Periodic Enhancement of the Electron-Electron Interactions and the Magnetoresistance in Magnetic Co/(Cr/Ag)/Co Multilayers

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Electrical transport and magneto-optical Kerr effect have been measured on Co/(Cr/Ag)/Co multilayers in which the thickness λ of the bimetallic nonmagnetic spacer Cr/Ag varies from 0 to 35 Å. The measurements clearly indicate the presence of antiferromagnetic coupling for $9 < \lambda < 23$ Å. At low temperatures ($T < 20$ K), the resistivity shows a logarithmic increase which is most probably caused by the two-dimensional electron-electron interactions. The magnitude of the $\log_{10} T$ term and of the negative magnetoresistance varies periodically with a period corresponding approximately to one monolayer of Cr. [S0031-9007(96)02041-8]

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Since the discovery of antiferromagnetic interlayer exchange coupling [1], giant magnetoresistance (GMR) due to magnetization rotation [2] and oscillatory interlayer coupling [3], the transport properties of magnetic multilayers (MML) have attracted much attention. The GMR effect is usually accounted for by spin-dependent scattering of electrons at the ferromagnet-spacer interfaces [4]. The periodicity of the oscillations, observed in the dependence of the coupling parameter on the spacer thickness, is determined by extremal spanning vectors of the Fermi surface of the nonmagnetic metal [5,6]. It was shown theoretically and confirmed experimentally that the interlayer coupling also depends on the thickness of the magnetic films [7,8] and the nonmagnetic cap layers [9]. The amplitude and phase of the oscillations in the coupling parameter depend on the properties of all individual layers in a multilayer [10]. Moreover, interlayer coupling can also occur in more complex systems, for instance, when the nonmagnetic spacer consists of *two different metallic layers.* By varying the thicknesses of those layers it is then possible to change systematically the properties (e.g., disorder) of the interface inside the nonmagnetic bimetallic spacer and therefore to influence the interlayer coupling and transport properties.

In this Letter we report on two new phenomena observed in Co/(Cr/Ag)/Co multilayers with the bimetallic Cr/Ag spacer. First, it is shown that there is an antiferromagnetic coupling between Co layers across Cr/Ag bilayer for its spacer thickness λ varying between 9 and 23 Å. Second, and more interesting, we found a pronounced logarithmic term in the temperature dependence of the electrical resistivity, $\rho(T)$. The slope of the $\log_{10} T$ contribution is not affected by magnetic fields up to 11 T and the resistivity does not show saturation at least down to 30 mK. We interpret the logarithmic behavior of the resistivity as arising predominantly from two-dimensional (2D) electron-electron (e-e) interactions in the presence of disorder, although contribution due to the interaction of electrons with two-level systems (TLS) cannot be excluded. It is shown that the logarithmic term varies as a function of λ with a periodicity of one Cr monolayer, while the periodically enhanced disorder at the Cr/Ag interface also affects the magnetoresistance.

The Co/(Cr/Ag)/Co multilayers were prepared in a Riber MBE deposition system (base pressure 2×10^{-11} mbar) using electron beam guns and a mass spectrometer control system to stabilize the growth rate. During evaporation the temperature of the MgO(100) substrate was held at 20° C. In order to vary λ systematically in a single sample, the Cr and Ag films were grown in a wedge shape configuration. The following multilayer composition was prepared: [Co(45 Å)/Cr(0–15 Å)/Ag(0–20 Å)/Co(45 Å)] covered by 20 Å of Ag as a protection layer. The slope of the Cr and Ag wedge was 1 and 1.35 Å/mm, respectively. From these slopes and the λ, total spacer thickness, the thickness of the individual layers λ_{Cr} and λ_{Ag}, are calculated as $\lambda_{\mathrm{Cr}} = (1/2.35)\lambda$ and $\lambda_{\mathrm{Ag}} = (1.35/2.35)\lambda$. The sample surface and structure were studied in detail by atomic force microscopy (AFM), x-ray diffraction (XRD), and magnetic force microscopy (MFM). The AFM measurements on the thinnest part of the wedge gave an rms roughness of 0.4 nm over a $2.5 \times 2.5\ \mu\mathrm{m}^2$ area, while for the thickest part of the wedge an rms roughness of 1.5 nm was obtained for the same area. The average grain diameter observed using AFM images is 50 nm. Low-angle specular XRD spectra clearly showed a series of well-defined finite size oscillations, again an indication of low film roughness. As estimated from MFM measurements, the magnetic domain size was of the order of 1 μm. The magneto-optical Kerr effect (MOKE) with laser spot size of about 0.2 mm was used to measure the magnetic hysteresis loops at room temperature for different λ values with the magnetic field applied parallel to the wedge plane. After the MOKE measurements, using combined photolithography and Ar bombardment

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(keeping the substrate temperature below 60° C), the sample was patterned to strips of about 1 cm long, 80 μm wide, and separated from each other by about 30 μm. Magnetotransport measurements were carried out on the strips in the temperature interval $1.6 < T < 300$ K and in magnetic fields up to 11 T by using the standard four-contact dc method.

Figure 1 shows the dependence of the saturation field H_S on the spacer thickness λ as obtained from the MOKE measurements. It is clearly seen that over a broad range of the λ values, the Co layers are coupled antiferromagnetically. Outside this region, the MOKE hysteresis loops were typical for either uncoupled or ferromagnetically coupled magnetic films. There are indications of the presence of a minimum in the saturation field, as marked by the arrow in Fig. 1.

In the region of ferromagnetic coupling $\lambda(\mathrm{Cr/Ag}) <$ 7 Å, the magnetoresistance in a field H parallel to the current $\mathbf{I}$ ($H \| \mathbf{I}$) is always positive and changes sign for $H \perp \mathbf{I}$. This is a feature of the anisotropic magnetoresistance (AMR) [11]. For the spacer thickness 10 Å $< \lambda <$ 23 Å, the magnetoresistance is typical for the spin-valve (SV) effect, being negative and weakly dependent on the direction of the in-plane magnetic field. This weak dependence follows from the fact that the total magnetoresistance is a superposition of two contributions, AMR and SV MR, with the latter being dominant. In the range 7 Å $< \lambda <$ 10 Å the MR as a function of magnetic field displays both positive and negative contributions. The magnetoresistance and MOKE data clearly show the transition from ferromagnetic to antiferromagnetic coupling in the Co/(Cr/Ag)/Co multilayers with increasing thickness of the bimetallic nonmagnetic spacer.

Figure 2 shows the temperature dependence of the resistivity for two Co/(Cr/Ag)/Co strips with $\lambda \simeq 14.5$ Å and $\lambda \simeq 24.6$ Å. For all strips the resistivity always shows a minimum at $T \sim 20-30$ K, followed by a logarithmic increase of the resistivity with decreasing T according to the relation $\rho \simeq A \log_{10}(T) + C$. To be sure that the behavior is not caused by the lithography or argon bombardment, we measured the temperature dependence of the resistivity of a piece of the unpatterned wedge sample with a λ varying between 10 and 20 Å, and observed qualitatively a similar behavior. The temperature dependence of the resistivity for a [Co(45 Å)/ (Cr(6.4 Å)/Ag(8.6 Å))/Co(4.5 Å)] sample was also checked at temperatures below 1.4 K by using a dilution refrigerator. No saturation of the logarithmic slope in the resistivity down to 30–50 mK was observed (see the inset of Fig. 2).

The logarithmic increase of the resistivity at low temperatures may be caused by (i) the Kondo effect [12], (ii) weak electron localization effects [13,14], (iii) disorder enhanced two-dimensional electron-electron interactions [13,14], or by (iv) interaction of conduction electrons with two-level systems (TLS) [15]. The first two effects are sensitive to low magnetic fields and give rise to a negative magnetoresistance. They can be distinguished from the others interactions by applying a sufficiently strong magnetic field [13]. The estimated upper limit for the Kondo temperature $T_K \simeq 7$ K defined as the middle point of the temperature interval where the resistivity grows logarithmically. Therefore, for the usual Kondo effect, the temperature dependence of the resistivity should be

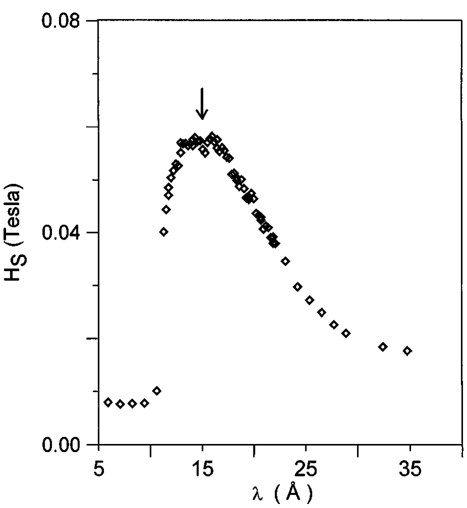

FIG. 1. Saturation field H_S obtained from MOKE measurements as a function of the thickness λ of the Cr/Ag spacer.

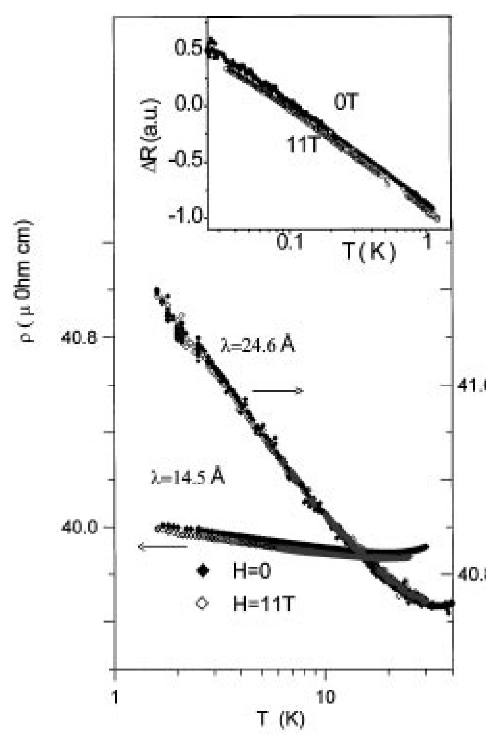

FIG. 2. Temperature dependence of the resistivity in magnetic fields $H = 0$ and $H = 11$ T for two strips with $\lambda = 14.5$ Å and $\lambda = 24.6$ Å. The inset shows variation of the resistance of Co(45 Å)/[Cr(6.4 Å)/Ag(8.6 Å)]/Co(45 Å)] sample at ultralow temperatures.

substantially changed by a field $H \sim 11$ T. Characteristic fields which suppress weak localization effects are given by $H_\Phi \sim (hc/2e)(L_i L_e)^{-1}$ (L_i and L_e are the inelastic and elastic scattering lengths, respectively) and are usually lower than 0.1 T [13]. Figure 2 clearly shows that even a magnetic field of 11 T has almost no influence on the slope of $\rho(T)$. The same behavior was observed in all measured strips.

The lack of saturation of the resistivity down to ultralow temperatures in $H = 0$ as well as in magnetic field of 11 T (Fig. 2) implies that the logarithmic term in the resistivity is likely due to the 2D type electron-electron interactions in the presence of disorder. If the two-level system, normally described by a standard *s-d* exchange (Kondo) model with pseudospin operators [15] would be involved, one would observe the Fermi-liquid type saturation of the resistivity for $T \to 0$. The quasi-2D character of the electronic transport indicates a possible "channeling" of the current in less resistive nonmagnetic layers. Although we believe that the observed $\log_{10}(T)$ behavior of the resistivity is predominantly due to the *e-e* interactions in the presence of disorder, the present experimental data do not allow us to exclude the presence of some contribution to the resistivity due to scattering on TLS. Some indication of the possibility of such an additional contribution comes from a deviation from the $\log_{10}(T)$ behavior in the resistivity, seen below 50 mK (see the inset of Fig. 2).

The resistivity minimum followed by a logarithmic increase of the resistivity at low temperatures down to 0.1 K was already observed in Ni [16] and Fe [17] films and was interpreted in terms of electron localization and/or electron-electron interaction effects. However, to the best of our knowledge, no systematic study of the $\log_{10} T$ term in the resistivity has been reported.

The relative change of the resistance R_S of a square film due to *e-e* interactions is given by [14] $(\Delta R_S)/R_S = -\alpha(e^2 R_S/2\pi^2\hbar)\log_{10}(T\tau_e/\hbar)$, where α is the electron-electron interaction coefficient and τ_e is the elastic scattering time. For $\tau_e \sim (10^{-9} - 10^{-13})$ s the ratio of the coefficients A/C is close to $-\alpha(e^2 R_S/2\pi^2\hbar)$ within the accuracy of more than 0.01, and therefore we will further analyze the thickness dependence of $(-A/C)$. We emphasize that such a plot is not affected by an error in the determination of the absolute values of the resistivity which may be induced by contact configurations and/or possible presence of weakly conducting bridges between adjacent strips. For all studied strips the coefficient A was always negative and the factor C positive.

Let us consider now the thickness dependence of the observed logarithmic term in the resistivity. Figure 3(a) shows the variation of the normalized slope of the resistivity $n_e = -A/C$ as a function of the spacer thickness. *The most intriguing feature is the presence of sharp peaks occurring periodically with increasing λ.* The distance between two successive peaks is approximately $\Delta\lambda \sim 5$ Å. The first peak near $\lambda \sim 10$ Å is relatively broad and has a small amplitude. The other peaks are much more pronounced. We checked whether the presence of those peaks is reflected in the MR and MOKE data. In the spacer thickness interval 10 Å $< \lambda <$ 23 Å, where the spin valve effect dominates, there are dips in the magnetoresistance at $\lambda \approx 15$ Å and 20 Å while the MR is negligible at $\lambda \approx 25$ Å [see Fig. 3(b)]. Moreover, the saturation field H_S as a function of λ, obtained from the MOKE measurement, indicates at least one minimum at $\lambda \approx 16$ Å (see the arrow in Fig. 1).

Although neglected up to now in the evaluation of the properties of magnetic multilayers, the $\log_{10}(T)$ term in the electrical resistivity seems to be a general feature of magnetic multilayers. This is due to the fact that some disorder inside the layers and particularly at the interfaces is unavoidable. We have found the presence of similar $\log_{10} T$ in the following systems: Co/Cr/Co, Co/(Ag/Cr)/Co, and Co/Ag/Co. In the Co/(Cr/Ag)/Co system three types of interfaces should be taken into account: (i) the interface between Co/Cr whose properties remain more or less unchanged and (ii) whose properties may change significantly along the wedge (the interfaces between Cr/Ag and Ag/Co). When R_S is a monotonous function of λ, the periodic peaks in $n_e \approx \alpha e^2 R_S/2\pi^2\hbar$ can only be induced by a change of the *e-e* interaction

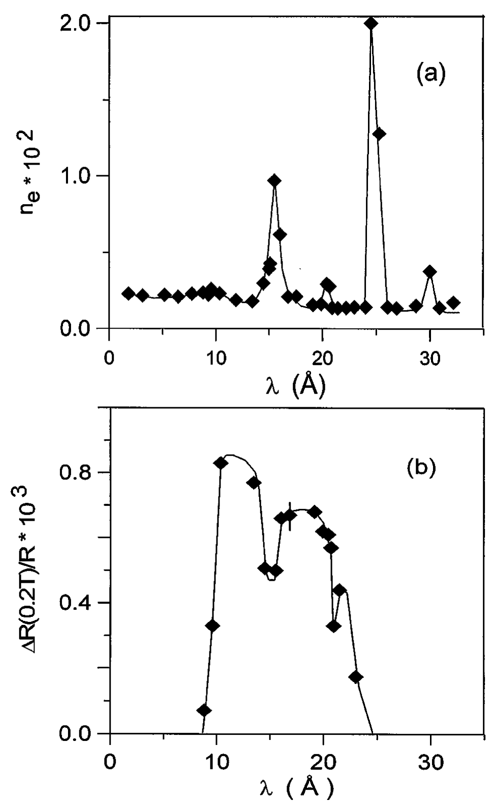

FIG. 3. (a) The normalized electron-electron interaction term, $n_e = -A/C$, as a function of the Cr/Ag spacer thickness λ. (b) Magnetoresistance as a function of λ measured at $T = 200$ K. The lines are a guide to the eye.

coefficient α, due to a change of disorder at the Cr/Ag interface. The observed periodicity $\Delta\lambda \sim 5$ Å in $n_e(\lambda)$ corresponds to the thickness of about 2.1 Å for the Cr and 2.9 Å for the Ag layer. If we assume that the bcc Cr layer grows along the preferential (110) direction [18], the single Cr layer thickness should be $d \approx 2.04$ Å, which is in good agreement with 2.1 Å estimated for above Cr. Concerning the role of Ag in the bimetallic spacer layer, the observed periodicity could be explained by assuming a (110) growth direction. It is, however, well know that Ag preferentially grows along the (111) direction [19].

The interface morphology induced oscillations with a 1 monolayer (1 ML) periodicity have recently been observed in the magnetic properties and the in-plane lattice spacing of Co films [20–22]. Similar oscillations, but with a relative amplitude less then 1%, were also found in resistance of ultrathin gold films [23]. In our view, the sharp periodic peaks in the electron-electron interaction observed in the present work are also due to variation in the interface morphology. As an additional mechanism contributing to the periodically enhanced disorder, one may also assume 1 ML variation of the Cr lattice spacing, analogous to that observed recently for Co films [20]. For the above scenarios the effect of *additional* disorder should be diluted as λ increases. An intriguing feature seen in Fig. 3(a) is a 2 ML modulation of the peak amplitude, which may be caused by some kind of interference phenomena. Further experimental work is, however, required to determine the microscopic origin of these effects and to reveal a possible specific character of the Cr/Ag interface found in the present work.

In conclusion, we observed antiferromagnetic interlayer coupling in magnetic multilayers with a bimetallic nonmagnetic spacer layer. We also found an additional low temperature contribution to the resistivity which varies as $\log_{10}(T)$ with the logarithmic slope unaffected by a magnetic field up to 11 T. We interpret this behavior as being predominantly due to electron-electron interactions in the presence of disorder. A pronounced oscillatory behavior of the electron-electron interaction term in the resistivity with period corresponding to one Cr monolayer was found. However, we cannot exclude an additional contribution to the $\log_{10}(T)$ term in the electrical resistivity due to scattering on TLS, which is also dependent on structural disorder. Only systematic studies at ultralow temperatures ($T < 50$ mK) and in various applied magnetic fields may resolve these contributions.

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