Temperature dependent magnetic domain structure in ultrathin Fe films on Cr(100)

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Magnetic microscopy is used to study the temperature dependent magnetization structures in 2 nm Fe films on Cr(100). Above the Cr Néel temperature, the Fe films can be magnetized into a single domain state. When the films are cooled below the Néel temperature the Fe magnetization has a tendency to turn perpendicular (in-plane) resulting in a spatially varying magnetization direction. The resulting magnetization structures are highly reproducible. The tendency of the Fe magnetization to rotate is attributed to frustration due to atomic steps. It is suggested that the local angle of magnetization rotation reflects the average step density. © *2000 American Institute of Physics.* [S0021-8979(00)65608-6]

Exchange coupling at ferro/antiferromagnetic (FM/AF) interfaces can lead to interesting magnetic properties. The effect of exchange biasing has been known for a long time.[1] It has become of increasing technological importance recently. However, on an atomic scale the effect is not well understood and interest in the subject has recently been increasing.[2] The combination of well characterized samples with novel magnetic probes promises to shed new light on this old problem. This study reports on the temperature dependent magnetization in 2 nm Fe films on Cr(100). The Fe/Cr systems have been studied extensively in conjunction with exchange coupling in Fe/Cr/Fe layered structures. An advantage of this system is that it offers very high quality epitaxial samples. Although, to our knowledge, exchange biasing has not been reported for Cr as the antiferromagnet a recent magneto-optical Kerr effect (MOKE) study revealed unusual temperature dependent properties of the hysteresis curves of thin Fe films on Cr(100).[3] In particular, the coercive field and the remanent magnetization in films thinner than 5 nm showed anomalies that were clearly associated with the magnetic ordering of Cr. Thus, this is an example in which the FM properties are influenced or even dominated by the AF magnetic structure due to strong interface coupling. In the present study we use magnetic microscopy to examine the temperature dependent magnetization structures to show how a uniform in-plane magnetization breaks up into a domain structure when cooled below the AF (Cr) ordering temperature. This article gives additional information to what has already been reported in a recent letter on the subject.[4]

The experiments were performed in a new ultrahigh vacuum system that allows for molecular beam epitaxy sample growth and surface characterization (low-energy electron diffraction and Auger) and *in situ* magnetic microscopy by secondary electron microscopy with polarization analysis (SEMPA). A scanning tunneling microscope (STM) has just been added to the system which will allow us to characterize atomic scale structure and study correlations between morphology and magnetic structure. Ultrathin Fe films (2 nm) were grown on bulk Cr(100) (see Ref. 3 for growth conditions). In our SEMPA we can measure the two in-plane magnetization components in a medium-energy Mott detector. See Fig. 1 for a schematic of the measurement geometry. A coil allows us to apply magnetic fields in the x direction. The SEMPA images are acquired in zero magnetic field. The spatial resolution is approximately 500 nm. The sample can be cooled by LN_2 or heated indirectly on the SEMPA stage.

Above the Néel temperature of Cr ($T_N = 311$ K) the Fe films can be magnetized into a single domain state. Figure 2 shows the evolution of the magnetization starting with the magnetized state in the top panel. The left column shows the x component and the right column the y component. When the film is cooled the single-domain state (x magnetization) breaks up into irregular magnetization structures and a strong y component develops with spatial variations on the scale of micrometers to tens of micrometers. A polarization analysis shows that the magnetization magnitude is conserved and only an in-plane rotation takes place (see Fig. 3 of Ref. 4 for typical angular distributions). When the films are warmed to above T_N the magnetization direction relaxes into the easy-axis directions of Fe (x and y axes). This is clearly visible as a sharpening and increased contrast of the images. When, however, this structure is cooled down again the image re-

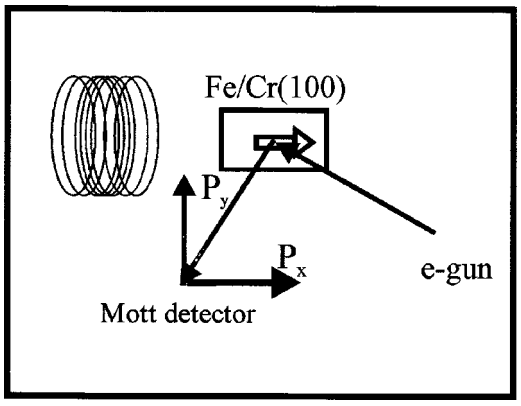

FIG. 1. Geometry of the experiment. Two in-plane magnetization components (x and y) are measured. The films can be magnetized by a magnetic field pulse in the x direction.

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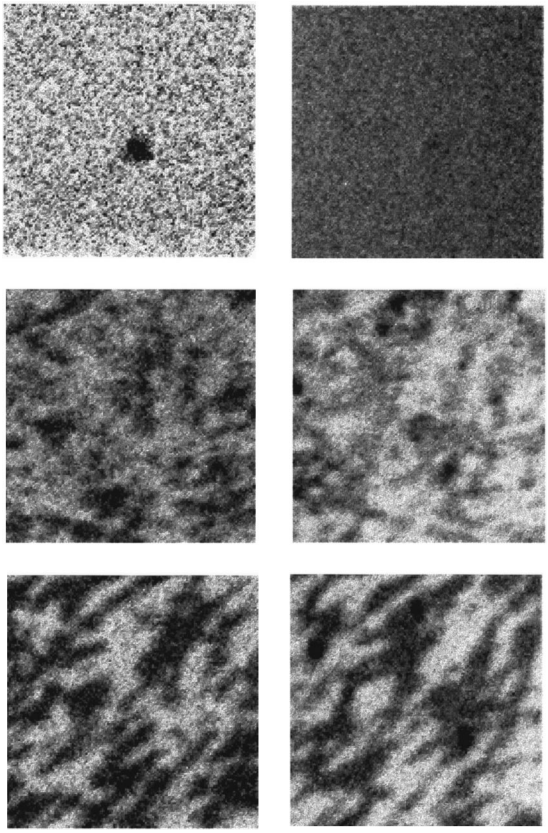

FIG. 2. Effect of cooling and warming on the magnetic structure of a 2 nm Fe film. The images are of an area about 50 μm$\times$50 μm. Left panels show the x component and the right panels the y component. The series start from the top with a fully magnetized sample above T_N. The second row was taken at low temperature while the third row is after warming to above T_N.

verts to the previous low-temperature ''fuzzy'' image in which the Fe magnetization directions varies locally. Thus, we have three different magnetization structures: (1) The fully magnetized single domain state after magnetizing above T_N; (2) The low temperature state with a locally, continuously varying magnetization direction; (3) The state after warming in which the magnetization lies only along the easy magnetization axes of the Fe film.

Even though the magnetization structures are very irregular it is interesting to note that there is a high degree of reproducibility. This is shown in Fig. 3. When the magnetic structure is erased by warming and magnetizing and then the film is cooled down again we find a high degree of reproducibility of the magnetic structure.

What causes certain areas to rotate their magnetization direction upon cooling while other areas remain close to their original direction? It is well known that roughness can lead to frustrated magnetization structures at AF/FM interfaces. The Fe–Cr exchange interaction cannot be minimized in the presence of atomic steps without inducing magnetic transition regions either in the Fe or the Cr (see Ref. 3). This can lead to 90° alignment of the magnetic moments. This has been quite well documented in exchange coupling between FM films through interlayers, where this phenomenon is called ''biquadratic coupling'' as opposed to ''bilinear coupling,'' in which case the moments align parallel or antiparallel to each other. We suggest that in the present case we have an effective perpendicular coupling already at the single AF/FM interface.

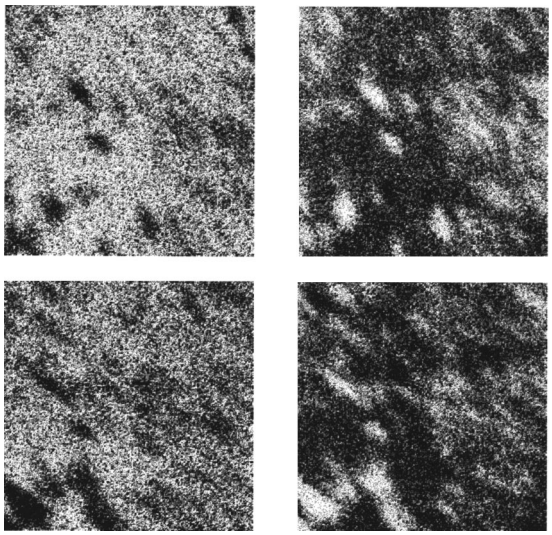

FIG. 3. Images (50 μm$\times$50 μm) of the two in-plane magnetization components (as in Fig. 2) at low temperatures. The second row was taken after the sample had been warmed up above T_N, then magnetized into a single domain, and then cooled again.

We have recently added an STM to our system which allows us to characterize the surface topography of our samples. Fig. 4 shows one of the first STM images obtained for our sample. It shows a 500 nm$\times$500 nm randomly chosen area on a well prepared clean Cr surface before deposition of an Fe film. As expected, atomic terraces in the range of tens of nanometers are observed, a range typical for high-quality single-crystal metal substrates. One has to keep in mind that the magnetic structures observed are much larger (micrometers) than these terrace widths. Thus, the magnetic structures ''average'' over many terraces and it is suggested that they are a reflection of the *average* of the *local* atomic step density.

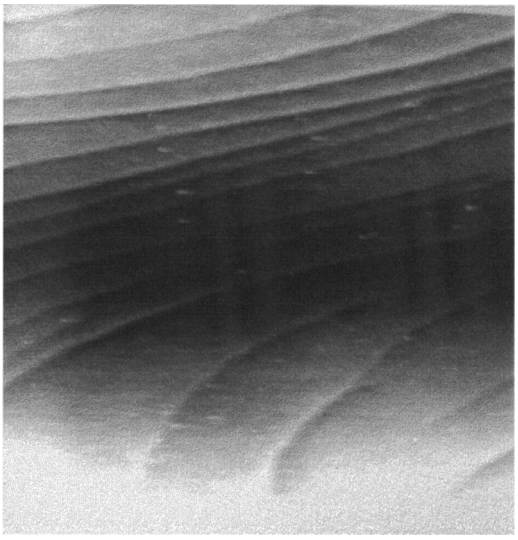

FIG. 4. STM image of a 500 nm$\times$500 nm area of the Cr(100) substrate after the cleaning and annealing procedures. The area was randomly chosen.

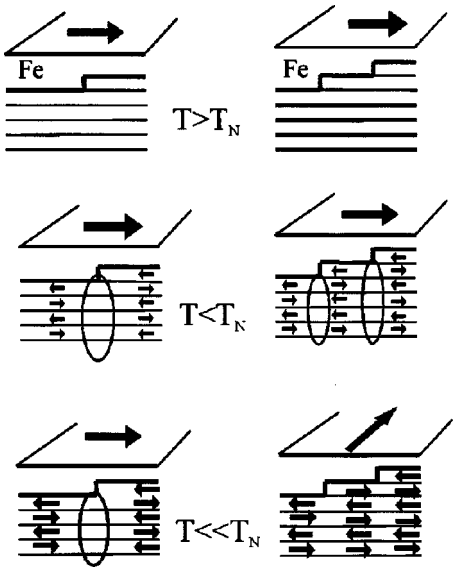

FIG. 5. Schematic of the temperature dependent magnetic structure of the Fe films and the Fe/Cr interface: Left column: low step density area; right column: high step density area. Top panels: Above T_N; fully magnetized Fe film and no bulk magnetic order in Cr; center panels: Magnetic order develops in Cr induced by the Fe magnetization. The magnetic mismatch is accommodated in the Cr. Lower panels: At low step density locations (left) the Fe magnetization remains fixed and the mismatch is still accommodated in the Cr. At high step densities (right) the Fe starts turning in-plane towards 90°.

Figure 5 shows, schematically, the proposed magnetization structures as the temperature is lowered. The left column shows an area with a small step density and the right column is at high step density. What exactly ''high'' and ''low'' mean will have to be determined in a systematic survey of step densities by STM in the future. Above T_N the Fe films are magnetized and there is no long-range magnetic order in the Cr, except for possibly some interface magnetization induced by the Fe. As the sample is cooled below T_N the Cr magnetization develops, induced by the Fe due to the Fe–Cr exchange coupling, i.e., the Cr moments order, starting at the Fe interface. In this situation the magnetization mismatch is accommodated in the Cr and the Fe remains essentially fully magnetized. As the temperature is lowered further it cost more energy to accomodate the mismatch in the Cr because of the increased Cr magnetic order. If the step density is low enough the mismatch stays in the Cr. However, if the step density is large it costs too much energy to accomodate the mismatch in the Cr. Also, Fe domains on the scale of the atomic terraces are energetically unfavorable and therefore the Fe magnetization tends to turn 90°. The resulting magnetization structure is then a compromise between the fluctuating interface exchange interaction and the stiffness of the Fe magnetization. For the real sample, of course high and low step densities vary continuously and this leads to the spatially varying magnetization direction observed.

We want to stress that the Fe magnetization turns away from the direction of the Cr surface moments. The direction of the Cr moments was, of course, determined by the Fe magnetization when the sample was cooled through T_N. That means that the Fe magnetization should always turn away from its original direction at high temperature, independent of the actual initial magnetization direction. This is observed experimentally from which one can conclude that it is really an exchange coupling to the Cr surface moment alignments that drives the Fe reorientation and not, e.g., anisotropies induced by step orientations.

In summary, we have shown that thin Fe films on Cr(100) develop a nonuniform magnetic structure as the temperature is lowered sufficiently below T_N. It is suggested that the driving mechanism is the atomic scale roughness that leads to a locally varying in-plane turning of the magnetization because of varying steps densities and frustration. In the future we hope to be able to correlate magnetization images with atomic terrace structure studied by STM.

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[2] For a recent review on exchange bias see: J. Nogués and I. K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999).
[3] A. Berger and H. Hopster, Phys. Rev. Lett. **73**, 193 (1994).
[4] H. Hopster, Phys. Rev. Lett. **83**, 1227 (1999).