Giant magnetoresistance in Ag/Ni superlattices

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A comparison of the evolution of magnetoresistance and magnetic coupling in the Ag/Ni superlattice system is presented as a function of the silver thickness, for a nickel thickness kept at 8 Å. This system exhibits a magnetoresistance effect as large as 28% and gives rise to an ideal thickness of 10–12 Å for antiferromagnetic coupling. No further clear oscillations are observed. Both the position and amplitude of the oscillations are in agreement with recent theoretical calculations.

Antiferromagnetic coupling between ferromagnetic iron layers through chromium and the alignment of the magnetization of the two iron magnetic sublattices under an external magnetic field were observed by Grünberg *et al.*[1] Then it was discovered by Baibich *et al.*[2] that a giant-magnetoresistance effect was related to this magnetic behavior. These authors showed that at 4.2 K the resistivity of a Fe(30 Å)/Cr(9 Å) superlattice decreased by a factor close to 2 when a 20-kOe field was applied on the sample. The effect was interpreted by a two-current model in which spin-up and -down electrons are subjected to identical scattering potentials in the antiferromagnetic state, but different ones in the aligned magnetic state. In this latter case, one of the electron flows is very conductive and the resultant resistivity is low.

Since the discovery of giant magnetoresistivity in Fe/Cr, several multilayered systems have been explored, and up to now some of them, such as Co/Cu,[3,4] Ag/Co,[5] and Ni/Ag (Ref. 6) have been shown to exhibit the same phenomenon. From these systems it appears that the effect is not due to the peculiar magnetic behavior of chromium, but is something more general.

The interest increased further when Parkin, More, and Roche[7] showed that the coupling between iron layers decreased as expected when increasing the chromium thickness, but with oscillations. Such oscillations were observed clearly in the Co/Cu system[3,4] through the amplitude of the magnetoresistance effect. At 4.2 K the resistivity exhibits 80%, 40%, and 20% drops for $t_{Cu}=9$, 20, and 35 Å, respectively, with very small effects between these maxima.[4]

Following the experimental studies, theoretical works were devoted to the magnetoresistivity effect and oscillating coupling mechanism.[8–11] Giant magnetoresistivity is qualitatively explained by the two-current model, but the details of the scattering at the interface and/or in the bulk are still under discussion. The antiferromagnetic coupling mechanism of magnetic layers through a nonmagnetic spacer seems now to be understood by a "vernier effect" on the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction.[12,13] Such an effect explains the long-wavelength oscillation of the coupling. In reciprocal space it is equivalent to an "umklapp" process. The q_s wave vectors of the coupling oscillation join two points of the Fermi surface of neighboring Brillouin zones. The possible q_s vectors and phase shift of the oscillation have been calculated recently by Bruno and Chappert[12] for copper, silver, and gold with different cristallographic orientations. However, experimental results are available for copper, but very few data have been published with silver,[14] which has even been recently presented as a noncoupling element.[15,16]

In this Brief Report, we present a comparison of the evolution of magnetoresistance and magnetic coupling in the Ag/Ni superlattice system as a function of silver thickness. We focus this report on a set of samples where the Ni thickness was kept at 8 Å and where the Ag thickness varies from 8 to 40 Å. We confirm that the thickness for the maximum antiferromagnetic coupling is 10–12 Å, but we did not observe further clear oscillations.

The samples were obtained by dc sputtering and by alternative deposition of Ag and Ni layers onto glass substrates kept at a temperature of 100 K. The total thickness of the samples was 5 μm. X-ray-diffraction experiments showed that good-quality (111)-textured superlattices were obtained down to very small layer thicknesses.[17] From diffraction experiments in transmission geometry, the in-plane size of the crystallites was found to be of the order of 100 Å. The magnetoresistance measurements were performed in fields up to 60 kOe applied in the plane of the layers, the current flowing in the plane, perpendicular to the applied field.

Previous magnetic measurements[6] performed in fields up to 40 kOe showed the occurrence of antiferromagnetic coupling between nickel layers and allowed one to determine the saturation field H_s beyond which the magnetic sublattices are aligned. Antiferromagnetic ordering was confirmed by neutron-scattering experiments.[18] From the field dependence of the antiferromagnetic diffraction peak, it was shown that between 0 and H_s the increase of the resultant magnetization was due to the orientation of the spontaneous magnetization of the antiferromagnetic sublattices toward the field direction. The evolution of

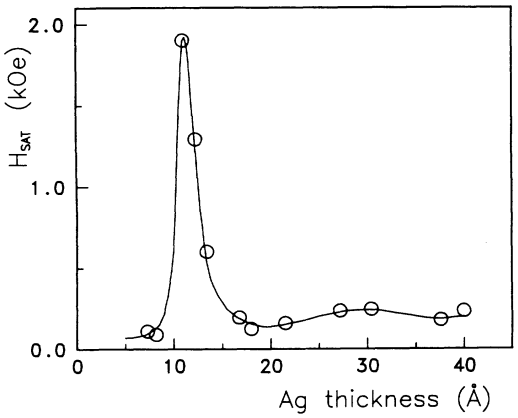

FIG. 1. Variation of the saturation field H_s as a function of the thickness of silver (t_{Ag}) for Ni(8 Å)/Ag(t_{Ag}) multilayers at 5 K.

H_s as a function of the silver thickness is shown in Fig. 1. The values of H_s exhibit a maximum of 2 kOe near 11 Å, but the second maximum, if it exists, is of very small amplitude compared with the case of Co/Cu superlattices.[3,4]

The magnetoresistance ratio

$$\frac{\Delta R}{R}=\frac{[R(H)-R(H_m)]}{R(H_m)},$$

obtained at 4.2 K for selected samples, is presented in Fig. 2. (We choose to normalize the data with the resistance at $H_m=5$ kOe.) For every sample two curves are obtained, depending on whether the data are collected while increasing or decreasing the magnetic field, the curves being shifted from each other by twice the coercive field. For $t_{Ag}=11$ and 13.4 Å [Figs. 2(a) and 2(b)], $\Delta R/R$ decreases in a parabolic way, whereas a sharp peak is observed for larger Ag thicknesses [Fig. 2(c)]. It has to be noted that the shape of these curves is very similar to that observed in Co/Cu samples.[3] When the magnetoresistance effect is large, the shape is parabolic; when it is small, sharp peaks are obtained.

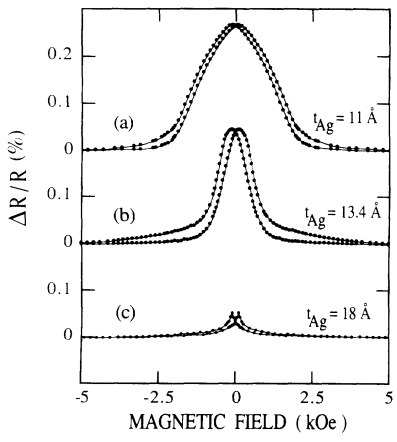

FIG. 2. Magnetoresistance curves of Ni(8 Å)/Ag(t_{Ag}) multilayers at 4.2 K [$\Delta R/R=\{R(H)-R(H_m)\}/R(H_m)$ with $H_m=5$ kOe]: (a) $t_{Ag}=11$ Å, (b) $t_{Ag}=13.4$ Å, and (c) $t_{Ag}=18$ Å.

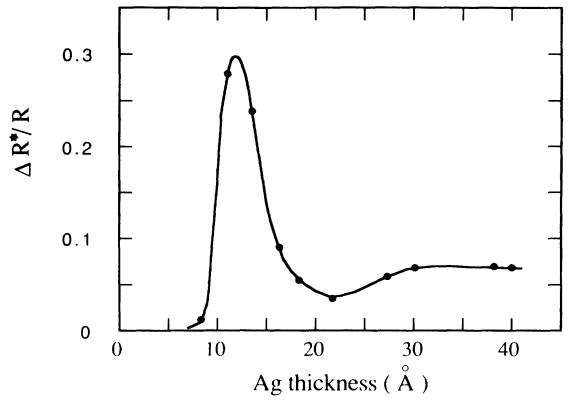

FIG. 3. Transverse saturation magnetoresistance vs Ag layer thickness (t_{Ag}) for Ni(8 Å)/Ag (t_{Ag}) multilayers at 4.2 K [$\Delta R^*/R=\{R(H=0)-R(H_m)\}/R(H_m)$].

The evolution of the magnetoresistance ratio

$$\frac{\Delta R^*}{R}=\frac{[R(H=0)-R(H_m)]}{R(H_m)},$$

as a function of the Ag thickness, is shown in Fig. 3. One sees that the variation of $\Delta R^*/R$ follows closely that of the saturation field H_s obtained from magnetization data.[6] Both sets of data exhibit a maximum for a Ag thickness close to 11–12 Å, at which a magnetoresistance ratio as large as 28% is obtained. A second maximum similar to the second maximum of H_s is only guessed at around 30 Å.

Nevertheless, it should be noted that the first maximum of $\Delta R^*/R$ is broader than that of H_s. This can be clearly seen in Figs. 2(a) and 2(b), where increasing the Ag thickness from 11 to 13.4 Å leads to a rather small decrease of $\Delta R^*/R$ (from 0.28 to 0.23), but to a noticeable decrease of the saturation field (from about 2.0 to 0.8 kOe), in agreement with magnetization results. This non-one-to-one relationship between magnetoresistance ratio and saturation field can be explained by the fact that the observed $\Delta R/R$ is a consequence of the evolution of the relative orientation of the magnetization directions in successive magnetic layers and not of the strength of the magnetic coupling. The "potential" $\Delta R/R$ is the resistivity change occurring in a system where the magnetic moments turn, for whatever reason, from antiparallel to parallel orientation.[19,20] It has been shown recently that this potential $\Delta R/R$ decreases monotonously with increasing the thickness of the nonmagnetic spacer.[20] As a result, the observed $\Delta R/R$ is expected to vary from 0 in the ferromagnetic region to its full potential value as soon as the coupling turns antiferromagnetic, independent of the strength of the coupling, that is, for any value of the saturation field. This would explain why we observe a magnetoresistance peak broader than the saturation field one.

The thickness corresponding to maximum coupling (12 Å) is larger than that observed with Cu(111) by Parkin, Bhadra, and Roche[3] and Mosca *et al.*,[4] where the first maximum is closer to 9 Å. The difference is consistent with the calculations of Bruno and Chappert,[12] which led

to a modulation wavelength of 9.36 Å for copper and 13.96 Å for silver and with Coehoorn's analysis[13] predicting periods 13% larger for systems with Ag and Au compared with systems with Cu interlayers. The very small amplitude of the second oscillation, theoretically expected to be around 27–28 Å, could be due to interfacial roughness and/or to the damping factor which is predicted to be maximum with Ag(111).[12]

Ferromagnetic coupling near 20 Å and the antiferromagnetic one near 13 Å will be tested by low-angle neutron scattering. The coupling should be weaker with nickel, which has not been studied much, except recently in Permalloy-based spin-valve structures.[21] For very weak coupling, in-plane anisotropy could modify the magnetic structure and thus the resistivity. Such effects were recently evidenced by Krebs and co-workers on Fe/Cr/Fe sandwich structures.[22,23]

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