Magnetic Properties of Fe Films on Cr(100)

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The magnetization behavior of thin (1–5 nm) epitaxial Fe films on Cr(100) is investigated by the magneto-optical Kerr effect. Hysteresis loops show a strong change of the coercive field in a very narrow temperature range around $T = 130$ K, independent of the film thickness. In addition, films below 3 nm thickness exhibit a strongly reduced remanent magnetization in an intermediate temperature range ($T \approx 140$–300 K). An explanation for both effects is based on the interface exchange coupling which connects the intrinsic antiferromagnetic properties of the Cr substrate to the Fe overlayer and therefore modifies its magnetic properties.

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The recent interest in the exchange coupling of ferromagnetic layers through spacer layers has also focused attention on the magnetic properties of interfaces between nonferromagnetic and ferromagnetic layers [1–5]. Besides the influence on transport properties in multilayers [6, 7], interfaces are of fundamental importance for an understanding of the interlayer exchange coupling. In the case of antiferromagnetic spacer layers the exchange coupling can be understood as being mediated by the magnetic order in the spacer material. The magnetic ordering in those spacer layer materials by an adjacent ferromagnet has been directly observed in Cr and Mn layers on Fe [8–10]. The reverse situation, namely the modification of the properties of ferromagnetic films due to the presence of antiferromagnetic substrates has also been of interest for many years, with special emphasis on the so-called exchange biasing effect, which produces unidirectional behavior of the ferromagnetic films [11]. In the present study we have investigated the magnetic properties of Fe films on Cr(100). A strongly temperature dependent hysteresis behavior is attributed to the effects of interface exchange coupling to the Cr substrate.

Iron films 1–5 nm thick were grown in an ultrahigh vacuum chamber at a deposition rate of 0.4 nm/min on a Cr(100) substrate, which was cleaned by ion sputtering and annealing to $T = 950$ K. A substrate temperature of $T = 480$ K was maintained to achieve smooth films and avoid substrate-overlayer intermixing. The film thickness was determined by a quartz microbalance. The sample quality was monitored by Auger electron spectroscopy and low-energy electron diffraction. Hysteresis curves were measured by the magneto optical Kerr effect in the temperature range 90–350 K. Our experimental setup allowed the observation of the in-plane (longitudinal Kerr effect) as well as the out-of plane magnetization component (polar Kerr effect) [12]. All data were taken with the sample slowly warming up after cooling down to $T = 90$ K. The temperature was measured by a Chromel/Alumel thermocouple spot welded to the sample holder.

Figure 1 shows a set of hysteresis loops for a 3 nm thick Fe/Cr(100) film at various temperatures. The data were taken with the external field along ⟨100⟩, parallel to an easy axis of the iron overlayer. The most significant feature of the hysteresis loops shown in Fig. 1 is the strong decrease of the coercive field H_c between

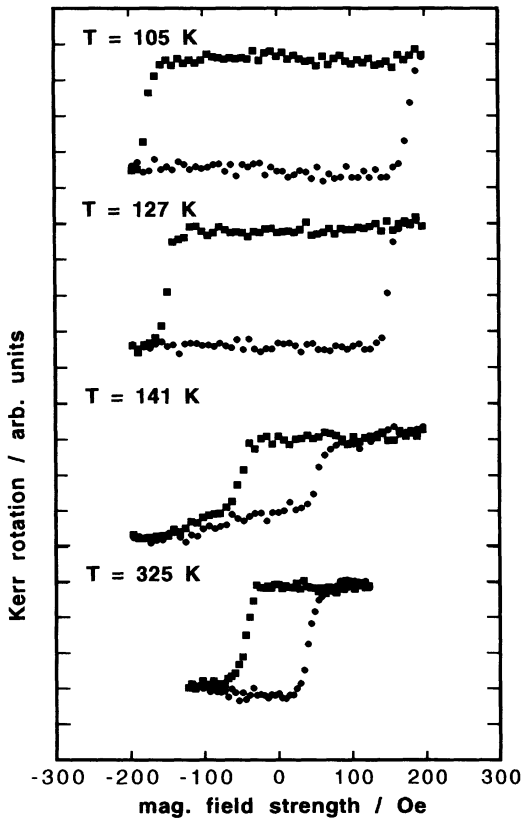

FIG. 1. Hysteresis loops measured for a 3 nm thick Fe/Cr(100) overlayer at the temperatures indicated. The external magnetic field was applied parallel to a ⟨100⟩ direction in the surface plane.

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$T = 127$ K and $T = 141$ K. This dramatic change becomes even more obvious in Fig. 2, where the coercive field is shown as a function of temperature for four different film thicknesses. All films are characterized by a high coercive field at low temperatures to about $T = 125$ K and a low coercive field at higher temperatures above $T = 135$ K. The change in H_c occurs in a very narrow temperature range, similar to a phase transition. In addition, the transition temperature is independent of the film thickness. This indicates that the transition is not determined by intrinsic properties of the Fe overlayer. On the other hand, the factor by which the coercive field changes at the transition temperature depends on the film thickness. The H_c change becomes more pronounced with reduced film thickness. Such a behavior is usually associated with a surface or interface effect. Measurements of the polar Kerr effect yielded no indication of an out-of-plane magnetization component over the entire temperature range investigated.

Below the Néel temperature $T_N = 311$ K bulk Cr is magnetically ordered [13]. The magnetic order is slightly incommensurate with the crystal structure and is described as a spin density wave (SDW) state. Below T_N the SDW is transverse, i.e., the magnetic moments are perpendicular to the SDW wave vector Q. At lower temperatures there is a phase transition to a longitudinal SDW state. This transition occurs at the spin flip transition temperature $T_{SF} = 123$ K [13]. Figure 3 shows a schematic of the SDW structure relative to a (100) surface for the transverse and longitudinal SDW, respectively. The SDW wave vectors Q are in $\langle 100 \rangle$ directions. For the discussion, we assume that the Cr magnetic surface structure is given by the bulk terminated magnetic configuration.

The temperature at which the H_c transition in the Fe overlayers is observed is very close to T_{SF} [14]. Although the magnetic structure in both SDW states are very similar, there is a significant difference between them regarding the (100) planes, depending on whether Q is

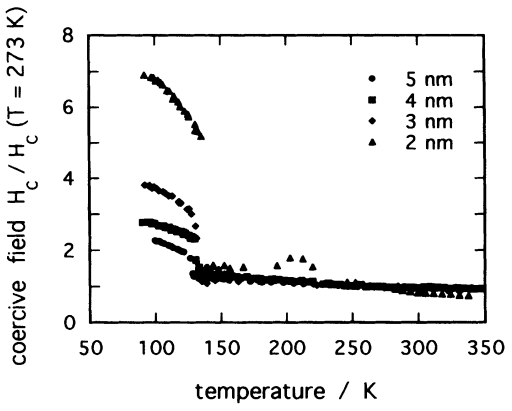

FIG. 2. Coercive field H_c vs temperature for Fe/Cr(100) overlayers of varying thickness. The H_c data are normalized to the value at $T = 273$ K.

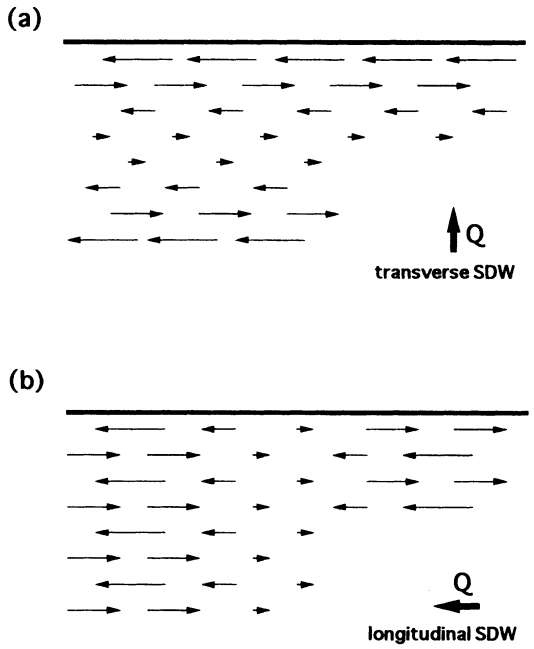

FIG. 3. (a),(b) Schematic representation of the SDW magnetic order of bulk Cr with respect to a (100) surface (see text).

perpendicular or parallel to the plane. Considering the observed longitudinal Kerr rotation and the absence of the polar Kerr effect, it is reasonable to assume that the magnetization in the Fe overlayer is oriented in the (100) film plane. Therefore, the antiferromagnetic exchange coupling at the Fe/Cr interface favors a ferromagnetically ordered spin structure at the Cr(100) surface with the moments also in plane. This magnetic ordering in the chromium matches very well the transverse SDW structure with Q perpendicular to the interface, but not the longitudinal SDW structure. Thus, it is not too surprising that the properties of Fe overlayers on a Cr(100) substrate change at T_{SF}.

The magnetization reversal in thin films proceeds by the occurrence of stable nuclei with reversed magnetization and their subsequent growth by domain wall movement [15]. A square hysteresis loop indicates that the reversal process is mainly due to domain wall movement, which implies that the limiting factor of the magnetization reversal is the nucleation rate [16]. Therefore, the coercive field is mainly determined by the activation energy for stable nucleus formation. For a free standing ferromagnetic film this energy would be determined by the material constants of the film only [17]. In the case of overlayers there is an additional contribution due to the exchange coupling at the interface. This interface contribution depends on the exchange coupling strength, but also on the spin configuration in the chromium. The phase transition in the chromium which changes the spin structure will also alter the activation energy and therefore result in the observed changes of the coercive field.

Besides the transition in the coercive field, one can also see (Fig. 1) that the Kerr rotation values in remanence are reduced at $T = 141$ K, just above the transition temperature. Figure 4 shows the Kerr rotation in remanence as a function of temperature for five different film thicknesses. For the thinnest Fe overlayers up to 3 nm the remanent Kerr rotation is significantly reduced between T_{SF} and T_N. At the spin-flip temperature, the remanent magnetization drops off very rapidly and increases with increasing temperature up to approximately T_N. The temperature dependence does not significantly change with the Fe film thickness. It is also obvious from the data that the reduction of the remanent magnetization is more pronounced for thinner films. For the 1 nm film no hysteresis loop could be measured below T_{SF} within the accessible range of magnetic fields (250 Oe). H_c might be very high in this case. Therefore, no data for the 1 nm film are shown in Fig. 2.

To find a possible explanation for the reduction of the remanent magnetization one has to realize that this effect occurs only in the temperature range where bulk Cr is characterized by the *transverse* SDW state. As discussed earlier, this SDW state matches very well to the ferromagnetic ordering in the iron overlayer at the (100) interface, but only if this interface is ideally smooth. The real Cr surface contains atomic steps. It was shown that monatomic steps are present on a Cr(100) substrate [18]. If one includes atomic steps the matching of the magnetic structures is disrupted and frustration of the spin alignment occurs. Figure 5 shows a simple picture of the spin structure at an interface between a ferromagnetic and an antiferromagnetic material for an ideal interface with matching conditions Fig. 5(a), as well as for an interface with steps Figs. 5(b)–5(d). In this nonideal case not all pair interaction energies can be minimized simultaneously. Therefore, different spin structures [Figs. 5(b)–5(d)] can minimize the total energy depending on the different coupling constants. In Fig. 5(b), the ideal ferromagnetic and antiferromagnetic order within the layers is conserved, producing excess exchange energy at the interface (gray shaded area) and therefore represents the case of weak interface coupling. If the antiferromagnetic interface ordering is preserved,

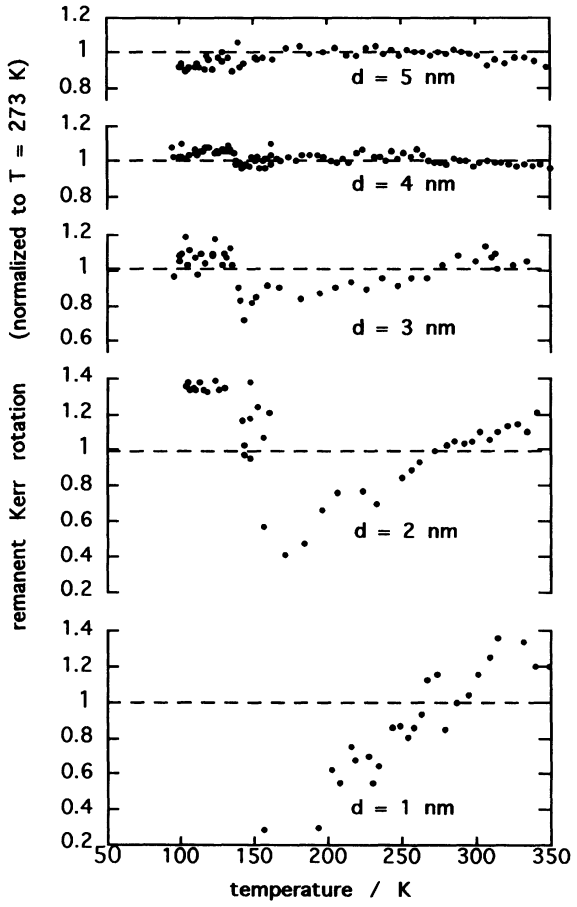

FIG. 4. Kerr rotation in remanence vs temperature measured for Fe/Cr(100) overlayers of varying thickness. The Kerr rotation data are normalized to the value at $T = 273$ K for each film.

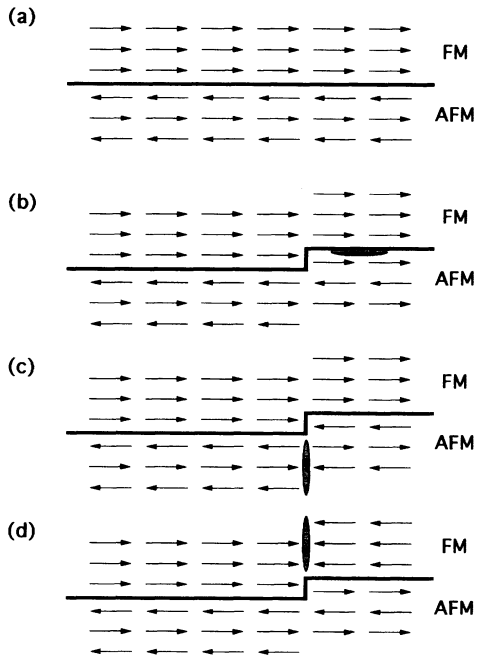

FIG. 5. Illustration of the spin arrangement at an interface between a ferromagnet (FM) and an antiferromagnet (AFM) with antiferromagnetic interface coupling. (a) Ideal interface, (b)–(d) interface with atomic step: the frustration of the spins at the step can result in several possible configurations depending on the coupling constants and the geometry involved; (b) ideal structure within each material, energy located at the interface (gray shaded area); (c),(d) ideal interface ordering, energy contained in a domain wall (gray shaded area), located in the AFM (c), or the FM (d).

a domain wall occurs, which can be located in the antiferromagnet [Fig. 5(c)] or the ferromagnet [Fig. 5(d)]. These cases are favorable when the total energy is dominated by the interface exchange coupling, which is usually fulfilled in ultrathin films or overlayers because the interface area is much larger than the domain wall area within the film. Therefore, the reduction of the remanent magnetization in the very thin iron overlayers can be understood as being caused by the exchange coupling through a nonideal interface similar to the picture given in Fig. 5(d). It should be mentioned that the model given here is too simple to describe the iron overlayer properties accurately because it does not include a realistic structure of the domain walls. Nevertheless, it gives a qualitative explanation for the breakdown of the long-range ferromagnetic order in thin Fe/Cr(100) overlayers above the spin-flip temperature T_{SF}.

In addition, the model also describes the behavior of Cr/Fe(100) overlayers, where a long-range ferromagnetic ordering in the topmost surface layer has been found [8,9]. This is shown in Fig. 5(c) where the bottom layer, representing the surface layer of the antiferromagnet, exhibits a long-range ferromagnetic alignment, although an interface with atomic steps is present. Therefore, the dominance of the interface coupling results in a long-range surface layer alignment for Cr films on Fe(100), which is actually equivalent to a breakdown of the long-range antiferromagnetic order in the Cr overlayer itself. Using this simple picture, the temperature dependence of the remanent magnetization in the Fe overlayer could then correspond to a gradual change from a suppression of the long-range order in the ferromagnetic overlayer [Fig. 5(d)] at low temperatures, just above the spin-flip temperature, to the breakdown of the long-range antiferromagnetic order [Fig. 5(c)] in the Cr at higher temperatures, just below the bulk Néel temperature T_N.

We should mention that the discussion has rested entirely on the assumption that the Cr surface magnetic structure is a termination of the bulk SDW structure. This is contrary to the currently accepted way of thinking about the magnetic order at Cr(100) surfaces. Calculations predict large surface magnetic moments, on the order of $3\mu_B$ and magnetic order well above T_N [19]. From this picture one might expect that the bulk magnetic structure is irrelevant. The present results are not necessarily in contradiction to this picture since the mismatch between the Cr surface ordering and the bulk SDW structure might be accommodated in subsurface layers (see the discussion in the previous paragraph).

In conclusion, we have investigated the magnetization behavior of Fe overlayers on Cr(100) in the thickness range of 1–5 nm and at temperatures between 90 and 350 K. The main result is a sharp transition of the coercive field at $T \approx 130$ K independent of film thickness. The origin of this transition is attributed to the spin flip transition in Cr, which influences the magnetization in the Fe overlayer. Therefore, this study presents an example of how the intrinsic structure in an antiferromagnet can influence the properties of an adjacent ferromagnetic layer through the interface exchange coupling. In addition, a significant reduction of the remanent magnetization in an intermediate temperature range has been observed for very thin iron overlayers. A possible explanation for this effect is given by a simple model taking into account the nonideal (100)-interface structure.

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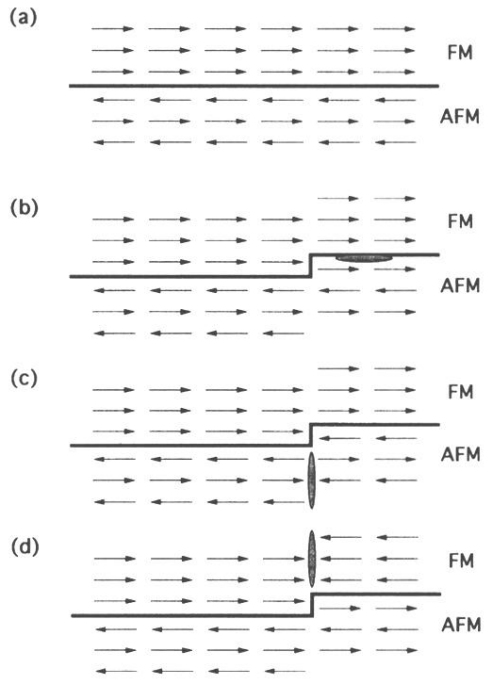

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