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Strong and weak electron spin-orbit scattering near the metal-insulator transition

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A detailed comparison of two disordered alloys, Ge_xAu_{1-x} and B_xCu_{1-x}, is carried out near their metal-insulator transition. In zero magnetic field these two materials have approximately linear mobility edges and similar temperature-dependent dc conductivity behaviors. However, the magnetoresistance is dramatically different in high fields for these two materials in spite of similar electron inelastic scattering times. This difference is attributed to the different spin-orbit scattering in these two materials.

Results of recent experiments[1-12] reveal the importance of both disorder and interaction effects in the metal-insulator transition in three-dimensional disordered systems. Transport measurements[1,2] on α-Si:Nb and α-Si:Au show a linear dependence of zero-temperature conductivity on electron density (the so-called mobility edge) as predicted by Al'tshuler, Aronov, and co-workers[13] and McMillan,[14] while measurements on Si:P (Refs. 3 and 4) show a square-root dependence as predicted by Grest and Lee.[15] A significant difference between Si:P and the other systems mentioned is spin-orbit scattering. Silicon and phosphorus have low Z and hence low spin-orbit interaction strengths while niobium and gold are relatively high-Z elements and have high spin-orbit interaction strengths. In addition, bulk disordered materials with weak spin-orbit scattering are often superconducting, which further complicates comparison. We have found a system, α-B_xCu_{1-x}, which is not superconducting and has weak spin-orbit interactions.

Measurements on three-dimensional disordered metallic systems in a magnetic field show negative magnetoresistance (MR),[5-7] no negative MR,[2,8,9] low-field negative MR that reaches a minimum and becomes positive at high fields,[8,10] and low-field positive MR that reaches a maximum and becomes negative a high fields.[11] Analyses of these experiments invoke localization to explain the negative MR, and electron interaction, Zeeman spin splitting, and spin-orbit effects to explain the positive MR, but no coherent model that describes the roles of these effects has been formulated.

We report on dc conductivity and MR measurements on amorphous Ge_xAu_{1-x}, a high-Z material, and B_xCu_{1-x}, a nonsuperconducting low-Z material, near the metal-insulator transition. The two materials' zero-field transport behaviors are shown to be similar while their field-dependent behaviors are strikingly different even though they have similar inelastic scattering lifetimes. We then find that a simple model,[16] which includes localization, electron interaction, and spin-orbit effects, describes both MR behaviors.

Conductivity and MR samples were quench condensed onto adjacent sapphire substrates at 20 K from resistively heated aluminum oxide boats in a dual-source configuration. Scanning electron microscopic analysis, x-ray fluorescence, x-ray diffraction, and Auger electron spectroscopic analyses on the GeAu samples showed no structure beyond 15 Å and long-range variations of less than 10% in metal concentration through each sample. X-ray diffraction and Auger electron spectroscopic analysis of the BCu samples yielded the same results.

GeAu approaches and goes through the metal-insulator transition when annealed. We believe this behavior is due to clustering of the Au atoms reducing the number of conduction electrons and hence reducing the system's Fermi energy. X-ray diffraction supports this model. The anneals varied from 50 °C for 20 min to 200 °C for 3 h. The dc conductivity data were collected during a series of anneals and measurements. The measurements were taken at room temperature and between 4.2 and 1.5 K. Conductivity measurements of the MR sample agreed with those of companion conductivity samples, confirming uniform sample composition. Annealing BCu does not have as strong an effect on the conductivity so this system was driven through the transition by changing composition. A series of samples with $x = 16\%$–25% were condensed, warmed to room temperature, measured, and cooled for the low temperature measurements.

We computed least-squares fits of the dc conductivity

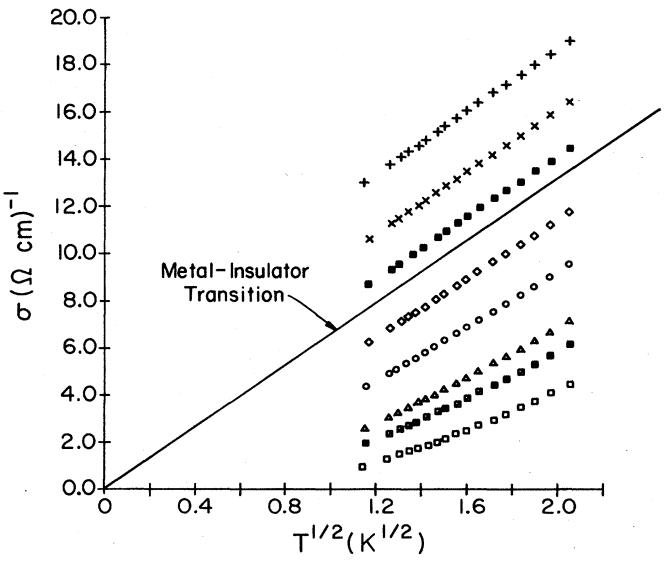

FIG. 1. σ vs $T^{1/2}$ for 1100 Å of $Ge_{0.84}Au_{0.16}$ near the metal-insulator transition. The slopes, $\sigma_1 \sim 6\ (\Omega\ \mathrm{cm})^{-1}\mathrm{K}^{-1/2}$ through the transition. The Mott conductivity is $100\ (\Omega\ \mathrm{cm})^{-1}$.

versus temperature data to $\sigma = \sigma_0 + \sigma_1 T^{\beta}$ with β both a free variable and fixed at $\frac{1}{2}$. For both GeAu and BCu β ranged between 0.3 and 0.8, approaching 0.4 near the transition. The slopes of the $T^{1/2}$ curves range between 1.0 and 10.0 $(\Omega\,\mathrm{cm})^{-1}\mathrm{K}^{-1/2}$, approaching 6.0 $(\Omega\,\mathrm{cm})^{-1}\mathrm{K}^{-1/2}$ at the transition (Fig. 1). This result is consistent with those of Hertel *et al.*[1] who saw virtually constant slopes of 7 $(\Omega\,\mathrm{cm})^{-1}\mathrm{K}^{-1/2}$ through the transition in their α-Nb:Si temperature data. Cochrane and Strom-Olson[12] also show slopes between 3 and 7 $(\Omega\,\mathrm{cm})^{-1}\mathrm{K}^{-1/2}$ in a variety of amorphous and disordered metals with high conductivities spanning an order of magnitude. These results contrast with the Si:P data[3,4] which have large slopes that diverge at the transition. In the context of McMillan's model, the slopes are proportional to $1/\sqrt{D}_{\xi}$, where D_{ξ} is the diffusivity of the system when it crosses over from microscopic to macroscopic behavior. Interpreting the data in this manner yields diffusivities at crossover on the order of the free-electron diffusivity, $\hbar/m \sim 1$ cm^2/s, for all of the systems. An explanation of the significance of this quantity awaits a more complete model of the system.

The annealing behavior of GeAu prevents the use of gold concentration as the parameter that characterizes the metal-insulator transition. The Drude electron concentration can be calculated from the Au concentration in a fresh sample, but there is no simple way to determine it after annealing. We chose the bare, i.e., unrenormalized, conductivity as the parameter. The renormalization-group models begin with a microscopic free-electron wave packet which expands in real space. At the critical length ξ the packet becomes macroscopic and continues expanding diffusively to infinity. The microscopic, or bare, conductivity is a reflection of the microscopic length scale, where the system can be treated as free electron like. A calculation using the simple Drude model expression relates this conductivity to the electron concentration.

In practice, we used room-temperature conductivity as the bare conductivity. In doing so, we assumed that phonons in the system cut the renormalization group off near the microscopic, i.e., atomic, length scale. Extrapolations of high-temperature data to infinite temperature showed $\sigma_{\mathrm{rm.temp.}}$ to be within 10% of σ_{bare} (which equals $\sigma_{T=\infty}$) for BCu. The GeAu extrapolations showed larger differences but $\sigma_{\mathrm{rm.temp.}}$ and σ_{bare} had a nearly linear relationship. The shape of the mobility edge was determined by fitting σ_0 from the $\beta = \frac{1}{2}$ fits as a function of room-temperature conductivity. Figure 2 shows the mobility edges for $B_xCu_{1-x}(0.75 < x < 0.84)$, $Ge_{0.82}Au_{0.18}$, and $Ge_{0.84}Au_{0.16}$. We fitted the points to $\sigma_0 = A\,(\sigma_{\mathrm{rm.temp.}} - \sigma_{\mathrm{crit.}})^{\nu}$ which yielded ν's of 1.5 ± 0.2, 0.91 ± 0.09, and 1.02 ± 0.15, respectively. These values are consistent with Hertel *et al.*[1] and Nishida *et al.*[2] and with McMillan's prediction.[14] The room-temperature conductivity at the transition $\sigma_{\mathrm{crit.}}$ is ~ 100 $(\Omega\,\mathrm{cm})^{-1}$ which equals σ_{Mott}. This is a manifestation of the Ioffe-Regel criterion as the microscopic criterion for the metal-insulator transition. The slopes of the mobility edge curves depend on microscopic details of each sample. The fact that the BCu points lie on a single line indicates that the disorder is independent of initial copper concentration.

Both the GeAu and the BCu samples had positive MR at low fields (Fig. 3). Neither material showed the temperature-independent high-field MR characteristic of localization-dominated[17] systems, indicating that Coulomb

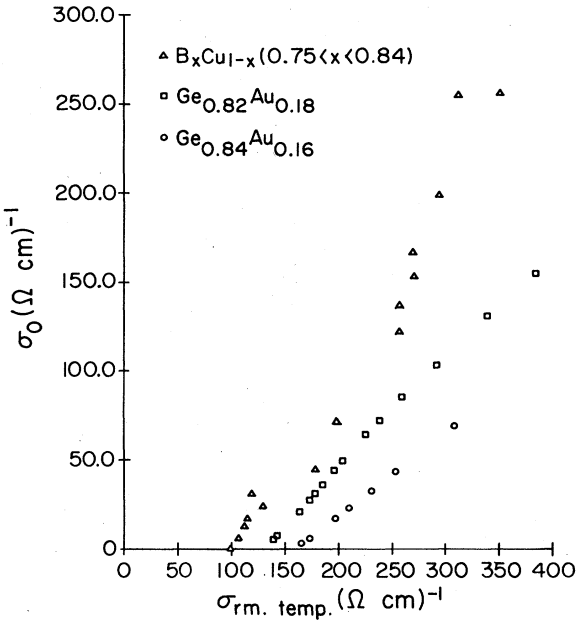

FIG. 2. σ_0 vs $\sigma_{\mathrm{rm.temp.}}$ (the mobility edge) for B_xCu_{1-x} $(0.75 < x < 0.84)$, $Ge_{0.82}Au_{0.18}$, and $Ge_{0.84}Au_{0.16}$ with power laws of 1.5 ± 0.2, 0.91 ± 0.09, and 1.02 ± 0.15, respectively. The room-temperature conductivity at the metal-insulator transition is ~ 100 $(\Omega\,\mathrm{cm})^{-1}$, σ_{Mott}.

interactions must play an important role in these materials. In GeAu, the positive MR persisted to the highest fields studied. These curves are qualitatively similar to the low conductivity Si:P samples of Rosenbaum *et al.*,[8] the Si:Au of Nishida *et al.*,[2] and the bismuth of MacLachlan.[9] In BCu, the slope of the MR became negative for $H \gtrsim 3T$. Similar crossover behavior was seen in CuZr, CuTi, and CuLu alloys of Bieri, Fert, Creuzet, and Ousset.[11]

Since the only negative MR mechanism proposed to date

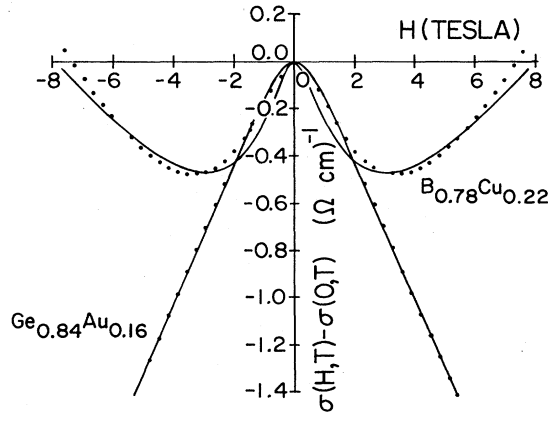

FIG. 3. $\Delta\sigma$ vs H for 1000 Å of $Ge_{0.84}Au_{0.16}$ $[\sigma_0 = 9.4$ $(\Omega\,\mathrm{cm})^{-1}]$ and 1000 Å of $B_{0.78}Cu_{0.22}$ $[\sigma_0 = 496$ $(\Omega\,\mathrm{cm})^{-1}]$ at 1.3 K. The solid curves are the best fits to a model of $\Delta\sigma(H)$ consisting of the sum of contributions due to localization, electron interactions, and spin-orbit effects.

is the relief of localization by the field,[17] we interpret the negative MR in BCu as domination of the Coulomb interaction contribution by the localization contribution at large H. Negative MR can be observed only[18] if, for some H within the experimental range, the inelastic and spin-orbit lifetimes, τ_i and τ_{so}, obey $1/\tau_i + 2/\tau_{so} \lesssim 4DeH/\hbar$. We therefore conclude that the spin-orbit coupling in BCu was weak enough to allow this condition to be met. No negative MR was evident in the GeAu samples. From this we conclude that localization effects in GeAu are either absent, which seems unlikely, or dominated by spin-orbit coupling. These results are consistent with MR measurements on two-dimensional Mg, MgAu, and Au films by Bergmann[19] and with the well-known result that spin-orbit coupling increases with Z.

We computed least-squares fits to the data, using a sum of localization[17] ($\Delta\sigma_L$) and electron-electron interaction[18] ($\Delta\sigma_i$) contributions to the MR. The functional form was

$$\Delta\sigma(H) = -\tfrac{1}{2}\Delta\sigma_1(H,H_1) - g(T)\Delta\sigma_i(H,H_i),$$

where $H_1 = \hbar/4De\tau_i$, $H_i = \pi kT/2De$, and $g(T)$, the phenomenological electron-electron interaction strength,[18] are the three adjustable parameters of the model. The factor of $-\frac{1}{2}$ reflects the assumption $1/\tau_{so} \gg 1/\tau_i$, and is omitted if instead we assume $1/\tau_{so} = 0$. Lee and Ramakrishnan[20] calculated the correction to the conductivity of an interacting electron gas due to Zeeman splitting. Numerical computation[16] showed this to be weak compared with the other effects, and it was neglected. GeAu data were fitted with the assumption $1/\tau_{so} \gg 1/\tau_i$, and BCu with $1/\tau_{so} = 0$. The solid lines in Fig. 3 represent the best-fit curves. Fitting the BCu data with $\tau_{so} \sim \tau_i$ instead of $1/\tau_i = 0$ reduces χ^2 by a factor of 3.

Inelastic scattering times were calculated from the localization crossover fields H_1 using diffusivities extracted from linear fits of the Coulomb interaction crossover fields H_i as a function of temperature. Both GeAu and BCu have τ_i on the order of 10^{-13} s from 1 to 8 K. These times, while rather short, are consistent with those found by others[2,5,6] (if one uses the measured diffusivity of ~ 10 cm^2/s, instead of the free-electron diffusivity). The scatter in the τ_i vs T results was too large to allow quantitative conclusions about the temperature dependence of τ_i.

We also carried out zero-field measurements on α-BAu, α-GeAg, and α-GeCu, and MR measurements on BAu. Their zero-field conductivity data showed the same behavior as GeAu and BCu. The BAu MR crossover behavior lies between that for GeAu and BCu, which is consistent with intermediate spin-orbit scattering.

In conclusion, zero-field transport measurements of three-dimensional GeAu and BCu near the metal-insulator transition yield mobility edges with power laws ~ 1, as predicted by McMillan.[14] Measurements in a magnetic field show that the two systems exhibit similar low-field positive magnetoresistance. In high fields, the GeAu magnetoresistance remains positive while the BCu curve turns around and becomes negative. A simple model consisting of a sum of localization, electron-electron interaction, and spin-orbit effects explains the high-field behavior of GeAu as being due to strong spin-orbit effects, while that of BCu is due to localization with weak spin-orbit effects. The BCu result is the first observation of this behavior in a nonsuperconducting material. These results show that the absence of spin-orbit effects does not explain the power law of $\frac{1}{2}$ found for the mobility edge of Si:P. Inelastic scattering times extracted from interaction crossover fields are on the order of 10^{-13} s.

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