On the fabrication of stacked monolayers of Fe/Cu on Cu(100) by pulsed laser deposition

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We report on the artificial fabrication of stacked monolayers of Fe/Cu on Cu(100) by pulsed laser deposition at 300 K employing reflection high energy electron diffraction (RHEED). In contrast to the thermally deposited films, an improved two dimensional growth of the Fe and Cu layers has been achieved by virtue of the dynamics of the pulsed laser deposition technique. The observed RHEED oscillations for each Fe and Cu layer and their growth mode as studied by scanning tunnelling microscopy indicate layer-by-layer growth. The magnetic properties studied by magneto-optical Kerr effect measurements show that the easy axis of magnetization is in plane with no specific anisotropy observed in the plane. Ferromagnetic response was absent for thicknesses less than 2 ML in total within the measured temperature range down to 100 K. The Curie temperature increases from 225 K for a trilayer Fe/Cu/Fe to 400 K for a total layer thickness of 10 ML. © *1997 American Institute of Physics.* [S0021-8979(97)44108-7]

INTRODUCTION

In the search for new metallic and ferromagnetic materials, artificially layered structures with nonmagnetic spacers offer interesting new magnetic properties both of fundamental and technological interest.[1] Takanashi and co-workers have recently reported a large uniaxial perpendicular anisotropy in monatomic multilayers of Fe/Pt,[2] [1 ML Fe/1 ML Pt]n (with $n=100$), and Fe/Au[3] which adds a new dimension to the efforts in this field. A monatomic stack is the low thickness limit of a magnetic multilayer consisting of alternating individual layers of magnetic and nonmagnetic elements.

The Fe–Cu system is no less interesting since its phase diagram indicates no possibility of any intermediate compounds while the solubility is very low at room temperature and is around 8% at elevated temperatures.[4] As this alloy does not exist naturally in the Fe–Cu phase diagram near the equiatomic composition, we attempt to fabricate it layer-by-layer artificially. Although Fe/Cu multilayers have been studied extensively with different modulation lengths ranging from 10 to 300 Å and with equal Fe and Cu thickness,[5,6] to our knowledge, there is no report on the study of monatomic stackings of the Fe/Cu system. Constructing such a multilayer relies strongly on the growth mode of the individual elements in monolayer thickness regime. While thermal deposition of Fe on Cu(100) does not produce an ideal two-dimensional morphology at monolayer thickness,[7,8] the morphology of a monolayer-thick Fe/Cu(100) film can be significantly improved by pulsed laser deposition (PLD).[9] The momentaneous deposition rate of PLD (which is typically 10^7 times larger than that of the thermal deposition) provides a high nucleation density thereby improving a two dimensional, layer-by-layer growth of Fe on Cu(100). The objective of this study has been to fabricate stacked monolayers of Fe and Cu alternatively, [1 ML Fe/1 ML Cu]n on Cu(100), employing the PLD technique and to analyze the initial growth mode of such a stacking by scanning tunnelling microscopy (STM) as well as to investigate the magnetic properties by the magneto-optical Kerr effect (MOKE). The stacking of [1 ML Fe/1 ML Cu] will be referred to in terms of the total numbers of monolayers, where the odd and even numbers indicate an Fe or Cu monolayer on the top of the multilayer, respectively.

EXPERIMENT

The Fe/Cu monatomic multilayers were grown on a Cu(100) substrate at room temperature in an ultrahigh vacuum (UHV) system with a base pressure of 3×10^{-11} mbar equipped with *in situ* facilities for STM, MOKE, reflection high energy electron diffraction (RHEED), and low

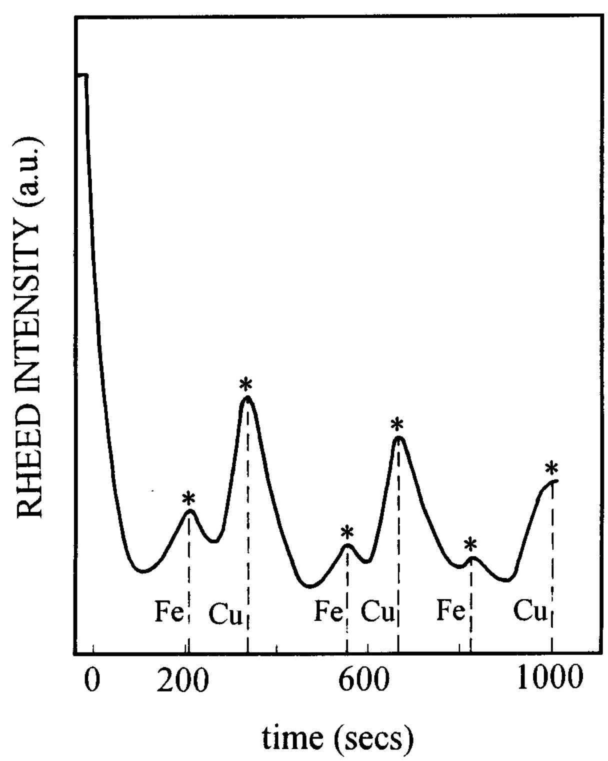

FIG. 1. A typical RHEED oscillation for 6 ML Fe/Cu stacking on Cu(100) prepared by PLD method. The first maximum corresponds to 1 ML filling of Fe and the second maximum to 1 ML Cu.

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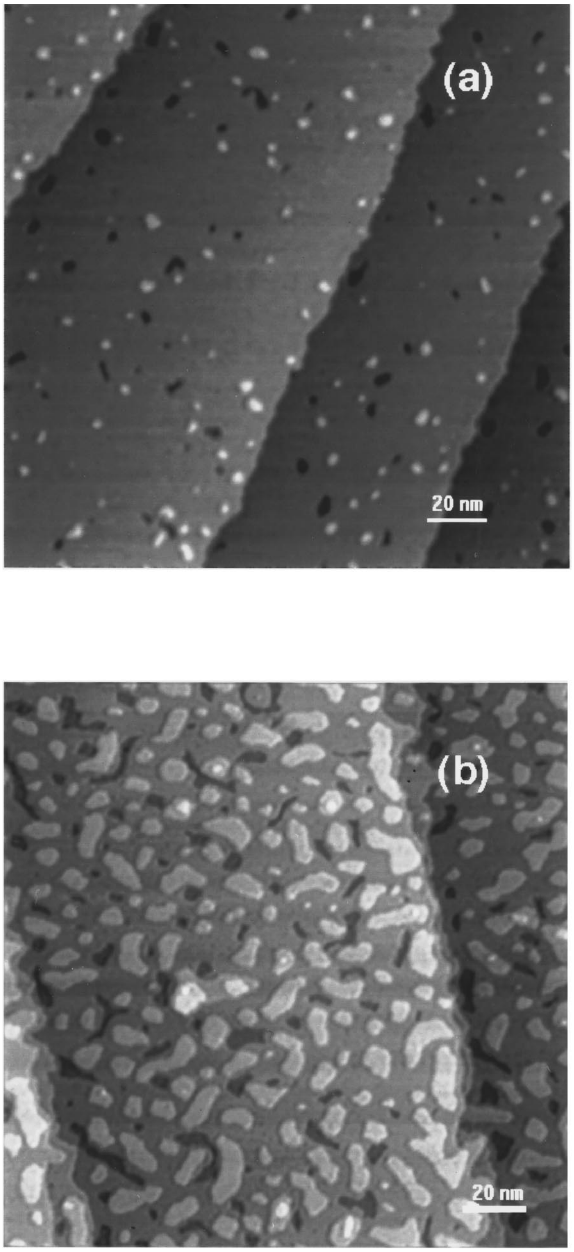

FIG. 2. STM images of (a) total thickness of 2 ML Fe/Cu on Cu(100) and (b) total thickness of 8 ML Fe/Cu stacking on Cu(100) showing the sequential layer filling.

energy electron diffraction (LEED) measurements. The Cu(100) substrate was cleaned *in situ* by cycles of sputtering with Ar^+ (1 keV and 600 eV) and annealing to 870 K. The surface cleanliness was checked by Auger electron spectroscopy (AES). A KrF excimer laser ($\lambda=248$ nm) with a fluence of 5 J/cm^2 and repetition rate of 5 Hz was employed for depositing the Fe and Cu monolayers alternatively. Completion of each monolayer coverage was monitored by the RHEED oscillations recorded during the film growth. The growth rate can be varied by changing the laser repetition rate. The base pressure of the UHV chamber was no worse than 5×10^{-10} mbar during the deposition. The magnetic properties were probed by MOKE.

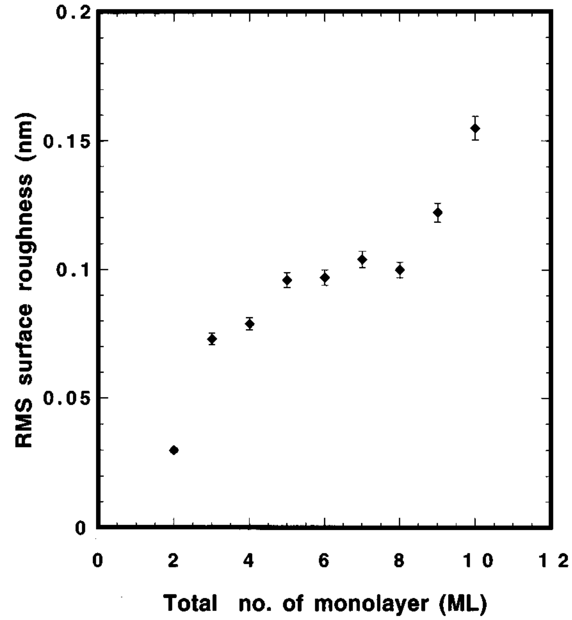

FIG. 3. Plot of root-mean-square (rms) roughness against total monolayer thickness as measured from the STM topography.

RESULTS AND DISCUSSION

Figure 1 shows a typical RHEED oscillation measured for a 6 ML Fe/Cu stacking. The first maximum corresponds to 1 ML of Fe and the second maximum corresponds to the layer filling due to Cu. At each maximum (asterisk marked in Fig. 1), the target is changed (manually within 6 s). Note that the deposition at room temperature results in a degrading of the RHEED intensity although the layer-by-layer sequential filling is maintained. Although deposition at elevated tem-

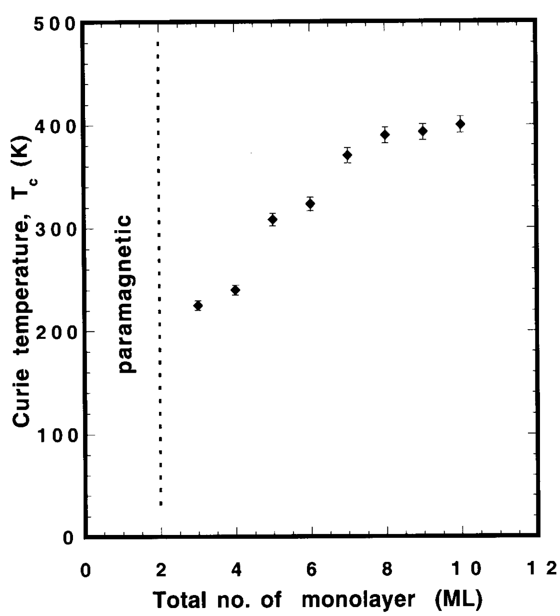

FIG. 4. Plot of Curie temperature, T_c against total monolayer thickness for [1 ML Fe/1 ML Cu] on Cu(100).

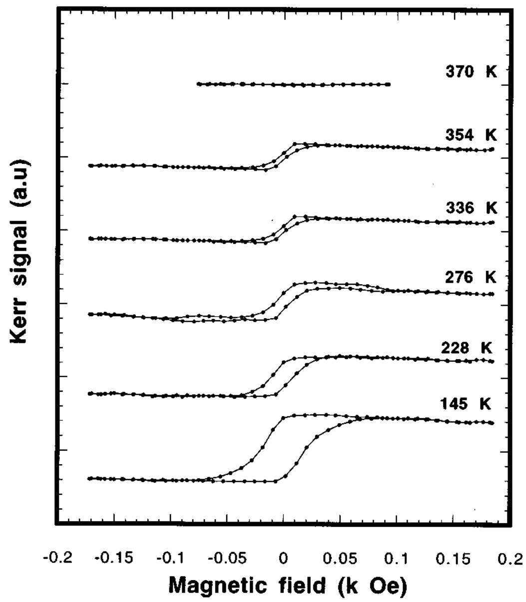

FIG. 5. Hysteresis loops from MOKE measurements for a total 7 ML of [1 ML Fe/1 ML Cu] on Cu(100) measured in the plane.

peratures would improve the surface ordering, the possibility of diffusion of Fe into the Cu substrate might lead to mixed interfaces.

Figure 2 shows STM images of 2 and 8 ML Fe/Cu multilayers. For the 2 ML film, 98.5% of the first layer is filled and less than 2% of the third layer starts growing (the bright islands). At a total of 8 ML, the 7th, 8th, and 9th monolayer contribute about 7%, 69%, and 23% of the surface area, respectively. The surface roughness measured by root-mean-square analysis from the STM topography indicates an increase in roughness with the increase in the number of monolayers as shown in Fig. 3. Such a trend is to be expected since the RHEED oscillations (Fig. 1) indicate a decreasing intensity for Fe layers and an increasing intensity for Cu layers suggesting that the layer roughness increases for the growth of Fe layers while the roughness decreases for the Cu layer. The LEED patterns of the films, with varying total thickness, are identical to the $p(1\times1)$ pattern of the bulk Cu(100) confirming the fcc structure of the whole stack.

The magnetic properties of the monatomic Fe/Cu stackings have also been characterized. The Fe/Cu layers are ferromagnetically ordered at and above a total of 3 ML of (1 ML Fe/1 ML Cu). Upon increasing the number of monolayer stackings, the Curie temperature T_c increases from 220 K for 3 ML to 400 K for the 10 ML film beyond which there is very little increase in the T_c value (Fig. 4). We do not observe any ferromagnetic response for a total monolayer of 2 ML [comprising of (1 ML Fe/1 ML Cu)] within the measured temperature range down to 100. This is in line with the observation for Fe on Cu(100) films grown by thermal deposition which shows no ferromagnetic signature below 1.8 ML.[10] The absence of ferromagnetic response in the thermally deposited films may be attributed to the inadequate magnetic percolation between Fe islands although structural percolation is achieved at 0.8 ML.[11]

The MOKE hysteresis loops for a total 7 ML (1 ML Fe/1 ML Cu) film are shown in Fig. 5. The magnetization of the films exhibit a nearly rectangular loop in plane while there was no component of the magnetization perpendicular to the plane, indicating that the easy magnetization axis is parallel to the surface. This might be associated with the fact that PLD-grown oligatomic Fe/Cu(100) show in plane easy magnetization axis in a thickness range where the thermally deposited Fe/Cu(100) films are perpendicularly magnetized.[12] The hysteresis loops measured with the magnetic field applied parallel to the surface along ⟨110⟩ and ⟨100⟩ directions do not show any change in the shape of the loops indicating that the films are in-plane magnetized with no specific anisotropy within the plane of the film. The coercivity Hc of these films is in the range of 15–20 Oe with higher values for films where Fe is on the top and lower for Cu layers on the top revealing the influence of the nonmagnetic layer.

In conclusion, we have described the growth mode of stacked monolayers of Fe and Cu on Cu(100) deposited by PLD, the calibration of the deposited layers by RHEED, and their topography by STM. At all thicknesses, the films have easy axis of magnetization in plane with no measurable anisotropy in the plane.

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[1] B. Heinrich and J. F. Cochran, Adv. Phys. **42**, 523 (1993), and references therein.
[2] K. Takanashi, S. Mitani, M. Sano, H. Fujimori, H. Nakayama, and A. Osawa, Appl. Phys. Lett. **67**, 1016 (1995).
[3] S. Mitani, K. Takanashi, M. Sano, H. Fujimori, H. Nakayama, and A. Osawa, J. Magn. Magn. Mater. **148**, 163 (1995).
[4] W. B. Pearson, *Handbook of Lattice Spacing and Structure of Metals and Alloys* (Pergamon, New York, 1958), p. 602.
[5] M. Pechan, E. E. Fullerton, W. Robertson, M. Grimsditch, and I. K. Schuller, Phys. Rev. B **52**, 3045 (1995); D. Pescia *et al.*, Phys. Rev. Lett. **58**, 2126 (1987); Y. Darici *et al.* Surf. Sci. **182**, 477 (1987).
[6] E. E. Fullerton, I. K. Schuller, F. T. Parker, K. A. Svamarich, G. L. Eesley, R. Bhadra, and M. Grimsditch, J. Appl. Phys. **73**, 7370 (1993).
[7] D. A. Steigerwald, I. Jacob, and W. F. Egelhoff, Jr., Surf. Sci. **202**, 472 (1988).
[8] K. E. Johnson, D. D. Chambliss, R. J. Wilson, and S. Chiang, J. Vac. Sci. Technol. A **11**, 1654 (1993).
[9] H. Jenniches, M. Klaua, H. Höche, and J. Kirschner, Appl. Phys. Lett. **69**, 3339 (1996).
[10] J. Thomassen, F. May, B. Feldmann, M. Wuttig, and H. Ibach, Phys. Rev. Lett. **69**, 3831 (1992).
[11] J. Giergiel, J. Shen, J. Woltersdorf, A. Kirilyuk, and J. Kirschner, Phys. Rev. B **52**, 8528 (1995).
[12] H. Jenniches, J. Shen, S. Sundar Manoharan, J. Barthel, M. Klaua, and J. Kirschner (unpublished).