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Structure and magnetic properties of epitaxial Fe films on GaAs(1 0 0) and InAs(1 0 0)

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Abstract

Single crystal BCC Fe films have been stabilized on both GaAs(1 0 0)-4 × 6 and InAs(1 0 0)-4 × 2 substrates at room growth temperature. The magnetic properties of the Fe/GaAs were found to proceed via three phases determined by the growth morphology; a non-magnetic phase, a short-range-ordered superparamagnetic phase and a ferromagnetic phase above about five monolayers. A uniaxial magnetic anisotropy (UMA) was observed in ultrathin Fe/InAs(1 0 0)-4 × 2 films within a narrow thickness range of about 5–10ML. The easy axis is along the [0 1 1] direction rather than $[0\,\bar{1}\,1]$, the easy axis in Fe/GaAs(1 0 0)-4 × 6 and 4 × 2. As ultrathin Fe films tend to be compressed in-plane on GaAs and expanded on InAs, the strikingly different anisotropy behaviour in the Fe/GaAs(1 0 0) and the Fe/InAs(1 0 0) may indicate the importance of magneto-elastic interactions. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Epitaxy; Magnetic anisotropy; Magnetic phase; Metal–semiconductor interface

Ferromagnetic metal (FM)/semiconductor heterostructures are of growing interest for the study of fundamental magnetism of ultrathin films and for the development of magneto-electronic devices [1]. Due in part to the fact that the lattice constant of GaAs ($a_0 = 5.654$ Å) is almost exactly twice that of BCC Fe ($a_0 = 2.866$Å), single crystal Fe films have been stabilized on GaAs using molecular beam epitaxy (MBE) growth. Although the Fe/GaAs system has been extensively studied [2–4], the magnetic properties of the first few monolayers are poorly understood, and there is still debate over whether or not there are magnetically dead layers [2], or a nearly half-magnetized phase $Fe_3Ga_{2-x}As_x$ at the interface [4] due to interdiffusion of As into the Fe overlayer. In this paper we show that the growth morphology of the ultrathin films plays an important role in determining the magnetic properties in this system.

From the point of view of magneto-electronics, Fe/InAs may be a better system than Fe/GaAs. As Fe forms a rectifying contact on GaAs, the Schottky barrier (~ 0.8 eV for Fe/GaAs [5]) prevents efficient current injection from the FM pads to the semiconductor substrates. The fabrication of ever-smaller devices leads to higher current densities, which in turn need low resistance ohmic contacts to reduce thermal dissipation. Metals on narrow gap semiconductors, such as InAs (which has a direct band gap as small as 0.36 eV at 300 K) form low resistance contacts [5]. The crystal structure of InAs is very similar to that of GaAs, namely a zincblende structure composed of two nested face-centred-cubic cells. Though the lattice mismatch of Fe and InAs ($a_0 = 6.058$ Å) of -5.4% is much larger than that of Fe/GaAs ($+1.3\%$), BCC Fe may possibly stabilize on InAs through a lattice relaxation process. It is well known that in semiconductor growth, such as InAs on GaAs [6], high quality epitaxy can be achieved despite a large lattice mismatch, 7.1%, of these two materials. Here we demonstrate that single crystal BCC Fe can be grown epitaxially on InAs(1 0 0). The uniaxial magnetic anisotropy (UMA) in Fe/InAs(1 0 0)-4 × 2 shows

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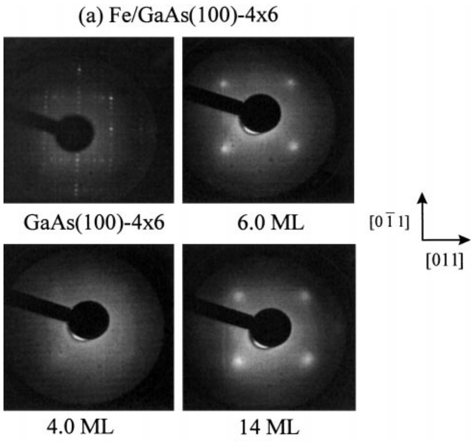

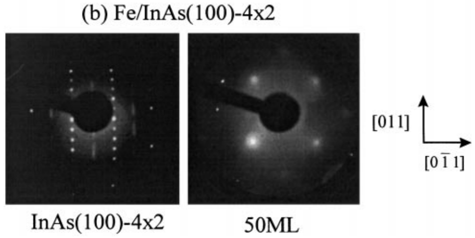

Fig. 1. LEED patterns of (a) GaAs(1 0 0) substrate, 135 eV, and after Fe deposition, 120 eV; (b) InAs(1 0 0) substrate, 68 eV, and after Fe deposition, 136 eV.

important differences from that of Fe/GaAs(1 0 0)-4 × 6 and 4 × 2.

This study was carried out in a ‘multiple-technique’ molecular beam epitaxy (MBE) system which includes in situ magneto-optical Kerr effect (MOKE) and low energy electron diffraction (LEED). Experimental details are described elsewhere [7].

The GaAs substrates used in this study are As capped GaAs(1 0 0) prepared in another UHV chamber. A buffer layer (~ 0.5 μm) of homoepitaxial GaAs was grown on the commercial wafer to provide the smoothest possible GaAs surface. The substrate was annealed to 550°C for one hour to obtain a clean and ordered surface before growth. The substrates were at room temperature during growth on both sytems. The LEED picture (Fig. 1(a)) of the substrate shows a very clear (4 × 6) reconstruction, typical for Ga rich surfaces. No Fe LEED pattern was observed for the first 4ML deposited. After the deposition of 5ML faint LEED spots from the Fe film appear. Clear BCC Fe LEED patterns were observed after the deposition of 6ML. The lack of Fe LEED patterns for the first four monolayers indicates that the growth proceeds via the three dimensional (3D) Volmer–Weber growth mode.

Fig. 2 shows the development of the MOKE loops with thickness. The magnetic field is applied along the [0 1̄ 1] direction, the easy axis of the UMA in Fe/GaAs(1 0 0)-4 × 6. A significant MOKE signal was first detected at a thickness of 3.5ML, with the intensity linearly proportional to the applied magnetic field. With further Fe deposition the MOKE-loop curves become s-shaped around 4–4.3ML. The lack of hysteresis indicates that the ferromagnetic phase has not yet developed. The magnetization curves indicate the presence of either paramagnetism or superparamagnetism. The loop in Fig. 2(c) clearly shows hysteresis, indicating the onset of the ferromagnetic phase after 4.8ML of Fe. Fig. 2(d)–(f) shows the hysteresis loops after the onset of the ferromagnetic phase.

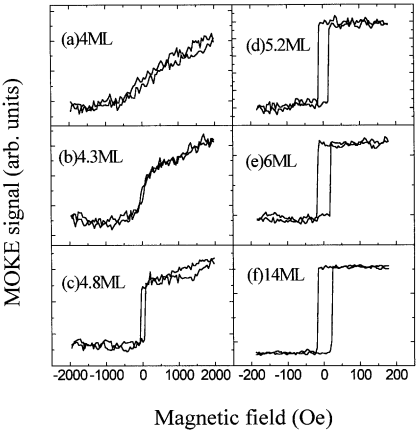

Fig. 2. In situ MOKE hysteresis loops for the Fe/GaAs(1 0 0)–4 × 6 of different Fe thicknesses with the magnetic field applied along the [0 1̄ 1] direction.

The lack of magnetic signal for the first 3.5ML might be due to the smaller initial cluster size, which prevents the development of magnetic ordering, or the ordering above room temperature. This is in agreement with the LEED patterns which suggest that the films are not continuous below 4ML. As more Fe is deposited, the islands will grow and coalesce to form bigger clusters. The exchange interaction within these clusters becomes stronger and leads to internal ferromagnetic ordering [8], so giving rise to the well known superparamagnetic phase. With further increase in the coverage, the islands coalesce and long range ferromagnetic ordering develops. In combination with ex situ magnetization measurements, we found that the *entire* Fe film is ferromagnetic with a bulk-like moment: $1.6 \pm 0.2 \times 10^3$emu/cm^3 after the onset of the ferromagnetism.

InAs(1 0 0) ‘epi-ready’ substrates were cleaned using a combination of oxygen plasma etching and wet etching (HCl : H_2O = 1 : 4). The LEED pattern (Fig. 1(b)) of the InAs substrate after annealing at 510°C for 30 min, shows an In-terminated 4 × 2 surface reconstruction. After the deposition of 5ML of Fe, LEED patterns with cubic symmetry were observed. The LEED picture of a 50ML film is shown in Fig. 1(b), which confirms

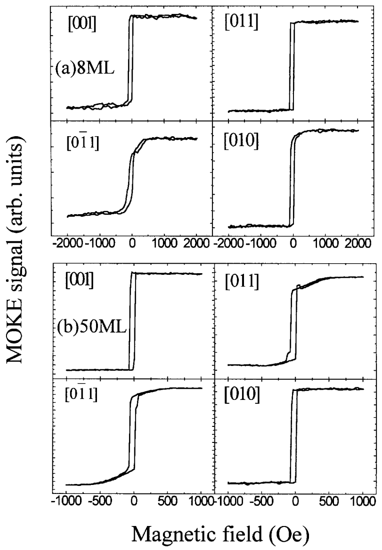

Fig. 3. In situ MOKE hysteresis loops of (a) Fe(8ML)/InAs(1 0 0), and (b) Fe(50ML)/InAs(1 0 0), for the magnetic field applied along four major axes.

the epitaxial growth and the epitaxial relationship Fe(1 0 0)⟨0 0 1⟩||InAs(1 0 0)⟨0 0 1⟩.

Fig. 3 shows the hysteresis loops of two Fe/InAs(1 0 0)-4 × 2 samples, (a) Fe(8ML)/InAs and (b) Fe(50ML)/InAs. The films show uniaxial anisotropy in the ultrathin region of about 5–10ML. The easy axis of this UMA is along the [0 1 1] direction, as shown clearly in Fig. 3(a). This is contrary to that of the Fe/GaAs(1 0 0)-4 × 2 [3] and 4 × 6 systems, in which the easy axis is along [0 $\bar{1}$ 1]. Here we should note that the UMA has not been observed in Fe/InAs grown at 175°C [7]. Above about 10 ML of Fe, the films display a cubic anisotropy, with the magnetic easy axes along ⟨0 0 1⟩, the easy axes of bulk BCC Fe, as shown in Fig. 3(b) for an Fe(50ML)/InAs(1 0 0) film. Fig. 3(b) indicates a cubic anisotropy, $H_k = 2K_1/M$, of about 500 Oe. This value is comparable with the cubic anisotropy, 550 Oe, of bulk BCC Fe. This again shows that high quality BCC Fe films with well defined magnetic properties have been stabilized on the InAs(1 0 0)-4 × 2 substrate at room growth temperature.

The uniaxial anisotropy of Fe/GaAs has been observed by several groups [2,3,9], but its origin is still an open issue. There are several potential mechanisms responsible for the UMA observed in FM/semiconductor heterostructures. (a) Shape anisotropy as the films show 3D island growth. However, a recent study of Fe/GaAs(1 0 0)-2 × 4 and *c*(4 × 4) by Kneedler et al. [9] showed that shape anisotropy does not contribute to UMA. STM images of ultrathin films are needed in order to know the possible shape anisotropy in the Fe/InAs(1 0 0)-4 × 2 system. (b) Gester et al. [3] proposed that atomic scale structures at the GaAs–Fe interface are a source of the UMA in Fe/GaAs. (c) If a nearly half-magnetised phase exists at the interface, then this may be partly responsible for the UMA as suggested by Filipe et al. [4]. (d) Most recently, Kneedler et al. [9] found that the magnetic properties and growth mode of Fe/GaAs(1 0 0) are similar for both 2 × 4 and *c*(4 × 4) reconstructed structures and they proposed that there is an intrinsic anisotropy due to the unidirectional nature of Fe–As bonds at the interface or oriented Fe–As pairs within the film. (e) Magneto-elastic interactions due to strain in the ultrathin epitaxial films caused by lattice mismatch. This was proposed by Prinz and Krebs et al. in their earlier work [2]. Although it is difficult to identify exactly the contribution of each of these terms without detailed structural and compositional analysis, the strikingly different UMA behaviour of Fe/InAs(1 0 0)-4 × 2 compared with that of Fe/GaAs(1 0 0)-4 × 6 and 4 × 2 [3] may indicate the importance of magneto-elastic contributions. During the initial stage of growth, the Fe films may be strained to match the lattice of the substrate. In this case the Fe film may be *compressed* (in plane) on GaAs whilst *expanded* on InAs along a certain crystal direction, as the lattice constant of Fe is larger than half of the lattice constant of GaAs but smaller than that of InAs. This will lead to opposite strain tensor components and then different magneto-elastic energies in these two systems. However, we would like to note that Farrow et al. [10] found that the magnetic moment and anisotropy of the Fe films on GaAs(1 0 0)-1 × 1 and $In_{0.2}Ga_{0.8}As$ on GaAs(1 0 0) show virtually no dependence on the nature of the $In_{0.2}Ga_{0.8}As$ buffer layer. This may be due to the large thicknesses 300–900 Å of these Fe films.

In summary, single crystal BCC Fe films have been successfully grown on both GaAs(1 0 0)-4 × 6 and InAs(1 0 0)-4 × 2 substrates at room growth temperature. A uniaxial anisotropy was observed in ultrathin Fe/InAs(1 0 0)-4 × 2 with the easy axis direction opposite to that in Fe/GaAs(1 0 0)-4 × 6 and 4 × 2. This suggests the importance of magneto-elastic interactions near the interfaces. We also demonstrated, in the case of Fe/GaAs, that the morphological structure of the film plays a significant role in determining the magnetic properties in FM/Semiconductor heterostructures.

Acknowledgements

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