Comparison between the in-plane anisotropies and magnetostriction constants of thin epitaxial Fe films grown on GaAs and $Ga_{0.8}In_{0.2}As$ substrates, with Cr overlayers

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Thin epitaxial Fe films grown on GaAs(100) and $Ga_{0.8}In_{0.2}As(100)$ substrates were investigated to determine how tuning the lattice constant mismatch between the Fe and the substrate may change the in-plane anisotropies and the magnetostriction. Two sets of Fe films were grown using molecular-beam epitaxy, each capped with a Cr overlayer. For each film, the in-plane anisotropy constants were determined from the normalized magnetization loops measured using a magneto-optic Kerr effect magnetometer. The lattice mismatch was found to give no contribution to the in-plane anisotropies. For all the films the magnetostriction constants, determined by the Villari method, were negative and became more negative as the Fe thickness decreased. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2158974]

I. INTRODUCTION

The study of Fe films on semiconductor substrates is of interest for spintronic devices.[1,2] Previous research has investigated Fe films on GaAs,[3,4] on InAs[5,6] and on $Ga_{0.5}In_{0.5}As$[7] substrates. For all these Fe films an in-plane uniaxial anisotropy was present when the Fe thickness was less than 25 nm, as well as the magnetocrystalline cubic anisotropy characteristic of the bulk.[3–6] For Fe films on GaAs(001), the uniaxial anisotropy easy axis is along the [110] direction,[4] while for Fe/InAs(001) films, the uniaxial easy axis is along the $[1\bar{1}0]$ direction.[5] 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. From previous works, we determined that Fe films on GaAs(100) substrates,[8,9] also had the uniaxial easy axis was along the [011] direction and the anisotropy constants determined were in good agreement with those for the Fe/GaAs(001) films. The origin of this uniaxial anisotropy is still uncertain, but it is believed to be due to the interface between the Fe and the substrate.[10] The reasons given in the literature include the presence of $Fe_3Ga_{2-x}As_x$,[11] formation of Fe–As bonds,[12] and the strain due to the lattice mismatch.[13]

One possible reason for the difference in the uniaxial easy axis direction between Fe/GaAs films and Fe/InAs films is the lattice-constant 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 coupled with the magnetostriction of the Fe film caused the uniaxial anisotropy and the different easy axis directions. Thus it might be expected that no uniaxial anisotropy would be present in Fe films grown on a $Ga_{0.8}In_{0.2}As$ substrate, which has the same lattice constants as Fe.[13] This was determined from the published change in the lattice parameters of the substrates $Ga_xIn_{1-x}As$ from $x=1$ to 0.[2] In this paper we compare the in-plane anisotropies and magnetostriction constants of Fe films grown on GaAs(100) and $Ga_{0.8}In_{0.2}As(100)$ substrates to determine whether the lattice mismatch is an important factor.

II. EXPERIMENTAL DETAILS

The Fe films were fabricated using molecular-beam epitaxy (MBE) on to the GaAs(100) and $Ga_{0.8}In_{0.2}As(100)$ substrates.[14] The surface flatness and reconstruction were determined using reflection high-energy electron diffraction (RHEED). For the GaAs(100) substrates the surface reconstruction was 1×1, while for the $Ga_{0.8}In_{0.2}As(100)$ substrates, the surface reconstruction was 4×2. The Fe films were then grown at 50 °C and 1×10^{-10} mbar. For the Fe film, the flatness and the uniformity along the [011] direction were checked using RHEED. The patterns showed epitaxy on both substrates with the relationship $Fe(100)\times\langle001\rangle\|Ga_xIn_{1-x}As(100)\langle001\rangle$ (where $x=1$ or 0.8). The thicknesses of the $Fe/Ga_{0.8}In_{0.2}As$ films were 1.45 nm [10 monolayers (MLs)], 2.18 nm (15 ML), and 4.35 nm (30 ML). The evaporation procedure was then repeated for the Cr overlayer material, with thickness 2 nm. From RHEED images, it was determined that the Cr and Fe were well matched and were aligned with the same orientation.

The magnetization (presented as normalized to saturation) was measured on a magneto-optic Kerr effect (MOKE) magnetometer. The MOKE was set up in transverse geometry, which means that before the sample the polarizer was set so that the laser's electric field was parallel to the plane of incidence, the analyzer was set close to extinction and the applied field was perpendicular to the plane of incidence of the laser.[15] The films were strained using a specially designed bending tool,[16] over four different bend radii ($R=220-280$ mm), along the [011] direction and the normal-

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ized magnetizations were measured along the $[01\bar{1}]$ direction. The magnetostriction constants were obtained from the strain dependence of the anisotropy field, H_K (Villari effect) given by the relation[16]

$$\lambda_s = \frac{dH_K}{d1/R}\frac{2\mu_o M_s(1-\upsilon^2)}{3\varepsilon Y}, \tag{1}$$

where υ is the Poisson ratio, ε is the thickness of the substrate, Y is Young's modulus of the substrate, μ_o is the permeability of free space, and M_s is the saturation magnetization [established by vibrating-sample magnetometer (VSM)].

III. RESULTS AND DISCUSSION

To determine the symmetry and magnitude of the in-plane anisotropies present in the $Cr/Fe/Ga_{0.8}In_{0.2}As$ films, the normalized magnetization loops were measured for the field along different crystal axis directions. Using a fitting method, the cubic and uniaxial anisotropy constants of each film were determined from the normalized magnetization data.[15] The method assumed that the magnetization process in the film proceeds by coherent rotation, so that the in-plane magnetic energy density (F) was described by

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

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). Both anisotropy constants are allowed to be functions of the Fe layer thickness, t. For a MOKE magnetometer, the output signal of the photodetector depends on the angle (θ_a) between the pass plane of the analyzer and the plane of incidence of the laser.[17] Thus the normalized intensity at the detector (I/I_o) is[15,17]

$$\frac{I}{I_o} = A\cos^2\theta_a + (B\cos^2\theta_a)\cos\varphi + (C\sin\theta_a\cos\theta_a)\sin\varphi + (D\sin^2\theta_a)\sin^2\varphi, \tag{3}$$

where A, B, C, and D are constants which depend on the refractive index of Fe, the magneto-optic constant, and the angle of incidence of the laser beam on the film. These constants are derived elsewhere.[15,17] For each film, the anisotropy constants were determined by convoluting the magnetic energy density [Eq. (2)] with the output of the photodetector [Eq. (3)], which was then fitted to the measured normalized magnetization data. In Table I, the anisotropy constants for the $Cr/Fe/Ga_{0.8}In_{0.2}As$ films are presented, along with the Cr/Fe/GaAs film's anisotropy constants.[9] The signal-to-noise ratio on the 1.45 nm $Cr/Fe/Ga_{0.8}In_{0.2}As$ film magnetization loops were too poor to determine the anisotropy constants. For the 2.18 nm $Cr/Fe/Ga_{0.8}In_{0.2}As$ film and the 1.45 and 2.9 nm Cr/Fe/GaAs films, it is observed that the in-plane uniaxial anisotropy was dominant. For the 4.35 nm Fe films the cubic anisotropy was stronger than the uniaxial anisotropy. These

TABLE I. In-plane anisotropy constants for the Fe/GaAs and the $Fe/Ga_{0.8}In_{0.2}As$ films.

Film substrate	Fe thickness (nm)	Cubic anisotropy constant (Jm^{-3})	Uniaxial anisotropy constant (Jm^{-3})
GaAs(100)[9]	1.45	12 000±300	80 000±2500
	2.9	15 000±400	35 000±1100
	4.35	22 000±500	9 000±200
$Ga_{0.8}In_{0.2}As(100)$	2.18	14 000±1100	46 000±3600
	4.35	25 000±1500	20 000±1200

cubic and uniaxial anisotropy constants are plotted in Fig. 1, together with the anisotropy constants for Fe/GaAs(100) films with Au overlayer (black solid and dashed lines).[8] From Fig. 1, it is observed that the Au/Fe/GaAs films' anisotropy constants are larger than the anisotropy constants of the Cr/Fe/GaAs and $Cr/Fe/Ga_{0.8}In_{0.2}As$ films. This is attributed to the intermixing between the Fe and the Cr at the interface.[9] The magnitudes of the cubic anisotropy constants for the $Cr/Fe/Ga_{0.8}In_{0.2}As$ films are similar to the Cr/Fe/GaAs films. Hence the cubic anisotropy constants of the Fe films grown on GaAs and $Ga_{0.8}In_{0.2}As$ substrates do not appear to be affected by the substrate interface. For the 1.45 and 2.9 nm Cr/Fe/GaAs films and the 2.18 nm $Cr/Fe/Ga_{0.8}In_{0.2}As$ film, the magnitudes of the uniaxial anisotropy constants followed the same inverse thickness dependence. This suggests that the uniaxial anisotropy constants of Fe films ($t<3$ nm) are independent of the lattice mismatch at the substrate interface. For the 4.35 nm Fe films, the strength of the uniaxial anisotropy is influenced by the overlayer and the substrate, as the Cr/Fe/GaAs film uniaxial anisotropy constant was 10 000 Jm^{-3}, less than the $Cr/Fe/Ga_{0.8}In_{0.2}As$ film uniaxial constant. As both films have the same overlayer (Cr), the difference in the uniaxial anisotropy is mostly likely due to the substrate, but not the

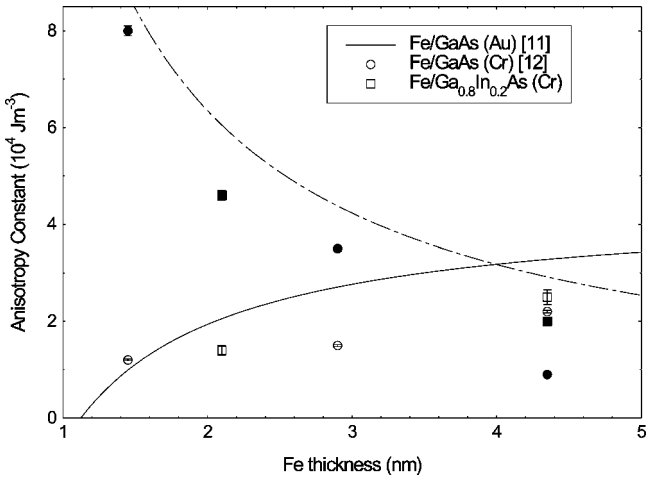

FIG. 1. Cubic and uniaxial anisotropy constants for Fe films on GaAs(100) (Ref. 9) substrates and $Ga_{0.8}In_{0.2}As(100)$ substrates as a function of Fe film thickness. For the Au overlayer Fe/GaAs films (Ref. 8), the solid line is the cubic anisotropy constant and the dashed line is the uniaxial anisotropy constant. For the Cr overlayer films, the solid shapes represent the uniaxial anisotropy constants and the open shapes represent the cubic anisotropy constants.

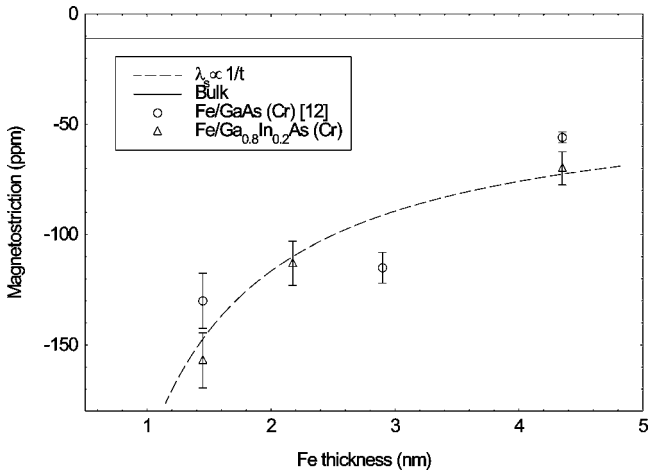

FIG. 2. Magnetostriction constants of Fe films on GaAs(100) (Ref. 9) and $Ga_{0.8}In_{0.2}As(100)$ substrates function of Fe film thickness. The solid black line is the magnetostriction constant of bulk Fe in the [110] direction, and the dashed line is proportional to the inverse thickness, and is a guide for the eye.

lattice mismatch as any epitaxial uniaxial strain would be less in the $Cr/Fe/Ga_{0.8}In_{0.2}As$ case.

The magnetostriction constants for the $Cr/Fe/Ga_{0.8}In_{0.2}As$ films were determined using Eq. (1) and are plotted in Fig. 2, along with the Cr/Fe/GaAs films' constants.[9] It is observed that all the magnetostriction constants were negative, and became more negative as the Fe thickness decreased. The 1.45 and 4.35 nm $Cr/Fe/Ga_{0.8}In_{0.2}As$ films magnetostriction constants were a factor of 1.2 more negative than the same thickness Cr/Fe/GaAs films magnetostriction constants. This suggests that the magnetostriction constant of an Fe film depends on the substrate on which it was grown. The magnetostriction constants follow Néel's phenomenological model[18] (black-dashed line), which states that magnetostriction constants can increase or decrease as a function of thickness, due to interface affects.

As uniaxial anisotropy was observed in both the Cr/Fe/GaAs films and the $Cr/Fe/Ga_{0.8}In_{0.2}As$ films, this means that the strain due to the lattice constant mismatch at the interface coupling with the magnetostriction is not the source of the uniaxial anisotropy. The probable cause for the in-plane uniaxial anisotropy is the distortion in the Fe bcc structure caused by Fe–As bonds forming during fabrication.[19] First-principles calculations of Fe on GaAs(001) (Ref. 12) have predicted that these Fe–As bonds in the lowest-energy configuration cause the bcc Fe unit cell to be distorted, along the [110] and $[1\bar{1}0]$ directions, which has been observed experimentally.[19] 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 on 1 ML As, the $[1\bar{1}0]$ direction expands by +0.51% and the [110] direction contracts by −1.83%. This gives asymmetry to the [110] and $[1\bar{1}0]$ directions, which seems to be the likely cause of the uniaxial anisotropy and the increase in the magnetostriction constant observed in these Fe films. The differences in the magnitudes for the uniaxial constants between the $Cr/Fe/Ga_{0.8}In_{0.2}As$ films and the Cr/Fe/GaAs films will be due to the size of the distortions to the bcc cell depending on the other atoms in the substrate, i.e., Ga and In and the surface reconstruction. As uniaxial anisotropy has also been observed in Fe/InAs films,[5] $Fe/Ga_{0.5}In_{0.5}As$ films,[7] and Fe/AlAs films,[20] this backs up the idea that it is the Fe–As bonds rather than the Ga or In, which causes the uniaxial anisotropy.

IV. CONCLUSIONS

The in-plane uniaxial anisotropy observed in the latticed matched $Cr/Fe/Ga_{0.8}In_{0.2}As$ films was similar to the Cr/Fe/GaAs films. This means that the source of the uniaxial anisotropy is not the lattice-constant mismatch between the Fe and the substrate, although the substrate does affect the magnitude of the uniaxial anisotropy and the magnetostriction constant. The uniaxial anisotropy was stronger in the 4.35 nm $Cr/Fe/Ga_{0.8}In_{0.2}As$ film compared with the 4.35 nm Cr/Fe/GaAs film. Similarly the 4.35 nm $Cr/Fe/Ga_{0.8}In_{0.2}As$ film's magnetostriction constant was more negative compared with the 4.35 nm Cr/Fe/GaAs film constant. 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 directional Fe–As bonds which distort the bcc cell in the [110] and $[1\bar{1}0]$ directions.

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