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Magnetoresistance Behavior of Ni Layer under Cu Film

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The weak-localization effect is very sensitive to the presence of magnetic moments. We use it to study the formation of localized moments in thin Ni layers under a 100 Cu film. The Ni thickness varies between 0 and 4 Å. We measured the magnetoresistance (MR) of these samples at temperatures ranging from 0.4 to 21 K. The magnetic field with the strength of up to 1 T, was applied normal to the film surface. We find that **MR** is more positive In samples with Ni underlayer than in Cu film. Comparing our results with the prediction of weak localization theory, the magnetic moment is detected only in Ni underlayers thicker than 2 Å.

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I. Introduction

The spin of a conduction electron can be scattered by isolated or clustered localized magnetic moments. This process plays a crucial role in the Kondo effect [1], in quantum interference (weak-localization) effects [2], in giant magnetoresistance [3], etc. An important and interesting problem is whether the size of the isolated magnetic impurity has some influence on the formation of the localized magnetic moment which can scatter conduction electrons. It is now well established both theoretically and experimentally that the weak-localization (WL) effect is very sensitive to the localized moments and can therefore be used to examine the presence of the localized moments.

In this work, we investigate spin-spin scattering between conduction electrons and Ni particles in noble metal using a magnetoresistance (MR) measurements. It is expected that the localized moments should be formed gradually as the size of the Ni particles grows, but our results indicate that the particles cannot form localized moments if the thickness of the Ni layer is below 2 Å.

II. Experimental methods

All our samples were prepared by thermal evaporation deposition onto SiO buffered glass substrates held at room temperature. The background pressure was below 3 x 10^{-6} mbar. A 100-A thick Cu film (from 99.9999% pure source) is deposited in situ atop the Ni layer. In all samples, the thickness of Cu film is fixed as 100 Å, and that of Ni layer is varied between 0 and 4 A. At these thicknesses, nickel cannot form a continuous uniform film and is deposited as particles. The sizes of these particles varies with the nominal thickness of the Ni-film.

The resistances per square $R_\square$[2] at liquid helium temperature ($R_\square = R \times W/L$, W is the width, and L is the length of the film) are $\sim 40\Omega/\square$ for the all Cu film, $19\Omega/\square$ for a Cu/2-Å-Ni film, and $17\Omega/\square$ for a Cu/4-Å-Ni film. The magnetoresistance of our films is measured by the standard four-probe technique, using a low-frequency ac bridge (AC Resistance bridge LR-400) and a Keithley 182 nanovoltmeter. For each sample, thirteen magnetoresistance curves are measured. Each curve is obtained in a magnetic field of up to 1 T at a fixed temperature between 0.4 and 21 K. In all the cases, the magnetoresistance is measured with the field applied perpendicularly to the film and the current I perpendicularly to the field.

III. Results **and discussion**

In a twodimensional system, the general expression for the weak-localization induced variations in resistivity in a perpendicular magnetic field H is given by [2]

$$\begin{aligned}\frac{\Delta R_\square(H)}{R_\square^2} &= \frac{R_\square(H) - R_\square(0)}{R_\square^2}\\ &= \frac{e^2}{2\pi^2\hbar}\left\{\begin{array}{c}\Psi\left(\frac{1}{2}+\frac{H_1}{H}\right) - \frac{3}{2}\Psi\left(\frac{1}{2}+\frac{H_2}{H}\right) + \frac{1}{2}\Psi\left(\frac{1}{2}+\frac{H_\phi}{H}\right)\\ -\ln\left(\frac{H_1}{H}\right) + \frac{3}{2}\ln\left(\frac{H_2}{H}\right) - \frac{1}{2}\ln\left(\frac{H_\phi}{H}\right)\end{array}\right\}.\end{aligned} \tag{1}$$

Here ψ is the digamma function and the fields H_1, Hz, and H_ϕ, are defined as

$$H_1 = H_e + H_{so} + H_s$$

$$H_2 = H_\phi + \tfrac{4}{3}(H_{so} - H_s)$$

$$H_\phi = H_i + 2H_s.$$

The characteristic fields $H_j = \hbar/4eD\tau_j$ where the index j = e, so, s and i refers to the elastic spin-orbit, spin-spin, and inelastic scattering fields (times) respectively. The electron dephasing scattering field is given by $H_\phi = AT^n$ t BT t C, where A B, and C are constant values independent of temperature. The first term is due to electron-phonon scattering, the second due to electron-electron scattering, and the third term is independent of temperature and arises from spin-spin scattering. (Spin-spin scattering means that the spin of conduction electron is scattered by localized moments.) The vahle $\Delta R_\square(H)/R_\square^2$ was obtained by MR measurement and by comparison with Eq. (1) we can extract **H+(T)** by least-squares fitting procedure. Only data up to magnetic fields of 0.3 T were used in the fitting procedure in order to exclude possible contributions to magnetoresistance from enhanced electron-electron interaction [2] at higher fields. In this work, we focus on variations of $H_\phi(T)$ for various samples. The electron dephasing scattering field H_ϕ contains 3 terms (three kinds of dephasing scattering mechanism) and the spin-spin scattering rate is the only temperature independent term. We can extract the spin-spin scattering field H_s by getting the constant term from H_ϕ with the temperature behavior.

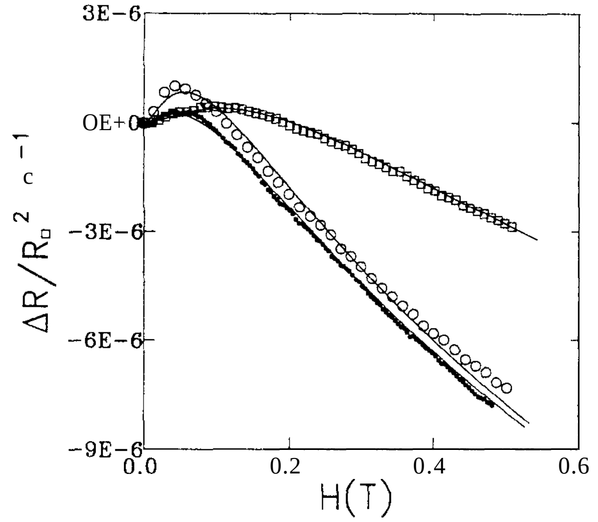

FIG. 1. The normalized magnetoresistance $\Delta R_\square(H)/R_\square^2$ as a function of magnetic field ***H*** at 12 K for pure Cu (close circles), Cu/2-Å-Ni (open circles) and Cu/4-Å-Ni films (open squares), respectively. The symbols represent experimental results and the solid curves are the predictions of Eq. (1).

There are three parameters in Eq. (1), H_1, H_2 and H_ϕ. In performing least-squares fits of our experimental results to the prediction of Eq. (1), we treated two characteristic fields H_2 and $H\phi$ as adjustable parameters and fixed the characteristic field $H_1 = 10$ T for all fitting procedures. Because the elastic field H_e is generally much larger than any of other fields (because $\tau_e \ll \tau_x$, $x = i$, so and s), $H_1 = H_e$ is a fixed parameter. In fact, H_1 cannot influence the results of our fittings even though it is 1, 10 or 100 T. This is due to that the digamma function $\Psi(Z)$ is limited to be a constant when $Z \geq 3$. Only with two adjustable parameters H_ϕ and H_2, Fig. 1 is the best fittings of Eq. (1), especially in a very small signal, $\frac{AR}{R} \sim 10^{-4}$ at 0.5 T. Actually, the recent investigation [4] for thin metal films shows that the WL theory encounters difficulties in describing the magnetoresistance of thin metal film. Except the spin-orbit scattering rate is temperature dependent. The spin-orbit scattering is a material property and its strength should be fairly independent of system dimensionality and temperature. It is an issue about that the temperature dependent spin-orbit scattering rate is very difficult to understand [4].

Figure 1 shows the normalized magnetoresistance $\Delta R_\square(H)/R_\square^2$ as a function of magnetic field ***H*** at 12 K for the Cu (close circles), the Cu/2-Å-Ni (open circles) and the Cu/4-A-Ni films (open squares), respectively. The symbols denote experimental results and the solid curves are predictions of Eq. (1). Clearly, the shown $\Delta R_\square(H)/R_\square^2$ dependence on ***H*** is characteristic of WL effects. We see that MR is positive and increasing with increasing H at low fields. At higher fields, on the other hand, MR decreases with increasing ***H*** and becomes negative. By comparing the MR of the Cu/2-Å-Ni and Cu films, their MR behaviors are similar but the MR of the Cu/2-Å-Ni film is slight more positive than that of the Cu film. The WL theory predicts that a disordered system displays a more negative MR while the dephasing scattering field H_ϕ increases and the spin-orbital scattering field $H_{s.o}$ is fixed. The spin-orbital scattering field $H_{s.o}$ in Cu film ($H_{s.o}$ = 0.016 T) is close to that in Cu/2-Å-Ni film (H_{so} = 0.017 T). If the dominant mechanism is the WL effect, then this slight positive is due to the difference of H_ϕ (at higher temperature $T > 10$ K, $H_\phi(\mathrm{Cu}) > H_\phi$ (Cu/2-Å-Ni), see Fig. 2). The MR behavior for Cu/4-Å-Ni film is very different from Cu and Cu/2-Å-Ni films, this difference is due to that H_{so} and H_ϕ change very much (see Fig. 2). We therefore conclude that Ni cannot change the MR behavior in Cu film while the thickness of Ni layer is less than 2 A.

Figure 2 shows the variations of $H_\phi(T)$ with temperature between 0.4 and 21 K for the Cu (close circles), the Cu/2-Å-Ni (open circles), and Cu/4-Å-Ni films (open squares), respectively, the solid lines guide to the eye. The figure shows that above 10 K the dependence of H_ϕ = AT” + BT + C on temperature is similar for all samples, i.e., that the exponent n is the same. In other words, the nature of the electron-phonon interaction is not changed in the Cu, Cu/2-Å-Ni, and Cu/4-Å-Ni films. The figure also shows that the T-independent constant, C is larger in the Cu/4-Å-Ni film than in the Cu and Cu/2-Å-Ni films. The constant term C comes from spin-spin scattering and our result indicates that the localized moment, in the Cu/4-Å-Ni film is larger than in Cu and Cu/2-Å-Ni films. That is, under the 100-A thick Cu layer the 4-A Ni film is sufficiently thick to form localized moments which destroy the backscattering effects. We also find that the values of C are very close for the Cu and Cu/2-Å-Ni films. (The little difference between these two films may be due to a fitting or experimental deviation). This similarity implies that the spin-spin

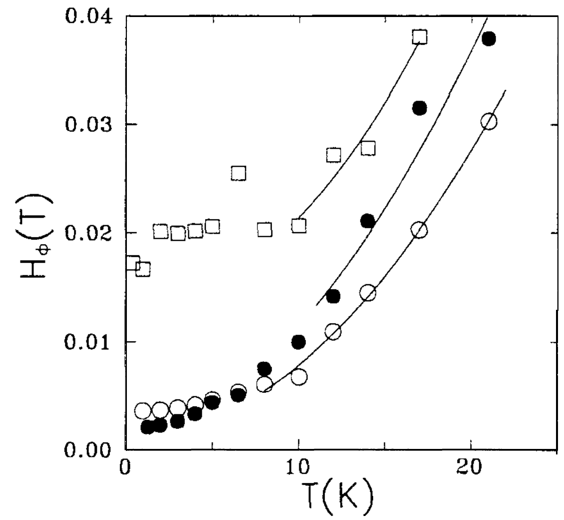

FIG. 2. Variations of $H_\phi(T)$ with temperature between 0.4 and 21 K for pure Cu (close circles), Cu/2-Å-Ni (open circles), and Cu/4-Å-Ni films (open squares), respectively. The solid lines guide to the eye.

scattering field H_s in these two films is the same, i.e., Ni layers of less than Å thickness cannot provide any localized moments in the Cu/Ni film.

Both theoretical predictions and experimental results indicate that a few Ni atomic *layers* in Cu bulk cannot form any localized moments. These are the so-called "dead" layers in noble metals [5]. In Ref. 5, the existence of the dead layers is explained within the intinerant-electron theory of ferromagnetism: The absence of magnetic moment is ascribed to a local reduction in the number of 3 *d* holes as well as to the hole states being occupied by electrons of opposite spins. Recently, Lang et al. [6] calculated the magnetic moments of *3d* impurities on the surface of Cu using the spin-density functional theory. They found that the magnetic moment of Ni should vanish at the Cu surface. Experimentally, the observation of Bergmann et al. is contrary to this theoretical prediction in which even a monolayer of Ni shows magnetic moments on top of noble metals [7]. Our results, however, show that a "dead" layer (with mean thickness of about 2 Å) is present in a Cu film on top of a Ni layer.

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