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Electron–electron interaction dominated quantum transport in thick CuGe films

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Abstract

We have successfully made a series of thick Cu_xGe_{100-x} films spanning the weakly and strongly localized regimes. With decreasing mole concentration of Cu relative to Ge, the resistivity of film becomes bigger at a given temperature and demonstrates a stronger temperature dependence at low temperatures. When x is big, $46 \leqslant x \leqslant 56$, resistivity increases with the square root of the decreasing temperature, implying a weak-disorder behavior. For x small, $14 \leqslant x \leqslant 20$, resistivity increases exponentially with decreasing temperature, implying a strongly localized behavior. The results show that the low-temperature transport in these films is dominated by the disorder enhanced electron–electron interaction effects.

Keywords: Disordered metals; Electron–electron interaction; Hopping; Quantum transport

Increase in the static disorder in a metal, tend to localize electrons and degrade the electrical transport properties. When the disorder is strong, a metal–insulator transition can occur. The dynamics involved in the transition is quite complicated and still not well understood although the topic has been studied for over 20 years. We have successfully made a series of thick Cu_xGe_{100-x} films spanning the weakly and strongly localized regimes. The degree of disorder can be easily controlled by adjusting the relative molar concentration between Cu and Ge. Here we present the temperature dependence of the resistivities of these samples to show the gradual evolution in transport from metallic to insulating behavior.

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 an arc-melting method in a pure Argon gas. Film thicknesses were about 500 nm, measured by surface profile probe, Dektak III. The molar concentration ratios between Cu and Ge in all samples were examined using a SEM energy dispersion spectroscope. Four terminal DC and AC (16 Hz) resistance measurements were performed in a ^{4}He cryostat.

Fig. 1 shows the evolution of the temperature-dependent resistivities for numerous Cu_xGe_{100-x} samples with $14 \leqslant x \leqslant 52$. The room temperature resistivity starts out at ~ 200 μΩ cm, increasing rapidly with decreasing Cu content. Samples with x more than 50 demonstrate a positive temperature coefficient of resistivity (TCR) at high temperatures, $T^* \leqslant T \leqslant 300$ K, and a negative TCR at temperatures below T^*. As x decreases, T^* increases and therefore, the temperature range of positive TCR shrinks. As x is less than 46, resistivity increases monotonically with decreasing temperature even at room temperatures.

The low-temperature resistivities of less disordered samples with resistivity less than 1000 μΩ cm and $x \geqslant 46$ follow

$$\Delta\rho(T) \propto -\rho_0^{2.5}\sqrt{T} \quad (1)$$

which is a correction term due to the electron–electron interaction effects in the weakly disordered regime [1]. In samples with smaller x and higher resistivity, the growth in resistivity not only becomes stronger with temperature but also deviates from the square root T dependence. The relation between resistivity and temperature is

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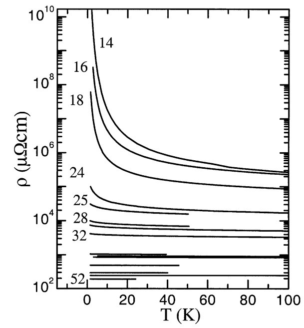

Fig. 1. Resistivity ρ versus temperature T for a series of Cu_xGe_{100-x} samples. x is shown for most of the films.

nearly logarithmic, being difficult to understand in terms of the current theoretical picture.

Deep in the insulating regime, the resistivity is much more sensitive to temperature. In Fig. 2 we show three samples with highest resistivities to demonstrate the relation between resistivity and temperature,

$$\rho(T) \propto \exp[(T_0/T)^v], \quad (2)$$

where $v = \frac{1}{2}$, which is expected for the transport in the variable range hopping regime, taking the Efros-Shkovskii–Coulomb interaction effect into account [2]. $k_B T_0$ characterize the size of Coulomb interaction and are 30.2 ($x = 14$), 17.6 ($x = 16$), and 7.7 meV ($x = 18$), respectively. Additional tunneling measurements in those samples also show the existence of a Coulomb cusp with the size of the cusp increasing with decreasing x (increasing disorder) [3].

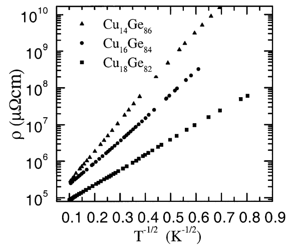

Fig. 2. Semilogarithmic plot of resistivity versus $T^{-1/2}$ for three CuGe samples in strongly localized regime.

In conclusion, the enhanced electron–electron interaction effects are important thick Cu_xGe_{100-x} films in both the weakly and strongly localized regimes.

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