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Influence of growth temperature on the easy magnetization axis switch and domain structure in Fe/GaAs(1 0 0) structures

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Abstract

Dependence of the easy magnetization axis switch (EMAS) and domain structure in Fe films grown on GaAs(1 0 0) substrates on the growth temperature and deposition rate was investigated. It was found that the EMAS can be observed at substrate temperature less than 140°C. The thickness of "switched" film nonmonotonically depends on the deposition rate. Domain structures in Fe/GaAs(1 0 0) films are discussed.

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Keywords: Anisotropy; Thin magnetic film

In-plane uniaxial magnetic anisotropy at Fe/GaAs(1 0 0) interface continues to be a topic for the study of fundamental magnetic properties of ultrathin films. Its occurrence is associated with some reasons like strains caused by lattices mismatch, nature of Fe–GaAs bonding at the interface, shape anisotropy of islands or surface reconstruction [1–4]. It is known that with decreasing Fe films thickness t up to some critical value t^* the uniaxial anisotropy can exceed the fourfold anisotropy and results to the easy magnetization axis switch (EMAS) from [1 0 0] to [1 1 0] [2–4]. It should be noted that the data concerned EMAS were obtained for films growing at fixed both substrate temperature T_S and Fe deposition rate v. This paper presents the results of EMAS in Fe/GaAs(1 0 0) structures growing under different parameters T_S and v .

The Fe films were grown by molecular-beam epitaxy at pressure of $\sim 10^{-7}$ Torr. Root-mean square roughness of the substrate was estimated as 12 Å using NT-MDT atomic force microscope Solver-P47. The substrates were cleaned analogously [1] and were outgassed at $\approx 600°C$. Films were grown at different substrate temperatures T_S between 50°C and 250°C and deposition rates 1.4; 3 and 4 Å/min. The deposition rate was defined using quartz monitor.

Anisotropic properties of the Fe films were investigated ex situ using ferromagnetic resonance at $f_0 = 9.8$ GHz at room temperature. The direction of easy magnetization axis was defined directly from the $H_r(\varphi)$ dependence, where H_r is the resonant tangential magnetic bias field, φ is the angle between bias field direction and [1 0 0] axis. In Fig. 1 the experimental dependencies $H_r(\varphi)$ for films with thicknesses $t \approx 90$, 21 and 15 Å are shown.

Taking in account the character of the experimental curve $H_r(\varphi)$ and the accuracy of measurements of angle $\varphi \pm 2°$ we calculate the dependencies $H_r(\varphi)$ in approximation that films characterized by the cubical fourfold anisotropy $H_c = K_1/M_0$, and in-plane uniaxial anisotropy $H_u = 2K_u/M_0$ fields, where K_1 and K_u are correspondent anisotropy's constants. The direction of in-plane uniaxial anisotropy axis makes an angle β with [1 0 0] axis direction. In this case equilibrium magnetization M_0 is in the films plane and directed at an angle ψ with respect to the bias field H_0. The $H_r(\varphi)$ dependencies were calculated from the equation

$$(H + 4\pi M_0)(H - 3H_c \sin^2 2\alpha - H_u \sin^2 \eta) = f_0^2/\gamma^2, \quad (1)$$

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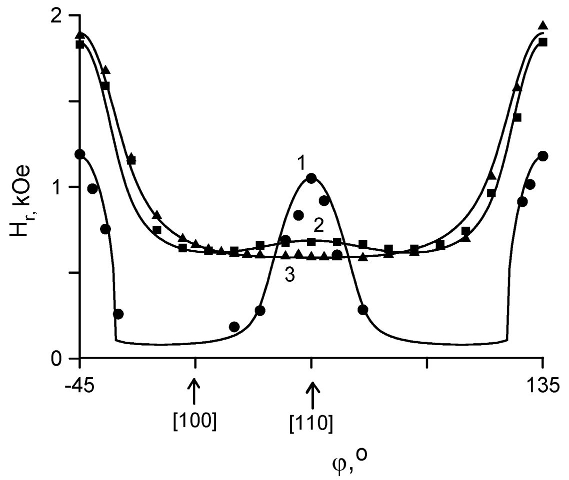

Fig. 1. The experimental (symbols) and calculated (lines) dependencies $H_r(\varphi)$. Marks 1–3 correspond to 90, 21 and 15 Å thickness of Fe film, respectively. Deposition rate is 3 Å/min. Substrate temperature $T_S = 50°C$.

Table 1
Parameters of the films

t (Å)	$4\pi M_0$ (kG)	$K_1 \cdot 10^{-6}$ (erg/cm^3)	$K_u \cdot 10^{-6}$ (erg/cm^3)
90	17.1	0.37	0.045
21	12.4	0.15	0.25
15	8.8	0.065	0.24

where $H = H_r(\varphi)\cos\psi + H_c(2 - \sin^2\alpha) + H_u\cos^2\eta$, $\alpha = \varphi - \psi$, $\eta = \beta + \alpha$ and angle ψ must be defined from the equation

$$-2H_0 \sin\psi + H_c \sin 4\alpha + H_u \sin 2\eta = 0. \quad (2)$$

The experimental and calculated curves demonstrate a good fit for the set of magnetic parameters shown in Table 1.

One can see from Fig. 1 that for films growing at deposition rate 3 Å/min and $T_S \approx 50°C$ axis [1 1 0] became easy for 15 Å thick film. From Eqs. (1) and (2) one can show that $H_r(\varphi)$ dependence in Fe(1 0 0) film at FMR frequency 9.85 GHz demonstrate easy magnetization axis along [1 1 0] if $K_u > 3K_1$. Note that the same relation between anisotropy constants is fulfilled for 15 Å thick film from Table 1.

It was found also that for fixed $T_S \approx 50°C$ and deposition rates 1.4; 3 and 4 Å/min EMAS take place at the film's thickness 21, 15 and 28 Å, respectively. As the substrate temperature increases up to more than 140°C EMAS could not be observed at decreasing the film's thickness to 10 Å.

The pointed temperature sensitivity of EMAS can be related to the increasing Fe–Ga bonds with respect to Fe–As ones at ~3 Å Fe coverage [5] as the T_S is decreased. As the covalent radius of Fe atom (1.24 Å) is smaller than Ga (1.26 Å), one can expect an increase of the lattice mismatch at the interface and existing of the EMAS.

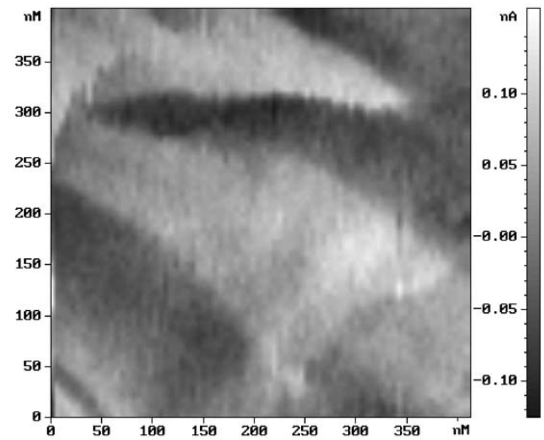

Fig. 2. Domain structure in 9 nm Fe/GaAs(1 0 0) film.

We have studied domain structure of Fe/GaAs(1 0 0) films by NT-MDT magnetic force microscope (MFM) Solver-P47. Fig. 2 shows a magnetic domain MFM image for Fe/GaAs(1 0 0) films with $t \approx 9$ nm. We have not found direct correlation between substrate temperature and domain structure of the grown film. It should be noted that the MFM domain structure could be observed in the Fe/GaAs(1 0 0) films having thickness in the range 8–11 nm. It looks like a compromise between MFM sensitivity and magnetization exit from the film's plane due to the presence of additional uniaxial anisotropy with axis directed at the same angle ζ to the film's plane normal. This suggestion was approved partly from the $H_r(\varphi, \theta_H)$ dependencies measured in the Fe/GaAs(1 0 0) structure at the oblique bias field directed at the angle θ_H to the films normal. For films with thickness 3–10 nm, dependencies $H_r(\varphi)$ for tangential ($\theta_H = 90°$) magnetization demonstrate the strong influence of uniaxial in-plane anisotropy. It was found that $H_r(\varphi, \theta_H)$ dependencies for $\theta_H \approx (20 \pm 5)°$ with changing angle φ have period $\approx 360°$ and its maxima were observed at values φ differ on 15–20° from the values shown in Fig. 1.

No domain MFM image was found for thicker films (up to 20 nm). Note that for films thicker then 11 nm uniaxial and fourfold anisotropy constants are in relation $K_1 > 3K_u$.

We suggest that the absence of MFM images is associated with "easy plane" type of anisotropy in the studied films. In that case magnetization lies in the plane of the film and sensitivity of MFM techniques is small. To verify this we have investigated the domain structure in Fe films grown on mica substrate. In this polycrystalline Fe films MFM domain image could be observed at thickness up to 90 nm.

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