Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices

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We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers: For example, with $t_{\mathrm{Cr}}=9$ Å, at $T=4.2$ K, the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.

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There is now considerable interest in the study of multilayers composed of magnetic and nonmagnetic metals and great advances have been obtained in the understanding of their magnetic properties.[1-4] Recently the transport properties of magnetic multilayers and thin films have been investigated and have revealed interesting properties resulting from the interplay between electron transport and magnetic behavior.[5-7] In this Letter we present magnetoresistance measurements on (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy (MBE). In superlattices with thin Cr layers, the magnetoresistance is very large (a reduction of the resistivity by a factor of about 2 is observed in some samples). This giant magnetoresistance raises exciting questions and moreover is promising for applications.

The (001)Fe/(001)Cr bcc superlattices have been grown by MBE on (001) GaAs substrates under the following conditions: The residual pressure of the MBE chamber was 5×10^{-11} Torr, the substrate temperature was generally around 20° C, the deposition rate was about 0.6 Å/s for Fe and 1 Å/s for Cr. This deposition rate was obtained by use of specially designed evaporation cells in which a crucible of molybdenum is heated by electron bombardment. The individual layer thicknesses range from 9 to 90 Å and the total number of bilayers is generally around 30. The growth of the superlattices and their characterization by reflection high-energy electron diffraction, Auger-electron spectroscopy, x-ray diffraction, and scanning-transmission-electron microscopy have been described elsewhere.[8] Note that the Cr (Fe) Auger line disappears during the growth of a Fe (Cr) layer. This, as well as the main features of the scanning-transmission-electron-microscopy cross sections, rules out a deep intermixing of Fe and Cr.[8] However, the Auger effect, which averages the concentrations over a depth of about 12 Å, cannot probe the interface roughness at the atomic scale. Surface extended x-ray-absorption fine-structure experiments have been started to probe this roughness more precisely.

The magnetic properties of the Fe/Cr superlattices have been investigated by magnetization and torque measurements.[9] The magnetization is in the plane of the layers and an antiferromagnetic (AF) coupling between the adjacent Fe layers is found when the Cr thickness t_{Cr} is smaller than about 30 Å.[9] A signature of this AF interlayer coupling is shown in Fig. 1: As the Cr thickness decreases below 30 Å, the hysteresis loop is progressively tilted. For example, with $t_{\mathrm{Cr}}=9$ Å, a field $H_S\simeq 2$ T is needed to overcome the antiferromagnetic coupling and to saturate the magnetization at about the bulk Fe value. When the applied field is decreased to zero, the AF coupling brings the magnetization back to about zero. As can be seen from the variation of the low-field slopes in Fig. 1, the AF coupling steeply increases when t_{Cr} decreases from 30 to 9 Å. The existence of such AF couplings has already been found in Fe/Cr sandwiches by the light-scattering and magneto-optical measurements

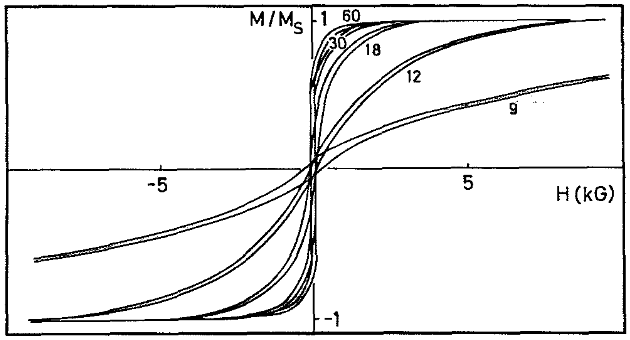

FIG. 1. Hysteresis loops at 4.2 K with an applied field along [110] in the layer plane for several (001)Fe/(001)Cr superlattices: [(Fe 60 Å)/(Cr 60 Å)]$_5$, [(Fe 30 Å)/(Cr 30 Å)]$_{10}$, [(Fe 30 Å)/(Cr 18 Å)]$_{30}$, [(Fe 30 Å)/(Cr 12 Å)]$_{10}$, [(Fe 30 Å)/(Cr 9 Å)]$_{40}$, where the subscripts indicate the number of bilayers in each sample. The number beside each curve represents the thickness of the Cr layers.

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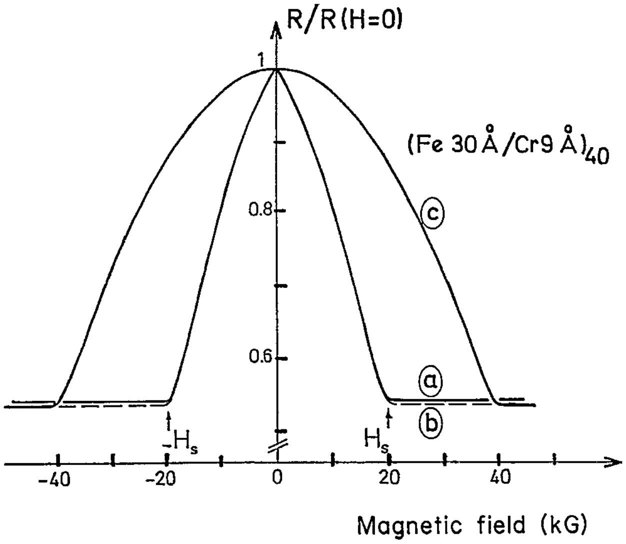

FIG. 2. Magnetoresistance of a [(Fe 30 Å)/(Cr 9 Å)]$_{40}$ superlattice of 4.2 K. The current is along [110] and the field is in the layer plane along the current direction (curve a), in the layer plane perpendicular to the current (curve b), or perpendicular to the layer plane (curve c). The resistivity at zero field is 54 $\mu\Omega$ cm. There is a small difference between the curves in increasing and decreasing field (hysteresis) that we have not represented in the figure. The superlattice is covered by a 100-Å Ag protection layer. This means that the magnetoresistance of the superlattice alone should be slightly higher.

of Grünberg *et al.*[4] and by the spin-polarized low-energy electron-diffraction experiments of Carbone and Alvarado.[10] The AF coupling between the Fe layers has been ascribed to indirect exchange interactions through the Cr layers, but a theoretical model of these interactions is still lacking.[4,9]

The magnetoresistance of the Fe/Cr superlattices has been studied by a classical ac technique on small rectangular samples. Examples of magnetoresistance curves at 4.2 K are shown in Figs. 2 and 3. The resistance decreases during the magnetization process and becomes practically constant when the magnetization is saturated. The curves a and b in Fig. 2 are obtained for applied fields in the plane of layers in the longitudinal and transverse directions, respectively. The field H_S is the field needed to overcome the AF couplings and to saturate the magnetization (compare with Fig. 1). In contrast, fields applied perpendicularly to the layers (curve c) have to overcome not only the AF coupling but also the magnetic anisotropy, so that the magnetoresistance is saturated at a field higher than H_S.

The most remarkable result exhibited in Figs. 2 and 3 is the huge value of the magnetoresistance. For $t_{\mathrm{Cr}}=9$ Å and $T=4.2$ K, see Fig. 2, there is almost a factor of 2 between the resistivities at zero field and in the saturated state, respectively (in absolute value, the resistivity change is about 23 $\mu\Omega$ cm). By comparison of the results for three different samples in Fig. 3, it can be seen

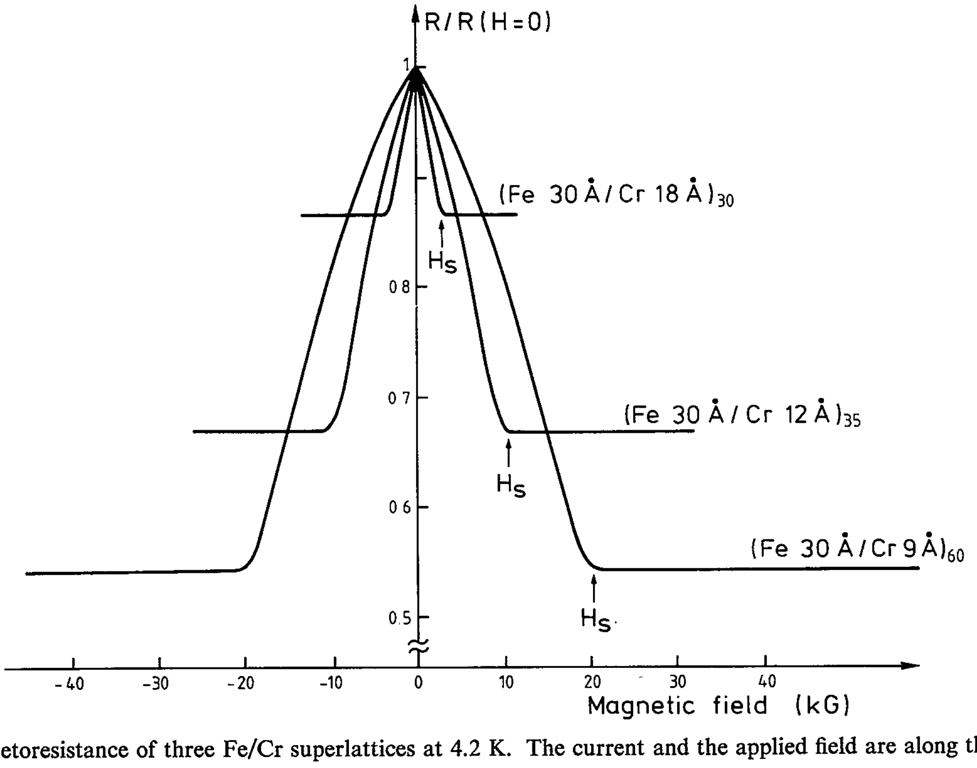

FIG. 3. Magnetoresistance of three Fe/Cr superlattices at 4.2 K. The current and the applied field are along the same [110] axis in the plane of the layers.

that the magnetoresistance is lowered when the Cr thickness increases. At the same time, an increase of t_{Cr} weakens the AF coupling and the saturation field H_S decreases. Similarly, we find that both the magnetoresistance and H_S decrease when the temperature increases: typically, from 4.2 K to room temperature, the saturation magnetoresistance is lowered by about a factor of 2, while H_S is reduced by about 30%. We point out that the magnetoresistance is still very significant at room temperature.

Summarizing the data simply, giant magnetoresistance effects are obtained in antiferromagnetically coupled Fe/Cr superlattices by our aligning the magnetizations of adjacent Fe layers with an external field. We propose that this magnetoresistance arises from spin-dependent transmission of the conduction electrons through the thin Cr layers. First, we point out that perfect interfaces would produce only specular reflections and diffractions of the electron waves, without significant change of the longitudinal resistivity. Significant effects on the resistivity are expected only from scattering by interface roughness. Second, we note that the scattering can be strongly spin dependent in a ferromagnetic transition metal.[11] For Cr impurities in bulk Fe, the resistivity cross section for spin-down→spin-down scattering is about 6 times smaller than for spin-up→spin-up scattering (we call up and down the majority and minority spin directions, respectively).[11] This leads us to propose the following explanation for the giant magnetoresistance of the Fe/Cr superlattices. Thin Cr layers (9 Å $\approx$ 3 lattice constants) between thicker Fe layers having parallel magnetizations should scatter the conduction electrons roughly as Cr impurities in bulk Fe, which implies weak interface scattering and a high coefficient of coherent transmission for the spin-down electrons. Thus, at $H > H_S$, the current is carried by the spin-down electrons with a low resistivity, $\rho \approx \rho_\downarrow \ll \rho^\uparrow$, where $\rho_\uparrow$ and $\rho_\downarrow$ are the resistivities for the spin-up and spin-down currents, respectively. At zero field, with Cr layers between two Fe layers having antiparallel magnetizations, the resistivity is expected to be definitely higher for two reasons. First, for the electrons of one of the Fe layers, not only the Cr atoms but also the Fe atoms of the antiparallel layer represent possible scattering potentials and reduce the coherent transmission. Second the spin-up and spin-down currents are averaged, which suppresses the short-circuit effect by one direction of the first case. An applied field, by aligning the magnetizations, progressively opens the spin-down→spin-down channel and lowers the resistivity. For thicker Cr layers, or at higher temperatures, the probability of spin-flip scattering within the Cr layers increases and, by mixing the spin channels, weakens the magnetoresistance. Similar concepts have been introduced by Cabrera and Falicov[12] for the resistivity of Bloch walls, and more recently by Johnson and Silsbee[13] for the problem of spin injection from a ferromagnet, and their formalisms could probably be adapted to be applied to the magnetoresistance of our multilayers. This is not at all within the scope of this Letter which is aimed only to present experimental results and to suggest an interpretation.

In conclusion, we have found a giant magnetoresistance in (001)Fe/(001)Cr superlattices when, for thin Cr layers (9, 12, and 18 Å), there is an antiparallel coupling of the neighbor Fe layers at zero field. The highest magnetoresistance is observed in [(Fe 30 Å)/(Cr 9 Å)]$_{40}$: The resistivity is reduced by almost a factor of 2 when the magnetization is saturated. We interpret our results in terms of spin-dependent transmission between ferromagnetic layers. The giant magnetoresistance of the Fe/Cr superlattices may result from an interplay of the orientation of the Fe layers by an applied field with the spin-dependent transmission between Fe layers through a Cr layer. If one considers that strongly spin-dependent conduction occurs in many ferromagnetic transition-metal alloys,[11] the type of magnetoresistance found in Fe/Cr should be observed in other transition-metal superlattices. The existence of a giant magnetoresistance in Fe/Cr is promising for applications to magnetoresistance sensors. In the samples we have studied, the saturation fields are obviously too high for applications but a large magnetoresistance at relatively small fields can probably be obtained by thickening of the Fe layers (in a given field, this enhances the torque on the magnetic layers). Alternatively high magnetoresistance effects with weaker AF couplings should probably be observed with other couples of transition metals.

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