Interface Magnetic Properties of Epitaxial Fe–InAs Heterostructures

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***Abstract*—The growth and interface magnetic properties of epitaxial Fe films grown on InAs (100)-4 × 2 have been studied using low-energy electron diffraction, *in situ* magneto-optical Kerr effect, and X-ray magnetic circular dichronism. The magnetic properties at room temperature were found to proceed via three phases with thickness; a nonmagnetic phase, a superparamagnetic phase, and a ferromagnetic phase. The initial ferromagnetic phase might be stabilized by interparticle interactions. The films show bulk-like spin moments of $1.90 \pm 0.15\ \mu_B$ with the thickness above about 20 ML and a large enhancement $\sim 260\%$ of the ratio of orbital versus spin moment in the ultrathin region.**

***Index Terms*—Fe–InAs, interface magnetism, spin electronics, ultrathin films.**

I. Introduction

INTERFACE magnetism in ferromagnetic metal (FM)/semiconductor (SC) heterostructures continues to be an important topic for the study of fundamental magnetic properties of ultrathin films and for the development of the next generation of spin-electronic devices. While Fe–GaAs has received much attention [1]–[5], Fe–InAs offers excellent opportunities for controlling electrical as well as magnetic properties [6], [7]. InAs has a higher low-field mobility than GaAs and InP, which makes it a suitable candidate for high-speed field effect transistors. The low-contact resistance between metals and the narrow gap semiconductors such as InAs can reduce thermal dissipation in devices. The fabrication of ever-smaller devices leads to higher current densities, which in turn need low-resistance contacts. The magnetic properties of the first few monolayers are expected to be determined by both possible intermixing at the interface and the growth structures. Previous studies of Fe–GaAs found that there are "magnetically" dead layers due to the formation of nonferromagnetic compounds at the interface, which is detrimental to the spin-dependent transport in spin electronic devices. Recent studies [2], however, demonstrated that there are no "magnetic dead" layers at the interface when Fe is grown on Ga-rich 4×6 GaAs(100) substrate at room temperature and the Fe films grows via three phases: a nonmagnetic phase, a superparamagnetic phase, and a ferromagnetic phase. In this paper, we report a combined low-energy electron diffraction (LEED), *in situ* magneto-optical Kerr effect (MOKE), and X-ray magnetic circular dichronism (XMCD) study of the interface magnetic properties of the Fe–InAs(100) system.

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II. Sample Fabrication and Measurements

The Fe films were grown on InAs(100) at a rate of approximately one monolayer (ML) per minute with the substrate held at room temperature. The InAs(100) substrates were cleaned using a combination of oxygen plasma etching and wet etching ($HCl : H_2O = 1 : 4$) before loading into the UHV system and annealed in the chamber at 510 °C for half an hour before growth. The MOKE loops were collected during growth in the longitudinal geometry using an electromagnet with a maximum field of 2 kOe. For *ex situ* measurements, the samples were capped with 20 ML of Au. The XMCD experiment was performed at beam line 1.1, CLRC Daresbury Laboratory, with 80% circularly polarized X-rays. The experimental details were given in a previous publication on Fe–GaAs [8].

III. Results and Discussions

Fig. 1 shows the LEED patterns of (a) the InAs substrate before growth and (b)–(f) after Fe deposition. The clear and sharp pattern from the substrate indicates that the InAs surface is very flat and well crystallized. Auger spectroscopy measurements show that the substrate is free of O, but has a tiny C peak. No Fe LEED pattern was observed for the first 5 ML as shown in Fig. 1(b). After about 8ML faint LEED spots from the Fe film appear. The clear LEED patterns in Fig. 1(e) and (f) show that the Fe grows epitaxially on InAs(001) at room temperature. The lack of LEED patterns for the first five monolayers indicates that the growth proceeds via the three dimensional (3-D) Volmer–Weber growth mode as in Fe–GaAs [2].

Fig. 2 shows a detailed *in situ* MOKE study of the evolution of the magnetic phase. The magnetic field is applied along the $\langle 011 \rangle$ direction. Our previous MOKE measurements at certain thicknesses showed that the easy axis of the uniaxial anisotropy in Fe–InAs (100)-4×2 is along the $\langle 011 \rangle$ direction [7]. A MOKE signal was first detected at a thickness of 2.5 ML, with the intensity linearly proportional to the applied magnetic field. With further Fe deposition the MOKE-loop curves become s-shaped at about 3 ML. The MOKE loops after 3.5 ML clearly

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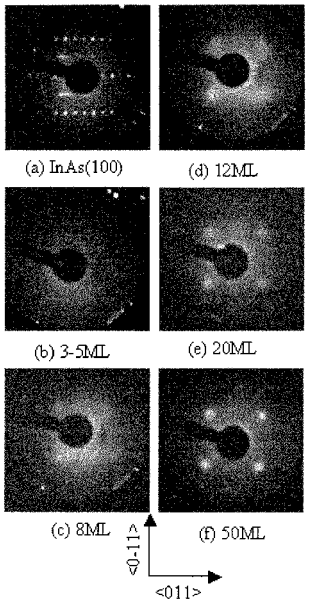

Fig. 1. LEED patterns of (a) the InAs (001)-4 × 2 substrate after annealing, 68 eV and (b)–(f) after Fe deposition, 120 eV.

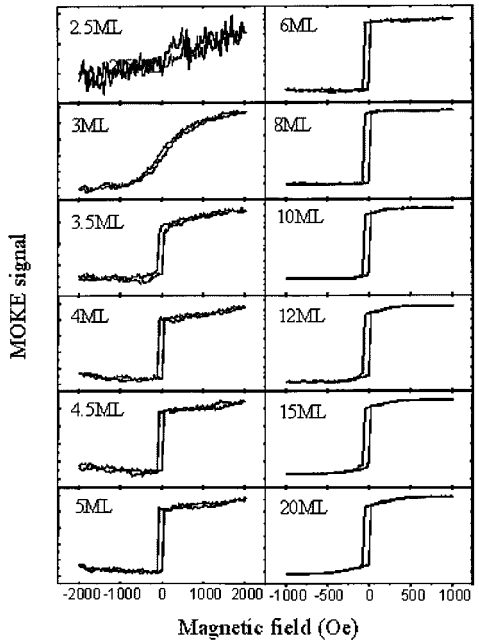

Fig. 2. *In situ* MOKE hysteresis loops for the Fe–InAs (100)-4 × 2 of different Fe thicknesses.

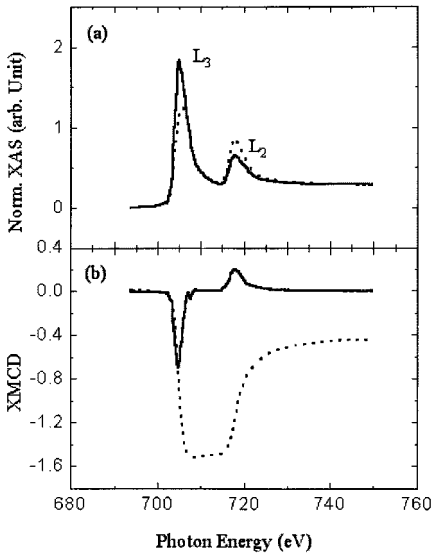

Fig. 3. (a) Normalized XAS and (b) normalized (solid line) and integrated (dotted line) XMCD spectra of an 8-ML film with both the external magnetic field and the photon beam applied perpendicular to the film plane.

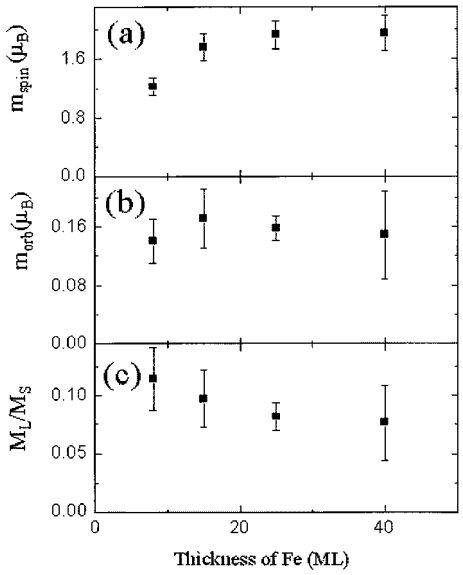

Fig. 4. (a) Spin moment, (b) orbital moment, and (c) the ratio of orbital moment versus spin moment as a function of film thickness determined from the XMCD measurements.

show hysteresis, indicating the onset of the ferromagnetic phase. The square loops in a thickness range of about 4–10 ML further confirm that the uniaxial anisotropy dominates in the ultrathin region [7].

Fig. 3(a) is typical normalized X-ray absorption spectra (XAS), as shown by an 8-ML film, with two opposite magnetizations. The spectra were collected at normal incidence to minimize possible saturation effects in the total electron yield [9]. A linear background has been subtracted from the raw data. The XMCD spectrum (solid line) and its integration (dotted line) are shown in Fig. 3(b). The spin and orbital moments are determined by applying the XMCD sum rule with $n_h = 6.61$ [9], [10] and by subtracting a simple two-step background from the XAS spectra. Fig. 4 shows the thickness dependences of (a) spin moments $m_{\rm spin}$, (b) orbital moments $m_{\rm orb}$, and (c) the ratios of orbital versus spin moment M_L/M_S. The spin moments of the 25 and 40 ML films are about $1.90 \pm 0.15\ \mu_B$, which are very close to the bulk value of $1.98\ \mu_B$ [10]. With decreasing the thickness, the spin moment is reduced. The spin moments of the 8 and 15 ML films are about $1.22 \pm 0.12\ \mu_B$ and $1.75 \pm 0.15\ \mu_B$, respectively. The orbital moment of the films is enhanced by about 70% compared with the bulk value, but shows little variation with the thickness. The M_L/M_S ratio, however, increases with decreasing thickness and is enhanced by about 260% compared with the bulk value in the 8 ML film.

The lack of magnetic signal for the first 2.5 ML might be due to the smaller initial cluster size, which prevents the development of magnetic ordering or ordering above room temperature. The lack of LEED patterns from the Fe suggests that the films are not continuous and that clusters are formed in the initial stage of growth as shown by our STM studies [11]. As more Fe is deposited, the islands grow to form bigger clusters. The exchange interaction within these clusters becomes stronger and leads to internal ferromagnetic ordering, so giving rise to the well-known superparamagnetic phase. We have demonstrated in Fe–GaAs [2] that a superparamagnetic phase develops within a narrow thickness range of about 3.5–5 ML before the onset of long range ferromagnetic ordering. The MOKE loops in Fig. 2 show that the superparamagnetic phase also develops in Fe–InAs, but in an even narrower thickness range of about 2.5–3 ML. The s-shaped loop from the 3-ML film is consistent with the Langevin function used to describe the magnetization of superparamagnetic clusters [12], [13]. By fitting the curve, the effective magnetic moment per cluster is obtained to be $(1.6 \pm 0.2) \times 10^4\ \mu_B$. With further increase in the coverage, the islands grow and coalesce and long-range ferromagnetic order develops. The films have a well-defined magnetic coercivity and remanence ratio after 3.5–4 ML. We should note that the long range ordering might develop before the complete coalescence of the islands due to interparticle interactions. In this aspect, there is an important difference between Fe–GaAs and Fe–InAs. In Fe–GaAs, the onset of the long-range ferromagnetic phase and the LEED pattern of Fe were observed at about the same critical thickness of around 5 ML. This suggests that the long-range ferromagnetism occurs when the film becomes continuous. In Fe–InAs, however, the long-range ferromagnetism in a thickness range of about 3.5–5 ML might be stabilized by interparticle interactions, as the films are not continuous in this thickness range.

The large spin moments for the 25- and 40-ML films demonstrate that the films have a bulk like moment. This also confirms that it is the growth morphology rather than Fe–InAs intermixing which plays a dominant role in determining the evolution of the ferromagnetic phases. The spin moment is reduced in the ultrathin films as shown by the 8-ML film. This might be due to a decrease of the Curie temperature in the ultrathin films and/or some of the clusters are still not ferromagnetic. We also would like to point out that while we have demonstrated that the Fe films have a bulk like moment, the possibility of having a submonolayer of "magnetic dead" layer at the interface cannot be excluded due to the resolution limit.

An enhancement of the orbital moment is expected at surfaces and interfaces due to a reduction of the symmetry. First principle calculations on bcc Fe surfaces have predicted a 100% enhancement of orbital moment as compared to the bulk value [14], which should be partially responsible for the observed orbital moment enhancement. However, the giant enhancement in M_L/M_S ratio in the 8-ML film suggests an additional mechanism. As pointed out by van der Laan *et al.* [15], the presence of surface roughness, interdiffusion, steps, or terraces will lead to more localized atomic-like 3-D wave functions and an enhanced orbital moment. One of the distinct features of a reconstructed semiconductor surface is the formation of regular atomic scale structures, such as the In dimer row along the $\langle 011 \rangle$ direction in the InAs (100)-4×2 surface [7]. We thus propose that this atomic scale structure leads to more localized wavefunctions for the Fe atoms close to the interface and a corresponding large enhancement in M_L/M_S as we found in Fe–GaAs [8].

IV. Conclusion

We have studied the interface magnetic and structural properties of epitaxial bcc Fe films grown on InAs (001)-4×2. The evolution of the magnetic phase was found to be dominated by the film structure rather than possible intermixing at the interface. The Fe clusters formed at the initial growth stage show both superparamagnetism and ferromagnetism depending on the thickness. The films show bulk-like spin moments of about $1.90 \pm 0.15\ \mu_B$ for the thicknesses above about 20 ML, which is important for spin electronic devices. A large enhancement of the ratio of orbital moment versus spin moment in the ultrathin region might be due to more localized wavefunctions at the interface.

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