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Structural and magnetic studies of fcc Fe films with self-organized lateral modulation on striped Cu(110)-O(2×1) substrates

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Face-centered cubic (fcc) Fe wedges of 0–12 ML were grown by means of molecular beam epitaxy onto a novel substrate: flat Cu(110) with an oxygen-induced, long-range ordered striped phase, and studied *in situ* with medium energy electron diffraction (MEED) and the surface magneto-optical Kerr effect (SMOKE). In contrast to Fe growth on either clean or oxygen-saturated Cu(110), the films on the striped substrates retain a layer-by-layer growth mode up to 6–7 ML and are fcc at least up to 12 ML. In addition, satellite peaks were observed on both sides of the MEED (0, 0) streak, indicating a long-range-ordered lateral modulation of the Fe surface. We postulate that the Fe films grow conformally onto the original striped substrate. SMOKE studies show that these fcc Fe wedges are ferromagnetic with an easy axis along the original stripes for Fe thickness >4 ML and a remanent magnetization that increases linearly with thickness beyond 4 ML. © 1999 American Institute of Physics. [S0021-8979(99)40408-6]

While quasi-two-dimensional (2D) magnetic thin films and multilayers have generated tremendous excitement with new scientific discoveries and technology breakthroughs in the past several years, there has also been growing interest in the growth and magnetic properties of laterally confined magnetic structures.^{1–6} For example, 2D to one-dimensional (1D) finite-size scaling has been observed in random-shaped Fe nanowires at the mosaic step edges for growth on a nominally flat W(110) single crystal substrate.¹ The impact of steps on magnetic anisotropy has also been the subject of recent systematic investigations.^{2,3} The growth of lateral magnetic nanostructures with uniform width and regular spacing would open new avenues to study the magnetic properties of low-dimensional systems. It is known that oxygen adsorption on Cu(110) can form long-range-ordered Cu–O stripes with a period of 6–14 nm.⁷ Our initial motivation was to use such a novel substrate as a template to grow Fe nanowire arrays through self-organization. In this work, we show that Fe films of thickness at least up to 6–7 ML grow onto this striped substrate conformally with lateral long-range ordering.

Fe tends to grow on Cu substrates in a metastable face-centered cubic (fcc) phase, which has been the subject of numerous investigations due to its richness of structural and magnetic instabilities.^{8,9} On clean Cu(110), Fe grows pseudomorphically, but exhibits island growth starting at the first monolayer.^{10–12} And these films are ferromagnetic with an easy axis perpendicular to the surface when the thickness $d < 5–6$ ML, where a spin-reorientation phase transition occurs.¹³ Fe growth on oxygen-saturated Cu(110) is disordered.¹⁴ In the present work, we show that Fe films on the novel Cu–O striped substrate remain ordered in the fcc phase at least up to 12 ML. Unlike the cases of either clean

or oxygen-saturated substrates, layer-by-layer growth is observed for 6–7 ML. These fcc Fe films are ferromagnetic with in-plane easy axis of magnetization.

To prepare the samples, the flat Cu(110) single-crystal substrate was first mechanically and electrochemically polished *ex situ*, and then cleaned in the ultrahigh vacuum chamber via sputtering and annealing (900 K) cycles. Nominally 1 Langmuir (L, 1×10^{-6} Torr s) of oxygen was adsorbed onto the Cu(110) surface at 630 K. This results in a long-range-ordered striped phase with alternating (2×1) reconstructed Cu–O stripes and clean Cu with a period of ~ 8 nm.⁷ The stripes run along the Cu[001] direction. Fe was evaporated with a typical rate of 0.3 Å/min via electron-beam bombardment of a tantalum crucible. The base pressure of the chamber was 1×10^{-10} Torr, and the pressure during deposition was $2–4 \times 10^{-10}$ Torr. The Fe wedges of 0–12 ML were grown with a slope of ~ 1 ML/mm by moving the substrate behind a mask during deposition at ambient temperature. The ordering and cleanness of the crystal and the films were confirmed with reflection high-energy electron diffraction (RHEED), low-energy electron diffraction (LEED), and Auger spectroscopy. The lateral long-range ordering discussed in this work was monitored by running the RHEED gun at 3 kV (medium electron diffraction, or MEED) and observing the satellite peaks around the (0, 0) specular peak with a charge coupled device (CCD) camera. The magnetic properties were studied *in situ* by means of the surface magneto-optic Kerr effect (SMOKE) at 135 K. A He–Ne laser beam focused to 0.2 mm was used to scan along the wedge to obtain hysteresis loops for different Fe thicknesses. The height of the Kerr loop in remanence denoted M_R is proportional to the remanent magnetization.

RHEED and LEED indicates that Fe films on the Cu–O striped substrate remain in the fcc phase at least up to 12 ML. In addition, MEED studies show that the films also possess a lateral long-range ordering with a periodic structure in the $[\bar{1}10]$ direction. As shown in the inset of Fig. 1, the incident 3 kV electron beam is along the Cu–O stripes,

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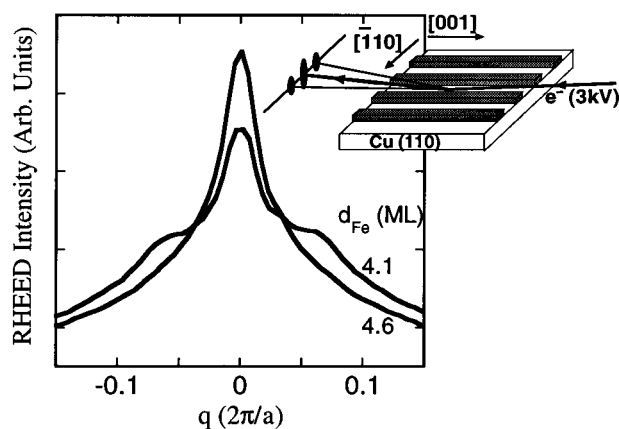


FIG. 1. Typical MEED profiles along the $[110]$ direction (perpendicular to the MEED streaks) for Fe films on the Cu-O striped Cu(110). Satellite peaks are seen for 4.1 ML of Fe. The MEED geometry is shown in the inset, where the incident beam is perpendicular to the $[110]$ direction.

i.e., the $[001]$ direction, while diffraction occurs perpendicular to the stripes, i.e., along the $[110]$ direction. Figure 1 shows typical MEED profiles (scans perpendicular to the MEED streaks) of Fe. For 4.1 ML of Fe, there are two satellite peaks at the wave vector $q = \pm 0.06 (2\pi/a)$ relative to the main specular peak, where $a = 2.54 \text{ \AA}$. As shown in the MEED schematic inset, this appears as two streaks around the main $(0, 0)$ streak. This indicates a long-range-ordered lateral modulation of the Fe films, which forms naturally during growth through self-organization. It is noted that the wave vectors of these satellite peaks double in value compared to the case of the Cu-O striped substrate ($0.03 (2\pi/a)$). For 4.6 ML of Fe, these satellite peaks disappear. After turning the crystal by 90° , no additional streaks are observed around the $(0, 0)$ streak. Therefore, these Fe surfaces have nanoscale stripe-like lateral structures.

In fact, the appearance/disappearance of the satellites occurs periodically as a function of Fe thickness. As shown in Fig. 2, the intensities of both the specular and satellite peaks

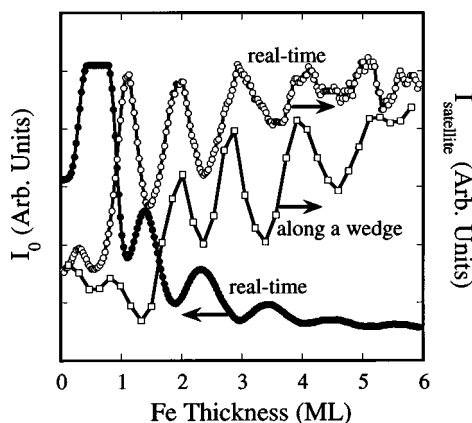


FIG. 2. MEED oscillations of fcc Fe growth on the Cu-O striped Cu(110). The circles were taken in real time during deposition, while the squares were deduced from individual images along a wedge. The filled symbols are the intensities of the $(0, 0)$ specular peak. The hollow symbols are the intensities of the satellites, normalized to the intensities at $q = 0.03 (2\pi/a)$.

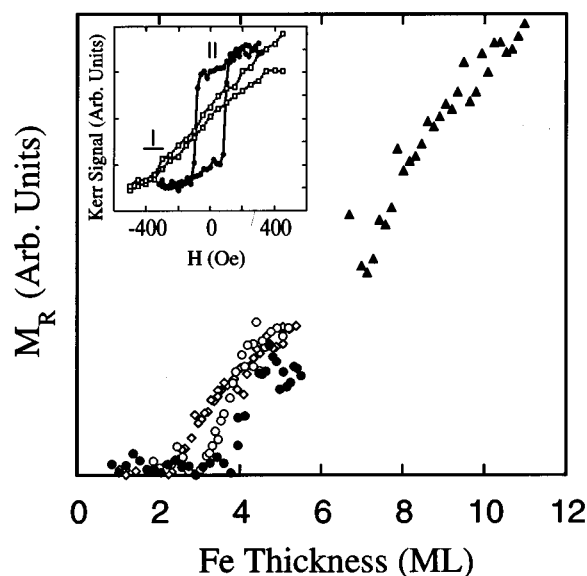


FIG. 3. Typical longitudinal remanant magnetization as a function of Fe thickness, measured *in situ* with SMOKE. Different symbols indicate individual wedges. The inset shows typical longitudinal and polar loops.

oscillate with Fe thickness with a period of 1 ML. The intensity of the satellite peaks is normalized to the intensity at $q = 0.03 (2\pi/a)$. The same effect is seen both in the real-time measurements during deposition [filled (specular) and hollow (satellite) dots] and by plotting the intensities from individual images (after normalizing with exposure time) along the wedges (square symbols). The specular peaks are the strongest around each half monolayer, while the satellite peaks are the strongest around each full monolayer.

The oscillation of the specular intensity clearly indicates a layer-by-layer growth of fcc Fe on the striped Cu-O substrate up to 6–7 ML. This is in strong contrast to the case of Fe growth onto clean Cu(110) substrate, where the fcc Fe films exhibit three-dimensional (3D) growth with no RHEED oscillations. It is also different from the case of Fe growth onto an oxygen-saturated Cu(110) surface, where the Fe films are disordered. Such an improved growth mode may be related to the reduced terrace size of the striped substrate, which allows the atoms with the same mobility to find a step edge easier and therefore allows a step-flow growth at a lower temperature. The poor growth on oxygen-saturated Cu(110) suggests that the possible surfactant effect caused by oxygen floating to the surface may not be the main cause of the layer-by-layer growth on the striped substrate, though surfactant effects cannot be completely ruled out.

Longitudinal SMOKE signals were measured with the field along the Cu $[001]$ direction. As shown in Fig. 3, these fcc Fe films are ferromagnetic and have an easy axis along the $[001]$ direction when the Fe thickness is >4 ML. The remanant magnetization (M_R) increases linearly with the film thickness as expected. Below 4 ML, the magnetic properties vary from sample to sample, with a different onset of the magnetization. This may be due to the ultrasensitivity of the magnetic anisotropy to the exact amount of oxygen adsorption, and therefore to the Cu-O stripe period, the rough-

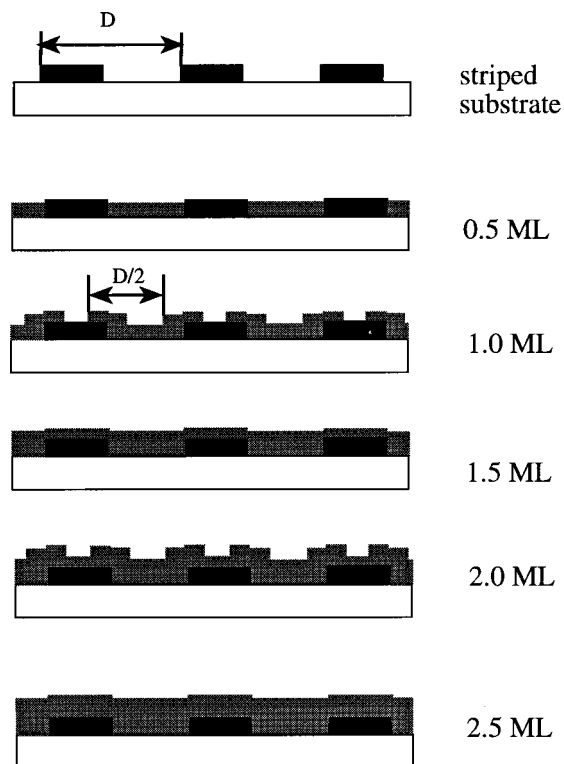


FIG. 4. Growth hypothesis for fcc Fe on Cu–O striped Cu(110). The black regions represent the (2×1) reconstructed Cu–O stripes. The shadowed regions indicate the Fe growth.

ness of the substrate, and the cleanliness of the Fe surface. Further studies are needed to understand the magnetic properties of the Fe films in the problematic regime <4 ML.

It is somewhat surprising to observe the stripe-like structure is preserved on Fe films as thick as 6–7 ML. It is even more surprising that the lateral periodicity on the Fe surface differs from that of the striped substrate. The wave vector doubling means that the period in real space is reduced to ~ 4 nm, half of its original value. In order to explain our data, we propose a growth model as shown in Fig. 4. We assume that the Fe grows conformally onto the striped substrate, and that growth always originates from the step edges and then is followed by step-edge flow growth. With the oxygen coverage values we employ on the substrate, roughly half of the surface is covered with Cu–O stripes.⁷ Therefore, the films are flatter around each half ML and are rougher around each full ML. Since the atoms are always centered around the step

edges with a very small thickness difference between growth on either Cu–O or clean Cu regions, the real-space periodicity appears to be reduced by half. There is little diffraction for the half ML films due to the small height difference. We cannot, however, rule out another possibility: that oxygen could keep floating to the top of the Fe(110) surface and reconstruct into a striped structure with period the half of that on Cu(110). The driving force for such a rearrangement at room temperature would be unclear, though. To further understand the growth of Fe on the striped Cu–O substrate, scanning tunneling microscopy experiments should be performed.

In summary, we have grown fcc Fe onto a novel Cu(110) substrate with ordered Cu–O stripes. The growth mode is layer-by-layer, and thus improved compared to that on either clean or oxygen-saturated Cu(110). Lateral long-range ordering of the stripe-like structure on Fe is retained up to 6–7 ML. These fcc Fe films are ferromagnetic with in-plane magnetic anisotropy. Thus we have identified a system worthy of further exploration.

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- ¹H. J. Elmers, J. Hauschild, H. Höche, U. Gradmann, H. Bethge, D. Heuer, and U. Köhler, *Phys. Rev. Lett.* **73**, 898 (1994).
- ²W. Weber, C. H. Park, A. Bischof, D. Pescia, and R. Allenspach, *Nature (London)* **374**, 788 (1995), and the references therein.
- ³R. K. Kawakami, E. J. Escorcia-Aparicio, and Z. Q. Qiu, *Phys. Rev. Lett.* **77**, 2570 (1996); Hyuk, J. Choi, Z. Q. Qiu, J. Pearson, S. J. Jiang, D. q. Li, and S. D. Bader, *Phys. Rev. B* **57**, R12713 (1998).
- ⁴T. Shinjo and T. Ono, *J. Magn. Magn. Mater.* **156**, 11 (1996).
- ⁵H. Takeshita, Y. Suzuki, H. Akinaga, W. Mizutani, K. Tanaka, T. Katayama, and A. Itoh, *Appl. Phys. Lett.* **68**, 3040 (1996).
- ⁶A. Sugawara, T. Coyle, and M. R. Scheinfein, *Appl. Phys. Lett.* **70**, 1043 (1997); A. Sugawara and M. R. Scheinfein, *Phys. Rev. B* **56**, R8499 (1997).
- ⁷K. Kern, H. Niehus, A. Schatz, P. Zeppenfeld, J. Goerge, and G. Comsa, *Phys. Rev. Lett.* **67**, 855 (1991).
- ⁸D. q. Li, M. Freitag, J. Pearson, Z. Q. Qiu, and S. D. Bader, *Phys. Rev. Lett.* **72**, 3112 (1994), and the references therein.
- ⁹D. q. Li, D. J. Keavney, J. Pearson, S. D. Bader, J. Pege, and W. Keune, *Phys. Rev. B* **57**, 10044 (1998).
- ¹⁰D. Tian, F. Jona, and P. M. Marcus, *Phys. Rev. B* **46**, 11216 (1992).
- ¹¹M. T. Kief and W. F. Egelhoff, Jr., *Phys. Rev. B* **47**, 10785 (1993).
- ¹²A. Theobald, S. Bao, V. Fernandez, K.-M. Schindler, O. Schaff, V. Fritzschke, A. M. Bradshaw, N. Booth, and D. P. Woodruff, *Surf. Sci.* **385**, 107 (1997).
- ¹³M. T. Kief and W. F. Egelhoff, Jr., *J. Appl. Phys.* **73**, 6195 (1993).
- ¹⁴E. Yagasaki and K. Kishi, *J. Electron Spectrosc. Relat. Phenom.* **69**, 133 (1994).