Electron Tunneling Experiments on Amorphous $Ge_{1-x}Au_x$

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(Received 17 July 1980)

Tunneling measurements of the electronic density of states of amorphous $Ge_{1-x}Au_x$ near the metal-insulator transition at $x = 0.12$ are reported. In the metallic phase there is a giant zero-bias anomaly with a minimum in the density of states at the Fermi energy. In the insulating phase a pseudogap opens, centered about the Fermi energy, with zero density of states at the Fermi energy.

PACS numbers: 71.30.+h, 73.40.Gk

We have recently reported[1] electrical conductivity measurements on amorphous $Ge_{1-x}Au_x$. The material exhibits a continuous metal-insulator transition at $x = 0.12$. On the metallic side $x > 0.12$ the conductivity extrapolates to a finite value at zero temperature and the quantum states near the Fermi energy E_F are extended. On the insulating side $x < 0.12$ the conductivity varies as $\exp[-(b/T)^{1/4}]$ which is characteristic of Mott's[2] variable-range hopping mechanism. The quantum states near the Fermi energy are therefore localized[3] and the transition has the character of an Anderson transition. In this paper we report electron tunneling experiments on $Ge_{1-x}Au_x$ to test the one-electron theory of localization and to look for the correlation effects predicted by Altshuler and Aronov.

The tunnel junctions were prepared by thermal oxidation of aluminum and flash evaporation in high vacuum of pellets of $Ge_{1-x}Au_x$. An x-ray study confirmed that the films are amorphous. In order to be sure that the junctions did not contain metallic bridges we checked the BCS characteristic of aluminum at 1 K and, in addition, verified that there was no popcorn noise at high bias. The normal state tunneling conductance dI/dV measurements were made at 2.5 K. Several junctions on one slide were measured and the tunneling conductance reproduced typically within 3% demonstrating that tunneling quantitatively and reproducibly measures the properties of the material near (within $\simeq 100$ Å) the tunneling surface. The material as prepared is apparently somewhat inhomogeneous and the conductance did not reproduce as well from one evaporation to the next. The tunneling conductance was measured with use of the four-probe geometry and a complex conductance bridge. With a 100-μV ac signal the bridge precision is 0.01% for a typical 10-kΩ junction.

The raw data for several samples is presented in Fig. 1; we arbitrarily normalize the conductance to unity for a positive bias of 0.3 eV. We observe an asymmetry and exponential increase of conductance at high bias typical of normal metallic tunnel junctions.[4] The anomaly is symmetric about zero bias. The $x = 0.20$ and 0.16 samples were conducting with $\sigma(T = 0) = 880$ and 630 $(\Omega\,\mathrm{cm})^{-1}$; several $x = 0.12$ samples were very near the transition and the $x = 0.08$ sample was insulating. Several samples were measured for each composition; we show data for only one. The anomalies are sharp except for thermal smearing $\simeq 2kT$.

We interpret the tunneling conductance at bias V as a direct measurement of the electronic density of states of $Ge_{1-x}Au_x$ at energy $E = eV$ from the Fermi energy, at least in the metallic phase. There are small corrections because of barrier phonon emission[4] and variation of tunneling matrix elements with bias.[4] We observe both effects but they are small enough below 0.1 V to be ignored in a qualitative interpretation of the data. A small zero-bias anomaly (less than 1%) is ob-

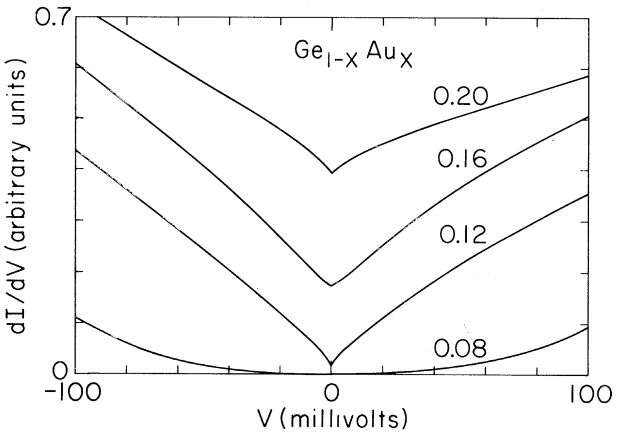

FIG. 1. The conductance dI/dV of the tunnel junction vs voltage on the $Ge_{1-x}Au_x$ electrode for four samples with $x = 0.08$, 0.12, 0.16, and 0.20. The conductance is arbitrarily normalized to unity at + 0.3 V.

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served in Al-Al and Al-Au tunnel junctions; clearly, the large effects reported here are because of the $Ge_{1-x}Au_x$, not the Al or the oxide barrier. We therefore interpret the conductance data in Fig. 1, apart from the weak asymmetry, as being directly proportional to the one-electron density of states. In the metallic phase ($x = 0.20$ and 0.16) we find an anomaly in the density of states, with a minimum at the Fermi energy, which deepens as one approaches the transition. At the transition ($x = 0.12$) the density of states vanishes at the Fermi energy and increases approximately linearly both above and below the Fermi energy; this is the critical behavior. In the insulating phase ($x = 0.08$) the tunneling conductance is small and varies approximately as V^2; the interpretation of the tunneling conductance as simply a density of states is probably invalid in the insulating phase, because of electric field penetration into the insulator.

The only plausible interpretation of our data is that an energy gap (or pseudogap) opens up in the insulating phase and that the metal-insulator transition has the character of a Mott[2] transition. The anomaly in the density of states in the metallic phase is a pretransition effect presaging the opening of the correlation gap in the insulating phase. The gap is clearly a correlation gap, rather than a semiconductor band-structure gap, since the anomalies occur at precisely the Fermi energy. The very small density of states in the insulating phase is presumably the band tail within the correlation gap.

This interpretation is supported by comparison with theoretical models of correlation effects. For the metallic samples with $x = 0.20$ the density of states can be fit with $N(E) = N(0)\{1 + [(E - E_F)/\Delta]^{\alpha}\}$ with $\alpha \simeq 0.6$. Altshuler and Aronov[5] studied a model of electron correlation in a dirty normal metal and predict such an anomaly with $\alpha = \frac{1}{2}$, which is in qualitative agreement with our data. Their model was proposed to explain tunneling data of Bermon and So.[6] One of us[7] has developed a scaling theory of the metal-insulator transition in amorphous materials including both localization and correlation. That model predicts the qualitative behavior of the density of states which we observe, the deepening anomaly in the metallic phase, and the correlation gap in the insulating phase. The correlation effect discussed by Altshuler and Aronov for weak interactions is an energy-level shift which is directly observable in tunneling. More generally, using the tunneling Hamiltonian formalism,[8] one can see that the tunneling conductance is proportional to the one-electron density of states. We note that Harrison's argument,[9] that band-structure effects do not appear in tunneling, does not apply to amorphous materials.

In conclusion, we have established experimentally that electron correlation effects are strong near the metal-insulator transition in amorphous $Ge_{1-x}Au_x$ and that a correlation pseudogap opens in the insulating phase. The giant zero-bias anomaly in the density of states in the metallic phase is a pretransition anomaly fortelling the opening of the correlation pseudogap in the insulating phase. The metal-insulator transition in amorphous $Ge_{1-x}Au_x$ therefore has the character of a Mott[2] transition, with a correlation gap in the insulating phase. These measurements complement the electrical conductivity measurements[1] which show Anderson localization[3] in the insulating phase. We therefore find that, near the metal-insulator transition in amorphous materials, correlation and localization go hand in hand. This behavior is consistent with the scaling theory.[7] It is inconsistent with the one-electron theory of localization which predicts no density-of-states anomaly.

We would like to thank P. W. Anderson and P. A. Lee for stimulating discussions of the correlation effects. We would also like to thank B. Dodson, R. C. Dynes, and D. Ginsberg for helpful discussions and assistance in various phases of this research. This work was supported in part by the National Science Foundation under Grant No. DMR-77-23999.

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