Electron-Electron Interaction Effect on Conductivities in Cobalt Thin Films

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Abstract

We have measured the temperature (T) dependence of the conductivity of cobalt films with various thickness (d). The conductivity shows lnT dependence for d <100Å, which is mainly caused by electron-electron interaction effect. The coefficient of the lnT dependence significantly decreases with decreasing thickness for d <50Å, where the conductivity approaches Mooij limit. The results suggest that the scattering for d <50Å is dominated by the inhomogeneity of the films such as grain boundaries.

Key words: electron-electron interaction, localization, percolation

1. Introduction

The quantum corrections to electrical conductivity in disordered metals and doped semiconductors have been extensively studied for the last two decades. In the inhomogeneous system the interplay between percolation and localization has been examined theoretically within the framework of the scaling theory of localization[1]. However the role of electron-electron interaction effect in percolating metallic films is still unexplored. This paper is devoted to a study of the quantum corrections in percolating cobalt films.

2. Experimental

The films were grown by an electron beam deposition of cobalt (99.99%+) onto thermally oxide silicon substrates at room temperature. The vacuum during evaporation was 10^{-6}Torr and the evaporation rate was 0.3∼0.5Å/s. The film thickness (d) was measured with a quartz-crystal thickness monitor mounted beside the sample holder. The samples were fabricated by an electron beam lithography and lift-off process. Each one was 200μm wide and 700μm long between voltage probes. The conductivity was measured at various temperatures (T).

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3. Results and Discussion

Figure 1 shows the temperature dependence of the conductivity in the film for d =50Å under magnetic fields (0, 4, 10T) perpendicular to the film. As T decreases, the conductivity has a maximum at ∼25K and then shows a logarithmic temperature dependence at lower temperatures. The lnT coefficient, *i.e.* the slope of the conductivity curves, is calculated to be 1.0 in units of $e^2/2\pi\hbar$, irrespective of the magnetic field strength. Both effects of weak localization and electron-electron interaction on the conductivity are known to provide the same lnT dependence for two-dimensional (2D) systems. However, no field dependence in the lnT behavior shows that the electron-electron interaction

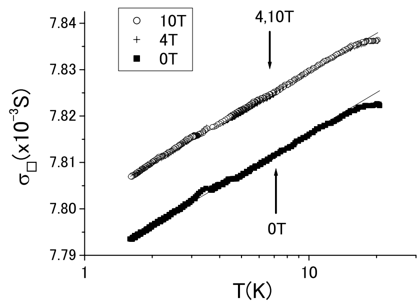

Fig. 1. Temperature dependence of the conductivity in the film with the thickness d =50Å under magnetic fields (0, 4, 10T).

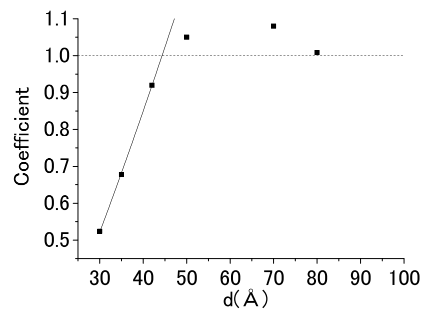

Fig. 2. Thickness dependence of the lnT coefficient in the units of $e^2/2\pi\hbar$.

is the dominant mechanism. This is simply understood by the fact that the weak localization effect is suppressed by the large internal magnetic field in magnetic materials. We have measured the conductivity of the films with various thickness, and found that a similar lnT dependence is observed for d <100Å.

Figure 2 shows the thickness dependence of the lnT coefficient. The coefficient seems almost independent of the thickness above 50Å, but a significant decrease is found below it. As d decreases, the resistivity shows steep increase for d <50Å and the thickness dependence deviates from a curve expected from Fuchs-Sondeheimer theory [2]. This fact suggests that the thin films for d <50Å are not homogeneous and that some additional scattering due to the inhomogenity is present. Actually, we can observe fine granular structure, *i.e.* percolating structure of the film for d =50Å by an atomic force microscope, whose size is of the order of 10nm. The phase coherence of the interacting two-electrons states is preserved within the characteristic length L_T given by $\sqrt{D\hbar/k_BT}$. The length L_T for cobalt is estimated to be 20nm at 10K, which is comparable to the size of the granular structure and much shorter than d. Therefore, this film is a well-defined 2D system and the lnT dependence can be consistently ascribed to the electron-electron interacting system.

For granular metals, the localization effect on the conductivity near the percolation threshold is theoretically obtained by Gefen *et al.*,

$$\sigma \sim \sigma(\xi_p) = \left(\frac{\xi_p}{\xi_l}\right)^{-t/\nu} \sigma(\xi_l) \propto (d-d_c)^t \sigma(\xi_l) \qquad (1)$$

where t and ν are critical exponents, ξ_l and ξ_p are the localization length and the percolation length, respectively[1]. The length ξ_p is proportional to $(d-d_c)^{-\nu}$, where d_c is percolation threshold. This theory predicts that both the conductivity and lnT coefficient decrease toward zero with decreasing d near d_c. This behavior is characterized by the critical exponent t which is theoretically obtained as t∼1.3 in the 2D percolation case [3]. For non-magnetic metal films, the critical behavior is already reported [4][5]. However, the result in Fig. 2 shows that a similar critical behavior appears even when the electron-electron interaction effect is dominant in the magnetic film. The solid line in Fig.2 is the fitted result with t =1.2 and d_c =10Å. The critical exponent is close to the theoretical value in the case of the localization effect.

The resistivity of the film for d =50Å is $64\mu\Omega cm$, which is close to Mooij limit(‘$100\mu\Omega cm$) [6][7]. The large resistivity suggests that the electronic states in the films for d <50Å could be close to the strong localization region. This is probably consistent with the above picture, *i.e.* the film thickness approaches the percolation threshold.

4. Summary

We observed the lnT dependence in the conductivity due to the electron-electron interaction for the cobalt thin films and found the critical behavior of the lnT coefficient towards the percolation threshold.

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