Magnetic anisotropies in GaAs/Fe(001) structures

Magnetic anisotropies in GaAs/Fe(001) structures

Bartek Kardasz[1], Oleksandr Mosendz[2], Bret Heinrich[1], Marek Przybylski[3], Jürgen Kirschner[3]

[1] Simon Fraser University, Physics Department, Burnaby, Canada

[2] Material Science Devision, Argonne National Laboratory, Argonne, IL, USA

[3] Max-Planck-Institut für Mikrostrukturphysik, Halle, Germany

E-mail: bkardasz@sfu.ca

Abstract. Fe ultrathin films on GaAs(001) substrates were prepared by thermal deposition (TD) and pulse laser deposition (PLD) using MBE. Conversion electron Mössbauer spectroscopy (CEMS) was employed to investigate the atomic arrangement of Fe at the GaAs(001) interface. The magnetic anisotropies were studied by FMR. They have strong interface and bulk contributions which undergo several transitions with increasing film thickness. The most pronounced effect was observed in the in-plane interface uniaxial anisotropy $K_{\parallel,u}^{int}$. $K_{\parallel,u}^{int}=0.10$ ergs/cm^2 for the TD films thinner than 30ML. For thicker samples it decreased to $K_{\parallel,u}^{int}=0.03$ ergs/cm^2 which is equal to that for the PLD samples. It will be shown that these transitions in magnetic anisotropies are driven by B_1 and B_2 magneto-elastic energies.

1. Introduction

GaAs/Fe(001) interfaces play an importasnt role in a number of basic studies and device applications using magnetic nanostructures. Magnetic anisotropies in GaAs/Fe(001) were investigated by several groups [1, 2, 3, 4], and [5] with references within. However no clear picture so far is present especially on the origin of the in-plane uniaxial anisotropy. We present the results of our recent structural and magnetic studies of ultrathin films of Fe(001) grown on GaAs(001) templates. The Fe films were deposited by thermal deposition (TD) and pulse laser deposition (PLD) techniques. The chemical environment of Fe at the GaAs(001) interface was investigated by conversion electron Mössbauer spectroscopy CEMS. The magnetic anisotropies were measured by ferromagnetic resonance (FMR). The details on FMR and CEMS experimental systems and measurements can be found in ref [6] and [7].

2. Growth and CEMS studies

The Fe films were deposited on a commonly used 4×6-GaAs(001) reconstructed template, see further details in [7]. After deposition of an equivalent of three atomic layers a continuous Fe film was formed having atomic terraces approximately 3-4 nm wide. Equivalent of two atomic layers of ^{57}Fe was used as a probe layer for Mössbauer spectroscopy. They were deposited using TD and PLD at the GaAs(001) interface and inside the Fe film. The CEMS studies in this paper were carried out using the following structures:

GaAs/2^{57}Fe$_{PLD}$/8Fe$_{TD}$/20Au(001),

GaAs/2^{57}Fe$_{PLD}$/8Fe$_{PLD}$/20Au(001),

GaAs/2^{57}Fe$_{TD}$/8Fe$_{TD}$/20Au(001).

The integers represent the number of atomic layers, and the subscripts describe the deposition technique.

The Mössbauer spectroscopy (CEMS) studies were carried out at room temperature (RT). Computer fitting of the CEMS spectra for the ^{57}Fe probe layer grown directly on the GaAs(001) template required 8-10 components with a broad hyperfine field distribution, see further details in [7]. The hyperfine fields (H_f) and their relative contributions are summarized in Fig.1. The
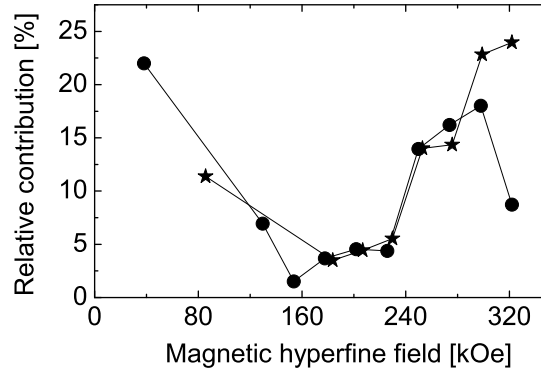

Figure 1. CEMS studies with the ^{57}Fe probe layer deposited directly at the GaAs(001) template. Relative contributions of the spectral components vs. corresponding magnetic hyperfine fields. The ($\bullet$) and ($\star$) points represent the PLD and TD deposited samples, respectively.

main difference between the TD and PLD samples was observed at the lowest and highest range of the hyperfine field H_f components. Otherwise the components between these extremes were remarkably similar. Clearly, a high kinetic energy of PLD deposited Fe clusters lead to a stronger incorporation of Fe into the GaAs lattice compared to that in the TD samples. The TD samples have a sharper interface lattice structure than those deposited by means of PLD. The lowest hyperfine field for the PLD samples corresponds to the Fe environment having mostly Ga and As atoms in its nearest neighbor configuration.

3. Uniaxial magnetic anisotropy

This article deals mostly with the uniaxial anisotropies which are unique to ultrathin films. In the bulk having the cubic symmetry these anisotropies are absent for the magnetization oriented in the (001) crystallographic plane. The magnetic anisotropies were measured by FMR. The perpendicular uniaxial anisotropy field as a function of the film thickness is shown in Fig. 2. It has the bulk and interface contributions. The bulk contribution, $4\pi M_s$, in ultrathin films arises from the dipolar field. Notice that for the films thinner than 100 monolayers (ML) the projected value of the bulk uniaxial field of 20.2 kOe is about 1.2 kOe lower than that expected from the saturation magnetization of Fe, $4\pi M_s$=21.5 kOe [8]. This difference can be accounted for by including the axial strain of the Fe films grown on GaAs(001). The magneto-elastic contribution B_1 can result in an additional uniaxial effective demagnetizing field,

$$4\pi M_{\text{eff}} \quad = \quad 4\pi M_S - \frac{2K_{\perp,u}^{\text{int}}}{M_S d_{Fe}} + \frac{2B_1(e_\perp - e_\parallel)}{M_S} \tag{1}$$

where $K_{\perp,u}^{\text{int}}$ is the perpendicular interface uniaxial anisotropy, B_1 is the magneto-elastic coupling coefficient ($B_1 = -3.43 \times 10^7$ erg/cm^3 for Fe) and the $e_\parallel$ and $e_\perp$ are the strains parallel

and perpendicular to the Fe film plane, respectively. The lattice mismatch between the Fe and GaAs(001) lattice meshes leads to the lattice strains $e_\parallel = (-0.011 \pm 0.004)$ and $e_\perp = (0.022 \pm 0.010)$, see also [9]. This results in the magneto-elastic field of -1.3 ± 0.5 kOe which is in excellent agreement with the observed offset shown in Fig.2 (a). The required
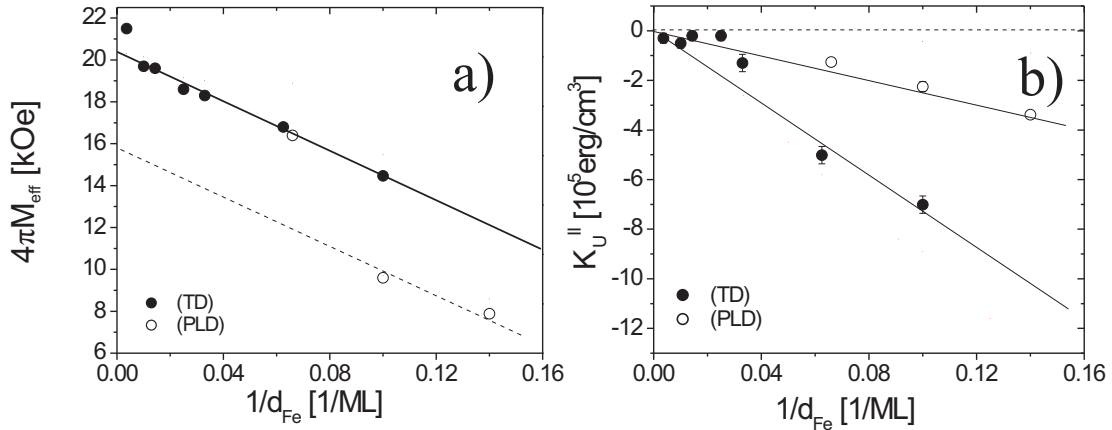

Figure 2. (a) The effective demagnetizing field , $4\pi M_{\mathrm{eff}}$, perpendicular to the film surface in GaAs/Fe/Au(001) structures is plotted as a function of $1/d_{Fe}$, where d_{Fe} is the Fe film thickness in monolayers (ML). The solid line is a linear fit to the data obtained on the TD films. The intercept with the y-axis corresponds to an infinite thickness and represents an effective bulk $4\pi M_{\mathrm{eff}}$. The slope is given by the interface contribution $K_{\perp,u}^{\mathrm{int}} = 0.7$ erg/cm^2. (b) In-plane uniaxial anisotropy $K_{\parallel,u}$ as a function of $1/d_{Fe}$. The hard magnetic axis is along $[1\bar{1}0]$. Notice zero contribution to the bulk in-plane uniaxial anisotropy. The $\bullet$ and $\circ$ symbols correspond to the TD and PLD films, respectively.

lattice mismatch for the TD samples appears to be constant up the thickness of $\sim$100ML. One would expect that the mismatch over 1% would be relaxed at a smaller thickness. In fact our recent results of FMR linewidth measurements as a function of the Fe film thickness have shown that some degree of lattice relaxation already appears above the thickness of 30ML [10]. This lattice relaxation leads to a formation of self-assembled network of misfit dislocations resulting in an additional FMR linewidth which can be described by two magnon scattering mechanism [11]. However the density of these misfit dislocations is low and thus affecting little the overall magneto-elastic contribution to $4\pi M_{\mathrm{eff}}$. Notice that the lattice strain is fully relaxed for the films thicker than 100ML, see the last black point close to the y-axis in Fig. 2(a). The PLD films behave differently. For the PLD films thinner than 10ML the bulk like uniaxial field is increased by $\sim$4 kOe compared to those grown by TD. However this additional contribution disappears at the thickness of 15ML, see Fig. 2(a).

In all our Fe films grown on 4x6 GaAs(001) reconstructed templates the in-plane uniaxial anisotropy is of interface origin, see Fig 2 (b) and [2].

As expected from the previous studies [2] the 10 and 16 ML thick TD Fe films have a large interface uniaxial anisotropy, $K_{\parallel,u}^{int} = -0.10 \pm 0.01$ erg/cm^2. It is interesting to note that $K_{\parallel,u}^{int}$ quoted in Ref. [2] and [1], in the thickness range from 10 to 30 ML, were about 25 % larger than that above. GaAs substrate was sputtered by Ar$^+$ ions for several hours at RT in [2], and sputtering at an elevated temperature was employed in [1], while in the work presented in this paper we used H atom cleaning prior to a brief sputtering at RT. This indicates that $K_{\parallel,u}^{int}$ is sensitive to the details of the GaAs cleaning and preparation procedure. Note that the interface

contribution to the in-plane uniaxial anisotropy dramatically decreases for the Fe films thicker than 30 ML, see Fig. 2 (b); the corresponding interface uniaxial anisotropy dropped by a factor of three to $K_{\parallel,u}^{int}$ = -0.03± 0.01 erg/cm^2, see Fig. 2(b).

The occurrence of a uniaxial in-plane anisotropy has attracted considerable scientific interest, but a conclusive answer as to its precise origin is still missing [5]. A significant decrease of the interface uniaxial in-plane anisotropy for thicker films suggests that the interface uniaxial anisotropy is not caused by purely chemical interactions between the Fe and GaAs atoms. This is further supported by a dramatic change in $K_{\parallel,u}^{int}$ in the Fe films covered by Cr, [12]. A Cr cover layer deposited far away from the GaAs/Fe(001) interface can significantly decrease the in-plane uniaxial anisotropy. The recent observation by Gordon et. al [13] of interface shear at the GaAs/Fe(001) interface suggests that the in-plane interface uniaxial anisotropy can be explained by a magneto-elastic term B$_2$ due to the lattice shear strain ϵ_6

$$\left(\frac{B_2\epsilon_6}{2}\right)\cos^2(\varphi - \frac{\pi}{4}), \tag{2}$$

where φ is the angle between the magnetization and the in-plane [100] axis. Gordon et. al [13] polarization-dependent XAFS studies on a 2 ML Fe film have shown that the Fe nearest-neighbor distances along the [1$\bar{1}$0] direction is larger than that along the [110] direction due to an interface lattice shear. This lattice shear has the right sign to produce a uniaxial anisotropy, $K_{\parallel,u}^{int}$, with the hard axis oriented along [1$\bar{1}$0]$_{Fe}$ [14], but it is about a factor 5 smaller than the measured experimental value. The importance of the interface shear is also supported by the results using the Fe films grown by PLD. For the 7,10 and 15 ML Fe films grown by PLD on GaAs(001), see Fig 2, b), the in-plane interface uniaxial anisotropy $K_{\parallel,u}^{int}$ was found to be the same as that found for the thick Fe films grown by TD, see Fig. 2(b). The above presented Mössbauer studies have shown that Fe films prepared by PLD exhibit a more intermixed interface than those prepared by TD. Consequently the Fe lattice in the PLD films can be expected to be clamped more strongly to the GaAs(001) and exhibit a smaller interface lattice shear than that in the films grown by TD.

Significant decrease of the in-plane interface uniaxial anisotropy in the PLD films compared to that in the TD films can be explained by a decrease of the interface lattice shear due to clamping of the Fe lattice in the PLD samples by the GaAs interface .

References
[1] Brockmann M, Zolfl M, Miethaner S and Bayreuther G 1999 *JMMM* **198** 384
[2] Urban R, Woltersdorf G and Heinrich B 2001 *Phys. Rev. Lett.* **87** 217204
[3] Monchesky T L, Heinrich B, Urban R, Myrtle K, Klaua M and Kirschner J 1999 *Phys. Rev. B* **60** 10242–10251
[4] Moosbuhler R, Bensch F, Dumm M and Bayreuther G 2002 *J. Appl. Phys.* **91** 8757
[5] Wastlbauer G and Bland J A C 2005 *Advances in Physics* **54** 137–219
[6] Heinrich B and Bland J (eds) 2005 *Ultrathin Magnetic Srtuctures* vol II (Springer Verlag) chap 3, 5, pp 195, 327
[7] Kardasz B, Zukrowski J, Przybylski M, Mosendz O, Heinrich B and Kirschner J 2007 *J. Appl. Phys.* **101** 09D110
[8] Bozorth R M 1951 *Ferromagnetism* (D. Van Nostrand Company)
[9] Gordon R A, Crozier E D, Jiang D T, Monchesky T L and Heinrich B 2000 *Phys. Rev. B* **62** 2151
[10] *publication in progress*
[11] Woltersdorf G and Heinrich B 2004 *Phys. Rev. B* **69** 184417
[12] Aktaş B, Heinrich B, Woltersdorf G, Urban R, Tagirov L R, Yildiz F, Ozdogan K, Ozdemir M, Yalcin O and Rameev B Z 2007 *J. Appl. Phys.* **102** 013912
[13] Gordon R A and Crozier E D 2006 *Phys. Rev. B* **74** 165405
[14] Heinrich B and Cochran J 2007 *Handbook of Magnetism and Magnetic Materials,* vol. 4 edited by: H. Kronmuller and S. Parkin (Wiley and Sons) chap Magnetic Ultrathin Films, pp 2285–2302