Magnetoresistance and magnetization oscillations in Fe/Cr/Fe trilayers

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The 2-ML (monolayer) oscillation period has been observed in the magnetization as well as in the magnetoresistance of Fe/Cr/Fe trilayers. Kerr effect measurements were performed in order to verify the periodicity and determine the kind of the coupling between the Fe layers. The magnetoresistance loops show characteristic steps at magnetic field values at which the size of the magnetization changes.

I. INTRODUCTION

Magnetic multilayers have attracted much attention since 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 switch between ferromagnetic and antiferromagnetic depending on the thickness of the Cr interlayer.[1] This was seen first in 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 measurements (MOKE) confirmed this period for the coupling between Fe layers.[5] With improvements in the layering quality, an 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 SEMPA and MOKE 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 epitaxially on MgO(100) substrates without any buffer layer. Both the magnetoresistance (MR) and the MOKE measurements clearly display the existence of the short period oscillation. At the same time the MOKE measurements are used to identify the nature of the coupling between the Fe layers. This also allows the direct comparison of the Kerr loops with the magnetic field dependence of the MR. The magnetoresistance displays steps at values of the magnetic field at which the absolute value of the magnetization of the sample changes.

II. SAMPLE PREPARATION

The Fe/Cr/Fe trilayers were prepared in a Riber molecular beam epitaxy (MBE) deposition system (base pressure 2×10^{-11} mbar) equipped with two electron-beam guns and four Knudsen cells. Fe and Cr (both starting materials of 99.996% purity) were e-beam evaporated at a rate of 1 Å/s on MgO (100) substrates held at 150 °C. A homemade feedback control system using Balzers quadrupole mass spectrometers was utilized to stabilize the rate to within 1%. *In situ* reflection high-energy electron diffraction (RHEED) was used to monitor the quality of the substrate, the epitaxial relationship and the quality of the growth.

The Fe thickness of the top and bottom layers was 50 Å and the Cr thickness varied, respectively, from 4 to 20 Å and from 0 to 40 Å with slopes of 1 and 2 Å of Cr per mm for the two samples. The wedges were prepared using a computer controlled movable shutter. 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 alignment with the magnetic field during the MOKE and MR experiments. The trilayer was then covered with 30 Å of Ag as protection against oxidation of the Fe.

First, MOKE experiments were performed at room temperature, using a Kerr effect configuration which is sensitive for the longitudinal Kerr effect. The field was applied 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.

Subsequently, one sample was patterned using standard photolithographic techniques to produce a stripe pattern. The stripes used for transport measurements were 80 μm wide and about 1 cm long and separated from each other by about 30 μm. Each stripe has a Cr thickness variation of 0.2 Å, due to the wedge itself and any possible misalignment during the lithography procedure. 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 cryostat equipped with a 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 in such a way that the Fe [010] direction was parallel to the field.

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 resistivity at $H=0$ Oe and ρ_s is the saturation resistivity at $H=3$ kOe. We define the magnetization saturation field as the field, H_s at which the Kerr signal reaches its saturation value.

III. RESULTS AND DISCUSSION

Figure 1 shows a plot of H_s from the MOKE measurements and the MR of the transport measurements versus Cr

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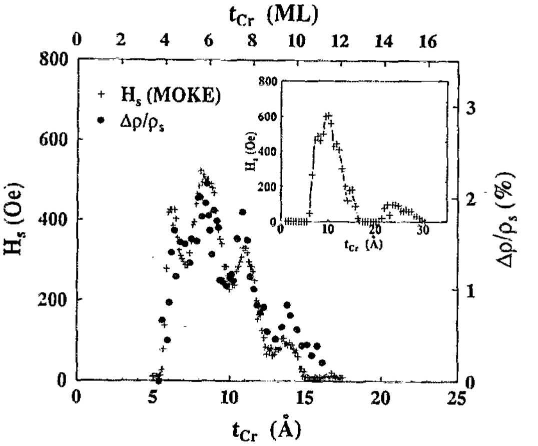

FIG. 1. The saturation field H_s (crosses, scale at left) for the Kerr rotation, and MR (filled circles, scale at right) for the magnetoresistance vs Cr interlayer thickness in angstroms and monolayers. The inset shows a plot of the saturation fields obtained from the MOKE measurements over a wider range of t_{Cr}.

thickness in both angstroms and monolayers. Both sets of data clearly show four peaks in the range 4 to 10 ML (monolayers). This 2-ML oscillation period is in agreement with the value reported from SEMPA measurements.[9] The inset in Fig. 1 shows a plot of the saturation fields over a wider range of t_{Cr} determined from the MOKE measured on a sample with a larger variation in t_{Cr}. The oscillation with the period of 18 Å in t_{Cr} is clearly visible.

Figure 2 shows typical MR and MOKE hysteresis curves for different values of t_{Cr}. With increasing t_{Cr} the nature of the coupling changes from biquadratic coupling [at about t_{Cr}=7 Å, see Fig. 2(a)], over to a combination of bilinear and biquadratic coupling [around t_{Cr}=8.5 Å, see Fig. 2(b)] to again biquadratic coupling [at t_{Cr}=13 Å, see Fig. 2(c)]. The arrows on the figures indicate the orientation of the magnetization of the top and bottom Fe layers.

In the case of biquadratic coupling, there is a remnant field at zero applied field and the magnetization vectors in the layers of Fe are not parallel, but differ by 90°. As the field increases, the magnetization of the layers becomes aligned parallel at the saturation field. The sample with t_{Cr}=8.5 Å is antiferromagnetically coupled at zero field, and switches to 90° coupling at a higher field before being saturated at H_s. The 90° coupling is explained in terms of biquadratic coupling possibly due to a roughness at the interfaces of 1 ML 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 the 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, respectively, -0.46 mJ/m^2 and -0.20 mJ/m^2.

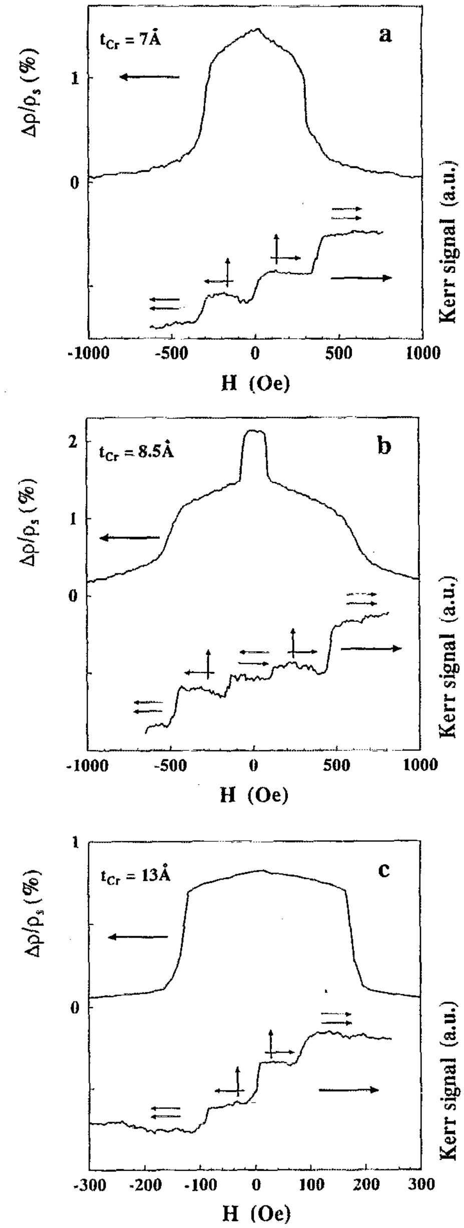

FIG. 2. MR at 4.2 K and Kerr effect at 300 K over applied magnetic field of Fe/Cr/Fe trilayers for three different values of t_{Cr}: (a) t_{Cr}=7 Å, showing biquadratic coupling; (b) t_{Cr}=8.5 Å, showing a combined bilinear and biquadratic coupling; (c) t_{Cr}=13 Å, showing biquadratic coupling. The arrows indicate the direction of magnetization of the two Fe layers. The corresponding MR loops show steps at field values at which the size of the magnetization changes.

Figure 2 also shows the measured MR loops for the different values of t_{Cr}. In the case of biquadratic coupling [Figs. 2(a) and 2(c)] the MR displays steps at values of the magnetic field at which the 90° coupling is saturated. The reversal of the sign of the magnetization at zero field produces only a step in the Kerr loop but not in the MR. This can be easily explained by the fact that the MR is sensitive only to changes in the size of the magnetization but is not sensitive to changes of its orientation.

In Fig. 2(c) the magnetic field values of the steps in the Kerr effect (measured at 300 K) and the MR (measured at 4.2 K) do not match, a fact which is likely due to the temperature dependence of the coupling constants. This temperature dependence is changing with t_{Cr},[15] which is in qualitative agreement with the decrease of H_s with increasing temperature at t_{Cr}=13 Å [Fig. 2(c)].

The MR loop at t_{Cr}=8.5 Å [Fig. 2(b)], corresponding to the maximum of the MR oscillations, reproduces all four steps visible in the magnetization. Each of the steps in the magnetization corresponds to a change in its absolute value and accordingly causes a change in the magnetoresistance. Small differences in the values of the switching fields can be explained by the different coupling strength due to the different measuring temperature.

The MR curves of Fe/Cr superlattices do not display sharp steps but have more bell-shaped or triangular-field dependencies[2,16,17] This may be due to an averaging effect over many layers which have different coupling strengths. A bell-shaped MR curve would correspond to either biquadratic coupling as in Fig. 2(a) or to bilinear coupling which should naturally produce a similar shape. The triangular shape would be a reminiscent of the combined bilinear and biquadratic coupling as in Fig. 2(b).

IV. CONCLUSION

We have observed the 2-ML period in the oscillations of the magnetoresistance 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 90° degrees off. The magnetoresistance displays characteristic steps at values of the applied magnetic field at which the amplitude of the magnetization changes.

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