Spin and Orbital Moments of Ultra-Thin Fe Films on Various Semiconductor Surfaces

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The magnetic moments of ultrathin Fe films on three different III–V semiconductor substrates, namely GaAs, InAs and $In_{0.2}Ga_{0.8}As$ have been measured with X-ray magnetic circular dichroism at room temperature to assess their relative merits as combinations suitable for next-generation spintronic devices. The results revealed rather similar spin moments and orbital moments for the three systems, suggesting the relationship between film and semiconductor lattice parameters to be less critical to magnetic moments than magnetic anisotropy.

Index Terms—Fe/InGaAs, interface magnetism, spin electronics, ultrathin films.

I. INTRODUCTION

NEXT-GENERATION spintronic devices are expected to revolutionize conventional electronic circuitry by utilizing both the charge and spin of the electron while retaining links with present day semiconductor technologies [1]–[3]. However, the development of such devices is at present limited by our abilities in transporting spin into nonmagnetic media [4], [5]. And so research into breaching the gap in characteristics between the magnetic materials and semiconductor technologies has become a hot topic of debate. Several technologies have been put forward to overcome this barrier such as magnetic semiconductors [5], where great advances have brought Curie temperatures up to 173 K [6] and methods based on ferromagnet/semiconductor contacts [5], including epitaxially grown ferromagnetic metal contacts, which appear to offer the promise of room temperature spin transport.

After many years of investigation [7]–[11], it has recently been shown that ferromagnetic films have the capability to retain magnetic properties to interface thicknesses [12]. However, with predicted levels of spin transport still to be realized [4], many questions still remain unanswered about the degree to which interface magnetism and hence spin transport relates to the stability of growth and hence to the lattice match and surface of the materials involved.

In order to determine whether the property of lattice match and related film strain might be important for magnetic behavior close to the interface we have undertaken room temperature X-ray magnetic circular dichroism (XMCD) investigations into the properties of ultrathin films grown on substrates of varied lattice constant. The substrates chosen for study, GaAs, InAs, and $In_{0.2}Ga_{0.8}As$ were chosen for their lattice constants which, in a 2:1 relationship with Fe give mismatches of −1.56%, 5.32%, and 0%, respectively.

II. SAMPLE FABRICATION AND MEASUREMENT

The specialist substrates used to establish the different lattice matches were constructed by the EPSRC's UK National Centre for III–V Semiconductor Technologies in Sheffield and took the form of GaAs (100) wafers topped with a 0.3 μm epilayer of GaAs, InAs or InGaAs followed by an As capping layer. The As capping layer allowed for safe transit between systems and removed the requirement for pre-growth wet etching usually required to achieve the reconstructed surfaces.

Once in our own MBE system all substrates were initially heated to 350°C to desorb the As capping layer and then further annealed for 1 h to 560°C for GaAs, 525°C for InGaAs and 514°C for InAs RHEED analysis of the surface indicated an As rich 2×4 reconstruction was achieved for GaAs and InAs while a 1×1 surface was observed for $In_{0.2}Ga_{0.8}As$. Following cooling to room temperature 7 ML Fe, chosen for the large uniaxial anisotropy displayed at this thickness for the Fe/GaAs system [15], was deposited at a rate of 0.66 ML per minute, followed by the 15 ML Cr cap to protect against oxidation. All stages of growth were monitored by RHEED measurement and the samples' uniaxial magnetic qualities were confirmed *ex situ* with longitudinal MOKE measurements.

XMCD measurements were conducted at station 1.1 of the Synchrotron Radiation Source at Daresbury Laboratory (U.K.) which was equipped with a flipper magnet with a maximum field of 0.6 T. This configuration allows illumination of the samples with 85% circularly polarized X-rays parallel/antiparallel to an applied magnetic field and attainment of XAS spectra measured in these opposite applied field conditions, I^+ and I^-. The flipper magnet offers the ability to reverse the magnetization at each measurement point and thus reduces anomalies in the XMCD or difference spectra. Measurements were made with the samples at an angle of 45° to the incident X-rays to maximize the effect of both the incident light and the applied field.

III. RESULTS AND DISCUSSION

During growth RHEED patterns were obtained both prior and subsequent to the deposition of Fe on the reconstructed semi-
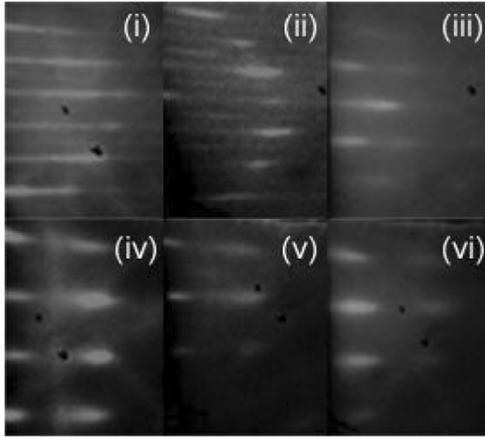
Fig. 1. RHEED images collected before (i, ii, iii) and after (iv, v, vi) deposition of 7 ML Fe onto the respective reconstructed GaAs, InAs, and $In_{0.2}Ga_{0.8}As$ surfaces.
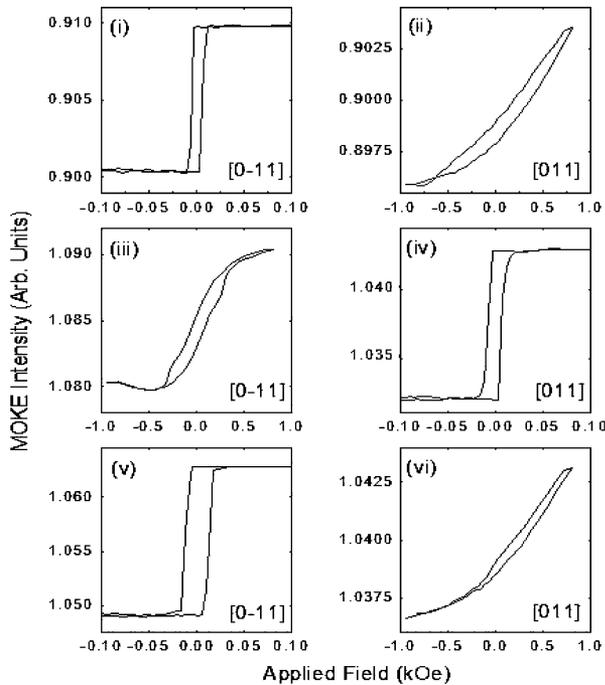

Fig. 2. MOKE loops taken along, the easy (i, iv, and v) and hard (ii, iii, and vi) axes of the Fe/GaAs, Fe/InAs, and $Fe/In_{0.2}Ga_{0.8}As$ samples respectively, show uniaxial anisotropy in all samples. Note the 90° rotation of hard and easy axes in the case of Fe/InAs.

Fig. 3. XMCD spectra for Fe $L_{2,3}$ edge studies of 7 ML Fe on GaAs (i), InAs (ii) and $In_{0.2}Ga_{0.8}As$ (iii). Solid lines correspond to XMCD spectra, while dashed and dotted lines represent the XAS spectra taken for opposite applied fields I^{+} and I^{-} spectra, respectively.

conductor surfaces. The images, which are shown in Fig. 1, confirm the epitaxial growth of bcc Fe on the three different surfaces with the same epitaxial relationship of Fe(100)<001> | $In_xGa_{1-x}As(100)\langle 001\rangle$, where x = 0, 1, 0.2.

Ex situ longitudinal MOKE measurements were also made, shown in Fig. 2. Although the hard axis of the Fe/GaAs and the $Fe/In_{0.2}Ga_{0.8}As$ films could not be saturated, the hysteresis loops clearly show the films to be uniaxial in nature. An interesting aspect of these results is the confirmation of the reversal of easy axis and hard axis directions between the GaAs and InAs substrates. This result is in good agreement with previous studies [14] and is thought to be indicative of the influence of the magneto-elastic effect in the establishment of the uniaxial anisotropy. The 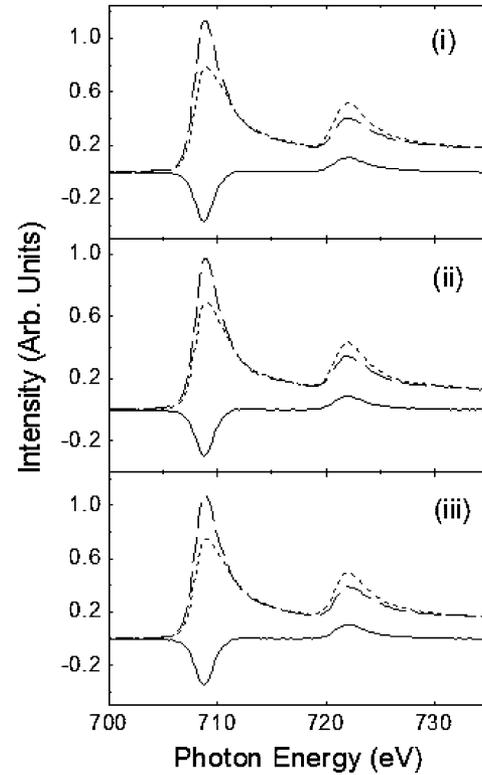magneto-elastic effect occurs as a direct result of the compression or expansion of the Fe film in order to fit the GaAs or InAs lattice respectively. However, in these results we can also see that the perfectly lattice matched system $Fe/In_{0.2}Ga_{0.8}$ As also displays uniaxial characteristics. While this can not be explained by magneto-elastically induced uniaxial anisotropy the result would seem to support the "chemical" effect proposed by Kneedler *et al.* [9] in which the uniaxial magnetic anisotropy (UMA) is derived from the unidirectional nature of Fe-As or Fe-Ga bonds. The results show that both chemical and magneto-elastic effects are in some part responsible for the observed UMA in Fe/III-V semiconductor heterostructures.

The obtained XMCD spectra, shown in Fig. 3, were analyzed through application of the sum rules, see (1)–(2), with the values of the parameters p, q, and r derived from the integrals of the XMCD and XAS spectra in the manner of Chen *et al.* [15]. The number of holes, n_h, was taken as 3.39 for Fe [16] and the degree of polarization, P, was equal to 0.85

$$m_{\text{orb}} = -4qn_h/3rP \qquad (1)$$
$$m_{\text{spin}} = (4q - 6p)n_h/rP. \qquad (2)$$

The values of the spin and orbital moments found from sum rule analysis and those of the bulk values are described in Table I. By far the most striking aspect of the XMCD results is, within error, the similarity of observed magnetic moments between the three different substrates.

The highest spin moment of all the samples tested is seen for Fe/GaAs, however, this represents only 72% of the bulk value. This reduction compared with previous results on Ga rich

TABLE I
SPIN AND ORBITAL MOMENTS OF BULK FE IN COMPARISON TO 7 ML FE
FILM ON GaAs, InAs, AND $In_{0.2}Ga_{0.8}As$

Sample	m_{orb} (μ_B)	m_{spin} (μ_B)	m_{orb}/m_{spin}
Bulk Fe [6]	0.086	1.98	0.043
Fe/GaAs	0.184±0.025	1.43±0.18	0.129±0.021
Fe/InAs	0.151±0.038	1.35±0.17	0.112±0.026
Fe/$In_{0.2}Ga_{0.8}As$	0.186±0.021	1.42±0.24	0.131±0.026

4×6 surface [17], [18] may originate from the different nature of the interface for these samples, which were grown on As rich reconstructions in this study, thought to give rise to reacted phases and hence reduced Fe moments [19]. It is also possible that the clustered growth phase that occurs in Fe at this thickness just prior to the establishment of a continuous film [12], [20] could require a higher external field, than was available to fully saturate these films. The Fe/GaAs result is commensurate with the similarly reduced values of spin moment derived from Fe/InAs and Fe/$In_{0.2}Ga_{0.8}As$, which are in close agreement with the Fe/GaAs result representing 68% and also 72% of the bulk value, respectively.

In contrast to the reduction in spin moment the orbital moment, and hence the ratio m_{orb}/m_{spin}, for all samples shows a marked enhancement, with an orbital increase of around 200%, with respect to the bulk value, as witnessed in earlier studies of Fe/GaAs and Fe/InAs [17], [18]. This orbital enhancement is thought to derive from the brake-down in symmetry close to the interface as a result of qualities of the substrate surface including steps or terraces and surface roughness. It is expected that these features cause localization of the 3d Fe wave functions close to the interface [21], our evidence would appear to support this since such surface issues would not be overcome by a perfect lattice match.

IV. CONCLUSION

The spin and orbital moments and hysteresis loops of 7 ML Fe films grown on specially fabricated GaAs, InAs and $In_{0.2}Ga_{0.8}As$ epilayers have been measured using XMCD and MOKE, respectively. The results show that magneto-elastic effects provoked by the difference in substrate lattice constant have little effect on the spin and orbital moments which are found to be within error of one another for all substrates. The tolerance of the Fe films to withstand such magneto-elastic effects might further suggest Fe/III–V semiconductor heterostructures could, in future provide suitable solutions for spin-transport devices and hints that the flexibility of these systems may offer practical manufacturing solutions in the field of future spintronics device design.

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