Perpendicular magnetization and dipolar antiferromagnetism in double layer nanostripe arrays of Fe(110) on W(110)

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Fe(110) nanostripe arrays, consisting of alternating monolayer and double layer stripes, have been grown by step flow on vicinal W(110) substrates. The magnetic easy axis switches from in-plane in the monolayer to perpendicular in the double layer stripes. The data strongly suggest that magnetostatic interactions induce antiferromagnetic order in the double layer nanostripe array. It can be switched into a ferromagnetic arrangement by low external fields. © *1998 American Institute of Physics.* [S0003-6951(98)03824-8]

The progress in the field of epitaxial magnetic films, including the discovery of indirect exchange coupling[1–3] and giant magnetoresistance (GMR),[4,5] is based on techniques to control perpendicular profiles—both of composition and of magnetic properties—on a nanoscale. Recently, there has been increased interest in extending those concepts from perpendicular to lateral magnetic nanostructures—that means to two-dimensional arrays of magnetic nanowires or nanostripes—prepared either by lithographic techniques[6] or by self-organization on grooved[7,8] or on vicinal single crystal substrates.[9–11] A promising candidate for pronounced magnetoresistance would be given by a film containing an array of antiferromagnetically coupled magnetic nanowires, which could be switched from antiferromagnetic towards ferromagnetic order by low magnetic fields. For the case of perpendicularly magnetized nanowires, the antiferromagnetic coupling would be provided by magnetostatic interaction. The aim of the present letter is to show that arrays of pseudomorphic double-layer (DL) nanostripes of Fe(110) on W(110), prepared on vicinal W(110) substrates, present just this type of magnetic order. The DL stripe system then resembles a system of magnetic stripe domains in a homogeneous film of perpendicular anisotropy, which has been used recently as as giant magnetoresistance medium.[12] However, contrary to the 200 nm period in the stripe domain system, which is of pure magnetic origin, the magnetic ordering period in our samples is morphologically defined, and dramatically reduced to 18 nm only.

Our work is based on a previous experimental study of monolayer (ML) nanostripes of Fe(110), prepared on vicinal W(110) surfaces.[11] Their magnetic properties are dominated by a strong uniaxial magnetic anisotropy with an easy axis in the plane, but across the stripe axis, resulting in ferromagnetic interstripe coupling of magnetostatic origin, and in dipolar superferromagnetism. In the present letter, we focus on pseudomorphic Fe(110) nanostripes prepared on vicinal W(110) in the range between one and two pseudomorphic atomic layers (ALs). In this range, puzzling magnetic phenomena have been observed before for the case of films prepared on smooth W(110), which consisted of DL islands in a ML sea. Frustration of remanent magnetic order in the center of this range,[13] explained in terms of a quasi-antiferromagnetic interaction of unknown origin between DL islands, was alternatively interpreted in terms of magnetic freezing.[14,15] Only recently it could be shown that the origin of this frustration is given by an unexpected perpendicular anisotropy of the pseudomorphic DL islands,[16] and that the proposed quasi-antiferromagnetic interaction is of dipolar nature. Because both the pseudomorphic ML and films consisting of two complete AL or more show easy plane anisotropy, the perpendicular anisotropy of the DL patches is surprising. Its theoretical explanation, supposedly as a result of the enormeous (10%) pseudomorphic strain, remains a challenge. The interplay between ML and DL components with orthogonal anisotropies made the island system extremely complicated, and disentangling the properties of the components difficult. The goal of the present work was the preparation and magnetic investigation of similar films in a one-dimensional (1D) stripe rather than in the previous island geometry.

Fe films were grown at 700 K by evaporation onto vicinal W(110) substrates, with atomic steps along [001]. The growth rate was $R=0.3$ AL/min, the pressure p_p during preparation below 5×10^{-10} Torr. Because the perpendicular anisotropy of the DL supposedly results from the pseudomorphic strain, we were interested only in pseudomorphic DL stripes. Because the critical width for misfit dislocation formation in DL islands is about 9 nm,[17] we chose a W substrate with a step distance of $w_0=9$ nm, corresponding to $W_0=w_0/(a_w/2^{1/2})=40$ atomic rows. This resulted in dislocation-free pseudomorphic DL stripes, as checked *in situ* by STM. The morphology is shown in Fig. 1 for the case of a sample with coverage $\Theta=1.8$ AL. The sample consists of dislocation-free alternating ML and DL stripes, which were continuous, although with a considerable dispersion of stripe width.

After preparation, the samples were cooled down to 130 K, and then slowly warmed up to 165 K for Kerr magnetometry (MOKE). Using separate lasers, we measured in longitudinal fields along [1–10] (easy axis of the monolayer) the ellipticity ϵ_K of the longitudinal Kerr effect (because it was

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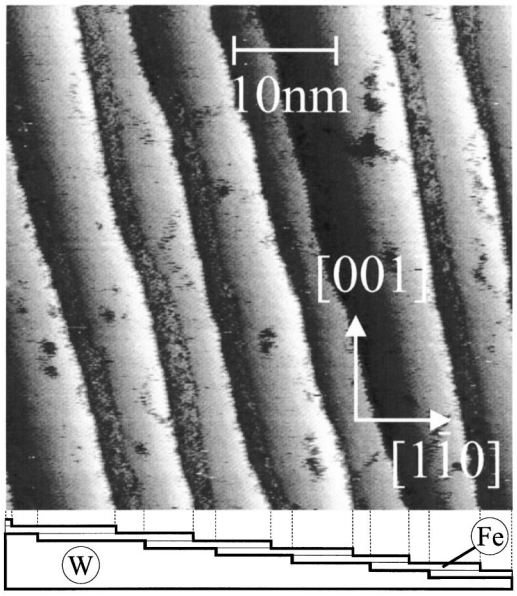

FIG. 1. STM image of $\Theta = 1.8$ AL Fe(110), prepared at 700 K on stepped W(110). Periodically alternating monolayer (ML) and double layer (DL) stripes, as indicated in the lower panel, are decorated by adsorption of an unknown species (CO?) which forms a (2×2) overstructure, more regular on the (wide) DL stripes, more irregular on the (narrow) ML stripes.

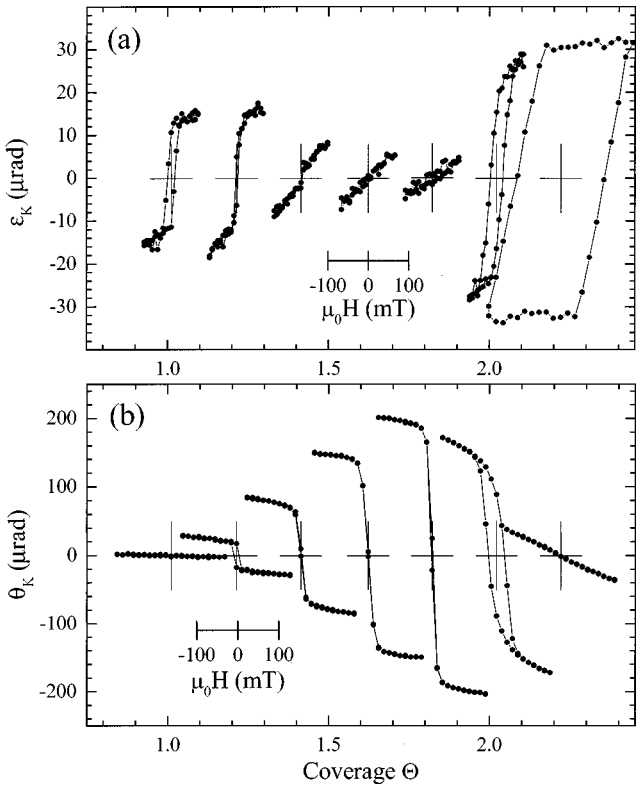

FIG. 2. MOKE loops for different Fe coverages Θ, taken at $T = (165 \pm 10)$ K on a sample prepared as a wedge of continuously changing Θ, indicated by the horizontal position of the loop center: (a) longitudinal Kerr ellipticity ϵ_K, (b) polar Kerr rotation θ_K.

larger than the rotation θ_K), and in polar fields the rotation θ_K of the polar effect (larger than ϵ_K in this case). Using a compensation technique,[18] both ϵ_K and θ_K were measured in absolute units. Temperatures were measured with a relative accuracy of 1 K, and an absolute accuracy of about 10 K, using a thermocouple fixed to the sample holder. They could be stabilized at 165 ± 10 K, which was used for all magnetic measurements of the present study. The residual gas exposure before completion of the magnetic measurements was below 0.5 L. This is important, because exposures above 1 L induce a rotation of the DL magnetization towards the film plane.[19] The samples could be transferred to a separate stage for STM, which was done at room temperature.

Figures 2(a) and 2(b) show longitudinal and polar loops, respectively, measured at 165 K, on a sample prepared as a wedge, with Fe coverages Θ increasing continuously from 0.8 to 2.4 AL (pseudomorphic layers) over a distance of 3 mm. Parameters of all measured loops, given by (i) the remanent values $\epsilon_{K,r}$ and $\theta_{K,r}$ and (ii) the extrapolation values $\epsilon_{K,e}$ and $\theta_{K,e}$ as indicated in the insets, are shown in Figs. 3(a) and 3(b), respectively, versus Θ.

The main experimental result is given by the dominance of perpendicular magnetization in the range $1 < \Theta < 2$ [see Figs. 2(b) and 3(b)]. The linear rise of $\theta_{K,e}$ with increasing Θ indicates a perpendicularly magnetized core of the DL stripes. The data for $\Theta < 1$ and $\Theta > 2$, in turn, confirm the previously[13] established easy-plane anisotropy of both the ML and of films above 2 ML, which are structurally relaxed. We conclude that the perpendicular magnetization in the range $1 < \Theta < 2$ must result from a perpendicular anisotropy of this DL caused by its 10% in-plane strain previously inferred from DL island data, but now clearly confirmed for the case of the DL stripes.

The switching of the easy axis may be modified by step anisotropy contributions. Note, however, that even for the

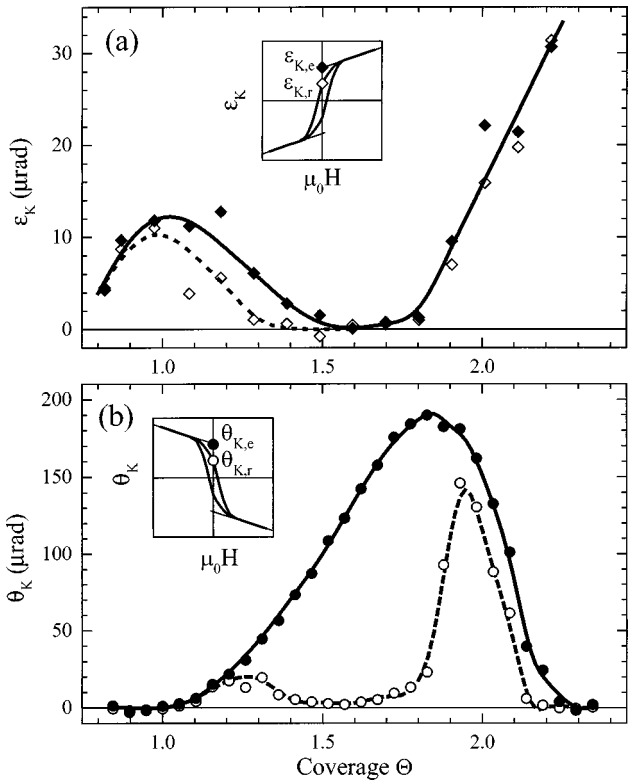

FIG. 3. Loop parameters vs coverage Θ for the wedge sample of Fig. 2. (a) Remanent and extrapolated Kerr ellipticities, $\epsilon_{K,r}$ and $\epsilon_{K,e}$, respectively, for longitudinal loops like those in Fig. 2(a). (b) Remanent and extrapolated Kerr rotations, $\theta_{K,r}$ and $\theta_{K,e}$, respectively, for polar loops like those in Fig. 2(b).

case of discontinuous anisotropy switching the magnetization direction changes continuously on a scale given by the exchange length $(A/K)^{1/2}$ (exchange constant A, anisotropy constant K), which is of the order of 2 nm in both components.[16] A micromagnetic model of this continuous rotation of magnetization as a result of discontinuous anisotropy switching is given elsewhere.[20] One result of this analysis is that a stripe of perpendicular anisotropy in a surrounding of easy-plane anisotropy must reach a minimum width of the order $(A/K)^{1/2}$ in order to show a perpendicular component of magnetization. The fact that $\theta_{K,e}$ in Fig. 3(b) is delayed in comparison with the DL coverage $(\Theta-1)$ may be connected with that result.

A prominent feature of the central DL range $1.4<\Theta<1.8$ is given by the absence of hysteresis [reversible loops in Fig. 2(b), disappearance of $\theta_{K,r}$ in Fig. 3(b)], in combination with saturation in comparatively low fields. This includes a demagnetized ground state which is a natural consequence of perpendicular magnetization and the resulting antiferromagnetic dipolar coupling between adjacent DL stripes. A potential ferromagnetic exchange coupling via the ML stripes apparently can be neglected, either because the ML Curie temperature is reduced from the 230 K for the extended ML[21] to below 165 K for the narrower ML stripes, or because the magnetization becomes completely in-plane in the core of the wider ML stripes, which switches off the exchange coupling between the adjacent DL stripes.[20] The dipolar nature of the antiferromagnetic coupling is confirmed by the order of magnitude of the saturation field H_s which we define by the intercept of the initial linear and the final saturation section of the loops, respectively. For $1.4<\Theta<1.8$ we obtained quite constant values of $\mu_0 H_s=(17\pm2)$ mT. We compare with the dipolar stray field $H_d=(2\pi/3)(\mu\Theta_{\mathrm{DL}}/W_0 a_w^3)$, which one stripe in a saturated sample feels by interaction with all other stripes ($a_W=0.3165$ nm is the lattice constant of the W substrate and μ the atomic magnetic moment). Using $\mu=2.2\mu_B$ and the parameters of the present experiment, one obtains, for $\Theta_{\mathrm{DL}}=0.5$, $\mu_0 H_d=21$ mT, in fair agreement with the experimental value for $\mu_0 H_s$. Of course this dipolar stray field in the saturated sample can be taken as a very rough measure only of a complicated coupling phenomenon. Nevertheless, the agreement in order of magnitude clearly confirms the basically dipolar nature of the antiferromagnetic coupling. The absence of hysteresis for $1.4<\Theta<1.8$ is easily explained by the natural assumption that remagnetization in an external field takes place by domain wall movement inside the continuous stripes. The steep rise of $\theta_{K,r}$ for $\Theta>1.8$ in turn apparently results from incipient third AL nucleation.

The data thus strongly suggest for the DL stripe system antiferromagnetic order of the dipolar origin, with antiparallel magnetization in adjacent stripes. Confirmation by electron diffraction or by magnetic microscopy would be interesting. Whereas our samples show some similarity to the usual stripe domains in homogeneus magnetic media of perpendicular anisotropy, the basic difference is given by the intrinsically anisotropic coupling in our samples, with strong exchange coupling along the stripes versus weak, mainly dipolar coupling between adjacent stripes. Consequently, the ''domains'' in our case are structurally preformed, whereas for the standard stripe domains they result from the interplay of exchange and anisotropy, and change widely with the magnetic parameters.

In conclusion, we prepared, on vicinal W(110) substrates, nanostripe arrays of pseudomorphic Fe(110), consisting of periodically alternating ML and DL stripes. Using MOKE, we observed magnetic ordering phenomena in those nanostructures at 165 K. In the range between 1.4 and 1.8 AL, where the pseudomorphic DL stripes dominate, the as-prepared nanostripe arrays show reversible polar loops with low saturation fields and neglectable remanence, giving clear evidence of perpendicular anisotropy of the DL stripes, with antiferromagnetic interstripe interaction of magnetostatic origin and antiferromagnetic ordering in the DL stripe system. It might be tempting to search for some nonvolatile coverage which would preserve this perpendicular antiferromagnetic order and then would make our system an interesting analog to the indirectly coupling multilayers. Recent techniques of preparing W(110) films by pulsed laser deposition[22] offer a chance to replace the bulk single crystal substrates by an ultrathin film. This would make the system accessible for interesting 2D magnetoresistance studies.

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