrier concentration remains finite. By measuring the magnetoresistance at low temperatures ($T \sim 30$ mK to 0.5 K) and extrapolating to $T = 0$, we find that the functional dependence of the magnetoresistance with field near the transition is consistent with an exponent of one. These results agree with recent theory including both disordered Coulomb interactions and localization, which predicts that the transition in strong magnetic fields has the characteristics of localization.

1. INTRODUCTION

Strong magnetic fields are useful probes of localization and interaction effects in degenerately-doped semiconductors [1,2]. Magnetic freezeout, which has been studied for many years [3,4], occurs in non-degenerate semiconductors when compression of the electronic wavefunctions of isolated impurity atoms by the magnetic field increases the electronic binding energy and thereby decreases the thermally excited carrier concentration. Degenerately-doped semiconductors can be driven insulating by strong magnetic fields, but the nature of the transition in this case is more complex. Electron-impurity and electron-electron Coulomb interactions, and localization are all potentially important. Recent theory for metal-insulator transitions [5-7] includes both disordered Coulomb interactions and localization. For the case of a metal-insulator transition in strong magnetic fields CASTELLANI et. al [7] predict that the type of transition will be localization in which the quasiparticle diffusion constant, rather than density of states, goes to zero. This is in contrast both to magnetic freezeout, and to the metal-insulator transition in low magnetic fields, which has been experimentally studied in Si [8] and Ge [9,10]. Possible collective electronic states including charge- and spin-density waves, and Wigner crystallization, have been theoretically predicted to occur [11-13] in strong magnetic fields when the impurity potential is weak.

Experimentally this is seldom the case, and, and the interpretation of experiments [14-16] in $Hg_{1-x}Cd_xTe$ and InSb remains controversial.

In this paper we present an experimental study of the magnetic-field-induced metal-insulator transition in degenerately-doped n-type Ge. The data show a transition at low temperatures $T < 1$ K and strong magnetic fields $H \sim 5$ Tesla, for which the magnetoresistance increases by as much as a factor ~ 5000, while the Hall coefficient increases by only a factor ~ 2. The variation of the extrapolated zero temperature conductivity with field H is consistent with an exponent of one. Thus the transition in strong fields is of the localization type as predicted by recent theory [5-7] including both Coulomb interactions and localization and not magnetic freezeout or a collective phenomenon. A preliminary account of some of these results has appeared elsewhere [17]. Experimental work along these lines in Si [18] was done at fields below the metal-insulator transition.

2. Ge SAMPLES AND APPARATUS

The material used for this study is uncompensated Czochralski-grown Ge degenerately-doped with Sb. Inhomogeniety of the impurity concentration can be a severe problem in heavily-doped crystals, both as slow variations in N_D across the crystal, and as narrow, planar impurity striations which form perpendicular to the growth direction, <100> for our crystals. We screened crystals for striations by cutting a thin, square sample with all faces perpendicular to <100> axes, and with the known growth direction along one side of the square. Contacts were attached to the four corners as described below, and the sample was driven through the metal-insulator trasition at low temperatures $T < 1$ K by a magnetic field $\mathbf{H}$ oriented perpendicular to the square face. The isotropy of the dopant concentration was tested by comparing two sets of four-terminal resistance measurements with the leads rotated by 90°, which should be identical for this experimental geometry by crystal symmetry. For the two crystals discussed below, the anisotropy due to striations was typically ~10% in H at the transition, and the difference in magnetoresistance at fields twice the transition was typically ~20%. This method is very sensitive and easily detects striations not found by other techniques, such as spreading resistance measurements.

The two samples discussed below, 4H596 and EP2, were cut from two different Ge crystals. The donor concentrations determined by room temperature resistivity measurements [19] on each sample were $N_D \cong 1.9 \times 10^{17}$ cm^{-3} and $N_D \cong 2.7 \times 10^{17}$ cm^{-3} respectively; these values were checked by room temperature Hall measurements. Both samples were cut with all faces perpendicular to <100> crystal axes, lapped, and etched in 3:1 HNO_3 to HF to remove saw damage. Electrical contacts were made using Sn solder, either nominally pure, or doped with Sb; typical measured contact resistances were ~ 2-4 Ω at low temperatures. Sample 4H596 was prepared in a Hall bar geometry with dimensions 10x1.7x0.3 mm^3, two current contacts across opposite 1.7x0.3 mm^2 ends, and three voltage contacts arranged along the sides for virtual-contact Hall measurements, as well as four terminal resistance measurements. Sample EP2 was made in a van der Pauw geometry with outer dimensions 10x10x0.7 mm^3. Care was exercised to mount the samples stress-free.

Low temperature electrical measurements were made both in a He dilution refrigerator at Harvard to temperatures $T \sim 30$ mK and fields

H ~ 7 Tesla, and in a pumped ^{3}He cryostat at the National Magnet Laboratory at M.I.T. to T ~ 0.5 K and H ~ 20 Tesla. Transverse and longitudinal magnetoresistance measurements were made with the field **H** oriented along a <100> axis by rotating the sample through 90°. Because the magnetoresistace signal can be as much as a factor ~10^4 larger than the Hall signal, low-noise Hall measurements posed special difficulties. These were minimized by using a 5-contact Hall bar geometry with a virtual Hall contact [20] to null out unwanted magnetoresistance pickup, and by subtracting two data sets taken with the magnetic field reversed. Conventional low-noise a.c. lockin amplifier detection was used for all electrical measurements, which were recorded on a microcomputer for analysis, and care was exercised to avoid heating and remain in the linear portion of the current-voltage characteristics.

3. EXPERIMENTAL RESULTS

3.1 Magnetoresistance

Figure 1 shows semilogarithmic plots of the transverse and longitudinal magnetoresistance ρ_{xx} and ρ_{zz} vs. field H for sample 4H596 at various temperatures between 30 mK and 400 mK. As shown, both ρ_{xx} and ρ_{zz} exhibit a strong increase in resistivity at low temperatures and high fields, by as much as a factor ≅ 5000 at 30 mK and 7 Tesla. Comparison of ρ_{xx} and ρ_{zz} in Fig. 1 shows that this resistivity increase is nearly isotropic. Furthermore, the raw data show evidence for a metal-insulator transition: at low fields H < 4 Tesla the magnetoresistance shows only a weak temperature dependence, whereas at high fields H > 4 Tesla this temperature dependence becomes activated. The transition sharpens somewhat at lower temperatures, but thermal rounding remains significant at the lowest temperature measured. The magnetoresistance of sample EP2 with higher donor concentration shows features very similar to Fig. 1, but shifted to higher fields by a factor ≅ 1.4, as discussed below.

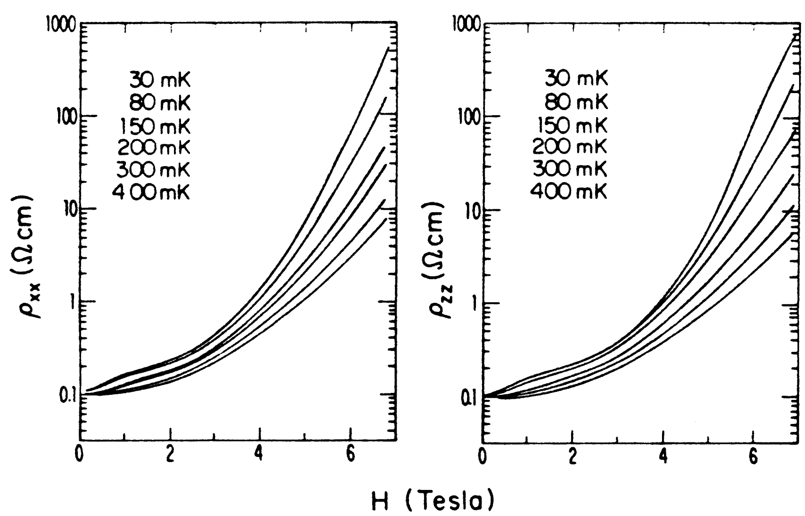

Fig. 1 - Transverse and longitudinal magnetoresistance ρ_{xx} and ρ_{zz} for sample 4H596 at temperatures indicated

3.2 Hall Effect

Figure 2 shows a linear plot of the Hall coefficient R_H measured for sample 4H596 over the same range of temperatures and fields as for Fig. 1. The data is normalized to the Hall coefficient at zero field and T = 0.3 K as indicated, so that a constant apparent carrier concentration would correspond to a horizontal straight line in Fig. 2. The surprising feature of these data is that the Hall coefficient shows little evidence of the transition in Fig. 1: while the transverse magnetoresistance increases by a factor ≅ 5000 at 30 mK and 7 Tesla, the Hall coefficient increases by only a factor ≅ 2.5. Furthermore, the Hall coefficient is essentially temperature-independent, both at low and high fields. As noted above, small Hall voltages are difficult to measure accurately in the presence of a large magnetoresistance signal, and the small field dependence shown in Fig. 2 may be caused in part by systematic errors, despite the precautions taken. The important result is that the Hall coefficient changes very little compared with the magneto- resistance as the field is swept through the transition. Hall data from sample EP2 show a similar lack of field and temperature dependence on both sides of the metal-insulator transition.

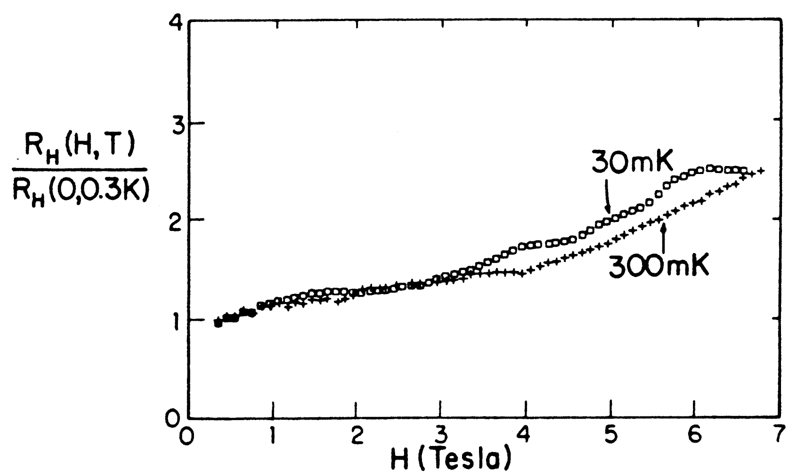

Fig. 2 - Hall coefficient R_H normalized to the value at H = 0 and T = 0.3 K for sample 4H596 at the temperatures indicated

The conclusion we draw from this data, is that the metal-insulator transition occurs as a reduction of the apparent carrier mobility, rather than the apparent carrier concentration, as for localization, and is thus different from magnetic freezeout and from the metal-insulator transition in low fields [8-10]. This type of transition is predicted in strong magnetic fields by the theory of CASTELLANI et. al. [7] which includes both disordered Coulomb interactions and localization. At finite temperatures, the high field regime above the transition represented in Fig. 1 would correspond to hopping conduction for localization. Thus it is somewhat surprising that the Hall coefficient in Fig. 2 remains unchanged at fields well above the transition, because for hopping conduction in the low temperature limit, the Hall coefficient must approach zero [1,2]. However, our data is not in this limit, and theory for the transitional case is less clear. Qualitatively similar Hall data have been found for the two-dimensional electron gas in Si MOSFET's [21].

3.3 Exponent of the Transition

An important characteristic of the magnetic-field-induced metal-insulator transition is the exponent ζ describing the variation of the conductivity with magnetic field near the transition on the metallic side:

$$\sigma \propto (H - H_c)^{\zeta} \tag{1}$$

The value of this exponent can help to distinguish different physical mechanisms which could be responsible for the transition. Recent theory [5-7] predicts $\zeta \cong 1$ for the transition in strong magnetic fields.

Because the amount of thermal rounding in our magnetoresistance data is significant even at 30 mK, we extrapolated the transverse conductivity to zero temperature in order to make a comparison with theory. Figure 3 shows a series of curves which illustrate the technique. Here the transverse conductivity σ_{xx} computed from magnetoresistance data for sample 4H596 and normalized to the value at H = 0 and T = 0.4 K, is plotted vs. $T^{1/2}$ on the metallic side of the transition for various magnetic fields. This temperature dependence is experimentally found at zero field in degenerately-doped Ge [22], and is characteristic of corrections to the conductivity of three-dimensional samples from Coulomb interactions and from certain cases of weak localization; as shown in Fig. 3 it fits the variation of σ_{xx} with T quite well. Least squares fits to the data for each magnetic field, shown as the straight lines in Fig. 3, were used to find the zero-temperature intercepts.

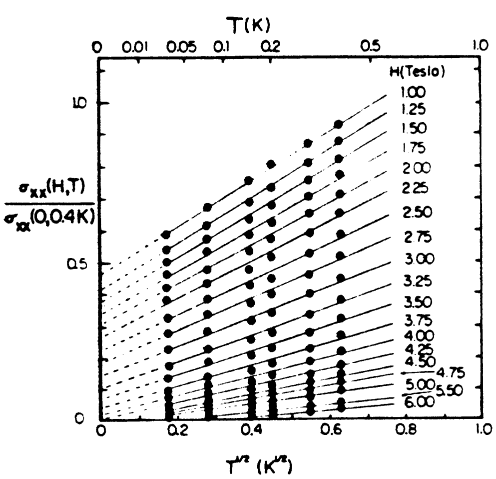

Fig. 3 - Extrapolation of the normalized conductivity σ_{xx} for sample 4H596 to T = 0 K. The straight lines are least squares fits to the data at each field indicated.

Figure 4 shows a linear plot of the extrapolated zero temperature transverse conductivity σ_{xx} (shown as the square points) for sample 4H596 vs. field H, together with plots of the finite temperature conductivity (shown as curves) computed from magnetoresistance and Hall data at the temperatures indicated; the conductivity curves are all normalized to the value at H = 0 and T = 0.4 K as indicated. As shown in Fig. 4 the rounding of the transition is considerably reduced for the extrapolated data, and the zero-temperature conductivity approaches the transition in an approximately linear manner. Thus this data is consistent with the exponent $\zeta = 1$ predicted by recent theory [5-7] which includes both disordered Coulomb interactions and localization. Earlier experiments for degenerately-doped Si [18] in high magnetic fields were not able to drive the samples through the metal-insulator transition, and thus their estimate of the exponent is much more indirect. The critical field $H_c \cong 3.8$ Tesla for Ge sample 4H596 can be deduced from the extrapolated zero-temperature data of Fig. 4 by assuming a linear field dependence for the conductivity. Similar extrapolated data were obtained from sample EP2 with higher donor concentration, except that the critical field obtained by this procedure is larger by a factor ≅ 1.4, as qualitatively expected for heavier doping.

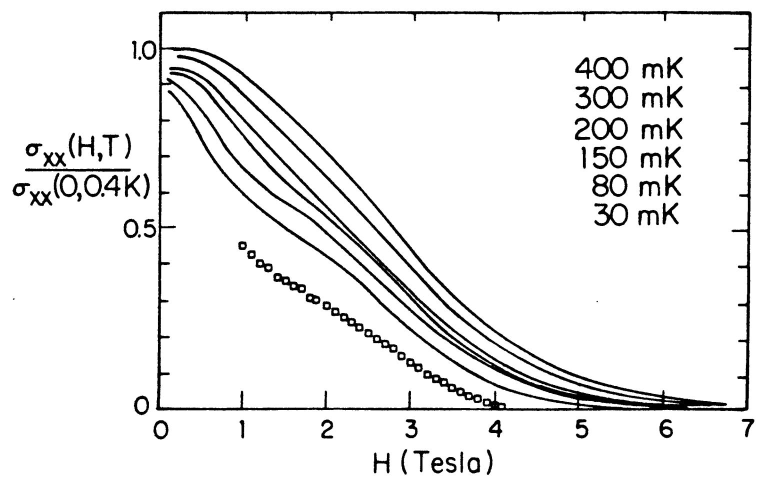

Fig. 4 - Linear plots of the extrapolated zero-temperature conductivity σ_{xx} (squares) and finite temperature data (curves) vs. magnetic field H for sample 4H596 at the temperatures indicated.

A number of cautionary remarks regarding exponents are in order. The critical region very near the transition, where scaling theory is strictly valid, is obscured by small variations in the impurity concentration in material such as ours, which is doped by conventional methods. The small rounding evident in the extrapolated data in Fig. 4 is comparable to the variation in transition field obtained in our isotropy tests described in Section 2. Away from the transition where the data is most reliable, the functional variation of conductivity with field predicted by theory is only approximately correct. These problems are of course more severe in cases other than ours where the transition is not observed, and extrapolations from low fields are used to deduce the exponent.

4. CONCLUSIONS

A magnetic-field-driven metal-insulator transition is observed in degenerately doped Ge:Sb at low temperatures $T < 1$ K. The Hall coefficient remains relatively unchanged while the transverse and longitudinal magnetoresistance increase by as much as a factor ≅ 5000, and the extrapolated zero temperature transverse magnetoconductivity varies approximately linearly with field H near the transition on the metallic side. These data support the recent theory of CASTELLANI et. al. [7] which includes both disordered Coulomb interactions and localization and predicts that the type of transition in strong magnetic fields is localization. Our results differ qualitatively from magnetic freezeout, which is driven by a reduction in the apparent carrier concentration, and from the metal-insulator transition in low magnetic fields in Ge [10].

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