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# In-plane momentum conservation in Fe/Cr/Au/Fe(001) layered structures

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We study the effect of an Au layer at one of the Cr/Fe interfaces in epitaxial Fe/Cr/Au/Fe(001) sandwich structures on the magnetic interlayer coupling behavior by magneto-optical Kerr effect measurements and on the growth by scanning tunneling microscopy. The main effect of the Au layer is the suppression of the long-period oscillations of the magnetic interlayer coupling, while the short-period oscillations become dominant although their amplitude is stronger attenuated than $\propto D^{-2}$, where $D$ is the total thickness of the nonferromagnetic spacer layers. These findings are explained with the shapes of the Fermi surfaces of the spacer materials (Au and Cr) and in-plane momentum conservation at the Cr/Au interface of the electrons that mediate the coupling. This interpretation implicates that the $N$-centered ellipse of the Cr Fermi surface is the origin of the long-period oscillations across Cr spacers. [S0163-1829(99)51030-8]

Magnetic interlayer coupling in layered magnetic structures can be understood by considering spin-dependent quantum well states that form due to spin-dependent reflection at the nonmagnetic/magnetic interfaces.[1] In analogy to the propagation of light in layered structures, the in-plane momentum of the electrons propagating perpendicular to the layers must be conserved. This should also be true for interfaces due to an additional layer of a further material inserted between the nonmagnetic spacer and a magnetic layer. Here we test this scenario for the well studied Fe/Cr/Fe(001) system by introducing an additional Au interface layer between Cr and the top Fe layer. However, one has to be careful because this system exhibits short-period oscillations with a period of 2 monolayers (ML) which are sensitive to changes of the interface morphology.[2–4] Therefore, the influence of the Au layer on the growth and in particular on the roughness of the interfaces must also be characterized in order to be able to draw meaningful conclusions.

Sample preparation and all measurements, with the exception of magneto-optical Kerr effect (MOKE) measurements, are performed in an ultrahigh vacuum (UHV) system with a base pressure of $5\times10^{-11}$ mbar which is equipped with an *e*-beam deposition system, scanning tunneling microscopy (STM), low-energy electron diffraction, and Auger and x-ray photoemission electron spectroscopy (AES and XPS). Ag(001) buffer layers grown on Fe precovered GaAs(001) wafers are used as substrates.[5] The 5 nm-thick bottom Fe layer is grown according to an optimized growth procedure reported in Ref. 6 that consists of two deposition steps at 100 and 570 K, respectively. The wedge shaped Cr spacer layer (0–25 ML), the 1.3 nm-thick Au interface layer, and the 5 nm-thick top Fe layer are all grown at room temperature. We prepare samples with only one half of the Cr wedge covered with Au in order to extract the effect of the interface layer from a direct comparison of otherwise identical halves of one sample. For the *ex situ* MOKE measurements the samples are coated with 5 nm Ag. The longitudinal Kerr geometry with the magnetic field applied along an easy in-plane [100] axis of Fe is used. All measurements are performed at room temperature.

STM images are taken after the deposition of each layer of the sample. The bottom Fe layer is the same for both types of samples. A representative STM image is shown in Fig. 1(a). It is characterized by truncated, 5–6 ML high pyramids with several nm wide, flat tops. The interface to the top Fe layer is different for the two halves of the samples to be compared: Cr/Fe in one case and Au/Fe in the other. The surface morphology of Cr and Au is compared in Figs. 1(b) and (c). The Cr surface is much rougher, i.e., it shows a larger roughness amplitude on a significantly shorter lateral length scale. Atomically flat, several nm wide areas bordered by a few ML deep holes on the Au films clearly contrast the irregularly arranged small hillocks of the Cr surface.

In Fig. 2 we compare the coupling strength $J$ as a function of the Cr spacer layer thickness for the pure half and the Au containing half of the sandwich structure. $J$ is determined from the transition fields $H_T$ defined by $M(H_T)=0.9M_S$ and the relation $J=-\mu_0 m d H_T$, where $m$ is the bulk saturation magnetization of Fe and $d=5$ nm the thickness of the Fe layers. The pure Cr spacer [Fig. 2(a)] shows the superposition of the two well-known oscillations of Cr with periods of 2 ML (short period) and about 12 ML (long period). Note that here the 2 ML oscillations are observed for a Cr spacer layer grown at room temperature. Obviously, the improvement of the bottom Fe/Cr interface due to the optimized growth of the bottom Fe layer[6] is sufficient and necessary for the observation of 2 ML oscillations as they have not been observed in samples entirely grown at room temperature.[2–4] For the Au covered part of the Cr wedge [Fig. 2(b)] the coupling curve looks clearly different: (i) the long-period oscillations are absent and the short-period oscillations dominate, (ii) the oscillations reside on a linearly increasing background, and (iii) the coupling strength is reduced by a factor of about 50 [note the different vertical scales of Figs. 2(a) and (b)]. An attenuation of the coupling is expected because

 

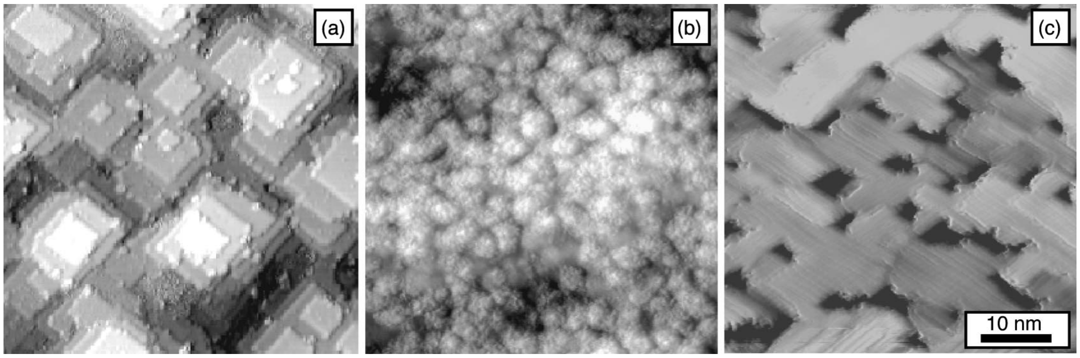


FIG. 1. STM images ($50\times50$ nm$^2$) of (a) the 5 nm-thick bottom Fe layer ($z$ range: 0.9 nm), (b) the Cr spacer layer at a thickness of 2.5 nm ($z$ range: 2.0 nm) grown on top of the Fe layer shown in (a), and (c) the 1.3 nm-thick Au interface layer ($z$ range: 1.5 nm) grown on top of one half of the Cr wedge imaged in (b).

the total thickness of the nonferromagnetic spacer, $D=d_{\mathrm{Cr}}+d_{\mathrm{Au}}$, is increased by 1.3 nm in the presence of the Au interface layer. Assuming a damping proportional to $D^{-2}$ we replot the data of Fig. 2(b) in part (c) after multiplying with the correction factor $(d_{\mathrm{Cr}}+d_{\mathrm{Au}})^2/d_{\mathrm{Cr}}^2$. Due to the complete nesting in Cr the damping is expected to be proportional to $D^{-1}$ (Ref. 7). Thus, our correction factor results in an upper limit for the coupling across Cr. Nevertheless the amplitude of the 2 ML oscillations is still 5–10 times weaker than for the pure Cr spacer.

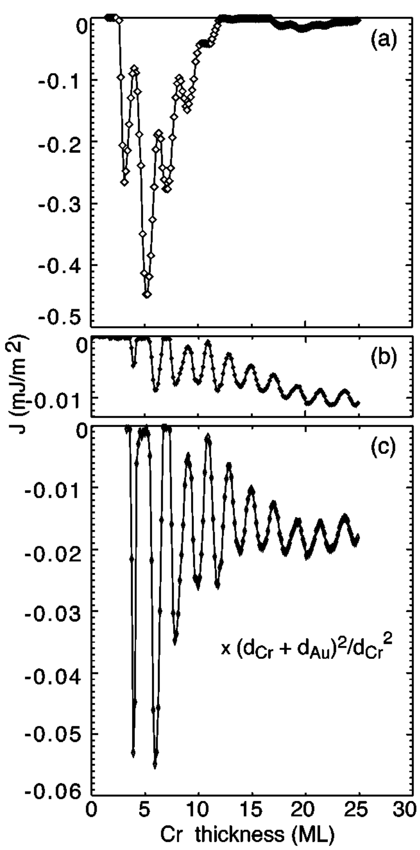


FIG. 2. Coupling strength $J$ as a function of the Cr spacer thickness (a) of Fe/Cr/Fe, (b) of Fe/Cr/Au/Fe with a 1.3 nm-thick Au interface layer, and (c) the same data as in (b) corrected for the $D^{-2}$ attenuation due to the Au layer (see text). Note that the vertical axes of (b) and (c) are stretched by a factor of 10 compared to (a).

The weak background results in two clear oscillations between antiferromagnetic ($J<0$) and ferromagnetic ($J>0$) coupling in the thickness range 4–7 ML of Cr. The type of coupling for larger Cr thicknesses can be identified from the MOKE hysteresis loops. Figure 3 presents a compilation of 175 hysteresis curves taken along the Au covered Cr wedge in a three-dimensional (3D) rendering. Starting from the third coupling maximum at 8 ML (1.2 nm), clear plateaus at $M/M_S=\pm0.5$ indicating 90° coupling develop, whereas the sloped plateaus at $M/M_S=0$ representing antiferromagnetic arrangement of the magnetizations disappear. Therefore there is a strong biquadratic contribution to the coupling for larger Cr thicknesses.

Similar morphological differences as presented in Figs. 1(b) and (c) have been deliberately induced in the Fe/Cr/Fe(001) system[4] by different growth conditions. It was found that they have a strong impact on the coupling behavior: Samples with smoother interfaces show a much larger amplitude of the short-period oscillations, while the long-period oscillations and the (antiferromagnetic or biquadratic) background are not affected. Although the Au interface layer leads to similar morphological differences, the modification of the coupling behavior is clearly different: The long-period oscillations are completely suppressed, the coupling background changes drastically, and the 2 ML oscillations are

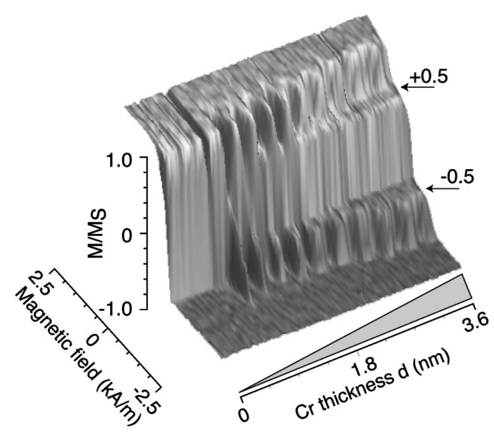


FIG. 3. 3D representation of 175 hysteresis curves taken along the Cr wedge of the Fe/Cr/Au/Fe sandwich. Each curve is normalized by its saturation magnetization $M_S$. Arrows indicate the plateaus at $M/M_S=\pm0.5$ due to 90° coupling.

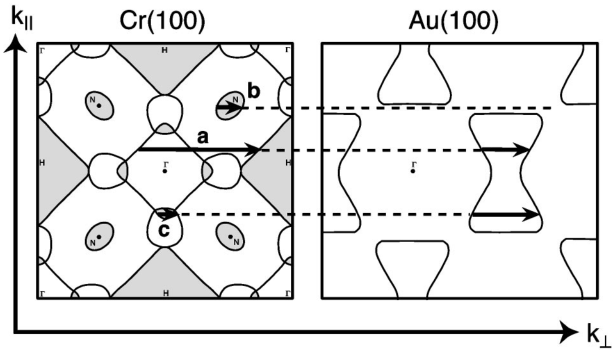


FIG. 4. (100) cross sections of the Fermi surfaces of Cr and Au. The arrows *a*, *b*, and *c* are stationary vectors of Cr. The horizontal broken lines indicate the $k_\parallel$ conservation and connect states of Cr at stationary points to Au states with the same $k_\parallel$.

stronger attenuated than expected due to the presence of the additional Au layer. Hence, we conclude that the coupling behavior cannot be explained by the different interface morphologies. Morphology plays at most a minor role.

The origin of the suppression of the long-period oscillations is related to the electronic structure of the multilayer. Within the quantum well picture certain electronic states are confined between the ferromagnetic layers. In order to be reflected at the two interfaces between the spacer and the ferromagnetic layers the electrons have to propagate through the Cr layer *and* the Au layer. As there is translational symmetry parallel to the layered structure, the component of the momentum parallel to the layers, $k_\parallel$, needs to be conserved at the Cr/Au interface. The component perpendicular to the layers, $k_\perp$, however, may change. For light propagation in transparent layered structures, these conditions lead to the law of reflection. Figure 4 shows to scale (001) cross sections of the Fermi surfaces of (paramagnetic) Cr and Au. The direction perpendicular to the layers in reciprocal space is along the horizontal axis. $k_\parallel$ of electrons propagating across the Cr/Au interface has to be conserved, and therefore the corresponding Cr states in this diagram must be connected to Au states by a horizontal line. First we consider the 2 ML oscillations which are related to the Cr nesting vector *a*. The corresponding states can couple to Au states, and the short-period coupling is mediated across the Au layer. The involved Au states do not originate from a stationary point of the Au Fermi surface. Therefore, some of the related standing electron waves cancel out. This explains the attenuation of the short-period oscillations which is stronger than expected on the basis of $D^{-2}$ damping for a stationary point without nesting.

The states connected by the stationary vector *b* at the *N* point have theoretically been shown to be the origin of the long-period oscillations.[8,9] These states lie in a gap if projected horizontally on the Au Fermi surface cross section. This explains the suppression of the long-period oscillations of the interlayer exchange coupling. Okuno *et al.*[10] recently measured for the same system the suppression of the long-period oscillations as a function of the Au thickness and found an exponential decay indicative of a tunneling process. This finding is in agreement with the above interpretation because the Cr states mediating the long-period oscillations cannot propagate in Au and therefore decay exponentially.

The stationary vector *c* has also been proposed as being responsible for the long-period oscillations.[11,12] Since in the above picture these states can propagate in Au there is no reason why the long-period oscillations should be completely suppressed. Hence, our results and their interpretation in terms of $k_\parallel$ conservation and the shapes of the Fermi surfaces indicate that the long-period oscillations across Cr spacer layers have their origin in the stationary vector spanning the ellipse at the *N* point. The same conclusion has recently been drawn by You *et al.*[13] from variations of the oscillation periods of magnetoresistance curves upon changing the V content in sputtered Fe/$Cr_{1-x}V_x$/Fe(100) and (211) superlattices.

Theoretical calculations confirming the mechanisms for the suppression of the long-period oscillations and the stronger than expected attenuation of the short-period oscillations due to the Au interface layer are highly desirable, as interface layers bear the potential for tailoring magnetic interlayer exchange coupling to meet special needs of applications.

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