PHYSICAL REVIEW B VOLUME 24, NUMBER 12 15 DECEMBER 1981

Magnetoconductive effects in an effectively two-dimensional system. Weak Anderson localization

Zvi Ovadyahu
Brookhaven National Laboratory, Upton, New York 11973

Yoseph Imry*
IBM Research Center, Yorktown Heights, New York 10598

(Received 18 March 1981)

Experimental results pertaining to the transport properties of thin indium oxide films are given and discussed. The data presented for the resistivity, the transverse magnetoresistance, the Hall constant, and their temperature dependences give consistent support to the basic ideas underlying weak-localization theories. In particular, the Hall constant, measured in small fields, is temperature independent.

The transport properties of two-dimensional (2D) electronic systems in the presence of disorder is a subject of fundamental interest.[1-10] Measurements on two classes of such systems—"dirty" metallic films[11,12] and semiconducting inversion layers[13-16] have revealed some anomalies in their transport properties such as the resistivity, ρ decreasing logarithmically with increasing temperature, negative magnetoresistance (MR), and nonlinear I-V characteristics. There are two theoretical frameworks for the explanation of these results: the scaling theory[2] of localization in 2D systems augmented by inelastic scattering effects,[3] and theories treating disorder and electron-electron interactions to low order on the same footing.[6] While both theories predict a $\ln T$ dependence of ρ their predictions for the MR and particularly the Hall effect, they are sufficiently different to be distinguishable by experiments.[6-10] Yet, it appears that the experimental results are ambiguous. For example, in the inversion layers[13-16] a negative MR was found[14] to be in agreement with the localization theory, whereas the temperature dependence of the Hall effect[15,16] suggests the relevance of the interaction theories (though difficulties concerning the value of the screening parameters were recognized).[16]

In this Communication we present results on the anomalous transport properties of effectively 2D indium oxide thin films. This is a third class of conductors (with semimetallic carrier densities of 10^{20} cm^{-3}) exhibiting the above-mentioned anomalies in the transport properties under easily accessible experimental conditions.

Samples have been prepared by vacuum deposition of pure (99.99+%) In_2O_3 in an O_2 atmosphere (partial pressure $\simeq 4\times 10^{-4}$ Torr), onto glass substrates held at 150 °C. Stainless-steel masks were used to obtain the desired geometry for electrical measurements. Samples reported here were rectangular strips ~5 cm long and ~1 cm wide with two current leads on either side and two pairs of "clover leaf" Hall contacts along the strip. The latter doubled as voltage contacts for the 4-probe resistivity measurements. In the thickness range used (150 Å and upward), the samples were found to be essentially physically continuous with very large grain size (~0.5 μm). X-ray-diffraction measurements showed a single bcc phase with ~1% volume decrease relative to the bulk value of the stoichiometric material. This volume change presumably reflects an oxygen deficiency[17] which is also believed to be responsible for the electrical conductivity in this material. Rutherford backscattering experiments confirmed that the material is indeed oxygen deficient (relative to the stoichiometric In_2O_3) and that the resulting films are rather chemically pure (in particular, no magnetic impurities on the level of 0.01% were detectable). Fuller details of preparation and material characterization are described elsewhere.[17]

Electrical measurements (resistivity, magnetoresistance, and Hall effect) were performed as a function of temperature in the range 1–77 K using vapor pressure or a calibrated Ge resistor for thermometry. The zero-field data (R vs T) were taken in a residual field of 1–2 mOe using a double μ-metal shield. Hall-effect data were taken in a standard way, employing fields in the range of 300–1500 Oe (the Hall angle being always less than 0.1°). The readings of the Hall voltage were averaged on the two perpendicular field orientations to cancel effects due to nonideal geometry or a nonuniform current distribution. The results were then averaged over the two sets of the Hall probes. The agreement between the latter was better than 2% which is close to our estimated experimental error for the lower range of fields used. For the highest fields ($H\sim 1.5$ kOe) we estimate an uncertainty of ~1% in the Hall voltage determination.

Eight thin samples (with thicknesses ranging from 150 to 250 Å and sheet resistances, $R_\square$, of 4000 to 500 Ω, respectively) have been measured in this study. Detailed experimental results are shown below for three typical samples with $R_\square$ of 640, 1000, and 4000 Ω (at 77 K) and thicknesses of 200, 170, and 150 Å, respectively. The resistance of each sample decreased upon cooling from ~300 K down to a certain thickness-dependent temperature below which it started to increase. This "resistance-minimum" temperature was lower the thicker the sample and occurred at 120, 160, and 230 K for the three samples shown. The resistance of these films as a function of temperature (and in zero field) exhibited a logarithmic temperature dependence between 77 and 1.08 K (Fig. 1) which is quite remarkable. (In fact, for the 150-Å sample the logarithmic dependence of the resistance was found to extend up to 140 K.)

A negative MR accompanied the anomalous $R(T)$ in the sense that it became more pronounced as the temperature was lowered and more importantly, *no* MR was observed in the "3D" temperature range of any sample (up to the highest fields used). For sufficiently large magnetic fields, the MR became proportional to log H (the field magnitude for this to happen decreasing with temperature). This is shown in Fig. 2 for the three samples of Fig. 1. For the sample with $R_\square = 4000$ Ω the logarithmic H dependence of the MR was unattainable up to the highest fields and lowest temperatures used (Fig. 2). On the other hand, the effects with this sample were large enough to warrant meaningful readings at the low-field limit and a quadratic dependence on H was found in this case for fields smaller than ~220 Oe (Fig. 3). The inset in Fig. 2 depicts a typical angular dependence of the MR from which it was verified that it is the perpendicular component of the field which is relevant—clearly a characteristic 2D effect[18] (at these temperatures and fields).

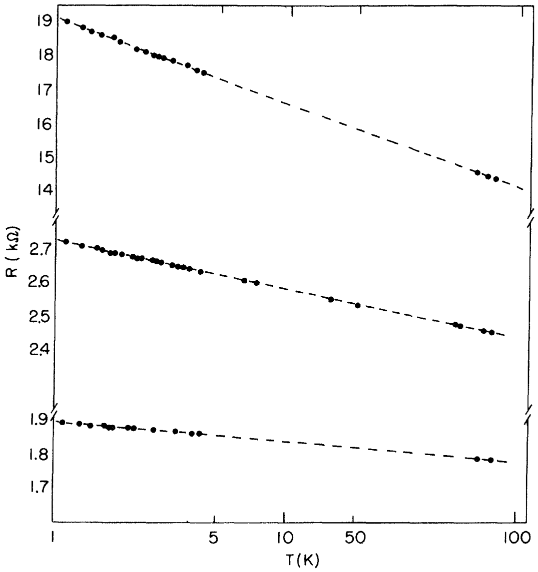

FIG. 1. Temperature dependence of the resistances for three typical samples with $R_\square$ of 640 (bottom), 1000 (middle), and 4000 Ω (top), respectively.

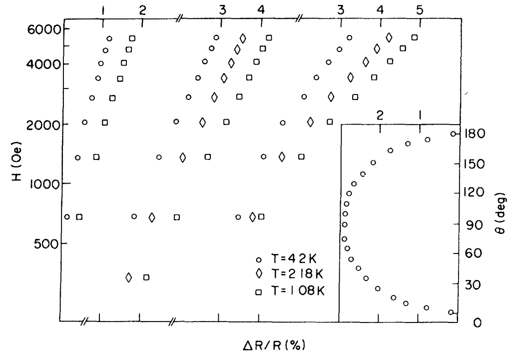

FIG. 2. The magnetoresistance for the samples of Fig. 1 (from left to right, respectively) at various temperatures. The inset on the right depicts the angular dependence of the MR for the middle sample for a constant field $H = 5.4$ kOe. (θ is the angle between the field and the sample's plane.)

We have attempted to fit the results for $R(H,T)$ to the quantitative predictions of the localization theories with assumed $\tau_{\text{in}} \sim T^{-P}$

$$\frac{\Delta R(T)}{R} = \frac{\alpha e^2}{\pi^2 \hbar} R_\square \frac{P}{2} \ln T \ , \tag{1}$$

$$\frac{R(H,T) - R(0,T)}{R} = -\frac{\alpha e^2}{2\pi^2 \hbar} R_\square Y(x) \tag{2}$$

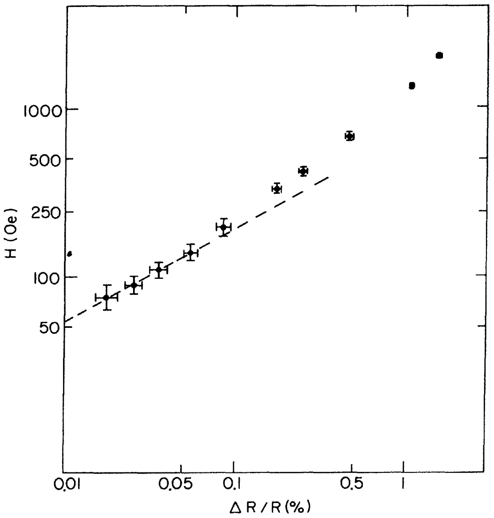

FIG. 3. A log-log plot of the MR in the low-field limit for the sample with $R_\square = 4000$ Ω measured at 4.2 K.

with

$$x \equiv \frac{4DeH\tau_{\rm in}}{\hbar c} = \left(\frac{l_{\rm in}}{l_H}\right)^2, \quad l_{\rm in}^2 = 2D\tau_{\rm in}, \quad l_H^2 = \frac{\hbar c}{2eH} \ ,$$

and

$$Y(x) = \ln x + \Psi\left(\frac{1}{2} + \frac{1}{x}\right) \rightarrow \begin{cases} \dfrac{x^2}{24}, & x \ll 1 \\ \ln x + \Psi(\frac{1}{2}), & x \gg 1 \ . \end{cases}$$

Where D is the diffusion coefficient, Ψ is the digamma function and α constant-of-order unity whose exact value may depend on the details of the system.[8] The $R(T)$ results can be fitted reasonably well to Eq. (1) with $\alpha P = 1.6 \pm 0.2$ for the eight thin samples studied (the scatter in the αP values showing no systematic dependence on either thickness or resistivity). The values of the logarithmic slopes correlate therefore with $R_\Box$ as they should. It was also found possible to fit the field dependence of the MR data for all the samples (and at each temperature) to Eq. (2) and the value we obtained for $l_{\rm in}$ from these fits is typically 1000 Å at 4.2 K. (For example, from the low-field data of Fig. 3 one gets $l_{\rm in} = 1100$ Å.) These values are certainly consistent with the 2D nature of the films at this temperature. We show elsewhere[19] that the temperature dependence of $l_{\rm in}$ estimated from the MR results *and* from the 2D to 3D crossover temperature is in good agreement with a $T^{-1/2}$ law (i.e., $p = 1$ in this system). Note that this is consistent with the 150 Å sample being 2D up to ~140 K. This indicates that $\tau_{\rm in}$ in the studied range of temperatures is dominated by electron-electron interactions. It is perhaps intriguing that electron-phonon interactions will not be more significant at such temperatures. That such may be the case, however, is not inconceivable considering the high Debye temperature of the material. (The Handbook value[17] for the stoichiometric $\rm In_2O_3$ is $\gtrsim 1000\,^\circ$C.) This is also consistent with our observation of a T^5 dependence of the resistivity in the range 120 to 200 K (for bulk samples).

We now want to address ourselves to the critical experiment concerning the Hall constant and its temperature dependence. The number of free carriers deduced from the Hall effect was typically $10^{20}\ e\ \rm cm^{-3}$ with a variation from one sample to another of ±15% (independent of thickness). The Hall voltage for each of the three samples shown above was measured at six different temperatures (77, 63, 4.2, 2.18, 1.45, and 1.08 K) and at two different magnetic fields (within the range 300–1500 Oe). In addition, the other five thin samples were similarly measured at 4.2, 2.18, 1.45, and 1.08 K. In each and every case the Hall voltage was constant, independent of temperature *or* field. The accuracy of the measurement (2% or better) is good enough to state that the expected[6] logarithmic temperature dependence of R_H (which ought to have been 20–50% over the 1–77 K temperature range) is not there. For higher fields, such that the localization effects are substantially reduced, the situation may however be different. Such was presumably the case in the work of Uren *et al.*[15] We are currently investigating the high-field Hall effect in our system and the results will be reported elsewhere.

In summary, we have presented measurements on a representative of a class of conductors with semimetallic carrier densities exhibiting characteristic 2D transport properties. The logarithmic dependence of the resistance was observed to extend over almost two decades in temperature with a total resistivity change of up to 25%. Thus the logarithmic temperature dependence of R is well established in this system for films thinner than 200 Å. Further, the correlation between the appearance of a negative MR and the logarithmic temperature dependence of R is quite suggestive in ascribing both to a *common* physical mechanism. With the absence of logarithmic corrections to $R_H(T)$ (in small fields) and the very good qualitative agreement of the results [for the MR and $R(T)$] with the predictions of weak localization theories, there is little doubt as to the relevance of the latter for the present system. It should, however, be emphasized that the present experiments (as well as those referenced above) do not directly address the basic equation of whether or not all 2D states are localized. To the best of our knowledge, this is the first system where all three measured transport properties [$\rho(T), \rho(H), R_H(T)$] are consistent with weak localization theories.

While the electron density in this system is lower by two orders of magnitude than in typical metals, the Thomas-Fermi screening length is of the order of 10 Å, i.e., much smaller than the films thickness (and comparable to interelectron distances). This may explain why electron-electron interactions, while possibly dominating inelastic scattering, are not of a more crucial importance for these particular experiments in our samples.

We believe that the large magnitude of these effects, observed in a convenient range of temperature and fields, makes this system very attractive for further studies of localization and interactions related to transport properties.

We wish to thank A. Fowler, S. Hikami, F. Stern, and M. Strongin for instructive discussions. This work was partially supported by the U.S. Department of Energy under Contract No. DE-AC02-76CH00016 and the U.S.-Israel Binational Science Foundation (BSF), Jerusalem, Israel.

[*] On leave of absence from the Department of Physics and Astronomy, Tel-Aviv University, Ramat Aviv, Israel.

[1] D. C. Licciardello and D. J. Thouless, J. Phys. C 8, 4157 (1975); 11, 925 (1978).

[2] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979).

[3] D. J. Thouless, Phys. Rev. Lett. 39, 1167 (1977).

[4] P. A. Lee, Phys. Rev. Lett. 42, 1167 (1979).

[5] E. Domany and S. Sarker, Phys. Rev. B 20, 4726 (1979).

[6] B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. 44, 1288 (1980).

[7] A. I. Larkin, Pis'ma Zh. Eksp. Teor. Fiz. 31, 239 (1980) [JETP Lett. 31, 219 (1980)].

[8] S. Hikami, A. I. Larkin, and Y. Nagaoka, Prog. Theor. Phys. 63, 707 (1980).

[9] Fukuyama, J. Phys. Soc. Jpn. 49, 644 (1980).

[10] A. Kawabata, J. Phys. Soc. Jpn. 49, 628 (1980).

[11] G. J. Dolan and D. D. Osheroff, Phys. Rev. Lett. 43, 721 (1979).

[12] N. Giordano, W. Gilson, and D. E. Prober, Phys. Rev. Lett. 43, 725 (1979).

[13] A. B. Fowler and A. Hartstein, Philos. Mag. 42, 949 (1980).

[14] Y. Kawaguchi and S. Kawaji, J. Phys. Soc. Jpn. 48, 699 (1980); I. Eisele and G. Dorda, Phys. Rev. Lett. 32, 1360 (1979).

[15] M. J. Uren, R. A. Davies, and M. Pepper, J. Phys. C (in press).

[16] D. J. Bishop, D. C. Tsui, and R. C. Dynes, Phys. Rev. Lett. 46, 360 (1981).

[17] Z. Ovadyahu and H. Kraner (unpublished).

[18] R. G. Wheeler (unpublished) and references therein.

[19] Z. Ovadyahu, S. Moelecke, and Y. Imry, in Proceedings of the Fourth International Conference on the Properties of Two-Dimensional Electronic Systems, New London, New Hampshire, 1981 (unpublished).