行政院國家科學委員會專題研究計畫成果報告

非有序材料的穿隧電子能階密度研究

Studies of the Tunneling Density of States in Disordered Materials

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一、中文摘要

我們測量了三維非有序銅鍺合金的穿隧電子能階密度和電阻率對溫度的變化。控制不同的銅鍺相對莫耳比例可以得到一系列不同程度非有序樣品，從弱無序到強無序區域。我們發現強無序樣品的穿隧電子能階密度展現明顯的庫倫異常而且隨著非有序程度(樣品電阻率)增大而增加，我們認為在研究的銅鍺合金系列中，非無序導致增強的電子-電子作用力在弱-強無序轉變扮演重要角色。

關鍵詞：銅鍺合金、庫倫異常、非有序程度、電子能階密度、電子-電子作用力。

Abstract

We have performed electronic tunneling density of states and resistivity measurementsin three dimensional Cu_xGe_{1-x} films spanning from the weakly and strongly localized regimes. We found that the Coulomb anomaly in tunneling density of states in the strongly localized regime is very profound and grows in strength with resistivity. 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.

Keywords: CuGe alloy, Coulomb anomaly, the degree of disorder, tunneling density of states, the electron-electron interaction effects.

二、緣由與目的

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 taken both effects into account can account for most experimental results in temperature dependent transport, magneto-resistance, 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]. The physical picture near the crossover is still unclear. Experiments such as electron tunneling that can probe electron-electron interaction effects are of great value.

In this work, we have performed tunneling measurements of the density of states in a series of three dimensional CuGe samples spanning from weakly to strongly disordered regimes. The goal is to understand how does the electron-electron interaction effects evolve through the crossover. The data shown below 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.

三、實驗技術

Our three dimensional Cu_xGe_{1-x} films were made by thermal evaporation at a rate of about 1nm/s in a vacuum($<3\times10^{-6}$torr). The alloy sources were fabricated by a standard arc-melting method in a pure Argon gas. In order to study the tunneling sensity of states in the CuGe films, a Al/AlO_y strip had been previously deposited serving as counter-electrode and barrier, respectively, for the tunneling junction, $Al(20nm)/AlO_y/Cu_xGe_{1-x}$. Thicknesses of CuGe samples were about 500nm 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 in a pumped Helium cryostat. The tunneling conductance was obtained by numerical differentiation of the current-voltage characteristics of the junction.

The conductance of $Al/AlO_y/Cu_xGe_{1-x}$ tunnel junction at a voltage V and temperature T is given by

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

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. 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_BT. Therefore, G(V,T) is proportional to N(E) and reveals corrections to N(E) due to the disorder effects.

四、實驗結果

Fig.1 shows the normalized junction conductance for four Cu_xGe_{1-x} samples, s1, s2, s4, and s6, at T=1.5K. All samples demonstrate a Coulomb cusp near the zero bias voltage (the Fermi energy). A slightly difference in junction conductance for both polarity voltages is caused by the asymmetry of the tunnel barrier and is small enough to neglect in the interpretation of the 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 resitivities 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 square root T dependence expected for a weakly disordered system. Therefore, the Coulomb anomaly presented here is for the sample with disorder beyond the weak disorder. The Coulomb anomaly is sample with less disorder than sample s6 has very weak energy dependence (≤2%) and cannot be resolved by our current technique.

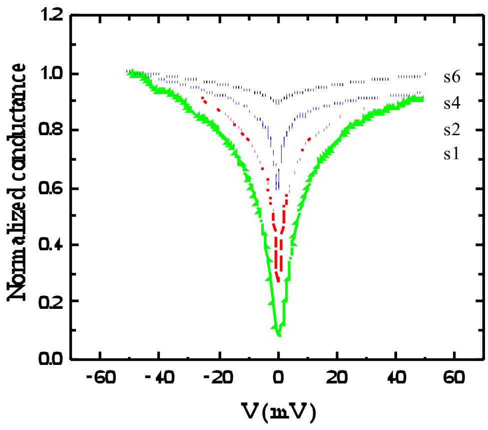

Fig.1. Junction conductance normalized to the conductance at ~50mV as a function of voltage for four Cu_xGe_{1-x} samples, s1, s2, s4, and s6 with $0.22 \leq x \leq 0.30$. Temperature dependent resistivities of them are shown in Fig.2.

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

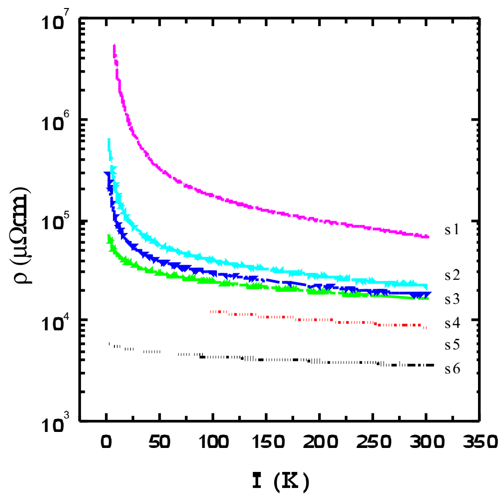

Fig.2. Semilogarithmic plot of resistivity versus temperature for six Cu_xGe_{1-x} samples.

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 analyses, we conclude that density of states increases with ℓn(E) at E>Γ 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 temperature 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 $5k_BT$, independent of the degree of disorder of the sample[4]. The zero bias conductance is sensitive to temperature due to smearing effects. Fig.4 shows energy dependent normalized conductance for samples s1 and s5 at several different temperatures.

Experimental results among different systems are somehow different. In three dimensional Au-Ge mixtures, $E^{0.6}$ was seen [5]. 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[6]. A set of experiments on three dimensional amorphous InO_x samples (thickness ~100 nm)

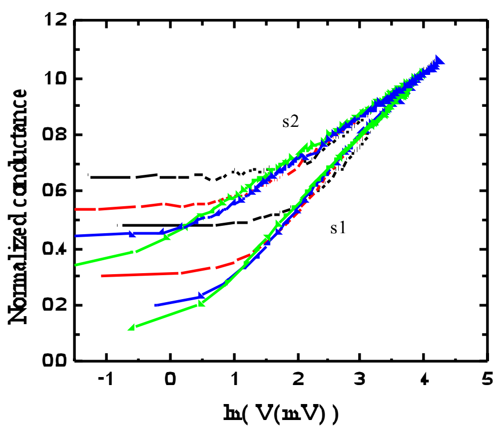

Fig.3. Normalized junction conductance versus V for two samples, s1(solid) and s2(open) at ( )38K, (o)17K, (Δ)8K, and (◆)1.5K.

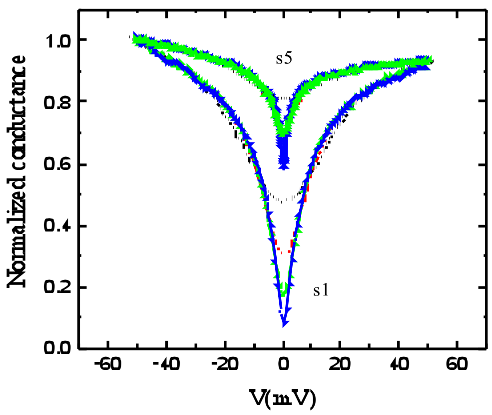

Fig.4. Normalized junction conductance versus V for two samples, s1(solid) and s5(open) at ( )38K, (o)17K, (Δ)8K, and (◆)1.5K.

by Pyun and Lemberger show that N(E) ∝ $\ell n(E)$ over two decades in energy. In addition, the size of the tunneling anomaly scaled with resistivity of film and not their sheet resistance as expected for $\ell n(E)$ behavior in two dimensions[7]. Our three dimensional CuGe samples (thickness ~500 nm) also demonstrate a $\ell n(E)$ dependence. The size of the anomaly relative to $\ell n(E)$ in the absence of smearing decreases with decreasing the degree of disorder in the system. Linear fit to normalization conductance for $\ell n(E)$ dependence give intercept A, the normalized conductance at zero bias, and the slope B, the rate of the decrease in normalized conductance to $\ell n(V)$. 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 s5, and 0.83 and 0.043 for s6, respectively. However, there is no reason for that A and B scale with resistivity since all samples have 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 to mention that Coulomb anomaly becomes ver weak when system approaches weak disorder. The result is consistent with the implication of magnetoresistance of CuGe samples[8]. Therefore, disorder enhanced electron-electron interaction effects dominate the electronic properties for samples with disorder beyond weak disorder.

五、結論

We present measurements of the electronic tunneling density of states and temperature dependent resistivities of three dimensional Cu_xGe_{1-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 $\ell n(E)$ cannot be described by current theory. In addition, when system becomes less disorder and approached the weakly disordered regime, this anomaly weakens rapidly and is smaller than our measurement resolution(2%) at T≥1.5K. The data suggest that the disorder enhanced electron-electron interaction effects play important role in driving the crossover from weak disorder to strong disorder in CuGe alloy system.

The analyses of the data and the results were presented in the international conference, Electronic Transport and Optical Properties of Inhomogeneous Materials 5, held in Hongkang this June. The results in this study have been accepted for publication in Physica B.

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