RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 36, NUMBER 14 15 NOVEMBER 1987-I

Field-dependent electrical conductivity in disordered $Ge_{1-x}Au_x$ alloys

J. R. Cooper,* W. P. Beyermann, S. W. Cheong, and G. Grüner
Department of Physics and Solid State Science Center, University of California, Los Angeles, California 90024

S. Von Molnar
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 29 April 1987)

The electric-field-dependent conductivity was studied on $Ge_{1-x}Au_x$ alloys near the metal-insulator transition. We have been able to rule out trivial heating effects, and our experiments are described in terms of electron heating. Our findings are in good agreement with theories which discuss electron-phonon relaxation time effects.

While many interesting localization effects have been explored recently in a variety of solid-state systems,[1,2] much less is known about the dynamics of localized states. Near the metal-insulator transition, the conductivity σ is expected to be frequency (ω) dependent and possibly also electric field (E) dependent because of the small energy scales involved. Complementary studies of $\sigma(\omega)$ and $\sigma(E)$ have proved to be very useful in investigating the dynamics of charge-density waves.[3] As part of a similar study of disordered systems, we report here measurements of $\sigma(E)$ for vapor-deposited GeAu films.

In principle, trivial sample heating (i.e., the heating of both electrons and phonons) may occur, especially for large applied dc voltages. This can be checked and sometimes ruled out experimentally. The electric field can also lead to a heating of the electron gas alone (with the phonon system remaining at the bath temperature), as was suggested[4] as the most likely explanation of the nonlinear conductivity observed in thin metal wires.[5] Finally, it is also possible that in some materials electric-field-induced delocalization can occur.

We have performed electric-field-dependent conductivity studies of the model system $Ge_{1-x}Au_x$, which undergoes a metal-insulator transition as x is varied[6] around a critical concentration $x=12\%$. By performing experiments using pulsed fields, and on samples with various thicknesses, we can rule out trivial heating effects. Also, by using a simple model of electron heating we can reproduce all our findings concerning $\sigma(T,E)$ over a broad temperature and field range. We argue that electron heating is the dominant mechanism for nonlinear effects in $Ge_{1-x}Au_x$ alloys.

$Ge_{1-x}Au_x$ alloys were prepared by flash evaporating premelted ingots of the appropriate concentrations. The qualitative features of $\sigma(T,x)$ were similar to those of earlier studies,[6] but more work is required to clarify which law best describes the temperature dependence below 1 K.

Both dc and pulsed-field methods were used. In later experiments, the instrumental dead time for the pulse measurements was reduced to 400 ns, and pulses as short as 1 μs could be employed. Samples were directly immersed in liquid ^{4}He or liquid ^{3}He in order to cover the temperature range 4.2–0.4 K. Examples of the experimental results obtained using 2 μs pulses are shown in Fig. 2.

Trivial sample heating was ruled out by initial experiments which showed that (a) the relevant thermal resistance was perpendicular to the plane of the film (since identical results were obtained for 2-lead and 4-lead measurements) and (b) two films with the same nominal concentration and similar $\sigma(T)$ dependences, but different thicknesses (1100 and 3000 Å), gave the same $\sigma(E)$ behavior. In other words, the effect of trivial heating (heating electrons and phonons together) could be separated from the other two possible effects since it depends on the power dissipated per unit area rather than the power per unit volume or the electric field strength E.

Thus, the nonlinearities observed could be due either to electron heating or to field-induced delocalization. In an electron-heating model, for small differences between the electron temperature (T_e) and the phonon temperature ($T_{\rm ph}$)

$$\sigma E^2 R_{e-{\rm ph}} = (T_e - T_{\rm ph}) = \Delta T \equiv \Delta\sigma/(d\sigma/dT) \ , \quad (1)$$

where $R_{e-{\rm ph}}$ is the electron-phonon thermal resistance at a temperature T_e (or $T_{\rm ph}$) and $\Delta\sigma$ is the initial increase in conductivity which is proportional to E^2 ($\Delta\sigma = \sigma''(0)E^2/2$). By measuring $\sigma''(0)$ and plotting $\sigma''(0)/[2\sigma(0)d\sigma/dT]$ vs $T_{\rm ph}$ (or equivalently $(d\sigma/dV^2)/[\sigma(0)d\sigma/dT]$) $R_{e\text{-ph}}$ can be determined at every base temperature T. This is shown in Fig. 1, where the various symbols represent data for 2- and 30-μs pulses and dc measurements. The full line shows T^{-4} dependence. It can be seen that the exponent $p=4$ gives an adequate fit to the data, although one can hardly distinguish between $p=4$ and $p=5$. We note that the large uncertainty in p arises from the fact that the E^2 term in $\sigma(E)$ is quickly overshadowed by higher-order terms, and is thus difficult to measure by pulse techniques.

A simple model was used to calculate $\dot{Q}$, the rate of energy transfer from electrons to phonons for arbitrary values of T_e and $T_{\rm ph}$. For $T_e \simeq T_{\rm ph}$ it gives $R_{e\text{-ph}} \sim T_e^{-4}$ in agreement with the above results. For general temperatures

$$\dot{Q}=A\int_0^\infty x^4dx\left[\frac{1}{(e^{x/T_e}-1)(1-e^{-x/T_{ph}})}-\frac{1}{(e^{x/T_{ph}}-1)(1-e^{-x/T_e})}\right]\equiv AF(T_e,T_{ph})\ . \tag{2}$$

In deriving this expression, momentum conservation is neglected and the rate of energy transfer from electrons to phonons is assumed to be limited by the requirement of energy conservation in electron-phonon collisions. This is a good approximation if the momentum relaxation time of the electrons is much shorter than their energy relaxation time or if the electron momentum is not a good quantum number and should be particularly appropriate for the disordered GeAu films considered here.

In the above expression, the x^2dx term arises from the phonon density of states, one power of x and one exponential factor come from the overlap of electron Fermi-Dirac functions before and after collision, and one x term comes from the energy loss (or gain) at a collision. The remaining exponential factor arises from the phonon occupation number. Equation (2) is only valid for T_e and T_{ph} much less than Debye temperature. For $T_e \gg T_{ph}$, $F(T_e, T_{ph})\sim T_e^5$. While for $T_e=T_{ph}+\Delta T$, $F(T_e,T_{ph}) =116T_e^4\Delta T$. Thus in equilibrium

$$\sigma(T_e)E^2=AF(T_e,T_{ph})\ . \tag{3}$$

We calculated $F(T_e,T_{ph})$ numerically for a given value of T_{ph}, and with one value of the parameter A we could solve Eq. (3) to obtain T_e as a function of E, i.e., $\sigma(T_e)$ as a function of voltage V. Using this procedure we were able to generate excellent fits to the experimental pulsed-field data over a wide range of electric field strengths and temperatures. These fits are shown in Fig. 2 by solid lines with the free parameter $A=1.19\ \mu\mathrm{W\,K^{-5}}$ throughout.

The model given in the previous section leads to an electron-phonon resistance which diverges as T^{-4} for small temperature differences between the electrons and the phonons. Such a power law was derived theoretically by Little[7] and was found experimentally for copper foil below 0.2 K some time ago by Anderson and Peterson.[8] More recently, Roukes *et al.*[9] found $R_{e\text{-ph}}\sim T^{-4}$ from a study of thin copper films between 25 and 320 mK. The above authors all obtain a value of $R_{e\text{-ph}}VT^4$ in the range 2 to $5\times10^{-4}\ \mathrm{K^5cm^3\,W}$.

In our case the value of $R_{e\text{-ph}}$ from the straight line in Fig. 1 is in good agreement with that obtained from the value of A which generates all of the curves in Fig. 2, namely,

$$R_{e\text{-ph}}=(1.0\pm0.1)\times10^{-3}\ \mathrm{K^5cm^3/W}\ . \tag{4}$$

For our GeAu alloys, $R_{e\text{-ph}}$ is thus about a factor of 3 larger than the value for copper. There are many factors which can cause this relatively small difference. Probably the electron density is lower, which would tend to increase $R_{e\text{-ph}}$. Within the free electron model and assuming that the electron-phonon interaction scales as the Fermi energy, $R_{e\text{-ph}}\sim n^{-2}$ where n is the electron concentration per unit volume. A larger value of the Debye temperature compared with copper would also tend to give larger

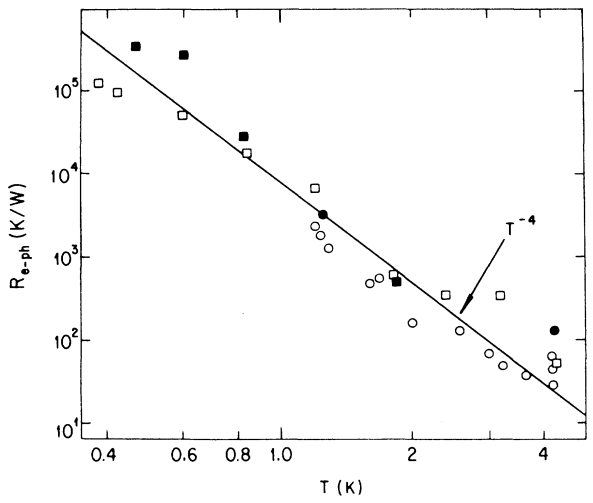

FIG. 1. Temperature dependence of $R_{e\text{-ph}}$ for an 1100-Å $Ge_{88}Au_{12}$ sample as determined from the electron-heating model using Eq. (1). Solid symbols, dc measurements; open squares, 2-μs pulses; open circles, 30-μs pulses.

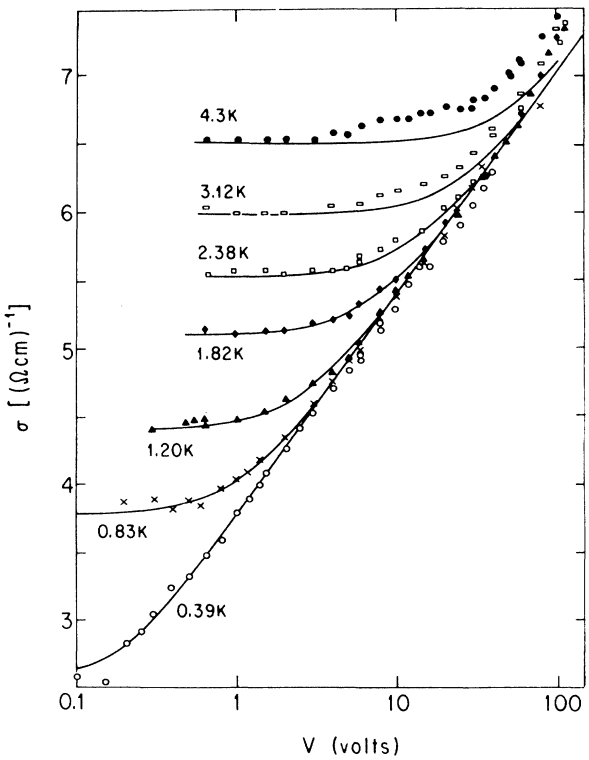

FIG. 2. Conductivity σ [$(\Omega\,\mathrm{cm})^{-1}$] vs applied voltage (volts) for a 2.6-mm-long $Ge_{88}Au_{12}$ film at various temperatures. The symbols represent 2-μs pulsed-field data. The solid lines are one-parameter fits to Eqs. (2) and (3) in the text, using the same value of the parameter A throughout.

values of $R_{e\text{-ph}}$. Because of these possible differences it is difficult to make a precise estimate of the inelastic electron-phonon scattering time τ in our GeAu films. If the electron specific heat (C_v) is the same as for Cu, then using the relation $\tau = R_{e\text{-ph}} C_v$ and the above value for $R_{e\text{-ph}}$, τ will be 10 times larger than was found for copper,[9] that is, $\tau \propto 1/T^3$ with a value of 10^{-7} sec at 1 K. We also note that, as in Ref. 9, at high enough electron temperatures $R_{e\text{-ph}}$ will become less than the Kapitza resistance and trivial sample heating will occur. This sets in for $T_e \simeq 10$ K, corresponding to $\sigma \simeq 7.5\ (\Omega\,\text{cm})^{-1}$ in Fig. 2.

In conclusion, we have found that a simple electron heating model gives an adequate description of presently available results for the field-dependent electrical conductivity of GeAu alloys near the metal-insulator transition. The results presented here provide a somewhat more quantitative basis for understanding electron-heating effects in such materials for arbitrary electron and phonon temperatures. In our opinion, it will be difficult to detect any field induced delocalization processes in the presence of substantial electron heating. We note that our interpretation is different from that advanced recently[10] in terms of delocalization effects induced by the electric field. The internal consistency of our description, we feel however, is strong evidence for electron-heating effects in the temperature and field range studied.

This research was supported by the Office of Naval Research Contract No. N00014-85-K0617. We are grateful to Al Torressen (IBM) for helping us prepare the GeAu films and to Anand M. Awasthi (UCLA) for computing the integral in Eq. (2).

*On leave from the Institute of Physics of the University, Zagreb, Yugoslavia.

[1]P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).

[2]G. Bergmann, Phys. Rep. **101**, 1 (1984).

[3]G.Grüner and A. Zettl, Phys. Rep. **119**, 3 (1985).

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

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

[6]B. W. Dodson, W. L. McMillan, J. M. Mochel, and R. C. Dynes, Phys. Rev. Lett. **46**, 46 (1981).

[7]W. A. Little, Can. J. Phys. **37**, 334 (1959).

[8]A. C. Anderson and R. E. Peterson, Phys. Lett. **38A**, 519 (1972).

[9]M. L. Roukes, M. R. Freeman, R. S. Germain, R. C. Richardson, and M. B. Ketchen, Phys. Rev. Lett. **55**, 422 (1985).

[10]M. Osofsky, J. B. Bieri, M. LaMadrid, W. Contrata, and J. M. Mochel (unpublished).