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Evidence of a magnetic-field-induced insulator-metal-insulator transition

M. C. Maliepaard, M. Pepper, R. Newbury, J. E. F. Frost, D. C. Peacock,* D. A. Ritchie, and G. A. C. Jones
Cavendish Laboratory, Cambridge, CB3 OHE, United Kingdom

G. Hill
Department of Electronic and Electrical Engineering, Sheffield University, Sheffield S1 3JD, United Kingdom
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We present measurements of the low-temperature conductivity of n-type GaAs doped just on the insulating side of the metal-insulator transition. In zero magnetic field the temperature dependence of the conductivity indicated that the sample was insulating. At moderate fields the conductivity extrapolated to a finite value at $T=0$, implying that the sample was driven metallic by the field. As the field was further increased, the sample became insulating once more due to wave-function shrinkage. These results support the phase diagram suggested by Shapiro.

It has long been known[1] that the effect of a strong magnetic field on a heavily doped semiconductor is to shrink the effective Bohr radius of the donor electron. If a sample is metallic in zero field this reduction of the electron wave function can cause a metal-insulator transition. This magnetic-field-induced metal-insulator transition has been widely studied.[2-5]

Recently, we have studied the magnetic-field-induced metal-insulator transition in metallic n-type GaAs samples.[6] The low-temperature conductivity was found to obey $\sigma=a+bT^{1/2}$ at low fields giving way to $\sigma=a+bT^{1/3}$ at fields near the metal-insulator transition, where a and b were constant at a given value of B. Such behavior had been theoretically predicted.[7] A positive value of a indicated the metallic state, while a negative value of a implied an insulator. For such an insulator hopping sets in at temperatures below the $\sigma=a+bT^{1/3}$ fit, and the conductivity will be zero at absolute zero. The form $\sigma=a+bT^{1/3}$ arises when either the interaction length[7] or the inelastic length[8] determines the conductivity near the transition. However, in the case of a strong magnetic field it is the interaction length that is relevant. The behavior of the conductivity was unchanged as the metal-insulator transition was scanned as long as the interaction length was the shortest length scale. These results showed that the shortest length scale determines the conductivity right through the metal-insulator transition.

In a metallic sample a negative magnetoresistance is expected at low fields due to quantum interference.[9] Similarly, in an insulator characterized by hopping conduction a negative magnetoresistance has been predicted[10,11] which has been interpreted as the magnetic field lowering the mobility edge E_c. It should be noted that these theories neglect the contribution of electron-electron interactions. Shapiro[12] has combined the low-field depression of E_c with the high-field localization to produce a possible phase diagram for the magnetic-field-induced metal-insulator transition. His phase diagram is reproduced in Fig. 1 along with the phase diagram including only the high-field localization. The main prediction is that a sample with electron concentration n_1 just below n_c (the critical concentration for a metal-insulator transition in zero field) will undergo an insulator-metal transition as E_c is lowered below the Fermi energy at low fields, followed by the usual metal-insulator transition at high fields due to wave-function shrinkage. At a concentration $n_2>n_c$ only a metal-insulator transition due to wave-function shrinkage occurs. Including only wave-function shrinkage, a sample insulating in zero field is insulating at all fields.

Evidence for the proposed phase diagram has been seen in InP (Refs. 13 and 14) and $Al_xGa_{1-x}As$ (Ref. 15), while in Si:As (Ref. 16) it appears unlikely. In Si:Sb the situation is more complex.[17] For the purposes of the metal-insulator transition a metal is defined as having a finite zero-temperature conductivity, while an insulator has $\sigma(T=0)=0$. Therefore, the most compelling evidence for the Shapiro phase diagram would be a sample with $\sigma(T=0)=0$ in zero field having a finite $\sigma(T=0)$ at

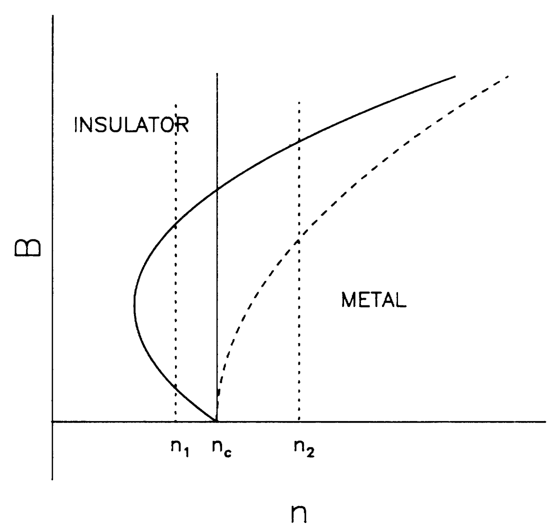

FIG. 1. Two possible phase diagrams for the magnetic-field-induced metal-insulator transition. The dashed line considers only wave-function shrinkage while the solid line is the result of Shapiro (Ref. 12) including interference effects.

moderate field and $\sigma(T=0)=0$ again at high field. In the present work it was attempted to obtain such evidence using n-type GaAs.

The material used was a 2-μm layer of Si-doped GaAs grown by molecular-beam epitaxy on a semi-insulating substrate. A 2.75×0.25-mm Hall bar was etched and Au-Ni-Ge contacts were evaporated. Low-temperature Hall measurements indicated the sample had an electron concentration of $n=N_D-N_A=1.7\times10^{16}$ cm^{-3} and comparison with a 77-K calibration curve[18] indicated a compensation of $K=N_A/N_D\sim0.18$. N_D is the number density of donors and N_A the number density of acceptors. Four-terminal low-frequency measurements were made to obtain the conductivity perpendicular to the magnetic field. Temperatures down to 60 mK were achieved in a top-loading dilution refrigerator with a superconducting solenoid capable of fields up to 13.6 T.

Three potential probes were present on each side of the device, six in total. Resistance measurements executed with any pair of probes agreed to within 1%. The vertical doping profile was examined using a photovoltage spectrometer and, aside from 0.1 μm of surface depletion, the doping was uniform to within the accuracy of the machine, $\sim$5%. The thickness was determined by measuring the step height produced by the spectrometer (it etches away the conducting layer in a circular region) using a Dektak step-height measuring machine, accurate to ±0.1 μm. In the region of the sample, the wafer thickness did not vary within that accuracy. The sample was homogeneous and uniform in doping and thickness.

Figure 2 shows a plot of sample resistance versus field at 58 mK. Three distinct features are seen. A large negative magnetoresistance is seen up to $B=0.5$ T where the resistance has dropped by 40%. Between $B=1$ and 2 T is a broad bump which in metallic samples is associated with Shubnikov–de Haas oscillations. Above $B=2$ T the resistance increases sharply due to wave-function shrinkage. All three of these features became sharper as the temperature was reduced.

In Fig. 3 the conductivity is plotted as a function of $T^{1/3}$

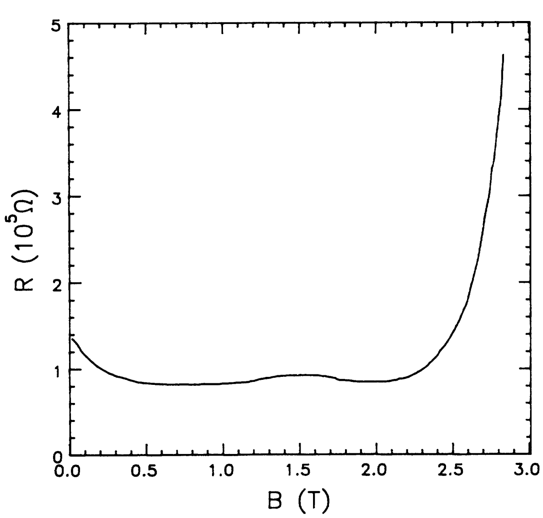

FIG. 2. Sample resistance vs magnetic field at a temperature of 58 mK.

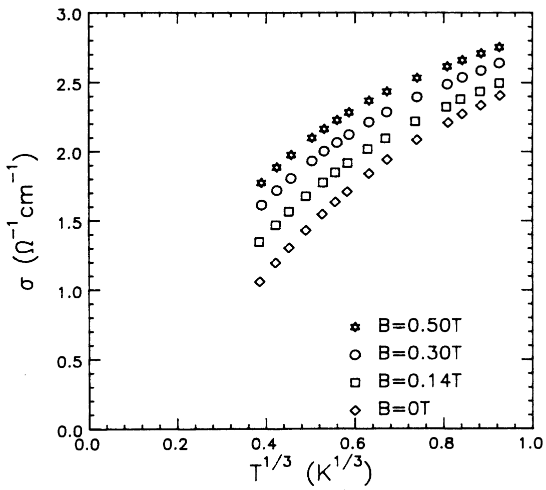

FIG. 3. Conductivity vs $T^{1/3}$ for $B=0$, 0.14, 0.30, and 0.50 T. At $B=0$ the conductivity is falling steeply and will not have a positive value at $T=0$, indicating the sample is insulating.

for $B=0$, 0.14, 0.30, and 0.50 T. For $B=0$ it is clear that the conductivity is dropping faster than $T^{1/3}$ and will not have a positive intercept. In fact, although there is no theoretical justification, the best fit to the data appears to be $\sigma\propto\ln T$. Therefore, it seems clear that at $B=0$ the sample is insulating. As the field is increased the conductivity increases dramatically, by as much as 70% at the lowest temperatures. A good fit to $\sigma=a+bT^{1/3}$ or any other functional form expected near the transition is not obtained. Thus, values for $\sigma(T=0)$ cannot be extracted. However, it is apparent the sample is in the vicinity of an insulator-metal transition. For temperature dependences at magnetic fields in the range $B=1$–2 T, the temperature dependence of the Shubnikov–de Haas oscillation considerably complicates matters and good fits to $\sigma(T)$ were not obtained.

For fields in the range $B=2$–2.5 T good fits were obtained to $\sigma=a+bT^{1/3}$ for $T\leq200$ mK, with $a>0$ for $B=2$–2.35 T, as is seen in Fig. 4. The positive values of $\sigma(T=0)=a$ indicate the sample is metallic at these fields. Although a is negative at higher fields, the conductivity will deviate above the $a+bT^{1/3}$ fit as hopping sets in at lower temperatures and will extrapolate to $\sigma(T=0)=0$. The data at $B=2.70$ T show such a deviation at low temperatures. Plotting $\sigma(T=0)=a$ vs B for $a>0$ it is found that $\sigma(T=0)$ decreases linearly to zero at $B_c=2.37$ T. Identical behavior was seen[6] in samples which were metallic at $B=0$ when pushed through a magnetic-field-induced metal-insulator transition. It can be concluded that the present sample underwent a metal-insulator transition as the field was increased through $B=2.37$ T. Also shown in Fig. 4 is the temperature dependence of the conductivity in zero field. It lies clearly below the data for $B=2.40$ T which has a negative value of a. This confirms that the sample is insulating at $B=0$. Since the sample was insulating at $B=0$, the sample has experienced an insulator-metal-insulator transition as the magnetic field was increased from zero to over 2.5 T. This is consistent with the Shapiro phase diagram (Fig. 1).

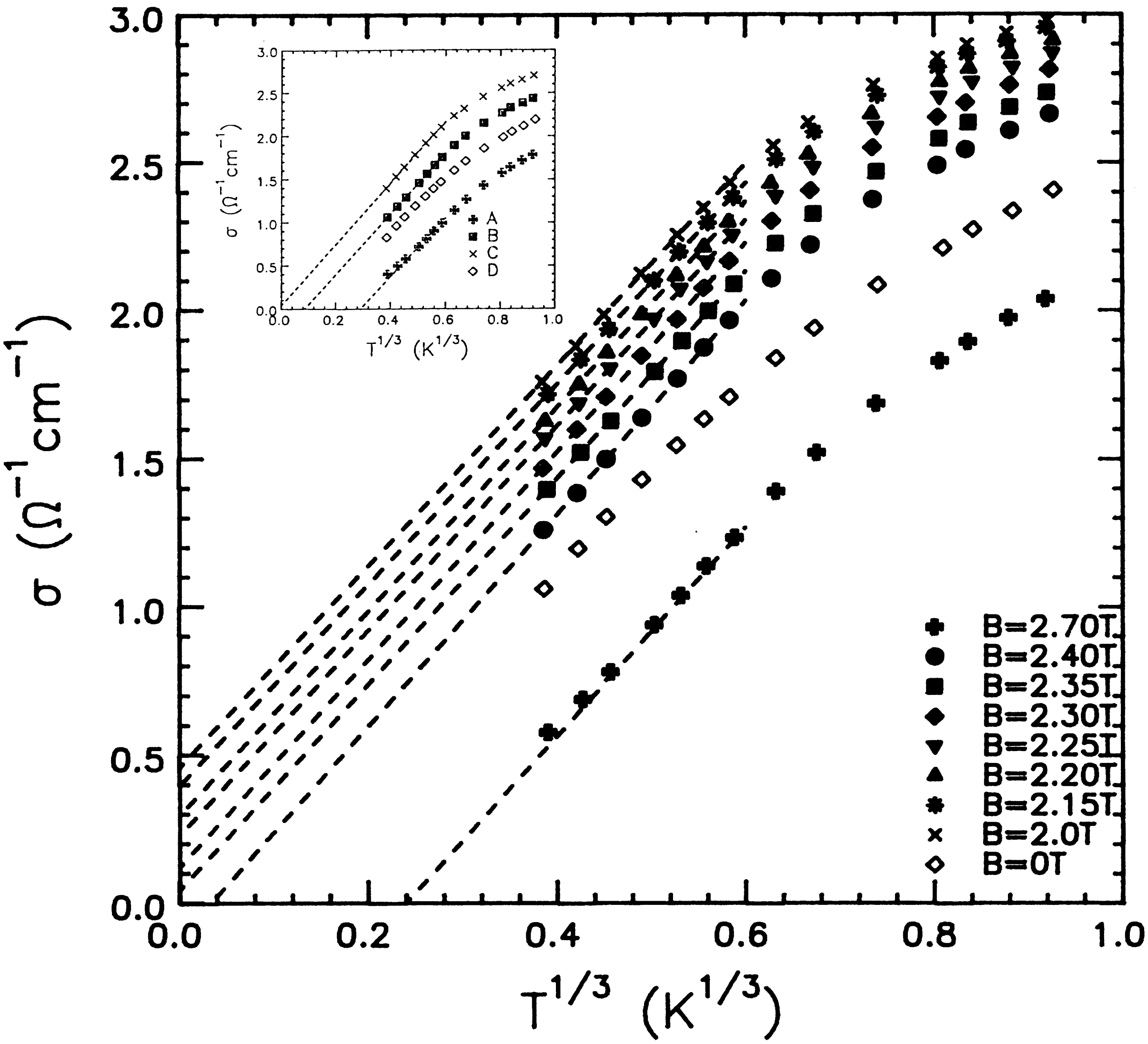

FIG. 4. Conductivity vs $T^{1/3}$ for $B=0$ and 2–2.7 T. The dashed lines are linear regressions to the data for $T \lesssim 200$ mK. The positive intercepts for $B=2$–2.35 T indicate the sample is metallic in this region. The inset is a plot of σ vs $T^{1/3}$ for a second sample with a slightly lower carrier concentration. The points marked *A*, *B*, *C*, and *D* were taken at applied fields of 2.70, 2.35, 2.00, and 0 T, respectively.

The data have been fit to $\sigma = a + bT^{1/3}$ near the metal-insulator transition because previous work[6] has shown it to be the best fit for GaAs samples that are metallic in zero field. The present data do not support a $T^{1/3}$ law near the transition over a $T^{1/2}$ law. The temperature range of the $T^{1/3}$ or $T^{1/2}$ law is limited, since at the fields in question ($B \sim 2$ T) full spin splitting occurs at temperatures such that $T < g\mu_B B/\pi k_B \sim 200$ mK. g is the Landé g factor which is 0.44 in bulk GaAs. μ_B is the Bohr magneton. The $T^{1/3}$ law is only predicted for the case of full spin splitting.[7] Employing either a $T^{1/2}$ or a $T^{1/3}$ law to extrapolate the data to zero temperature, the values of $\sigma(T=0)$ support the Shapiro phase diagram.

The insulator-metal transition occurs at a field of about 0.1 T where the magnetic length $(\hbar/eB)^{1/2}$ is about 800 Å. The average distance between impurities $n^{-1/3}$ is approximately 400 Å. This indicates that the backscattering loops giving the main contribution to localization are quite small, enclosing only a few impurities, as is expected in three dimensions.

Recent results[2,4,6] have shown that for a magnetic-field-induced metal-insulator transition the zero-temperature conductivity falls to zero as

$$\sigma(T=0) = \sigma_c \left[\frac{a_\perp^2 a_\parallel}{a_{\perp c}^2 a_{\parallel c}} - 1 \right]^\nu . \quad (1)$$

$a_\perp$ and $a_\parallel$ are the effective Bohr radii perpendicular and parallel to the applied field, respectively, as formulated by Yafet, Keyes, and Adams.[1] $a_{\perp c}$ and $a_{\parallel c}$ are their critical values. σ_c is a constant and ν is a constant known as the critical exponent. For the present experiment the data fit

Eq. (1) with $\sigma_c = 14 \pm 3\ \Omega^{-1}\text{cm}^{-1}$ and $\nu = 0.99 \pm 0.05$, in excellent agreement with the previous work[6] done on samples which are metallic at $B=0$. Also, the value of ν is in excellent agreement with the theoretical value[19] of 1 predicted for high magnetic field. It is unfortunate that the low-field data did not allow an extraction of $\sigma(T=0)$ and, hence, a detailed analysis of the critical behavior of the insulator-metal transition.

It should be noted that the range of electron concentration over which this effect can be seen is very small. A second sample, adjacent to the present sample on the same wafer, was investigated in a manner identical to the first. The sample showed the same features in a plot of resistance versus magnetic field and the conductivity showed the same temperature dependences, including $\sigma \propto \ln T$ at $B=0$ and $\sigma = a + bT^{1/3}$ for $2\ \text{T} \leq B \leq 2.5$ T. However, the conductivity was shifted down in value such that at only one field value did the $T^{1/3}$ extrapolation give a positive value. Because of the uncertainty in sample thickness and in choosing the form of the extrapolation, this does not give clear evidence for a transition to a metal. The Hall effect indicated the concentration was slightly lower at $1.6 \times 10^{16}\ \text{cm}^{-3}$. The inset of Fig. 4 is a plot of σ vs $T^{1/3}$ at a selection of magnetic fields for this sample. The general behavior of the conductivity is very similar to that for the initial sample, indicating that the behavior is not sample specific. A sample grown by metalorganic chemical-vapor deposition with a concentration of $1.8 \times 10^{16}\ \text{cm}^{-3}$ (sample Z of Ref. 6) again showed very similar behavior, but at $B=0$ the conductivity extrapolated to a finite value, and only a metal-insulator transition was seen.

In conclusion, the low-temperature conductivity of an n-type GaAs sample provided evidence for an insulator-metal-insulator transition as the magnetic field was increased from zero. This supports the proposed phase diagram of Shapiro.[10] We wish to emphasize that this conclusion is reached whether a $T^{1/2}$ law or a $T^{1/3}$ law is used to extrapolate the conductivity to zero temperature. The data did not allow a detailed study of the insulator-metal transition, but the metal-insulator transition was similar to those seen in samples metallic at $B=0$.

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*Also at GEC Hirst Research Centre, Wembley, Middlesex HA9 7PP, United Kingdom.

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

[2] R. Mansfield, M. Abdul-Gader, and P. Fozooni, Solid State Electron. **28**, 109 (1985).

[3] A. P. Long and M. Pepper, Solid State Electron. **28**, 61 (1985).

[4] G. A. Thomas, M. Burns, P. Hopkins, and R. M. Vestervelt, Philos. Mag. B **56**, 687 (1987).

[5] G. Biskupski, H. Dubois, J. L. Wojkiewicz, A. Briggs, and G. Remenyi, J. Phys. C **17**, L411 (1984).

[6] M. C. Maliepaard, M. Pepper, R. Newbury, and G. Hill, Phys. Rev. Lett. **61**, 369 (1988).

[7] B. L. Altshuler and A. G. Aronov, Pis'ma Zh. Eksp. Teor. Fiz. **37**, 349 (1983) [JETP Lett. **37**, 410 (1983)].

[8] Y. Imry, J. Appl. Phys. **52**, 1817 (1981).

[9] A. Kawabata, Solid State Commun. **34**, 431 (1980).

[10] B. L. Altshuler, A. G. Aronov, and D. E. Khmelnitskii, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 157 (1982) [JETP Lett. **36**, 195 (1982)].

[11] U. Sivan, O. Entin-Wohlman, and Y. Imry, Phys. Rev. Lett. **60**, 1566 (1988).

[12] B. Shapiro, Philos. Mag. B **50**, 241 (1984).

[13] J. P. Spriet, G. Biskupskii, and H. Dubois, Phil. Mag. B **54**, L95 (1986).

[14] D. M. Finlayson, P. J. Mason, and I. F. Mohammed, J. Phys. C **20**, L607 (1987).

[15] S. Katsumoto, F. Komori, N. Sano, and S. Kobayashi, J. Phys. Soc. Jpn. **56**, 2259 (1987).

[16] T. G. Castner, W. N. Shafarman, and D. Koon, Philos. Mag. B **56**, 805 (1987).

[17] A. P. Long and M. Pepper, J. Phys. C **17**, L425 (1984).

[18] G. E. Stillman and C. M. Wolfe, Thin Solid Films **31**, 69 (1976).

[19] C. Castellani, G. Kotliar, and P. A. Lee, Phys. Rev. Lett. **59**, 323 (1987).