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Uniaxial magnetic anisotropy of epitaxial Fe films on InAs(100)-4×2 and GaAs(100)-4×2

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The evolution of the uniaxial magnetic anisotropy of ultrathin epitaxial Fe films grown on InAs(100)-4×2 and GaAs(100)-4×2 has been studied *in situ* by means of the magneto-optical Kerr effect. In Fe/InAs(100)-4×2, the uniaxial magnetic anisotropy easy axis direction along [011] was found to be rotated 90° compared with that of Fe/GaAs(100)-4×2 along $[0\bar{1}1]$. Real-time reflection high energy electron diffraction measurements of Fe/InAs(100)-4×2 show that the lattice constant of the epitaxial Fe films relaxes remarkedly faster along the $[0\bar{1}1]$ direction than along the [011] direction in the same thickness range where the uniaxial magnetic anisotropy occurs. These results suggest that the symmetry-breaking atomic scale structure of the reconstructed semiconductor surface gives rise to the uniaxial magnetic anisotropy in a ferromagnetic metal/semiconductor heterostructure via surface magneto-elastic interactions. © *2000 American Institute of Physics.* [S0021-8979(00)51308-5]

INTRODUCTION

Ferromagnetic metal (FM)/semiconductor heterostructures have attracted great attention recently for the study of fundamental magnetic properties of ultrathin films and for the development of the next generation magneto-electronic devices.[1,2] An in-plane uniaxial magnetic anisotropy (UMA), unexpected from the crystal symmetry of bulk body-centered-cubic (bcc) Fe, was observed in the Fe/GaAs system,[3–7] but its origin still remains an open issue. Several mechanisms have been proposed to explain the origin of this uniaxial anisotropy.[3–7] For example, shape anisotropy due to the three-dimensional (3D) island growth of the films and a so-called nearly half-magnetized phase at the interface were excluded[6,7] as possible mechanisms. It is now generally believed that the atomic scale structure related to the reconstruction of the semiconductor surface is responsible for this uniaxial anisotropy. However, the precise role of the atomic scale structure of the substrate surface is unclear. In this article, we report a comparative study of the evolution of the magnetic anisotropy in Fe/GaAs and Fe/InAs systems. We have shown in our preliminary work[8] that epitaxial bcc Fe can be grown on InAs(100) at 175 °C despite their lattice mismatch of 5.4%. The lattice constant of Fe is slightly larger than half the lattice constant of GaAs but smaller than half that of InAs, and equivalent surface reconstructions can be stabilized on the GaAs(100) and InAs(100) surfaces. A comparison of the evolution of the uniaxial magnetic anisotropy in Fe/InAs and in Fe/GaAs may help to reveal the role of lattice relaxation and surface morphology. Furthermore, since the mismatch between Fe and InAs is reasonably large, Fe/InAs is also an ideal system in which to study lattice relaxation and its correlation with the evolution of magnetic anisotropy.

EXPERIMENTS

This study was carried out in a ''multitechnique'' molecular beam epitaxy (MBE) system that is described elsewhere.[7] The Fe films were grown on GaAs(100) and InAs(100) substrates at a rate of approximately 1 monolayer (ML) per minute using an e-beam evaporator. The pressure was around $7-8\times10^{-10}$ mbar during growth and the substrate was held at room temperature. The GaAs substrate used in this study is As capped GaAs(001) prepared in another ultrahigh vacuum (UHV) chamber. A buffer layer ($\sim$0.5 μm) of homoepitaxial GaAs was grown on the commercial wafer to provide the smoothest GaAs surface possible. The InAs(100) substrates were cleaned using a combination of oxygen plasma etching and wet etching ($HCl:H_2O=1:4$) before being loaded into the UHV system. The evolution of the magnetic properties has been probed using *in situ* magneto-optical Kerr effect (MOKE) measurements. The strain relaxation during epitaxial growth was studied by dynamic reflection high energy electron diffraction (RHEED) measurements.

The RHEED and low energy electron diffraction (LEED) images of the GaAs and the InAs substrates after annealing for 30 min at 550 and 510 °C, respectively, show exactly the same patterns. These diffraction patterns show that the surfaces of GaAs(100) and InAs(100) have Ga-rich 4×2 and In-rich 4×2 reconstructions, respectively. Auger spectroscopy measurements show that the substrate is free of O, but has a tiny C peak after the annealing. The epitaxial growth of the Fe films has been confirmed with both LEED and RHEED measurements with the epitaxial relationship $Fe(100)\langle 001\rangle \| GaAs(100)\langle 001\rangle$ and $Fe(100)\langle 001\rangle \| InAs(100)\langle 001\rangle$.

RESULTS

Figures 1 and 2 show the evolution of the hysteresis loops of Fe/GaAs(100)-4×2 and Fe/InAs(100)-4×2, respectively, with the magnetic field applied along four major axes.

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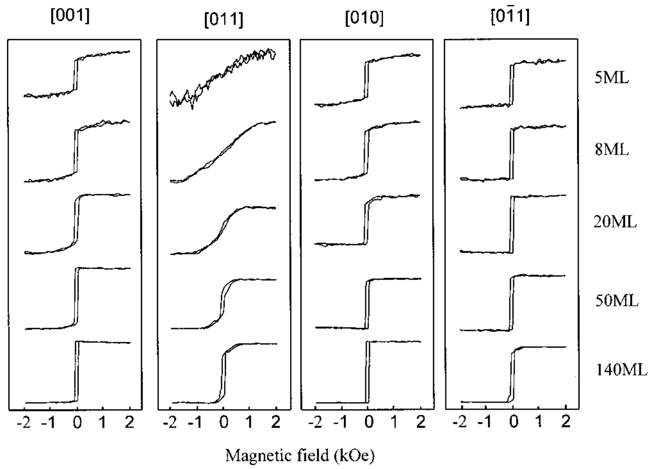

FIG. 1. *In situ* MOKE hysteresis loops of Fe/GaAs(100)-4×2 in the thickness range of 5–140 ML grown at room temperature with the magnetic field applied along four major axes.

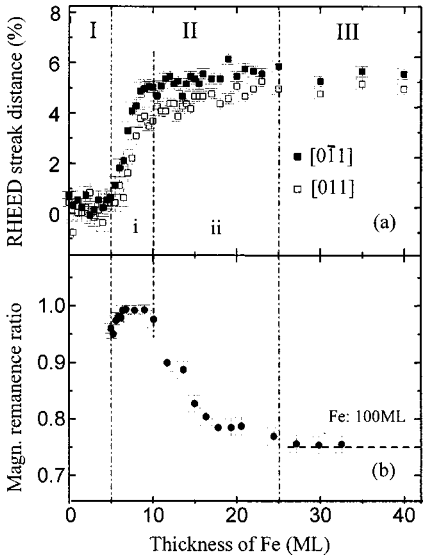

FIG. 3. (a) Relative changes of the RHEED streak distances compared with those of the InAs(100) substrate and (b) magnetization remanence ratios measured along the [011] direction as a function of Fe coverage in Fe/InAs(100)-4×2.

The Fe films grown on both substrates show the existence of uniaxial anisotropy. The UMA is dominant in the ultrathin regions as shown by the square loops along the ⟨011⟩ directions. Above critical thicknesses of about 50 ML for Fe/GaAs and 16 ML for Fe/InAs, the cubic anisotropy becomes dominant. The Fe films display a cubic anisotropy with the magnetic easy axes along the ⟨001⟩ directions, the easy axes of bulk bcc Fe. However, the hysteresis loops in Figs. 1 and 2 show clearly different features as well. *The easy axis direction of the uniaxial anisotropy is strikingly different in the two systems*. The easy axis in Fe/GaAs(100)-4×2 is along the $[0\bar{1}1]$ direction as shown in Fig. 1, which is in agreement with our previous results for films grown at 175 °C,[5] and the same as that in Fe/GaAs(100)-4×6.[7] Compared with the Fe/GaAs(100)-4×2 system, the uniaxial magnetic anisotropy easy axis direction along [011] in Fe/InAs(100)-4×2 was found to be rotated 90°. The thickness ranges and magnitude of the uniaxial anisotropy also show significant differences in the two systems. The uniaxial anisotropy in Fe/GaAs persists to a much larger thickness range than that in Fe/InAs.

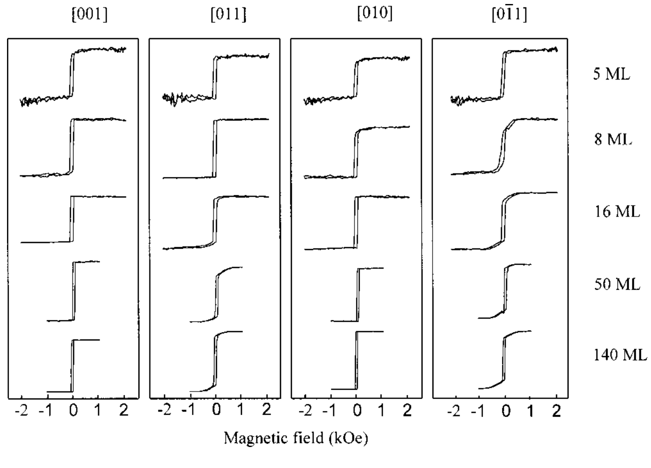

FIG. 2. *In situ* MOKE hysteresis loops of Fe/InAs(100)-4×2 in the thickness range of 5–140 ML grown at room temperature with the magnetic field applied along four major axes.

The strain relaxation in Fe/InAs(100)-4×2 has been studied using RHEED. Figure 3(a) shows the relative changes of the streak separations along the [011] and $[0\bar{1}1]$ directions compared to those of the InAs(100) substrate as a function of Fe coverage. The thickness dependence of the remanence ratio of the hysteresis loops obtained along the [011] direction is included in Fig. 3(b). The growth can be divided into three stages as shown in Fig. 3(a). In region I, up to 5 ML the film is highly strained (the pseudomorphic regime). The films begin to relax after about 5 ML along both directions (region II). However, the relaxation along the $[0\bar{1}1]$ direction is *significantly* faster than that along the [011] direction. Region II could then roughly be divided into two subregions: (i) 5–10 and (ii) 15–25 ML. In subregion (i), the lattice constant along the $[0\bar{1}1]$ direction changes rather sharply with increasing thickness and approaches the bulk value around 10 ML, whereas the lattice constant along the [011] direction changes much more slowly and levels off around 25 ML in region (ii), i.e., ''anisotropic lattice relaxation'' is clearly observed. Based on the scanning tunneling microscopy (STM) image of the InAs(100)-4×2 surface, we infer that the atomic scale structure, i.e., In dimer rows along the $[0\bar{1}1]$ direction of the reconstructed InAs(100)-4×2 surface break the lattice symmetry of the surface atoms and are responsible for the observed uniaxial strain relaxation.[9]

Figures 2 and 3(b) show that the UMA dominates in the ultrathin region of about 5–10 ML, which corresponds exactly to subregion II (i) in Fig. 3(a). The remanence ratio decreases above about 10 ML in the thickness range of 10–25 ML due to competition between the cubic and the uniaxial anisotropies. Beyond about 25 ML the magnetic hysteresis loops along four major axes were found to remain almost unchanged with increasing thickness. This is in good agreement with the thickness range of region III, which shows that bulk-like bcc Fe has been established above about 25 ML.

DISCUSSION

With regard to the exact role of the surface structure of the reconstructed semiconductor surface, two distinctly different mechanisms associated with ''chemical bonding'' and ''lattice relaxation,'' respectively, need to be considered. By examining the anisotropy of the Fe films deposited on two different kinds of GaAs substrates that show different reconstructions, Kneeler *et al.*[6] proposed that the unidirectional nature of Fe–As or Fe–Ga bonds is responsible for the UMA. This might be understood as a ''chemical'' effect, in which the electronic structure of the Fe atoms near the interface differs distinctly from that of ''normal'' bcc Fe. Another possibility is that the lattice constants of the ultrathin films deviate from that of bulk bcc Fe due to the mismatch, and the strain leads to magneto-elastic interactions. Magneto-elastic interaction was proposed to be the origin of the uniaxial anisotropy in the early work on Fe/GaAs by Prinz and co-workers,[1,3] although no conclusive experimental evidence has been reported so far to support this view. However, if the magneto-elastic model is correct, uniaxial magnetic anisotropy should be correlated with anisotropic strain. The present work provides two key observations, although quantitative analysis of the thickness range and magnitude of UMA needs further accurate determination of the cubic and uniaxial anisotropy. First is the observation of an easy axis direction of the UMA in Fe/InAs(100)-4×2 which differs by 90° with that in Fe/GaAs(100)-4×2. The Fe film in the ultrathin region is *compressed* (in plane) on GaAs while *expanded* on InAs. This will lead to opposite strain tensor components for the two systems which is in accord with the observed anisotropy behavior. However, it should be noted that a positive magnetostriction constant λ_{110}, in contrast to that of bulk bcc Fe,[10] has to be assumed in the ultrathin Fe films to have the easy axis direction in agreement with the experimental observations. Such a change in sign of the magnetostriction constants has been found in ultrathin Fe films (about 20 ML) on W(100).[11] Just as pointed out by Sander *et al.*,[11] the surface magneto-elastic coupling is thus a more appropriate description of the magneto-elasticity in ultrathin films. Second is the observation of uniaxial strain relaxation over the same thickness range in which the uniaxial magnetic anisotropy occurs. This may be the first direct experimental evidence, as far as we know, to show that the anisotropic strain contributes to the in-plane uniaxial anisotropy in ferromagnetic/III–V semiconductor systems, even though the contributions from the unidirectional Fe–As or Fe–Ga bonds cannot be excluded.

CONCLUSION

In summary, we have studied the evolution of the magnetic anisotropy in two epitaxial ferromagnetic metal/III–V semiconductor systems with the same reconstruction, namely, Fe/GaAs(100)-4×2 and Fe/InAs(100)-4×2, grown under the same conditions. One of the key observations of this study is the different easy axis direction of the UMA in Fe/InAs(100)-4×2 compared with that in Fe/GaAs(100)-4×2. Furthermore, an anisotropic lattice relaxation was observed in Fe/InAs(100)-4×2 which is correlated with the intrinsic atomic scale structure of the reconstructed semiconductor surface. These observations therefore represent direct experimental evidence of the role of the atomic scale structure of the semiconductor surface and the associated magneto-elastic interactions in giving rise to uniaxial anisotropy in ferromagnetic metal/semiconductor heterostructures.

ACKNOWLEDGMENTS

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