Transition to Localization in Granular Aluminum Films

G. Deutscher
Tel-Aviv University, Ramat-Aviv, Israel

and

B. Bandyopadhyay, T. Chui, P. Lindenfeld, W. L. McLean, and T. Worthington[(a)]
Serin Physics Laboratory, Rutgers University, New Brunswick, New Jersey 08903
(Received 2 November 1979)

The temperature dependence of the electrical resistivity of granular aluminum films changes from one regime to another as their superconducting transition temperatures drop towards absolute zero. In nonsuperconducting specimens we observe the exponential behavior associated with strong localization. In the other regime the specimens show a weaker, logarithmic dependence.

PACS numbers: 71.50.+t, 71.30.+h, 71.55.Jv

We have made measurements of the electrical resistance of granular aluminum specimens, which give information on electron localization and its relation to the occurrence of superconductivity. The experiment leads to two related results. The first is that between the two regimes of strong localization (characterized by an exponential dependence of resistivity on temperature) and metallic conduction, there exists an intermediate regime in which the resistivity varies approximately logarithmically with temperature. This raises the possibility that such a dependence may be more general than has recently been suggested.[1] The second result is that a resistive superconducting transition is observed in the weak localization as well as in the metallic regimes, but not in that of strong localization.

The specimens are about 1 cm long and 3 mm wide, and range in thickness between 1 and 10 μm. They were prepared by evaporation of pure aluminum from an electron-beam source, in a small amount of oxygen, onto water-cooled glass substrates. Under these conditions the metal deposits in the form of grains surrounded by amorphous aluminum oxide.[2] At the metal concentrations of our specimens the grain size is about 30 Å. The superconducting transition temperature is approximately constant at a little over 2 K for specimens whose resistivity is between 10^{-4} and 10^{-2} Ωcm.[3]

If specimens are prepared with slightly lower metal fractions a transition region is reached in which the resistivity rises very rapidly for small changes in metal content; T_c drops abruptly and then superconductivity disappears. Previous observations of the heat capacity and also its relation to the resistive transition[4] are well described by a model of metal grains which are coupled by Josephson tunneling.[5,6] Some details have also been confirmed by susceptibility measurements.[7] The disappearance of superconductivity is attributed to the lowering of the Josephson coupling energy and the increase in the electrostatic charging energy as the oxide thickness between the metal grains increases.[8]

The measurement of the electrical resistance is complicated not only by the existence of superconductivity and superconducting fluctuations which extend to well over twice T_c, but also by a large negative magnetoresistance in the normal state.[9,10] All specimens were measured in fields up to 9 T. For each specimen with any sign of superconductivity the value of the normal-state resistance in zero field, R_N, is found by extrapolation of the high-field part of the curve of R against H. We assume the dependence in the normal state to be parabolic for low fields, as is found to be the case in the absence of superconductivity, and in the superconducting specimens at fields high enough to suppress the fluctuations. At low temperatures and high fields the dependence of resistance on magnetic field is no longer quadratic, and shows a point of inflection followed by the onset of saturation. The point of inflection occurs at successively lower values of H/T for specimens closer to the regime of strong localization where superconductivity is absent.

In this Letter we present data for five specimens. Their characteristics are shown in Table I, and their variation of R_N against T is shown in Figs. 1 and 2.

The two specimens No. 3 and No. 6 do not become superconducting down to 1.2 K, nor do they show any signs of superconducting fluctuations, which show up as an initial positive magnetoresistance superimposed on the negative magnetore-

TABLE I. Characteristics of the speciments. ρ_{rt} is the resistivity at room temperature, $\rho_{4.2}$ the resistivity at 4.2 K. t is the specimen thickness and T_c the temperature at which the resistance has dropped to half of its maximum value.

Specimen number	ρ_{rt} (Ω cm)	$\rho_{4.2}$ (Ω cm)	t (μm)	T_c (K)	Form of R_N vs T
1	0.04	0.16	6	1.9	Logarithmic
2	0.02	0.12	10	1.8	Logarithmic
5	0.02	0.10	1	1.2	
6	0.05	3	1	⋯	Exponential
3	0.3	32	1	⋯	Exponential

sistance seen at higher fields. It can be seen from Fig. 1(a) that for both of these specimens R_N follows the relation $R_N = R_0 \exp[(T_0/T)^{1/2}]$. This form of the temperature dependence is found in a wide range of granular metals.[2,11] We refer to these specimens as being in the exponential or strong-localization regime.

Two of the specimens (No. 1 and No. 2) have resistive transitions at 1.9 and 1.8 K, respectively. As can be seen from Fig. 1(b) their temperature dependence is much weaker than exponential. Because of its possible relevance to the current work on localization which we discuss below, we show in Fig. 2(a) a graph of R_N against $\log T$ and note that the relation is close to linear. For the same reason we also tried R against $1/\sqrt{T}$ but the deviation from linearity was greater. If one forces a fit with $R = A + BT^{-\alpha}$, the value of α which gives the best fit is about 0.3 for specimen 1 and 0.4 for specimen 2. While the temperature range is too small to determine the functional

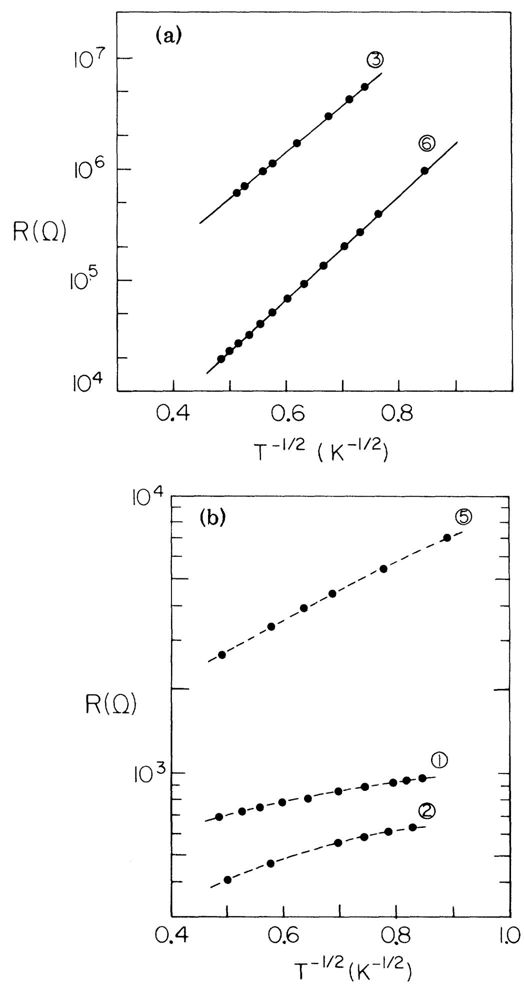

FIG. 1. The temperature dependence of the resistance plotted as $\log R$ against $T^{-1/2}$. (a) Specimens 3 and 6; (b) specimens 1, 2, and 5.

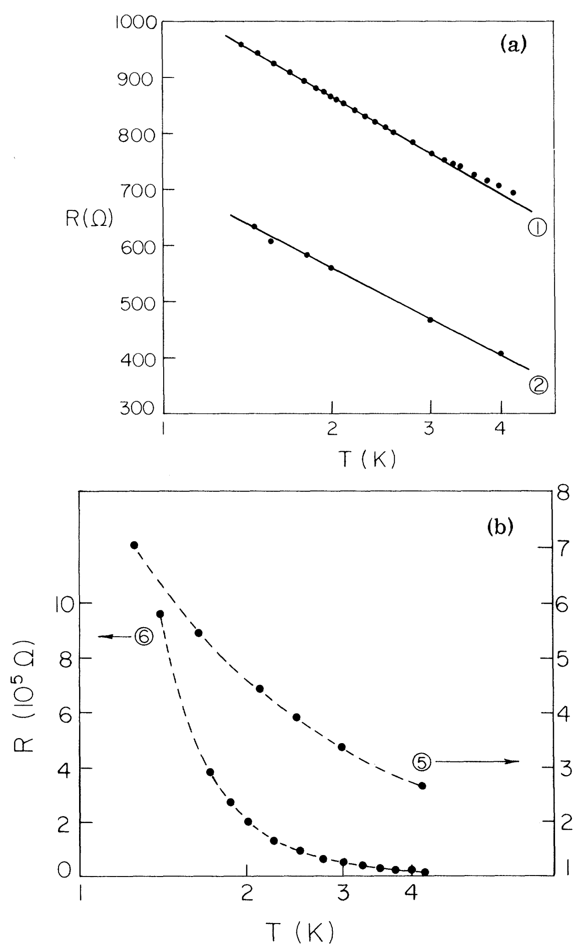

FIG. 2. The temperature dependence of the resistance plotted as R against $\log T$. (a) Specimens 1 and 2; (b) specimens 5 and 6.

form uniquely, there is no doubt that the variation of R_N with T is fundamentally different from that of the specimens in the exponential regime.

A fifth specimen (No. 5) has a resistive transition at 1.2 K. It is therefore extremely close to the threshold where superconductivity disappears. Its variation of R with T is close to but not quite exponential.

These results show that the value of T_c is a sensitive measure of how close a specimen is to the exponential regime. The resistivity is a less reliable indicator. This is presumably so, in part, because the resistivity depends more strongly on minute details of the specimen preparation, such as small variations of the substrate temperature and the residual gas pressure.

The close agreement of the temperature dependence of the normal-state resistance of our weakly localized specimens with the logarithmic form leads us to consider two interpretations. First of all, a logarithmic behavior is not expected for systems that are manifestly three-dimensional. The specimen thicknesses are more than two orders of magnitude larger than the grain size and all other relevant microscopic lengths. However, the specimens may be just above the percolation threshold so that they would contain chains of grains in quasimetallic contact (i.e., either with real metallic connections or with thin insulating barriers with negligible activation energy). The chains will form a network with many cross connections between the parallel paths. In that case the system can be described as being neither one-dimensional nor three-dimensional. The problem of defining dimensionality is well known in percolation theory,[12] where the concept of "fractal" dimensionality[13] has been introduced for such cases. Indeed, one study has shown that the fractal dimensionality of the infinite cluster in a three-dimensional system at the percolation threshold is equal to two.[12] A detailed theory of localization incorporating the percolation aspects has yet to be developed.

The second interpretation of the logarithmic temperature dependence, taken together with the similar forms found not only in two-dimensional systems[14] but also in one-dimensional wires,[15] is that it is of greater generality than is suggested by the recent theories[1] and applies regardless of dimensionality. A similar temperature dependence had been reported earlier for another system[16] that appears to be unquestionably three-dimensional and that is not open to the complications just discussed. It should also be noted that in our granular specimens, and perhaps in others, the localization arises primarily from the Coulomb interaction and not from the disorder in the lattice potential which is the basis of Anderson localization.

The relation between superconductivity and localization has been explored by Dynes, Garno, and Rowell in two-dimensional discontinuous metal films.[17] They concluded that a resistive transition exists only when the specimens are metallic, i.e., when the temperature coefficient of resistance in the normal state is not negative. In contrast, all the specimens which we have described in this Letter have a negative temperature coefficient of resistance.

A most interesting question arising from this work is whether superconductivity can exist in a system in which the electrons are truly localized at absolute zero. If the logarithmic (or some even faster) variation of resistance with temperature were to continue as T approaches zero this would indeed be the case. An alternative explanation of the comparatively weak temperature dependence of the normal-state resistance of our superconducting specimens is that there are metallic threads running from one end of the specimen to the other. In that case the resistance would reach a limiting value as T goes to zero.

We have already noted earlier[9] that the conductivity can be expressed as $\sigma = \sigma_m + \sigma_0 \exp[-(T_0/T)^{1/2}]$, where σ_m is a temperature-independent (metallic) component of the conductivity. However, the observation of such a dependence (in a limited temperature range) is not conclusive proof of metallic paths in parallel with activated ones. An effective-medium model of highly elongated metallic ellipsoids immersed in a medium having the exponential temperature dependence also leads to this form over part of the temperature range.[18]

We are now extending our measurements to lower temperatures to explore this question further and to look for signs of saturation of the resistance. So far it seems clear, in any case, that the existence of superconductivity is intimately related to electron localization, and is a particularly sensitive indicator of its presence.

We acknowledge useful discussions with Paul Leath. We would also like to acknowledge the technical help of G. Hughes. The research was supported by the National Science Foundation under Grant No. DMR-78 24213 and by the Rutgers University Research Council. Helium gas was supplied by the U. S. Office of Naval Research.

[a]Present address: IBM Thomas J. Watson Research Center, Yorktown Heights, N. Y. 10598.

[1]P. W. Anderson, E. Abrahams, and T. V. Ramakrishnan, Phys. Rev. Lett. 43, 718 (1979).

[2]B. Abeles, *Applied Solid State Science*, edited by R. Wolfe (Academic, New York, 1976), Vol. 6, p. 1.

[3]G. Deutscher, H. Fenichel, M. Gershenson, E. Grünbaum, and Z. Ovadyahu, J. Low Temp. Phys. 10, 231 (1973).

[4]T. Worthington, P. Lindenfeld, and G. Deutscher, Phys. Rev. Lett. 41, 316 (1978).

[5]G. Deutscher, Y. Imry, and L. Gunther, Phys. Rev. B 10, 4598 (1974).

[6]G. Deutscher, O. Entin-Wohlman, S. Fishman, and Y. Shapira, to be published; G. Deutscher and M. L. Rappaport, J. Phys. (Paris), Colloq. 39, C6-581 (1978), and J. Phys. (Paris) 40, L-219 (1979). This work is reviewed by G. Deutscher, O. Entin-Wohlman, M. Rappaport, and Y. Shapira, in Proceedings of the International Conference on Inhomogeneous Superconductors, Berkeley Springs, West Virginia, November, 1979 (to be published).

[7]M. Gershenson and W. L. McLean, to be published.

[8]B. Abeles, Phys. Rev. B 15, 2828 (1977); W. L. McLean and M. J. Stephen, Phys. Rev. B 19, 5925 (1979).

[9]W. L. McLean, P. Lindenfeld, and T. Worthington, in *Electrical Transport and Optical Properties of Inhomogeneous Media—1977*, edited by J. C. Garland and D. B. Tanner, AIP Conference Proceedings No. 40 (American Institute of Physics, New York, 1978), p. 403.

[10]W. L. McLean, T. Chui, B. Bandyopadhyay, and P. Lindenfeld, in Proceedings of the International Conference on Inhomogeneous Supercondcutors, Berkeley Springs, West Virginia, November, 1979 (to be published).

[11]P. Sheng, B. Abeles, and Y. Arie, Phys. Rev. Lett. 31, 44 (1973).

[12]D. Stauffer, Phys. Rep. 54, 1 (1979).

[13]B. B. Mandelbrot, *Les Objets Fractals: Forme, Hasard, et Dimension* (Flammarion, Paris and Montreal, 1975) [translation: B. B. Mandelbrot, *Fractals: Form, Chance, and Dimension* (W. H. Freeman, San Francisco, 1977)].

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

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

[16]C. C. Tsuei, Solid State Commun. 27, 691 (1978).

[17]R. C. Dynes, J. P. Garno, and J. M. Rowell, Phys. Rev. Lett. 40, 479 (1978).

[18]W. L. McLean, to be published.

Nonmetallic Conduction in Electron Inversion Layers at Low Temperatures

D. J. Bishop, D. C. Tsui, and R. C. Dynes
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 30 November 1979)

We have measured the resistance of electron inversion layers in Si metal-oxide-semiconductor field-effect transistors at low temperatures (~50 mK) and low electric fields (~0.1 V/m). At low values of $R_\square$ we observe logarithmic dependences of the resistance on both temperature and applied electric field which scale only on $R_\square$. We observe a gradual transition to an exponential dependence at $R_\square \gtrsim 10$ kΩ. The logarithmic dependences agree qualitatively but not quantitatively with current theories of localization.

PACS numbers: 73.40.Qv, 73.25.+i

A number of recent experimental and theoretical papers have addressed the subject of electron transport and localization in a quasi two-dimensional (2D) system.[1-5] We report measurements of the electrical conductivity of electron inversion layers in silicon metal-oxide-semiconductor field-effect transistors (MOSFET's) at low temperatures and compare them with recent theoretical ideas and experimental results on metal films.[5] Our measurements show that at sheet resistances $R_\square \sim 10$ kΩ/□ there is a smooth and gradual crossover from an exponential to a logarithmic dependence on temperature and applied electric field. Similar to the previous observations of Dolan and Osheroff,[5] we see no evidence for true metallic behavior below 10 kΩ/□. In addition, our results show that these effects scale only with $R_\square$ of the inversion layer.

Our measurements were performed on n-channel MOSFET's fabricated on (100) and 111) surfaces of p-type silicon with peak mobilities of ~2000 cm^2/V·sec at 4.2 K. The Si electron inversion layer is a 2D electron gas whose density is determined by the applied gate voltage. Also the mobility can be varied by applying a substrate bias which moves the electron wave function closer to, or further away from, the Si-oxide interface. This system has been extensively studied by a