Coulomb tunneling anomaly in disordered copper–germanium alloys

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Abstract

We have performed electronic tunneling density of states and resistivity measurements in three-dimensional Cu_xGe_{100-x} films spanning the weakly and strongly localized regimes. We found that the Coulomb anomaly in tunneling density of states in the strongly disordered regime is very profound and grows in strength with resistivity. However, when the system becomes less disorderly and approaches the weakly disordered regime, this anomaly weakens rapidly. The data suggest that the disorder enhanced electron–electron interaction effects can drive the crossover from weak disorder to strong disorder in CuGe alloy system. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Electron–electron interaction effects; Coulomb anomaly; Weak-to-strong disorder crossover

1. Introduction

The effects of static disorder on the electrical properties of disordered systems have been studied for more than two decades. It is generally accepted that both localization and disorder enhanced electron–electron interaction effects play important roles [1,2]. In particular, theories taking into consideration both effects can account for most experimental results in temperature dependent transport, magnetoresistance, and the depression in density of states at the Fermi energy in the weakly disordered regime ($k_F\ell > 1$ where k_F is the Fermi wave number and ℓ is the elastic mean free path) [1,2]. However, when the degree of disorder of the system is increased leading to the weak-to-strong localization crossover, both theories based on perturbation method are certainly not adequate any more [3,4]. The physical picture near the crossover is still unclear. Experiments such as electron tunneling that can only probe electron–electron interaction effects are of great value.

Disorder enhanced electron–electron interaction effects lead to poorer screening and stronger spatial correlations between electrons with closely spaced energies resulting in a singular reduction to the density of states at the Fermi energy. The theory proposed by Alt'shuler et al. explains for weak disorder that the density of states has a minimum at the Fermi level and increases as energy moves away from the Fermi energy. Moreover they predicted the correction in the density of states is proportional to $\sqrt{E}$ for three-dimensional systems and $\ln(E)$ for two-dimensional systems, respectively [2]. The Coulomb anomaly has been observed for numerous systems. It seems that the theory works well for two-dimensional systems in the weakly disordered regime [5–7]. However, some experimental results especially in three-dimensions disagree with theory [8,9].

In this paper, we present tunneling measurements of the density of states in a series of three-dimensional Cu_xGe_{100-x} samples spanning from the weakly to strongly disordered regime. The goal is to understand how does the electron–electron interaction effects evolve through the crossover. The data indicate that the disorder enhanced electron–electron interaction effects have significant influences in driving the crossover from one regime to the other and become very important in the strongly disordered regime.

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2. Experimental method

Our three-dimensional Cu_xGe_{100-x} films were made by thermal evaporation at a rate of about $1\,nm/s$ in vacuum. The alloy sources were fabricated by a standard arc-melting method in a pure Argon gas. In order to study the tunneling density of states in the CuGe film, an Al/AlO_x strip had been previously deposited serving as counterelectrode and barrier, respectively, for the tunnel junction, $Al(20\,nm)/AlO_y/Cu_xGe_{100-x}$. Thicknesses of CuGe samples were about 500 nm and junction areas were about $0.2\,mm^2$ measured by surface profile probe, Dektak III. Electron tunneling and transport measurements were performed using standard techniques. The tunneling conductance was obtained by numerical differentiation of the current–voltage characteristics of the junction.

The conductance of $Al/AlO_y/Cu_xGe_{100-x}$ tunnel junction at a voltage V and temperature T is given by

$$G(V,T) = C \int_{-\infty}^{\infty} N(E) \frac{\partial f(E+eV,T)}{\partial(eV)}\bigg|_T dE, \qquad (1)$$

where E is the single-particle energy measured relative to the Fermi energy, $N(E)$ is the density of states for the investigated CuGe sample, and $f(E+eV,T)$ is the Fermi distribution function. C is proportional to the density of states in Al and tunneling probability, both of which we assume to be energy and temperature independent. We neglect the thermal smearing represented by $\partial f/\partial(eV)|_T$ in the integral since observed features in $G(V,T)$ are much broader than thermal energy $k_B T$. Therefore, $G(V,T)$ is proportional to $N(E)$ and reveals corrections to $N(E)$ due to the disorder effects.

3. Results and discussion

Fig. 1 shows the normalized junction conductance for four Cu_xGe_{100-x} samples, s1, s2, s4, and s6, at $T = 1.5\,K$. All samples demonstrate a Coulomb cusp near the zero bias voltage (the Fermi energy). A slight difference in junction conductance for both polarities voltage is caused by the asymmetry of the tunnel barrier and is small enough to neglect in the interpretation of data. The size of the cusp is largest in sample s1 with the highest degree of disorder and decreases with decreasing the degree of disorder. The temperature-dependent resistivities for these four and additional two CuGe considered here is shown in Fig. 2. All samples exhibit insulating behavior; the resistivity increases monotonically with decreasing temperature even at room temperatures. The rate of the increase in resistivity respective to temperature at low temperatures is much more rapid than the square root T dependence expected for a weakly disordered system. Therefore, the Coulomb anomaly presented here is for the sample with disorder beyond the
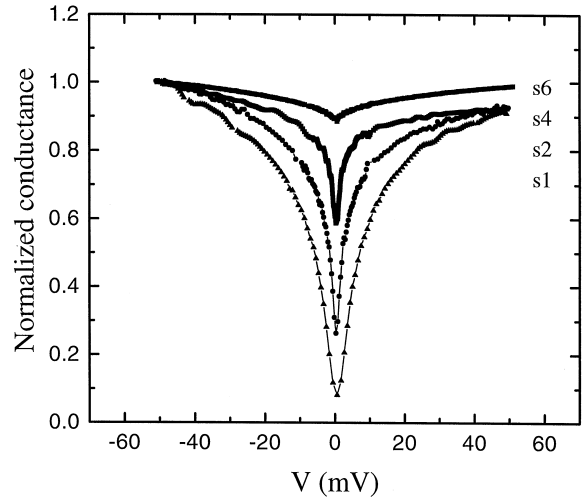

Fig. 1. Junction conductance normalized to the conductance at $-50\,mV$ as a function of voltage for four Cu_xGe_{100-x} samples, s1, s2, s4, and s6 with $22 \leqslant x \leqslant 30$. Temperature-dependent resistivities of them are shown in Fig. 2.
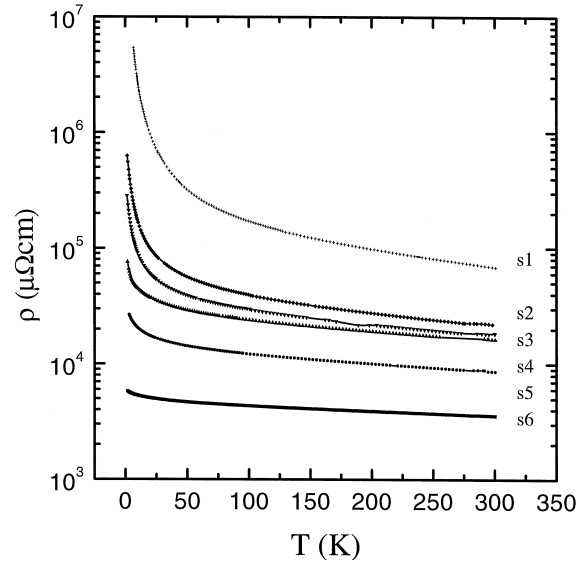

Fig. 2. Semilogarithmic plot of resistivity versus temperature for six CuGe samples.

weak disorder. The Coulomb anomaly in sample with less disorder than sample s6 has very weak energy dependence ($\leqslant 2\%$) and cannot be resolved by our current technique.

It should be noted that the junction conductance at a fixed high voltage such as 50 mV remains at different temperatures for all samples although the film resistance is very sensitive to temperature and can change quite a lot. It is important to know the functional form of the energy-dependent density of states. Through careful
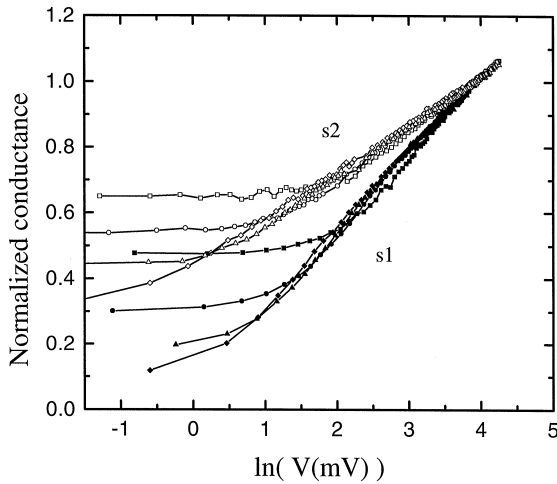
Fig. 3. Normalized junction conductance versus $\ln(V)$ for two samples, s1 (solid) and s2 (open) at (□) 38 K, (○) 17 K, (△) 8 K, and (◇) 1.5 K.

Fig. 4. Normalized junction conductance versus V for two samples, s1 (solid) and s5 (open) at (□) 38 K, (○) 17 K, (△) 8 K, and (◇) 1.5 K.

analyses, we conclude that density of states increases with $\ln(E)$ at $E > \Gamma$ where Γ is the energy characterizing the thermal smearing effect. The plot of the normalized conductance versus $\ln(V)$ for s1 and s2 at different temperatures shown in Fig. 3 confirms the above statement. As shown in Fig. 3 both samples demonstrate that the normalized conductance grows with $\ln(E)$ linearly at high-energy regime. The smearing effects due to the thermal energy in the system stop the depression in the density of states and broaden the Coulomb cusp. Γ is about $5k_{B}T$, independent of the degree of disorder of sample [5]. Since the size of the anomaly is big, the zero bias conductance ($\propto N(E_{F})$) is sensitive to temperature due to the smearing effects. Fig. 4 shows energy dependent normalized conductance for samples, s1 and s5, at different temperatures.

Experimental results among different systems are somewhat different. In three-dimensional Au–Ge mixtures, $E^{0.6}$ was seen [10]. In amorphous three-dimensional Nb–Si films (thickness ~ 100 nm), a crossover from $E^{0.5}$ (low E) to $E^{0.3}$ (high E) was seen [11]. A set of experiments on three-dimensional amorphous InO_x samples (thickness ~ 200 nm) by Pyun and Lemberger showed that $N(E) \propto \ln(E)$ over two decades in energy. In addition, the size of the tunneling anomaly scaled with the resistivity of film and not their sheet resistance as expected for $\ln(E)$ behavior in two dimesions [8,9]. Our three-dimensional CuGe samples (thickness ~ 500 nm) also demonstrate a $\ln(E)$ dependence. The size of the anomaly relative to $\ln(E)$ in the absence of smearing effects decreases with decreasing the degree of disorder in the system. Linear fit to normalization conductance for $\ln(E)$ dependence give intercept A, the normalized conductance at zero bias, and the slope B, the rate of the decrease in normalized conductance to $\ln(V)$. A and B for
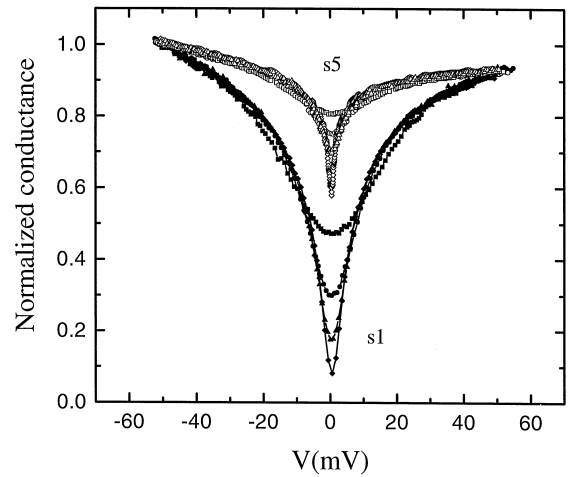
our six samples are 0.1 and 0.24 for s1, 0.4 and 0.16 for s2, 0.45 and 0.14 for s3, 0.62 and 0.1 for s4, 0.67 and 0.08 for s4, and 0.83 and 0.043 for s6, respectively. However, there is no reason that A and B scale with resistivity since all samples have a strong temperature-dependent resistivities in different manners. As mentioned previously, our samples are around the weak-to-strong disorder crossover and away from weakly disordered regime. At this moment, no theory provides a proper interpretation of the data. It is worth mentioning that the Coulomb anomaly becomes very weak when the system approaches weak disorder. The result is consistent with the implication of magnetoresistance in CuGe samples [12]. Therefore, disorder enhanced electron–electron interaction effects dominate the electronic properties for samples with disorder beyond weak disorder.

4. Conclusion

We have presented measurements of the electronic tunneling density of states and temperature-dependent resistivity of three-dimensional Cu_xGe_{100-x} films spanning the weakly and strongly localized regimes. A clear Coulomb cusp was observed in sample in the strongly disordered regime implying a strong depression in the density of states near the Fermi energy due to disorder enhanced electron–electron interaction effects. However, the result that $N(E)$ is proportional to $\ln(E)$ cannot be described by current theory. In addition, when system becomes less disorderly and approaches the weakly disordered regime, this anomaly weakens rapidly and is smaller than our measurement resolution (2%) at $T \geqslant 1.5$ K. The data suggest that the disorder enhanced electron–electron interaction effects play an important

role in driving the crossover from weak disorder to strong disorder in CuGe alloy system.

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