Nonmetallic Conduction in Thin Metal Films at Low Temperatures

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Resistance measurements were made on high-resistivity thin-film metal strips at temperatures as low as 10 mK. Unexpected logarithmic variations of the resistance with temperature and applied electric field were observed for strips with sheet resistance below $R_\square \sim 10$ kΩ/□ and widths $\gtrsim 1$ μm. Exponential increases in resistance were observed for similar films when the film width was decreased to about 0.1 μm or when $R_\square$ was increased to ~10 kΩ/□.

Recent theoretical work on disordered electronic systems predicts a maximum metallic resistivity at a resistance $R_{1D} \cong 2\hbar/e^2 \cong 8000$ Ω in one-dimensional systems and at a sheet resistance $R_{2D} \cong 8\hbar/e^2 \cong 30\,000$ Ω/□ in two dimensions.[1-6] Experimental evidence for this two-dimensional electron localization threshold has been presented by Dynes, Garno, and Rowell,[7] who observed exponential increases in the low-temperature resistance of quench-condensed thin films with $R_\square \gtrsim R_{2D}$. In studying the current-voltage (I-V) characteristics of thin films with $R_\square < R_{2D}$, we have observed unexpected logarithmic dependences of the film resistance on both temperature and applied field. The implication is that even films which are not localized, i.e., $R_\square < R_{2D}$, are still not truly metallic and the transition to localized or insulating behavior is a gradual one as suggested recently by Abrahams *et al.*[2] We also observed exponential resistance increases at low temperatures for films with sufficiently high $R_\square$ and also in several films with low $R_\square$ but with very small film widths. The latter cases may be evidence of the one-dimensional localization of electronic states predicted by Thouless.[1]

TABLE I. Length L, width W, and high-temperature sheet resistance $R_\square$, for samples discussed in the text. All had thickness $d \sim 3.0$ nm. For samples which exhibited logarithmic behavior, logarithmic slopes S_V', S_T', S_L (defined in the text) are listed. Values in parentheses denote high-temperature behavior. Samples E–G exhibited exponential $R(T)$ as indicated. The pairs (A, A'), (C, C'), and (E, E') were each prepared simultaneously on the same substrates.

	L (mm)	W (μm)	$R_\square$ (Ω)	S_V'	S_T'	S_L'	S_T/S_V
A	2.0	1	1100	.19	.84 (.49)	−.25 (−.31)	4.4 (2.6)
A′	2.0	1	1100	.19	-	-	-
B[a]	7.0	1.0	1600	.39	-	-	-
C	2.0	0.8	4600	.14	.36	−.23	2.6
C′	1.0	0.8	4800	.15	-	-	-
D	5.0	1200	5100	.21 (.14)	.51 (.26)	−.36 (−.30)	2.4 (1.9)
E	1.0	1	10,000	(-	.16	)[c]	($4K \leq T \leq 7K$[b])
E′	2.0	1	10,000	$R = R_0 \exp(.45/T)$, $(.07K \leq T \leq 4K)$			
F	2.0	0.1	400	$R = R_0 \exp(?)$			
G	2.0	0.1	1000	$R = R_0 \exp(5.0/\sqrt{T})$, $(.16K$[b] $\leq T \leq 4K$[b]$)$			

[a] Glass substrate—sapphire substrates were used for the other films.

[b] Denotes limits of measurements, not necessarily a change in temperature dependence.

[c] The characterization of the behavior as logarithmic is, in fact, less certain in this case because of the narrow temperature range covered.

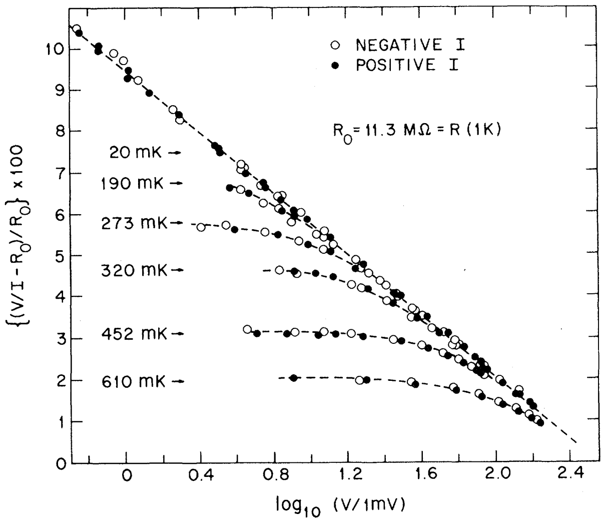

FIG. 1. $\Delta R \equiv [(V/I) - R_0]/R_0$ vs $\ln V$ is plotted for sample C in Table I at several temperatures.

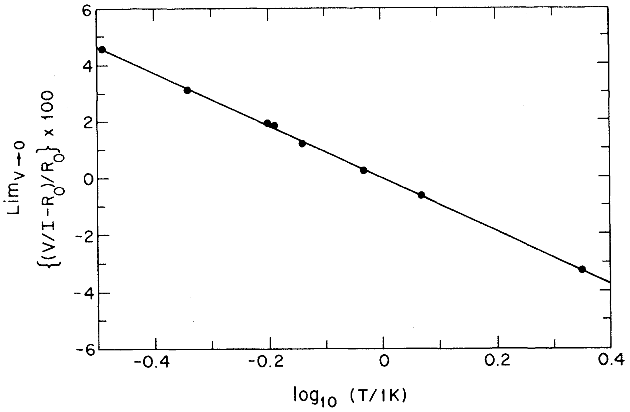

FIG. 2. The plateau values approached at small V in Fig. 1 are plotted vs $\ln T$ but a wider temperature range is covered.

According to Thouless,[1,8] any geometrically one-dimensional (i.e., simply long and narrow) wire whose length L exceeds L_{1D}, the length with resistance 8000 Ω, will have a resistance exponential in L at $T = 0$ because electrons are localized to lengths L_{1D} of the wire. At finite temperatures inelastic scattering processes delocalize the electrons. Instead of $L \gtrsim L_{1D}$, one must meet a more restrictive requirement $L_T \gtrsim L_{1D}$. According to Thouless, L_T is the distance an electron diffuses between inelastic collisions: $L_T(T) = (V_F \tau_{\text{inel}} l)^{1/2}$, where $\tau_{\text{inel}}(T)$ is the characteristic time for the inelastic scattering. Other delocalizing mechanisms can be imagined and Anderson, Abrahams, and Ramakrishnan (AAR)[3] suggest an alternative L_T important in two-dimensional systems and expand upon its significance. Our "wires" were actually thin films of width W and thickness d, with $L \gg W$ and $L \gg d$ but also $W \gg d$. In such samples one may expect either one- or two-dimensional behavior in different experimental regimes, i.e., two dimensional certainly when $R_\square > R_{2D}$ but *also* when $L_T(T) < W$ according to AAR.

The films were evaporated from weighed charges of 58 wt.% Au and 42 wt.% Pd onto room-temperature substrates which were usually polished sapphire. Table I provides values of L, W, and $R_\square$ [measured at high T where $R_\square(T) \sim$ const] for several of the films studied. The films were so thin, $d \cong 2$–4 nm, that they were almost certainly discontinuous or only partially continuous. For such films most of the observed resistance arises from the tunneling resistance between metallic islands[7] (presumably of size $\sim d$). The localization theory is sufficiently general that this granularity is irrelevant so long as the films appear homogeneous on a scale (e.g., L_{1D}, L_T, W) relevant to the localization of electronic states. Various lithographic procedures[9] were used to obtain the long narrow geometries including in all cases very large area contact pads. After fabrication, the samples were epoxied to copper tabs which were heat sunk to the mixing chamber of a He^3-He^4 dilution refrigerator. The minimum temperature achievable was ~10 mK. The I-V measurements were straightforward with simple precautions taken to minimize external noise inputs.

Two kinds of nonmetallic behavior were observed. The first kind was observed for wires A–D in Table I and is illustrated by the data for wire C shown in Figs. 1 and 2. Figure 1 shows the quantity $\Delta R \equiv (V/I - R_0)/R_0$ plotted versus $\log_{10} V$ for several temperatures. R_0 is the wire resistance at $T = 1.0$ K. ΔR is accurately logarithmic in $V \propto E$ at the lowest temperature. At higher temperatures ΔR approaches the logarithmic behavior at large V but approaches plateau values at low V. The plateau values are shown to be logarithmic in T in Fig. 2. This behavior can be summarized ($R \equiv V/I$):

$$\begin{aligned} R(T,E) &= R(T_0,E)[1 - S_T \ln(T/T_0)], \quad \text{small } E, \\ R(T,E) &= R(T,E_0)[1 - S_V \ln(E/E_0)], \quad \text{small } T, \end{aligned} \tag{1}$$

with T_0, E_0 arbitrary. Table I gives normalized values S_T', S_V', of the logarithmic slopes S_T, S_V

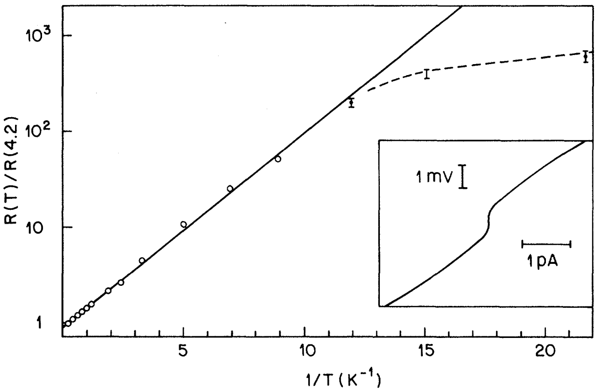

FIG. 3. The exponential dependence of (limit $V \rightarrow 0$) $R \equiv V/I$ vs T for sample E in Table I. Inset: I-V curve for this sample at $T \cong 20$ mK.

for samples A–D:

$$S_T' = \frac{\pi^2 \hbar}{e^2 R_\square} S_T, \quad S_V' = \frac{\pi^2 \hbar}{e^2 R_\square} S_V.$$

Identical values of these slopes for the different samples would indicate a proportionality of S_T and S_V to $R_\square$. Some evidence for such a proportionality, especially in S_V, is suggested but certainly not conclusively. The relatively large disparity in S_V for sample B, the only wire formed on a glass rather than a sapphire substrate, suggests the substrate plays a role in determining S_V. Where two values for S_T' or S_V' appear, an abrupt change in the logarithmic slope was observed. This was observed in later experiments where larger ranges of V and T were studied than those covered for sample C. The slope in parentheses corresponds to high-T behavior.

With the exception of E, E', all our wires were one dimensional in Thouless's sense. However, A–D in no way showed the sort of localization behavior at low T suggested by Thouless in 1977.[8] With use of the more stringent criteria that for a wire to be one dimensional, L_T must be greater than the width of the wire (if $L_T < W$ the electrons cannot tell they are in a wire of limited width), then at least wire D must have been two dimensional, even though we cannot estimate L_T with much certainty.[10] Since the same logarithmic behavior was seen in wire D as in A, B, and C, we conclude that the logarithmic behavior is a two-dimensional effect. The symmetric relation of E with T in (1) suggests that E and T play similar roles in some sense; AAR suggest electron heating as the source of the electric field dependence. In all of the films studied, the logarithmic increase in R appeared to saturate (i.e., R ceased to increase with decreasing temperatures) below about 70 mK.

A second, much more pronounced kind of nonmetallic behavior, was observed in two 1-μm-wide films with $R_\square$ raised to 10 k$\Omega/\square$ and in several films with low $R_\square$ but $W \sim 0.1$ μm. For wires E, E', the 1-μm-wide films, the resistance, $R(T, 0)$, was exponential in $1/T$ as shown in Fig. 3. Here again a saturation was observed at $T \sim 70$ mK. At high enough T, logarithmic behavior was suggested as indicated in Table I, but the temperature range covered was too small to determine this conclusively. A low-temperature I-V curve for the sample is shown in the inset to the figure and cannot be described by a simple mathematical expression. The narrow wires F and G and two others showed qualitatively similar behavior. In the only case where sufficient data were taken to accurately determine the exponent accurately, the variation was in $1/\sqrt{T}$.

Since wires E and E' have a width corresponding to two-dimensional behavior at lower $R_\square$, it seems likely that these films were localized as two-dimensional systems (at low T). If this is true, the localization occurs significantly below the accepted value of R_{2D}. Qualitatively the exponential behavior at low T with a crossover to logarithmic behavior at high T is consistent, however.[3] Since $R_\square$ was rather low for F and G and only W was reduced, it seems likely that these films were localized as one-dimensional systems. We have reservations about this conclusion, however, since it is possible that significant nonuniformities existed in the very narrow wires. In particular several earlier wires with nominally the same resistance and dimensions showed significantly different I-V characteristics and in one case such a wire showed only logarithmic behavior. Therefore the resolution of the width dependence of the localization threshold requires further study. It is worth remarking, however, that our experiments at least set bounds on the regimes of W, $R_\square$, E, and T, where the one-dimensional effect should be sought in future experiments.

Returning to the logarithmic wires, we note that their behavior contradicts the idea that the transition to localized behavior is an abrupt one and lends support to the AAR result that even two-dimensional systems of low resistivity (i.e., $R_\square < R_{2D}$) have a conductance which is scale dependent at $T = 0$. Suggestively, their predicted dependence is logarithmic in the sample size,

L: $R=R_0(1-S_L \ln L)+\text{const}$. AAR show how the observed T, E dependences in our experiments may be reconciled with the scaling-theory result. Their analysis requires that S_T and S_V be proportional to $R_\square$, as is only approximately observed, and predicts that the analogous scale slope, S_L' is given by $S_L'^{-1}=S_T'^{-1}-S_V'^{-1}$. Values of S_L' defined in this way are listed in Table I where possible.

The qualitative agreement of the AAR model with the observed nonmetallic behavior and the semiquantative agreement obtained for the logarithmic slopes encourages us to accept their explanation. However, the model would require an anomalously weak temperature dependence in $\tau_i(T)$ or an unexplained heating of the electrons below $T \sim 70$ mK where we observe temperature-independent resistances in virtually all our samples. Also the observation of localization when $R_\square$ is only $\sim 10^4$ $\Omega/\square$ is somewhat inconsistent. A disturbing and perhaps related problem is the lack of any change in the logarithmic behavior in our 1-μm-wide films in regimes where our estimates indicate that L_T becomes greater than W.

We would like to acknowledge gratefully the continued interest, encouragement, and generously given physical insights of P. W. Anderson and P. A. Lee in the course of these investigations. We have also benefitted from many conversations with and suggestions from Don Licciardello, D. J. Bishop, D. S. Fisher, D. J. Thouless, T. A. Fulton, and J. M. Rowell who first suggested the interest of the problem.

Note added.—The generality of the kind of behavior we describe above has been corroborated since submission of the manuscript by our measurements on similar films of a different alloy (Au-Cu) and by measurements of the conductance of the inversion layer of a silicon metal-oxide-semiconductor field-effect transistor (a strikingly different two-dimensional system) by D. J. Bishop, D. C. Tsui, and R. C. Dynes (to be published). We thank these authors for permission to refer to their work in this way.

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[10] Our estimates of L_T, essentially similar to those in Ref. 1, are somewhat larger than is permitted by the scaling-theory interpretation of our results but these estimates are suspect because of their need for exact values of $\tau_{\text{inel}}(T)$.