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In-plane anisotropy and magnetostriction constants of Fe/Ga$_{0.8}$In$_{0.2}$As films with Cr overlayers

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Abstract
Thin Fe films on the lattice-matched Ga$_{0.8}$In$_{0.2}$As substrate were investigated as part of a determination of the origin of the in-plane uniaxial anisotropy that is present in Fe/GaAs and Fe/InAs films. The epitaxial Fe films were grown using molecular beam epitaxy (MBE), and were capped with a Cr overlayer. The in-plane anisotropies of each film were inferred from the normalized magnetization loops measured using a magneto-optic Kerr effect (MOKE) magnetometer. Using a fitting method to the magnetization data, the cubic and uniaxial anisotropy constants for each film were determined. The Villari method was used to determine the magnetostriction constants. For all the films, they were negative, and became more negative as the Fe thickness decreased. The magnetic parameters of the Fe/Ga$_{0.8}$In$_{0.2}$As films were compared with those of the Fe/GaAs and Fe/InAs films, to determine the origin of the uniaxial in-plane anisotropy.

1. Introduction

The study of Fe films on semiconductor substrates is of interest for spintronic devices [1]. Previous research has investigated Fe films on GaAs [2–8] and on InAs [9–14] substrates. For Fe films thinner than 25 nm on GaAs(001), an in-plane uniaxial anisotropy was present with the easy axis along the [110] direction, as well as the magnetocrystalline cubic anisotropy characteristic of the bulk [2–8]. For Fe films thinner than 2 nm, only the uniaxial anisotropy was present. The origin of this uniaxial anisotropy is still uncertain, but it is believed to be due to the interface between the Fe and the GaAs [15]. The reasons given in the literature include the presence of Fe$_3$Ga$_{2-x}$As$_x$ at the interface with the substrate [16], dangling bonds of GaAs [17] and the strain due to the lattice mismatch [18]. For Fe films of thickness up to 1.9 nm on InAs(001), uniaxial anisotropy has also been observed with the easy axis along the [1$\bar{1}$0] direction [12]. Thus the direction of the uniaxial easy axis in Fe/InAs(001) films is perpendicular to the uniaxial easy axis direction in Fe/GaAs(001) films. Recently Fe films on Ga$_{0.5}$In$_{0.5}$As substrate have been studied [19]. For these Fe films it was determined that a uniaxial anisotropy was present with the easy axis along the [110] direction, i.e. along the same direction as the Fe/GaAs uniaxial easy axis.

However, there is a reported inconsistency over the direction of the uniaxial easy axis in Fe/GaAs films and Fe/InAs films. For Fe films grown on the (001) GaAs plane, the uniaxial easy axis was generally along the [110] direction [3, 5–8, 15, 20, 21], while for Fe films grown on the (100) GaAs plane the uniaxial easy axis was generally along the $[0\bar{1}1]$ direction [9, 22–24]. From the crystal structure, the GaAs planes (001) and (100) are identical [25], thus there should be no physical difference between these Fe films. The planes which have orthogonal symmetry are the (100) and $(\bar{1}00)$ planes of GaAs. It has also been shown that the GaAs surface reconstructions of 4 × 2 and 2 × 6 do not affect the uniaxial anisotropy easy axis direction [4, 7], also that the terminating atom (i.e. Ga or As) does not change the uniaxial easy axis [21]. For Fe films of thickness 1.9 nm grown on InAs(001), the uniaxial easy axis was along the $[1\bar{1}0]$ direction [12, 14, 26], but for Fe films of thickness 1.16 nm on InAs(100), the uniaxial easy axis was along the [011] direction [9–11]. Also, it has been noted that the RHEED patterns given in Xu *et al* [27] should have been rotated by 90° [15]. This inconsistency between the direction of the uniaxial anisotropy easy axis for the Fe/GaAs(100) and Fe/InAs(100) films has recently been reassessed [28]. In a review by Wastlbauer and Bland [28], the authors have reevaluated the experimental data, and determined that an error had been made in the assignment of the crystallographic axes for the GaAs(100) and InAs(100) substrates. Thus the universal agreement is now that the Fe/GaAs(100) films have the uniaxial easy axis along the [011] direction and the Fe/InAs(100) films have the uniaxial easy axis along the $[0\bar{1}1]$ direction. This is consistent with our previous work, which studied Fe films on GaAs(100) substrates [29, 30], where we determined that for these films the uniaxial easy axis was along the [011] direction. Also the magnitude of the anisotropy constants determined for our Fe/GaAs(100) films were in good agreement with those determined for the Fe/GaAs(001) films [29].

From the literature it has been observed that the direction of the uniaxial easy axis in Fe/GaAs(001) films is perpendicular to the direction for Fe/InAs(001). One possible reason for this difference is the lattice mismatch between the substrate and the Fe film. For Fe–GaAs the lattice mismatch is -1.3%, while for Fe–InAs the lattice mismatch is $+5.7\%$. Therefore, it is possible that the different lattice strains on the Fe film caused the uniaxial anisotropy, and it would be expected that no uniaxial anisotropy would be present in Fe films grown on $Ga_{0.8}In_{0.2}As$, which has the same lattice constants as Fe [18, 31]. In this paper we investigate the in-plane anisotropies present in three Fe/$Ga_{0.8}In_{0.2}As$(100) films, and compare them to Fe/GaAs(100) and Fe/InAs(001) films. The magnetostriction constants of these films are also presented in order to be able to quantitatively discuss strain-induced anisotropies.

2. Experimental set-up

The epitaxial Fe films on $Ga_{0.8}In_{0.2}As$(100) substrates with Cr overlayer were fabricated using molecular beam epitaxy (MBE) [22]. Prior to each film's deposition, the substrates were etched using H_2SO_4 (sulfuric acid):H_2O_2 (hydrogen peroxide):H_2O (deionized water) at a ratio of 4:1:1, followed by deionized water rinsing and dehydrating using isopropyl alcohol (IPA). Once in the MBE system, the substrates were cleaned using an ion sputter at 200 °C for 20 min. They were then annealed at 550 °C for 45 min, and allowed to cool. The surface flatness and reconstruction of the $Ga_{0.8}In_{0.2}As$(100) substrates were determined using reflection high-energy electron diffraction (RHEED). For these films the surface reconstruction was 4 × 2. The Fe films were then grown at 50 °C and 1×10^{-10} mbar. The growth rate was kept constant, by ensuring the emission current between the filament and the source

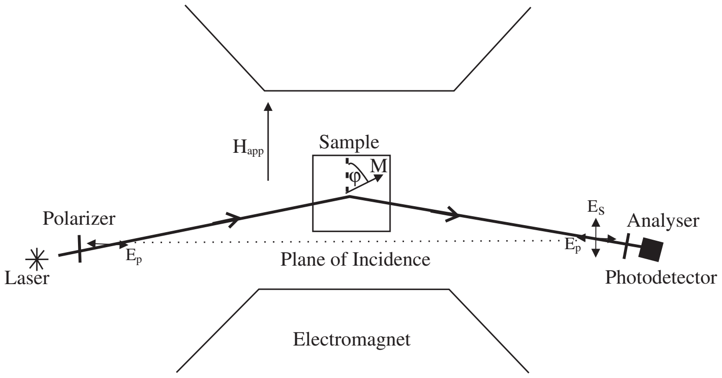

Figure 1. Diagram of the magneto-optic Kerr effect (MOKE) magnetometer.

material was constant. For the Fe film, the flatness and the uniformity along the [011] direction was checked using RHEED. The patterns showed epitaxy on $Ga_{0.8}In_{0.2}As(100)$ with the relationship $Fe(100)\langle 001\rangle \| Ga_{0.8}In_{0.2}As(100)\langle 001\rangle$. The evaporation procedure was then repeated for the Cr overlayer material, with thickness 2 nm. The thickness of the Fe films ranged from 1.45 nm (10 ML) to 4.35 nm (30 ML).

For each film, the normalized magnetization was measured on a magneto-optic Kerr effect (MOKE) magnetometer as a function of magnetic field and field direction relative to the [011] axis. The MOKE set-up (figure 1) was such that the polarizer angle was set so that the laser was plane polarized. The analyser angle was set at 2° from extinction, to increase the sensitivity of the measurement. The films were strained using a specially designed bending tool, over four different bend radii ($R = 220$–280 mm) along the [011] direction, and the normalized magnetizations were measured along the $[01\bar{1}]$ direction (Villari effect).

3. Results

To determine the in-plane anisotropies present in the Fe/$Ga_{0.8}In_{0.2}As$ films the normalized magnetization loops were measured on a MOKE magnetometer for the field along different crystal axis directions. For each direction, the magnetization loop was an average of the three measured loops. From inspection of the loops, it was found that the 1.45 nm Fe/$Ga_{0.8}In_{0.2}As$ film had an in-plane uniaxial anisotropy with the easy axis along the [011] direction. Similarly, for the 2.18 nm Fe/$Ga_{0.8}In_{0.2}As$ film, the dominant anisotropy was uniaxial, with the easy axis along the [011] direction (figure 2(a)). For the 4.35 nm Fe/$Ga_{0.8}In_{0.2}As$ film, there were cubic and uniaxial anisotropies present (figure 2(b)). The cubic easy axes were along the $[0\bar{1}0]$ and [001] direction, and the uniaxial easy axis was along the [011] direction.

To determine the cubic and uniaxial anisotropy constants of each film, a fitting method was used [29]. This assumes that the moments in the film have coherent rotation in an applied field, so that the in-plane magnetic energy density (F) is described by

$$F = \frac{1}{4}K_1(t)\sin^2 2(\varphi - a) + K_u(t)\sin^2\left(\varphi - a + \frac{\pi}{4}\right) - HM\cos\varphi \qquad (1)$$

where $K_1(t)$ is the cubic anisotropy constant, $K_u(t)$ is the uniaxial anisotropy constant, a is the angle between the magnetic field and the [001] direction in the film and φ is the angle between the magnetic field (H) and the in-plane magnetization (M) (figure 1). Both anisotropy constants are allowed to be functions of the Fe layer thickness, t. The direction of the magnetization in

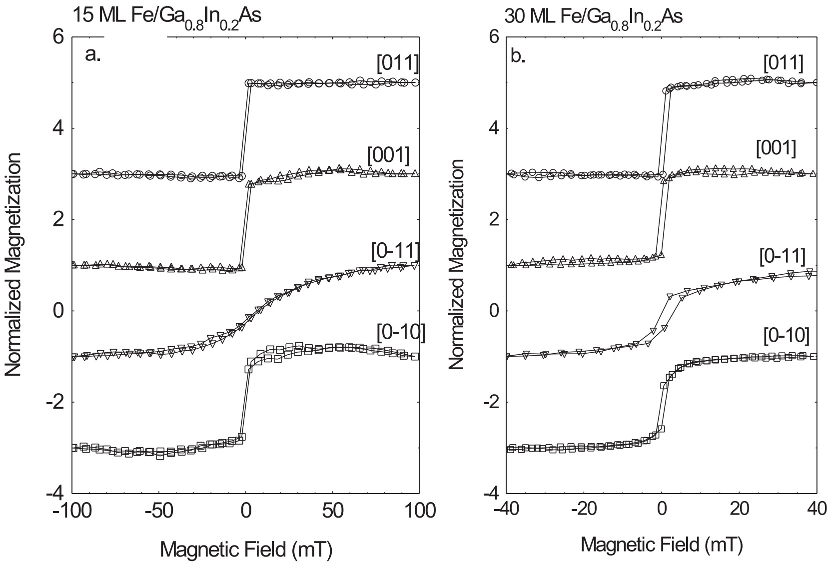

Figure 2. (a) Normalized magnetization for the 15 ML Fe/$Ga_{0.8}In_{0.2}As$ film with Cr overlayer as a function of magnetic field and crystal direction. (b) Normalized magnetization for the 30 ML Fe/$Ga_{0.8}In_{0.2}As$ film with Cr overlayer, as a function of magnetic field and crystal direction.

the film is found by solving $\frac{dF}{d\varphi} = 0$, for known anisotropy constants and field directions. Thus the normalized magnetization at a given field is $\frac{M}{M_{sat}} = \cos\varphi_{min}$, where φ_{min} is the equilibrium angle between the given applied field and the magnetization. For a MOKE magnetometer, the output signal of the photodetector depends on the angle (θ_a) between the pass plane of the analyser and the plane of incidence of the laser [32]. Thus the normalized intensity at the detector (I/I_0) is [32–34]

$$\frac{I}{I_0} = A\cos^2\theta_a + (B\cos^2\theta_a)\cos\varphi + (C\sin\theta_a\cos\theta_a)\sin\varphi + (D\sin^2\theta_a)\sin^2\varphi \qquad (2)$$

where A, B, C and D are constants which depend on the refractive index of Fe (n), the magneto-optic constant (Q), and the angle of incidence of the laser beam on the film. These constants are derived elsewhere [32–34]. For θ_a close to 90°, all four terms in equation (2) are the same order of magnitude. Hence the measured magnetization loop is asymmetric with respect to the applied field. For each film, the anisotropy constants were determined by convoluting the magnetic energy density (equation (1)) with the output of the photodetector (equation (2)), which was then fitted to the measured normalized magnetization data for the hard axes of the film (figures 2(a) and (b)).

For the 2.18 nm Fe/$Ga_{0.8}In_{0.2}As$ film, the anisotropy constants were determined to be $K_1 = 14\,000 \pm 1100$ J m^{-3} and $K_u = 46\,000 \pm 3600$ J m^{-3}. Thus as expected the uniaxial anisotropy was dominant, but there was also cubic anisotropy present, with easy axes along the [001] and $[0\bar{1}0]$ directions. For the 4.35 nm Fe/$Ga_{0.8}In_{0.2}As$ film, the anisotropy constants were determined to be $K_1 = 25\,000 \pm 1500$ J m^{-3} and $K_u = 20\,000 \pm 1200$ J m^{-3}. Thus the cubic anisotropy was stronger than the uniaxial anisotropy. The signal to noise ratio on the 1.45 nm Fe/$Ga_{0.8}In_{0.2}As$ film magnetization loop was too poor to determine the anisotropy constants.

For each film the magnetostriction constant was determined, by bending the film over known bend radii, and measuring the normalized magnetization loops. For each normalized magnetization loop, the anisotropy field (H_k) was plotted against the bend radius (R), and the magnetostriction constant was determined from [35]

$$\lambda_s = \frac{d(H_k)}{d\frac{1}{R}} \frac{2\mu_0 M_s(1-\upsilon^2)}{3\varepsilon Y} \tag{3}$$

where υ is the Poisson ratio, ε is the thickness of the substrate and Y is the Young's modulus of the substrate. The magnetostriction constants were $\lambda_s(1.45\ \text{nm}) = -157 \pm 25$ ppm, $\lambda_s(2.18\ \text{nm}) = -113 \pm 20$ ppm and $\lambda_s(4.35\ \text{nm}) = -70 \pm 15$ ppm. Thus all the magnetostriction constants were negative, and became more negative as the Fe thickness decreased (open triangles in figure 4).

4. Discussions

If the uniaxial anisotropy observed in Fe/GaAs films [29, 30], Fe/$Ga_{0.5}In_{0.5}As$ films [19] and Fe/InAs films [12] was due to the different lattice mismatch, it would be expected that the Fe films grown on the lattice-matched $Ga_{0.8}In_{0.2}As$ substrates would have no uniaxial anisotropy. From figure 2, it is observed that there is still uniaxial anisotropy present in the Fe/$Ga_{0.8}In_{0.2}As$ films. To determine why there is still this uniaxial anisotropy in these films, the anisotropy constants of the Fe/$Ga_{0.8}In_{0.2}As$ films are compared with those of the Fe/GaAs films with Au overlayer [29], the Fe/GaAs films with Cr overlayer [30], the Fe/$Ga_{0.5}In_{0.5}As$ film data published by Richomme [19] and the Fe/InAs film data published by Pelzl [12] (figure 3). Unfortunately the overlayers for both these last two film sets were not given in the papers. From previous work it was determined that the Cr overlayer changed the anisotropy constants of the Fe/GaAs films in comparison to the Fe/GaAs films with Au overlayer [30]. Thus both sets of data are included. Pelzl's Fe/InAs(001) data are used as they provide cubic and uniaxial anisotropy constants for a range of Fe thicknesses. It is also the only data in the literature which have Fe growing on InAs(001), and the uniaxial anisotropy easy axis along the $[1\bar{1}0]$ direction. The Fe/$Ga_{0.5}In_{0.5}As$ film's anisotropy constants were extracted by interpolation from the paper [19].

For the cubic anisotropy constants (figure 3(a)), it is observed that all the Fe films obey the following equation [23] (solid black lines in figure 3(a)):

$$K = K_v + \frac{K_s}{t} \tag{4}$$

where K_v is the volume component of the anisotropy, K_s is the surface or interface component of the anisotropy and t is the Fe film thickness. The volume and surface anisotropy constants for each film, determined from equation (4), are given in table 1. The Fe/InAs films have larger cubic anisotropy constants in comparison to the Fe/GaAs and Fe/$Ga_{0.8}In_{0.2}As$ films. The cubic anisotropy constants for the Au/Fe/GaAs films are larger than the cubic constants of the Cr/Fe/GaAs films and the Cr/Fe/$Ga_{0.8}In_{0.2}As$ films. It is also observed that both sets of Cr overlayer film have similar magnitude cubic anisotropy constants. Hence the cubic anisotropy constants of the Fe films grown on GaAs and $Ga_{0.8}In_{0.2}As$ substrates are only affected by the overlayer material. This is probably due to the Cr intermixing with the Fe at the interface. Intermixing occurs when the material being deposited has a larger melting point than the underlayer [36]. For the Fe–Cr interface, the melting point of Fe is 1808 K, while the melting point of Cr is 2130 K; thus intermixing will have occurred. For the Fe–Au interface, the melting point of Au is 1337 K; thus intermixing will not have occurred. This intermixing at the Fe–Cr interface is the probable cause of the reduction in the cubic anisotropy constants. The cubic anisotropy constants for the Fe/$Ga_{0.5}In_{0.5}As$ films are not plotted, as the author of

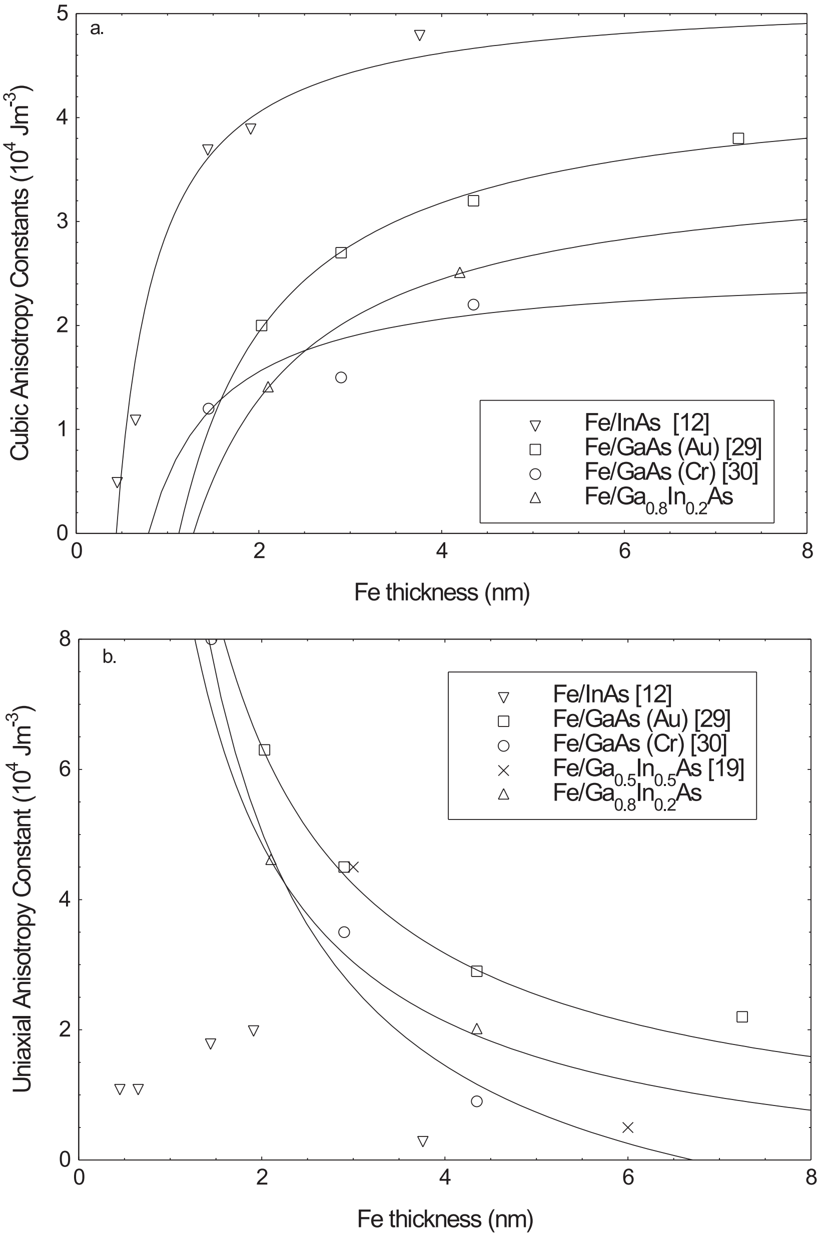

Figure 3. (a) Cubic anisotropy constants for Fe films on different substrates as a function of Fe film thickness. (b) Uniaxial anisotropy constants for Fe films on different substrates as a function of Fe film thickness. The solid lines are a guide for the eye, and are proportional to the inverse thickness.

the paper [19] assumed that the cubic constants were the same as bulk Fe, which is inconsistent with all other literature.

From figure 3(b) and table 1, it is observed that the in-plane uniaxial anisotropy constants for the Fe/GaAs, Fe/$Ga_{0.8}In_{0.2}As$ and Fe/$Ga_{0.5}In_{0.5}As$ films decrease as a function of increasing Fe thickness, obeying equation (4). For the Fe/InAs films, the in-plane uniaxial anisotropy is

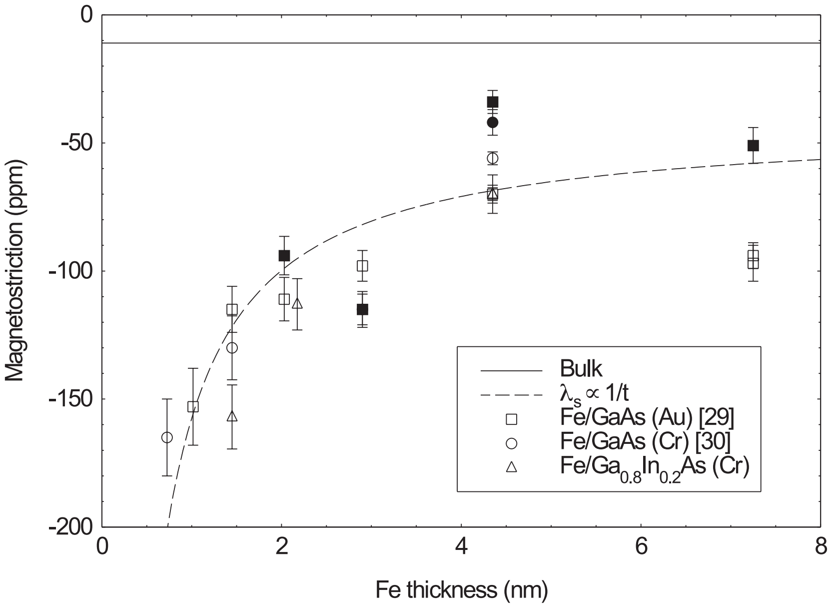

Figure 4. Magnetostriction constants of Fe films on different substrates as a function of Fe film thickness. The open shapes represent the experimental data, and the closed shapes represent the data determined from the fitting method. The solid black line is the magnetostriction constant of bulk Fe, and the dashed line is proportional to the inverse thickness, and is a guide for the eye.

Table 1. Comparison of the volume anisotropy constants and surface anisotropy constants for the different Fe films.

Film	Cubic K_v (J m^{-3})	Cubic K_s (10^{-5} J m^{-2})	Uniaxial K_v (J m^{-3})	Uniaxial K_s (10^{-5} J m^{-2})
Fe/GaAs with Au overlayer [29]	43 000 ± 600	−4.3 ± 0.1	0	12 ± 0.8
Fe/GaAs with Cr overlayer [30]	24 200 ± 4500	−1.87 ± 0.8	−21 400 ± 1700	14.9 ± 3
Fe/Ga$_{0.8}$In$_{0.2}$As with Cr overlayer	36 000 ± 500	−4.62 ± 0.4	−6000 ± 600	10.9 ± 2
Fe/InAs [12]	51 900	−2.28	N/A	N/A

present in the films, but is an order of magnitude smaller than for the Fe/GaAs films. For the ultrathin Fe films ($t < 2$ nm) on GaAs substrate, the in-plane uniaxial anisotropy constants are of similar magnitude; thus the uniaxial anisotropy at this thickness is not affected by the overlayer. For Fe films thicker than 2 nm on GaAs, the strength of the uniaxial anisotropy is dependent on the overlayer, which is observed in different values of the uniaxial anisotropy constant at 4.35 nm. For the Au overlayer film, no intermixing occurs at the Fe–Au interface, and the uniaxial anisotropy has an inverse thickness dependence, and no volume dependence (equation (4)) [3, 23, 29]. For the 4.35 nm Cr overlayer Fe/GaAs film, the uniaxial anisotropy constant has decreased by 20 000 J m^{-3} (a factor of 3) in comparison to the Au overlayer film, which can only be due to intermixing at the Fe–Cr interface. For the Fe/Ga$_{0.8}$In$_{0.2}$As films the uniaxial anisotropy constants were a factor 1.5 smaller than the Au/Fe/GaAs constants, while the 4.35 nm Cr/Fe/$Ga_{0.8}In_{0.2}As$ uniaxial constant was 10 000 J m^{-3} larger (a factor of 2) than the Cr/Fe/GaAs constant. This suggests that the substrate on which the Fe film is grown does affect the uniaxial anisotropy. This is confirmed by the uniaxial anisotropy constant determined for the Fe/$Ga_{0.5}In_{0.5}As$ films. The 3 nm Fe/$Ga_{0.5}In_{0.5}As$ film constant was the same order of magnitude as the Au/Fe/GaAs film, while the 6 nm Fe/$Ga_{0.5}In_{0.5}As$ film constant was a factor 4 smaller than the Au/Fe/GaAs film constant, but was of similar magnitude to the Cr/Fe/GaAs film constant. Thus the uniaxial anisotropy observed in these Fe films was affected by the substrate the films were grown on, as well as the overlayer. The Ga_xIn_{1-x} As substrates did change the magnitude of the uniaxial anisotropy, but did not change the uniaxial easy axis direction. As the Fe/$Ga_{0.8}In_{0.2}As$ films investigated had uniaxial anisotropy for film thicknesses less than 6 nm, this means that the uniaxial anisotropy observed in all the Fe films was not caused by the strain due to the mismatch between the lattice constants of the Fe and the substrate. This is because the $Ga_{0.8}In_{0.2}As$ substrate had the same lattice parameters as bulk Fe; thus there should be no strain at the interface. Thus the lattice mismatch between the substrate and the Fe film can be ruled out as the origin of the uniaxial anisotropy.

For all five sets of Fe films the common denominator is the As in the substrate. From first-principle calculations of Fe on GaAs(100), it was calculated that the interaction between the Ga and Fe at the interface was much weaker than the interaction between As and Fe [37]. These calculations also predicted that the Fe–As bonds at the surface would cause the bcc Fe unit cell to be distorted, along the [110] and $[1\bar{1}0]$ directions. The size of the contraction/expansion along each direction depended on the thickness of the Fe film and the As coverage. For example, for 5 ML Fe + 1 ML As, the $[1\bar{1}0]$ direction is under tension by +0.51% and the [110] direction is under contraction by −1.83% [37]. In general, the Fe [110] direction was under contraction, and the Fe $[1\bar{1}0]$ direction was either under less contraction or expansion. Hence the two directions are asymmetric within the Fe film. This distortion of the bcc unit cell has been experimentally observed using x-ray absorption [38]. Thus as all the Fe films grown on the four different substrates had in-plane uniaxial anisotropy, the origin has to be the Fe–As bonds, which form at the Fe–substrate interface. The Fe–As bond asymmetry between the [110] and $[1\bar{1}0]$ directions was determined for the Fe–GaAs interface [37], and it is likely that the strength of the bonds will vary with the introduction of In into the substrate. This would explain the difference in magnitude of the uniaxial anisotropy observed in the Fe/$Ga_xIn_{1-x}As$ films and the change in direction of the uniaxial easy axis in Fe/InAs films. For the thinner Fe/GaAs and Fe/$Ga_xIn_{1-x}As$ films, the uniaxial anisotropy constants were similar (figure 3(b)), which was unexpected. A possible reason for this is the surface reconstruction and the terminating ion of the substrate. Moosbühler *et al* [7] showed that the magnitude of the uniaxial anisotropy depended on the substrate surface reconstruction. For the GaAs(100) substrates, the surface reconstruction was 1 × 1, which is unique as it contains no trenches or dimers [25], while the $Ga_{0.8}In_{0.2}As(100)$ substrates had a 4 × 2 surface reconstruction. Thus the $Ga_{0.8}In_{0.2}As(100)$ surface would contain dimers and trenches, which also could affect the strength of the Fe–As bonds; hence the uniaxial anisotropy magnitude. As the Fe films got thicker, the influence of the Fe–As bonds would weaken, and effects such as intermixing at the overlayer interface would also change the anisotropies. Lepine determined that Fe/GaSb films did not contain an in-plane uniaxial anisotropy [5], but Fe/AlAs films did. This backs up the idea that it is the As, rather than the Ga or In, which causes the uniaxial anisotropy.

The magnetostriction constants determined for the Fe/$Ga_{0.8}In_{0.2}As$ films are plotted together with the magnetostriction constants determined for the Fe/GaAs films (figure 4). It is observed that the magnetostriction constants for all three sets of films have similar thickness dependence, and are of the same order of magnitude. Thus growing the Fe films on GaAs or $Ga_{0.8}In_{0.2}As$ substrates does not affect the magnetostriction constant of the film. Hence the

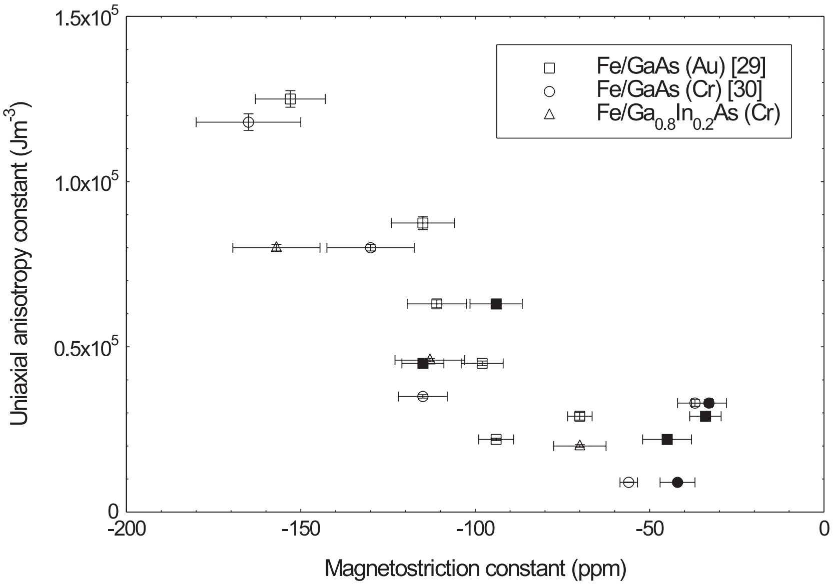

Figure 5. Uniaxial anisotropy constants for the Fe films on different substrates as a function of magnetostriction constants. The open shapes represent the experimental magnetostriction constants and the closed shapes represent the fitting methods' magnetostriction constants.

lattice mismatch between the Fe and the GaAs is not the cause of the magnetostriction constant becoming more negative as the film thickness decreases. As the Fe–As bonds formed at the interface during deposition [37] cause the bcc Fe cell to be distorted along the [110] direction, the increase in the magnetostriction constant observed in these films could be related to this distortion, rather than the lattice strain. The black dashed line is proportional to the inverse thickness, which suggests that the magnetostriction constants follow Néel's phenomenological model [39], which further suggests that magnetostriction constants can increase or decrease as a function of thickness, due to interface effects.

As uniaxial anisotropy was observed in Fe/Ga$_{0.8}$In$_{0.2}$As films and the magnetostriction constants were similar to those of the Fe/GaAs films, this suggests that the uniaxial anisotropy and the magnetostriction constant could be related. Figure 5 shows the uniaxial anisotropy constant as a function of the magnetostriction constant. It is seen that there is a linear trend within the data. This suggests that either the increase in the magnetostriction constant caused the uniaxial anisotropy or the presence of the uniaxial anisotropy caused the magnetostriction constant to become more negative. At a fundamental level magnetostriction is directly related to the strain dependence of the magnetic anisotropy, and a scaling is not unexpected.

5. Conclusions

The in-plane uniaxial anisotropy observed in Fe/GaAs and Fe/InAs films has also been observed in latticed-matched Fe/Ga$_{0.8}$In$_{0.2}$As films. This means that the cause of the uniaxial anisotropy is not the lattice mismatch between the Fe and the substrate. For all Fe films grown on substrates containing As, uniaxial anisotropy has been observed. Hence the most probable cause of the uniaxial anisotropy is the Fe–As bonds which form as the Fe is initially deposited, although the increase in the magnetostriction in the films cannot be excluded as a possible cause.

The magnetostriction constants of the Fe/$Ga_{0.8}In_{0.2}As$ films were of similar magnitude to those of the Fe/GaAs films. Thus the lattice mismatch between the Fe and the GaAs substrate was not cause of the uniaxial anisotropy or the increase in the magnetostriction.

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References

[1] Bobo J F, Gabillet L and Bibes M 2004 *J. Phys.: Condens. Matter* **16** S471
[2] Bensch F, Moosbühler R and Bayreuther G 2002 *J. Appl. Phys.* **91** 8754
[3] Brockmann M *et al* 1999 *J. Magn. Magn. Mater.* **198/199** 384
[4] Kneedler E M *et al* 1997 *Phys. Rev.* B **56** 8163
[5] Lepine B *et al* 1999 *J. Cryst. Growth* **201/202** 702
[6] Monchesky T L *et al* 1999 *Phys. Rev.* B **60** 10242
[7] Moosbühler R *et al* 2002 *J. Appl. Phys.* **91** 8757
[8] Zuberek R *et al* 2003 *J. Magn. Magn. Mater.* **260** 386
[9] Freeland D J *et al* 1999 *Thin Solid Films* **343/344** 210
[10] Moore T A *et al* 2001 *J. Appl. Phys.* **89** 7018
[11] Xu Y B *et al* 1998 *Appl. Phys. Lett.* **73** 399
[12] Pelzl J *et al* 2003 *J. Phys.: Condens. Matter* **15** S451
[13] Ruppel L *et al* 2002 *Phys. Rev.* B **66** 245307
[14] Meckenstock R *et al* 2004 *J. Magn. Magn. Mater.* **272–276** 1203
[15] Thomas O *et al* 2003 *Phys. Rev. Lett.* **90** 017205 1
[16] Filipe A, Schuhl A and Galtier P 1996 *Appl. Phys. Lett.* **70** 129
[17] Gester M *et al* 1996 *J. Appl. Phys.* **80** 347
[18] Sander D, Enders A and Kirschner J 1999 *J. Magn. Magn. Mater.* **200** 439
[19] Richomme F, Fnidiki A and Eymery J-P 2005 *J. Appl. Phys.* **97** 123902
[20] Doi M *et al* 2002 *J. Magn. Magn. Mater.* **240** 407
[21] Herfort J *et al* 2004 *Appl. Surf. Sci.* **237** 181
[22] Ahmad E *et al* 2004 *J. Appl. Phys.* **95** 6555
[23] McPhail S *et al* 2003 *Phys. Rev.* B **67** 1
[24] Xu Y B *et al* 1999 *J. Magn. Magn. Mater.* **198/199** 703
[25] Srivastava G P 1999 *Theoretical Modelling of Semiconductor Surfaces* (Singapore: World Scientific)
[26] Tolinski T *et al* 2003 *Solid State Commun.* **128** 385
[27] Xu Y B *et al* 2000 *Phys. Rev.* B **62** 1167
[28] Wastlbauer G and Bland J A C 2005 *Adv. Phys.* **54** 137
[29] Morley N A *et al* 2005 *J. Phys.: Condens. Matter* **17** 1201
[30] Morley N A *et al* 2005 *J. Appl. Phys.* **97** 10H501
[31] Sander D *et al* 1998 *J. Phys. D: Appl. Phys.* **31** 663
[32] Florczak J M and Dan Dahlberg E 1990 *J. Appl. Phys.* **67** 7520
[33] Florczak J M and Dahlberg E D 1991 *Phys. Rev.* B **44** 9338
[34] Morley N A *et al* 2005 *J. Magn. Magn. Mater.* doi:10.1016/j.jmmm.2005.05.034
[35] Hollingworth M P, Gibbs M R J and Hill E W 2003 *J. Appl. Phys.* **93** 8737
[36] Heinrich B *et al* 1996 *J. Appl. Phys.* **79** 4518
[37] Mirbt S *et al* 2003 *Phys. Rev.* B **67** 155421
[38] Gordon R A *et al* 2005 *Surf. Sci.* **581** 47
[39] Neel L 1954 *J. Phys. Radiol.* **15** 225