

## Tunneling and Transport Measurements at the Metal-Insulator Transition of Amorphous Nb:Si

G. Hertel, D. J. Bishop, E. G. Spencer, J. M. Rowell, and R. C. Dynes

*Bell Laboratories, Murray Hill, New Jersey 07974*

(Received 29 September 1982)

Tunneling and conductivity measurements through the metal-insulator transition in amorphous  $\text{Nb}_x\text{Si}_{1-x}$  are reported. The authors observe the correlation gap  $\Delta$  which varies with resistivity and have related this to the metal-insulator transition as observed in the conductivity. The samples were prepared by a process which allows precise control of the Nb concentration. The results as a function of voltage, temperature, and concentration are compared with current theoretical predictions.

PACS numbers: 71.30.+h, 71.50.+t, 72.15.Cz, 73.40.Gk

The metal-insulator transition in disordered materials has been recently studied in several transport measurements.<sup>1-4</sup> All experiments indicate that there is no minimum metallic conductivity.<sup>3,4</sup> In addition, tunneling measurements have shown a strong anomaly in the density of states at the Fermi level indicative of very strong many-body contributions to the metal-insulator transition.<sup>1,2</sup> Altshuler and Aronov<sup>5</sup> had earlier shown that many-body effects were important. In a phenomenological scaling theory McMillan<sup>6</sup> incorporated both localization and correlation effects on equal footing. He predicted a square-root singularity  $N(E) = N(0)[1 + (E/\Delta)^{1/2}]$  in the single-particle density of states at the Fermi level on the metallic side of the transition. This was later verified by the tunneling experiments. The parameter  $\Delta$  was interpreted as a correlation gap—the precursor of the energy gap in the single-particle density of states which opens up on the insulating side of the metal-insulator transition. At the metal-insulator (M-I) transition,  $\Delta$  goes to zero,  $N(0)$  goes to zero, and the energy gap begins to open up.

In this Letter we report high-precision tunneling and conductivity measurements through the metal-insulator transition in amorphous  $\text{Nb}_x\text{Si}_{1-x}$ . Our samples were prepared by simultaneously cosputtering Nb and Si onto a substrate producing a shallow concentration gradient. Unlike previous measurements which had difficulty in producing controlled, uniform concentration changes, our method allowed us to measure the properties of the amorphous material in a controlled and systematic way as we moved through the M-I transition in small, uniform increments. As in previous experiments we have observed a correlation gap  $\Delta$  which varies with resistivity. However unlike previous experiments we have made low-temperature transport measurements to correlate

our tunneling results directly with the metal-insulator transition. In addition we have observed the metal-insulator transition by the onset of the breakdown of the single-step tunneling process when the energy gap appears at the Fermi energy and localized states appear in the  $\text{Nb}_x\text{Si}_{1-x}$ . By controlling concentration as easily as voltage and temperature we can obtain experimental relationships among them and in this Letter these are presented and compared with current theoretical predictions.

Our samples were prepared by cosputtering Nb and Si from separate targets onto sapphire substrates (see inset in Fig. 1). The films had a thickness of  $\sim 1000 \text{ \AA}$  and the concentration, as determined by Rutherford backscattering with 1.8-MeV  $\alpha$  particles, varied linearly from  $\text{Nb}_{20}\text{Si}_{80}$  on one end to  $\text{Nb}_4\text{Si}_{96}$  on the other.<sup>7</sup> X-ray measurements of the films showed them to be highly disordered, demonstrating a liquidlike radial distribution function. To avoid edge effects for both the tunneling and transport measurements only the center region of the films ( $\sim 0.5 \text{ mm}$  wide) was probed. For the conductivity measurements the films were lithographically patterned after deposition to form a narrow stripe. 42 lead cross stripes were then evaporated on and the conductivity of the 41 regions of the sample could be measured as a function of temperature with a four-terminal technique.

An advantage of this sample preparation technique is that in all theories the universal parameter is the resistivity while in an experiment one measures a resistance. By virtue of all the samples being on the same substrate with the same thickness and a width precisely determined by photolithography the resistivities of each bin are simply related to the resistance by the same geometrical constant. Thus scatter in the data in comparing the results of different resistivity sam-

ples is reduced.

The samples for tunneling were prepared in an identical manner except for a Nb backing film sputtered prior to deposition of the  $Nb_xSi_{1-x}$  films. This Nb film reduced the spreading resistance in the tunneling measurements. After deposition, the tunneling samples were oxidized in air for several days. The edges of the film were then masked off with an insulating layer and lead cross stripes were then evaporated on. This technique produced 42 evenly spaced junctions along the sample with similar properties with only the Nb concentration slowly varying from one junction to the next. A total of four samples were examined—two via tunneling and two via conductance. The results for each measurement were the same to within one bin spacing. In addition the M-I transition was at the same position on the sample for all four films. This fact gives us confidence that the samples are identical and so we can combine the data for the various samples.

The resistivity was measured as a function of temperature from 10 mK to 5 K for the two conductance samples with a four-terminal bridge. At the most metallic end ( $\sim 20.5\%$  Nb) the  $Nb_xSi_{1-x}$  was superconducting with a  $T_c$  of 280 mK. The  $T_c$ 's decreased monotonically with decreasing Nb concentration to zero at a concentration of 18.0%.

For those regions at Nb concentrations less than 18% the conductance was finite down to  $T \sim 10$  mK. The conductivity as a function of temperature for those samples was fitted by a power-law

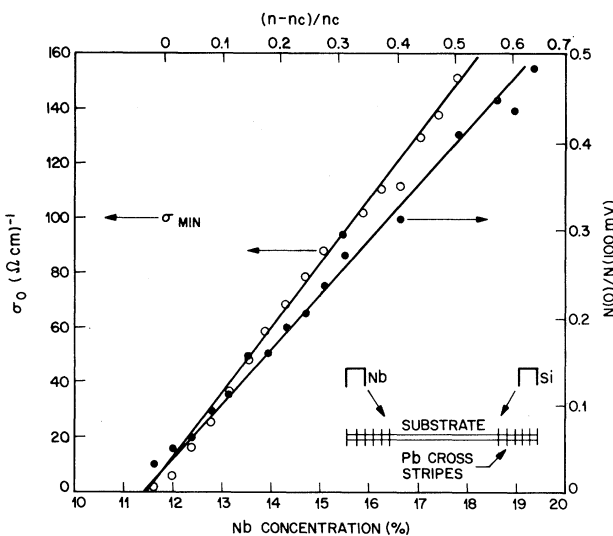


FIG. 1.  $\sigma_0$  and  $N(0)/N(100 \text{ mV})$  vs Nb concentration. Inset shows method of sample preparation.

dependence and the conductivity at zero temperature  $\sigma_0$  was obtained. At low temperatures  $\sigma(T)$  was not changing very much with temperature and the values of  $\sigma_0$  were almost independent of the functional form used. In Fig. 1 we have plotted the resultant  $\sigma_0$  versus  $n$ . As the Nb concentration is decreased  $\sigma_0$  decreases smoothly and the metal-insulator transition is reached at a Nb concentration of  $\sim 11.5\%$ . Two points should be noted: (a)  $\sigma_0$  goes smoothly to zero at  $n_c$  with many samples having a  $\sigma_0$  well below the  $\sigma_{\text{min}}$  suggested by Mott. (b)  $\sigma_0$  is linear in  $(n - n_c)/n_c$  in the limit  $\sigma_0 \rightarrow 0$ .<sup>8</sup>

The temperature-dependent part  $\sigma(T)$ , which is the measured conductivity  $\sigma_m(T)$  minus  $\sigma_0$ , is roughly the same for all samples and has a value of  $\sigma(T) \sim 7 (\Omega \text{ cm})^{-1}$  at 1 K. If one fits a power law to  $\sigma(T) \sim T^N$  one obtains a value  $N \sim 0.5-0.7$  for all metallic samples excepting for that immediately preceding the transition. This is in rough agreement with the  $T^{1/2}$  temperature dependence seen for Coulomb effects in Si:P.<sup>9</sup>

The tunneling measurements were performed at 2 K in a magnetic field just sufficient to suppress the superconductivity of the lead counterelectrode ( $\sim 2 \text{ kG}$ ). On the metallic side of the metal-insulator transition we observed a square-root zero-bias anomaly as previously seen in AuGe (Ref. 1) and granular aluminum.<sup>2</sup> This is shown in Fig. 2

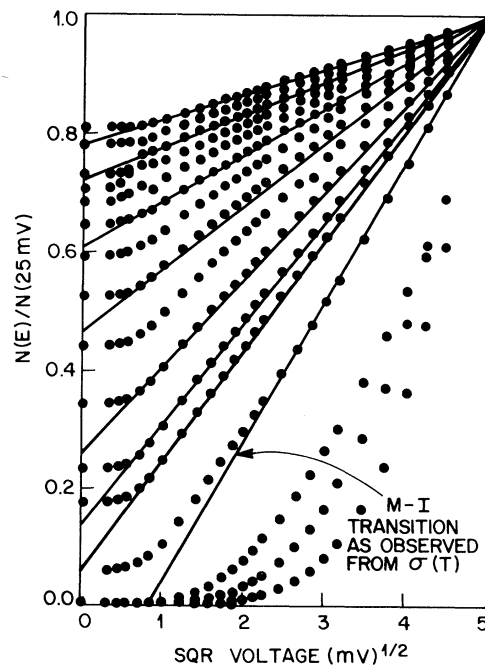


FIG. 2.  $N(E)$  vs tunneling voltage.

where we plot  $N(E)$  versus  $\sqrt{E}$ . All of the curves have been normalized at a voltage of 25 mV. The deviation at voltages below 1 mV is due to thermal smearing. As one approaches the metal-insulator transition the singularity in the tunneling conductance becomes much stronger and the density of single-particle states at the Fermi level which is proportional to the conductance at zero bias is found to decrease. This extrapolated  $N(0)$  is shown in Fig. 1.<sup>10</sup> Note the linear dependence. The metal-insulator transition occurs when the conductance extrapolated back to zero bias reaches zero. The junctions beyond the transition do not show a square-root dependence of the tunneling conductance on bias voltage. On the insulating side the curves indicate the opening up of the energy gap but these data are not an accurate measure of this gap.

Shown in Fig. 3 are the values of the correlation gap  $\Delta$  calculated from the data shown in Fig. 2 with the relation  $N(E) = N(0)[1 + (E/\Delta)^{1/2}]$ . The values of these gaps range downward from several hundred millivolts and decrease to the smallest measured value of 0.038 mV as the silicon concentration is increased. In addition Fig. 3 also shows data from another  $\text{Nb}_x\text{Si}_{1-x}$  sample as well as data from granular aluminum. This agreement is strong evidence that the correlation

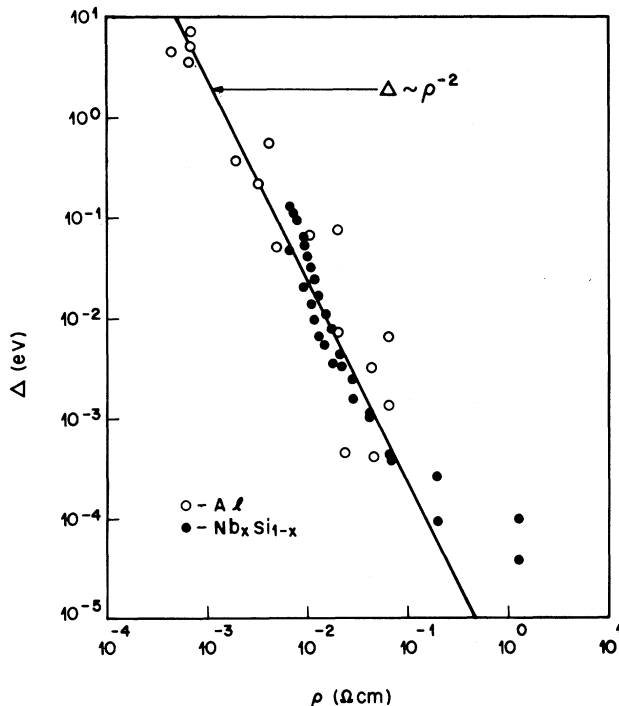


FIG. 3. The correlation gap  $\Delta$  vs resistivity for  $\text{Nb}_x\text{Si}_{1-x}$  as well as for granular aluminum (Ref. 2).

gap depends only on one single parameter, the resistivity, but is material independent.

The correlation gaps shown in Fig. 3 show an approximately  $\rho_0^{-2}$  dependence on the resistivity as shown by the straight line in the figure ( $\rho_0 \equiv 1/\sigma_0$ ).

At voltages much greater than  $\Delta$  the tunneling density of states no longer obeys the functional form  $N(E) = N(0)[1 + (E/\Delta)^{1/2}]$  but crosses over to the form  $N(E) \sim E^{1/3}$ . For samples with gaps  $> 1$  mV, this crossover was seen to occur for  $E \sim \Delta$  where  $\Delta$  is the correlation gap obtained at low voltages. It was observed that near the transition, the region where  $N(E)$  varied as  $E^{1/2}$  became rather small resulting in greater uncertainty in  $\Delta$ . This is evident in Fig. 3 for high  $\rho_0$ .

Our experimental observations can be summarized as follows. In amorphous  $\text{Nb}_x\text{Si}_{1-x}$  there is a metal-insulator transition at a Nb concentration of  $\sim 11.5\%$  as shown by the conductivity and the tunneling density of states. (a) At that transition,  $N(0), \sigma_0 \sim (n - n_c)$ , i.e., are linear functions of concentration. (b) For  $E < \Delta$ ,  $N(E) \sim N(0)[1 + (E/\Delta)^{1/2}]$ . (c) For  $E > \Delta$ ,  $N(E) \sim E^{1/3}$ . (d) The correlation gap  $\Delta \sim \rho_0^{-2} \sim (n - n_c)^{-2}$ . And (e)  $\sigma_m(T) \sim \sigma_0(1 + \alpha T^{1/2})$  and  $\sigma(T)$  is roughly independent of  $\sigma_0$  for all metallic samples.

In the theory of McMillan<sup>5</sup> the correlation length  $\xi$  is related to the concentration by

$$\xi \sim (n - n_c)^{-\nu} \quad (1)$$

with  $\nu$  expected to be close to 1. His second parameter  $\eta$  relates the energy and length scales in the critical region. He predicts  $1 < \eta < 3$ . He also predicts the following relations:

$$N(0) \sim \xi^{-\eta-3}, \quad (2a)$$

$$\sigma_0 \sim \xi^{-1}, \quad (2b)$$

$$\Delta \sim \xi^{-\eta}. \quad (3)$$

Taking (1) and (2) and comparing with (a) we obtain

$$-\nu(\eta - 3) = 1, \quad (4a)$$

$$(-1)(-\nu) = 1; \quad (4b)$$

and combining (1) and (3) and comparing with (d) we obtain

$$\eta\nu = +2. \quad (5)$$

(4) and (5) then imply  $\eta \sim 2, \nu \sim 1$ . McMillan also predicts the functional form  $N(E) \sim N(0)[1 + (E/\Delta)^{1/2}]$  observed in the tunneling for  $E < \Delta$ . Finally he predicts the functional form  $\sigma_m(T) = \sigma_0[1 + (kT/$

$\Delta)^{1/2}$ ]. This gives approximately the temperature dependence we see as well as the fact that  $\sigma_m(T) - \sigma_0$  is independent of  $\sigma_0$ . His form implies  $\sigma_m(T) - \sigma_0 \sim \sigma_0(kT/\Delta)^{1/2}$  which is independent of  $\sigma_0$  because  $\Delta \sim \rho_0^{-2}$ . It also predicts the right magnitude. For example, from our tunneling data for  $\rho = 0.0211 \Omega \text{ cm}$  we obtain a correlation gap of 3.25 mV. These imply  $[\sigma_0(kT/\Delta)]^{1/2} = 7.8 (\Omega \text{ cm})^{-1}$  at  $T = 1 \text{ K}$  which is in good agreement with our conductance measurements.

In their theory Gefen and Imry<sup>11</sup> have performed a self-consistent calculation taking into account both localization and interaction effects. They also define two parameters  $\eta'$  and  $\nu'$ . In their theory for  $E \gg \Delta$  they obtain  $N(E) \sim E^{\eta'/3}$  which implies  $\eta' \sim 1$  from our data. They find  $N(0) \sim \xi^{\eta'}$  which also implies  $\eta' \sim 1$ . In addition for  $E < \Delta$  they find a square-root dependence for the density of states,  $N(E) \sim [1 + (E/\Delta)^{1/2}]$ . However, they find  $\sigma_0 \sim \xi^{-(\eta'+1)}$  which is inconsistent with our results.

Lee<sup>12</sup> has pointed out that both theories have used the renormalized density of states  $N(E)$  to calculate the Thomas-Fermi screening constant  $\kappa$  in  $\kappa^2 = 4\pi e^2 N(E)$ . The screening length therefore diverges when  $N(E)$  goes to zero. Instead of  $N(E)$ , Lee has suggested that one should use the thermodynamic density of states  $dn/d\mu$  which does not contain any singularities. This screening term is used by Gefen and Imry in the calculation of  $\sigma_0$ , and so may explain the inconsistency of their prediction with our results.

In conclusion we have observed the metal-insulator transition in amorphous  $\text{Nb}_x\text{Si}_{1-x}$  by tunneling and transport measurements. Our results have shown that the zero-bias anomaly in the density of states can be correlated with the conductance to obtain the exponents in the scaling theories of localization. In addition we have shown that the

correlation gaps seen in amorphous materials at the metal-insulator transition are a universal function of resistivity independent of other material parameters.

<sup>1</sup>W. L. McMillan and J. Mochel, Phys. Rev. Lett. **46**, 556 (1981).

<sup>2</sup>R. C. Dynes and J. P. Garno, Phys. Rev. Lett. **46**, 137 (1981).

<sup>3</sup>B. M. Dodson, W. L. McMillan, J. M. Mochel, and R. C. Dynes, Phys. Rev. Lett. **46**, 46 (1981).

<sup>4</sup>M. A. Paalanen, T. F. Rosenbaum, G. A. Thomas, and R. N. Bhatt, Phys. Rev. Lett. **48**, 1284 (1982).

<sup>5</sup>B. L. Altshuler and A. G. Aranov, Zh. Eksp. Teor. Fiz. **77**, 2028 (1979) [Sov. Phys. JETP **50**, 968 (1979)].

<sup>6</sup>W. L. McMillan, Phys. Rev. B **24**, 2739 (1981).

<sup>7</sup>A linear dependence of concentration on position was observed from the  $\alpha$  backscattering spectra. Each individual point had a concentration uncertainty of  $\sim 1\%$  but a least-squares fit of the variation brought that down to  $\sim 0.2\%$ . The error was in the statistics of the measurement, not in concentration variation in the sample.

<sup>8</sup>A linear least-squares fit to the data suggests an exponent of  $1.0 \pm 0.1$ . Experiments in amorphous  $\text{Si}_{1-x}\text{Au}_x$  have been fitted with an exponent of 0.84 [N. Nishida, M. Yamaguchi, T. Furubayashi, K. Morigaki, H. Ishimoto, and K. Ono, Solid State Commun. **44**, 305 (1982)]; however, the scatter in the data is considerable and there is only one point below  $\sigma_{\text{min}}$ . In crystalline Si:P an exponent of  $0.49 \pm 0.07$  was obtained (Ref. 4).

<sup>9</sup>T. F. Rosenbaum, K. Andres, G. A. Thomas, and P. A. Lee, Phys. Rev. Lett. **46**, 568 (1980).

<sup>10</sup>What is shown is a plot of  $\overline{N(0)}/N(100 \text{ mV})$ . Sufficiently far from the Fermi level one expects that the square-root corrections to the density of states will be negligible and normalization by  $N(100 \text{ mV})$  will divide out geometrical differences in the junctions.

<sup>11</sup>Y. Gefen and Y. Imry, to be published.

<sup>12</sup>P. A. Lee, to be published.