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Two-monolayer-periodicity oscillations in the magnetoresistance of Fe/Cr/Fe trilayers

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Magnetoresistance oscillations with a period of two monolayers of Cr have been observed in Fe/Cr/Fe trilayers. Magneto-optic measurements were performed on the same sample in order to verify the periodicity and determine the nature of the coupling between the Fe layers. The saturation fields obtained from both the transport and optical measurements agree well at room temperature. These results indicate that the magnetoresistance is controlled by the coupling mechanism.

Magnetically coupled layered structures have recently attracted much attention as they display a wide variety of interesting physical properties.[1–11] In the Fe/Cr system, the coupling between adjacent Fe layers was found to be ferromagnetic or antiferromagnetic depending on the thickness of the Cr interlayer.[1] This displayed itself first as a giant magnetoresistance, the amplitude of which oscillated with the thickness of Cr with a period of 18 Å.[2,3] Magneto-optic Kerr-effect (MOKE) measurements confirmed this period for the coupling between Fe layers.[5] The observation of additional structure in this oscillation indicated the presence of a shorter period oscillation.[8] With improvements in the layering quality, this additional short period oscillation was seen in Fe/Cr/Fe trilayers, probed by scanning electron microscopy with spin polarization analysis (SEMPA).[9] The short period oscillation was found to have a length of two monolayers and be commensurate with the spin density wave found in bulk Cr.[12,13] However, the MOKE and SEMPA studies were performed on trilayers which were grown on Fe whiskers or thick metallic buffer layers, making these samples unsuitable for electrical transport studies.

We report here on electrical transport and magneto-optical studies performed on Fe/Cr/Fe trilayers grown on MgO (100) substrates without any buffer layer. The magnetoresistance (MR) measurements clearly display the existence of the short period oscillation, while the MOKE measurements identify the nature of the coupling between the Fe layers.

The Fe/Cr/Fe trilayers were prepared in a Riber MBE deposition system [base pressure $2(10)^{-11}$ mbar] equipped with several electron beam guns and Knudsen cells. Fe and Cr (99.996% purity) were *e*-beam evaporated at a rate of 1 Å/s on MgO (100) substrates held at 150°C. A home made feedback control system using Balzers quadrupole mass spectrometers was utilized to stabilize the rate to within 1%. *In situ* reflection high-energy electron diffraction was used to monitor the quality of the substrate, the epitaxial relationship and the quality of the growth. The wedge shaped sample with a slowly varying Cr thickness was prepared using a computer controlled movable shutter. The slope of the wedge was 1 Å of Cr per mm. The Fe thickness of the top and bottom layers was 50 Å and the Cr thickness varied from 4 to 20 Å. The trilayer was then covered with 30 Å of Ag as protection against oxidation of the Fe. Following the magneto-optical experiments, the sample was patterned and etched using standard photolithographic techniques to produce the pattern shown in Fig. 1. The strips used for transport measurements were 80 μm wide and about 1 cm long and separated from each other by about 30 μm. Each strip has a Cr thickness variation of 0.2 Å, due to the wedge itself and any misalignment during the lithography procedure. The wedge direction was chosen parallel to the [010] direction of the Fe/Cr layers (the [011] direction of the MgO) in order to facilitate align-

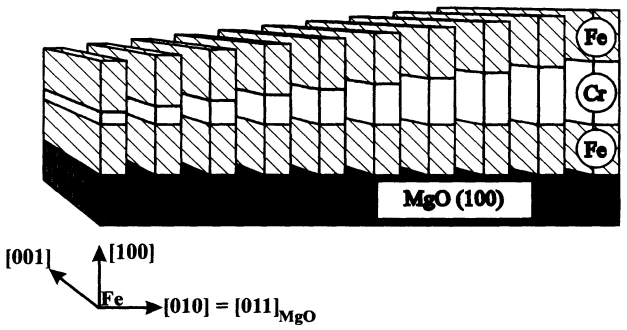

FIG. 1. Diagram of the Fe/Cr/Fe wedge grown on MgO (100) substrate, showing the crystallographic orientations and the strips used for transport measurements. The strips are 80 μm wide, 1 cm long, and separated by 30 μm.

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ment with the magnetic field during the MOKE and MR experiments.

Prior to etching, MOKE experiments were performed, using a standard Kerr effect configuration at room temperature, with the applied field parallel to the easy [010] axis of the Fe layers. A micrometer screw was used to move the wedged sample through the laser beam, with an alignment accuracy of 10 μm. The coupling strength between the Fe layers was estimated from the saturation field of the Kerr rotation.

To measure the MR, leads were attached to the sample by ultrasonic wire bonding. Four probe measurements were performed at 4.2 °K in a 10 T superconducting magnet. Since the signal was relatively small, a Linear Research bridge was used to measure the resistance versus field data. The sample was aligned such that the [010] direction was parallel to the field. In contrast to measurements performed on multilayers, small fields were needed to saturate the magnetoresistance ($H < 3$ kOe).

In the following, the magnetoresistance is defined as the ratio $\Delta\rho/\rho_s$, with $\Delta\rho = \rho_0 - \rho_s$, where ρ_0 is the maximum resistivity at $H = 0$ Oe and ρ_s is the saturation resistivity at $H = 3$ kOe. This definition of ρ_s ensures that the resistances of all samples are fully saturated. We define the magnetoresistance saturation field as the field, H_s at which the change in resistance has reached 80% of $\Delta\rho$ (see Fig. 3). The saturation field from the MOKE is easier to define, since the transition is sharper, therefore the MOKE H_s is essentially at 100% of the variation in the Kerr rotation [see Fig. 2(a)].

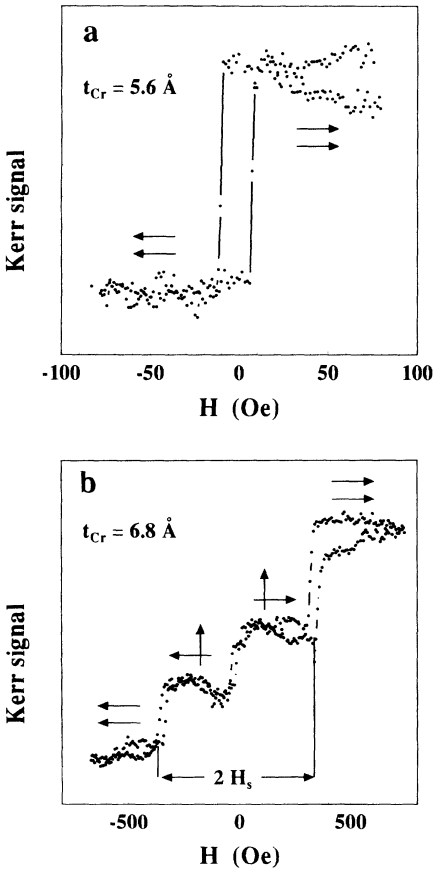

FIG. 2. (a) Ferromagnetic hysteresis loop for an Fe/Cr/Fe trilayer (t_{Cr} = 5.6 Å). (b) Hysteresis loop in the ninety degree coupling regime (t_{Cr} = 6.8 Å). The arrows indicate the direction of magnetization of the two Fe layers. Both loops were measured at room temperature.

Figure 2 shows typical MOKE hysteresis curves for ferromagnetic coupling [Fig. 2(a)] and ninety degree coupling [Fig. 2(b)] measured on different parts of the wedge (t_{Cr} = 5.6 Å and t_{Cr} = 6.8 Å, respectively). All MOKE measurements were performed at room temperature. The arrows on the figure indicate the orientation of the magnetization of the top and bottom Fe layers. In the case of ninety degree coupling, there is a remnant field at zero applied field but the magnetization vectors in the layers of Fe are not parallel, but differ by ninety degrees. As the field increases, the magnetization of the layers become aligned parallel at the saturation field. The ninety degree coupling is explained in terms of biquadratic coupling due to a roughness at the interfaces of one monolayer.[14] In all cases, the total strength of the coupling is well described by the saturation field. The surface energy per unit area as a function of the individual coupling strengths is given by

$$E_s = -J_1\cos\theta - J_2\cos^2\theta \ ,$$

where J_1 and J_2 are the bilinear and biquadratic coupling strengths and θ is the angle between the magnetization vectors in two Fe layers. From the MOKE measurements, J_1 and J_2 can be determined. For example, at t_{Cr} = 8.5 Å, J_1 and J_2 were found to be -0.46 and -0.20 mJ/m^2, respectively. This sample is antiferromagnetically coupled at zero field, and switches to ninety degree coupling at a higher field before total saturation.

A typical magnetoresistance curve (at 4.2 °K) in the region of the maximum magnetoresistance (t_{Cr} = 8.7 Å) is shown in Fig. 3. The sharp spike near zero may be an indication of ninety degree coupling between the Fe layers. Further investigations are necessary to verify this connection.

The size of the magnetoresistance effect is considerably smaller in the trilayer systems (a few percent) as opposed to the multilayer systems [as much as 150% (Ref. 15)]. This can be explained as follows. In multilayer systems

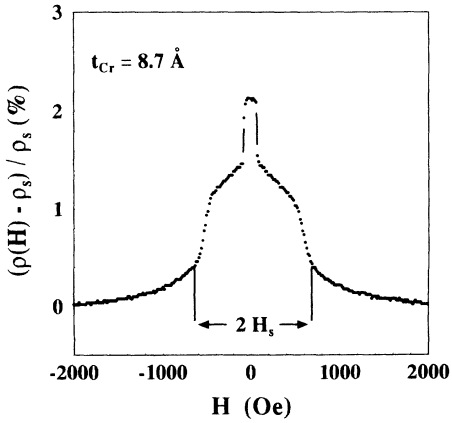

FIG. 3. Magnetoresistance curve taken at 4.2 °K for an Fe/Cr/Fe trilayer (t_{Cr} = 8.7 Å). The criterion for H_s, where 80% of the magnetoresistance effect is saturated, is shown.

with a bilayer thickness of 40 Å, an electron is likely to cross several interfaces before being inelastically scattered by boundaries (vacuum metal or metal substrate). Each bilayer which is crossed allows the electron to undergo a spin-dependent scattering process, which is controlled by the magnetic properties of the layers. In the case of a trilayer however, the electrons only have two opportunities to be scattered magnetically, once at the bottom Fe-Cr interface and once at the top Cr-Fe interface. In trilayers therefore, the boundary scattering is a relatively larger contributor to the total resistance than the magnetic scattering.

Figure 4 shows a plot of the saturation field from the MOKE measurements and the MR of the transport measurements versus Cr thickness in both angstroms and monolayers. All three sets of data clearly show four peaks in the range 4 to 10 monolayers. This two monolayer oscillation period is in agreement with the value reported from SEMPA measurements.[9]

The inset in Fig. 4 shows a plot of the saturation fields determined from the MR and MOKE measurements. The amplitude of the saturation fields in the MOKE experiments are smaller than the MR saturation fields. This is probably due to the temperature dependence of the spin fluctuations in the Fe layers. To check this, magnetoresistance measurements were done at room temperature and 4.2 °K. At room temperature the saturation fields agree completely while at lower temperatures the saturation fields increase by about a factor of 1.5. The amplitude of the saturation fields for these trilayers are significantly smaller than those seen in multilayer systems ($H_s \cong 10$ kOe),[15] although currently the reason for this is not known.

We have observed several oscillations of the magnetoresistance with a two monolayer periodicity in Fe/Cr/Fe trilayers. This periodicity arises from the antiferromagnetism of the Cr interlayer. MOKE measurements indicate that the Fe layers can be aligned parallel, antiparallel or ninety degrees off. The size of the magnetoresistance effect in trilayers is quite small, which is consistent with the interpretation that scattering across interfaces is the dominant contributor to the magnetoresistance seen in these systems. The amplitude of the saturation field of both the magnetoresistance and magneto-optical measurements agree well at room temperature, indicating that indeed, the magnetoresistance is controlled by the coupling mechanism.

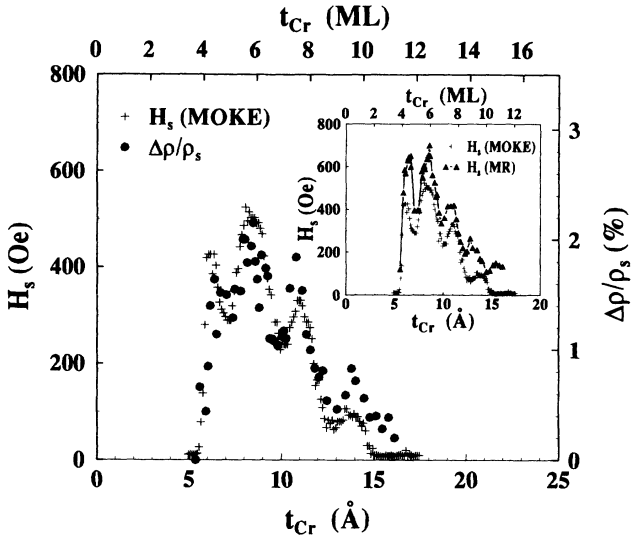

FIG. 4. H_s (crosses, scale at left) for the Kerr rotation, and MR (filled circles, scale at right) for the magnetoresistance vs Cr interlayer thickness in angstroms and monolayers. The inset shows a plot of the saturation fields obtained from both the MOKE (crosses) and MR (open circles) measurements. Both plots show the same oscillation with a period of two monolayers.

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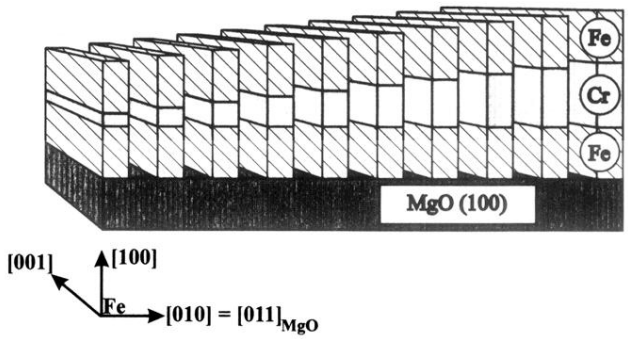

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