In-plane volume and interface magnetic anisotropies in epitaxial Fe films on GaAs(0 0 1)

M. Brockmann, M. Zöllfl, S. Miethaner, G. Bayreuther*

Institut für Experimentelle und Angewandte Physik, Universität Regensburg, Universitätsstr. 31, 93040 Regensburg, Germany

Abstract

Epitaxial Fe films were grown on Ga-terminated GaAs(0 0 1) surfaces by molecular beam epitaxy. Samples with constant Fe thickness as well as step patterned Fe films have been studied. In-plane magnetic anisotropy energies were determined from hysteresis loops measured by alternating gradient magnetometry and magneto-optic Kerr effect. A superposition of anisotropies with fourfold and uniaxial symmetry was found in all films. From the linear variation of both contributions with the inverse Fe thickness, the volume and the interface term are determined. The fourfold anisotropy constant of the Fe/GaAs(0 0 1) interface amounts to $(1.41 \pm 0.2) \times 10^{-2}$ erg/cm². As a consequence, the easy and hard directions of the fourfold term are rotated by $45^\circ$ below 6 ML. The uniaxial anisotropy turns out to be a pure interface term originating exclusively from the Fe/GaAs interface. The huge anisotropy constant, $K_{Fe-GaAs}^I = (1.2 \pm 0.2) \times 10^{-1}$ erg/cm², produces an in-plane anisotropy field up to 2 kOe. © 1999 Elsevier Science B.V. All rights reserved.

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Fe films grown epitaxially on GaAs(0 0 1) have served as a model system to study the possibility of injecting spin-polarized electrons into a semiconductor. This possibility would open the path to create novel devices in the framework of the emerging ‘spin electronics’. Epitaxial growth was demonstrated long ago [1,2]. Only recently, it has been shown that by low temperature growth on Ga-terminated surfaces the so-called ‘magnetically dead layers’ can be avoided [3]. Moreover, a pronounced in-plane magnetic anisotropy has been reported for Fe films on GaAs(0 0 1) with a fourfold and a uniaxial contribution, which both depend on the thickness of the Fe layer [1–5]. It is the aim of the present work to determine quantitatively the in-plane anisotropy in Fe on GaAs(0 0 1) and their thickness dependence. Such a systematic study is also expected to shed light on the microscopic origin of the uniaxial term.

Substrate preparation and film growth were carried out in an MBE chamber with a base pressure below $10^{-8}$ Pa. Commercial GaAs(0 0 1) wafers were cleaned by boiling in isopropyl alcohol and transferred into UHV without further chemical treatment. The procedure consisted of annealing in UHV for 1 h, followed by Ar⁺ ion etching (energy ~0.5 keV) for 10 min and a final UHV annealing for 1 h. During all steps, the substrate temperature was held at 550°C. Surface structure and chemical composition were studied in situ by low-energy electron diffraction (LEED), reflective high-energy electron diffraction (RHEED), scanning tunneling microscopy (STM) and Auger electron spectroscopy (AES).

All iron films were grown at RT and a rate of 1–2 ML/min (monolayers per min). During film growth, the pressure in the chamber was usually below $5 \times 10^{-8}$ Pa. In addition to single thickness films of 5 to 73 ML, a stair step structure sample with an Fe-film...
thickness range from 4 to 34 ML and a thickness increment of 2 ML from step to step was grown. Thus, a large number of Fe films of different thickness could be obtained on the identical substrate surface structure and under identical growth conditions. All iron films were covered by a protective layer of 20 ML Au. Film thickness of the single thickness films was determined by X-ray fluorescence spectroscopy (XFS) with an error of less than 2% [3]. For the stepped wedge sample the thickness was monitored using four quartz crystal monitors calibrated by X-ray fluorescence spectroscopy.

In order to determine the in-plane magnetic anisotropy from magnetization curves at RT, an alternating gradient magnetometer (AGM) (0–20 kOe) was used for the single thickness films and longitudinal MOKE (0–1.5 kOe) for the step patterned sample. The substrate preparation procedure as described above produced a clean surface with atomically flat terraces (Fig. 1). Over an area of 200 × 200 nm², only five terrace levels of the GaAs lattice are exposed, separated by steps with a height of half the lattice constant (2.83 Å).

LEED and RHEED showed the presence of a 4 × 6 superstructure. The periodic stripes seen in the STM image have a distance of 2.4 nm, which corresponds to 6 times the primitive GaAs(0 0 1) surface lattice constant. Up to now it is not clear whether this pattern is due to the ‘genuine’ 4 × 6 reconstruction described by Xue et al. [6] or to a coexisting 4 × 2 and 2 × 6 reconstruction (‘pseudo 4 × 6’) discussed by Biegelsen et al. [7]. In both cases, the stripes due to the sixfold period are parallel to the [1 1 0] direction and indicate a Ga-rich surface.

RHEED patterns during RT-growth of iron on the GaAs(0 0 1) surface clearly prove epitaxy and indicate the formation of three-dimensional growth nuclei followed by a gradual smoothing of the Fe surface. Coalescence occurs between 3 and 4 ML. After 5 ML no significant change of the RHEED-pattern could be observed. The roughness amplitude as seen by STM of 1–2 ML remained for increasing Fe thickness. This indicates a quasi layer-by-layer growth mode, which leaves the surface structure of the Fe film unchanged. This behavior during RT-growth differs from the one observed in a LEED-study by Gesters et al. [5] for growth at 150°C. They found pyramid-like structures and a step density which increased approximately linearly with film thickness.

In-plane magnetic anisotropy is determined from the angular variation of the magnetizing energy, w_m, obtained by integrating the hysteresis loops (MOKE or AGM) according to

\[ w_m = \int_0^{\phi_m} H \, dm \]  

For a 75 ML Fe(0 0 1) film, the polar plot of w_m(\phi) in Fig. 2 shows the superposition of a fourfold (‘cubic’) and a uniaxial component. The fourfold easy axes are along [1 0 0], [0 1 0], etc., as expected for bulk BCC-Fe. The uniaxial easy axis is along [1 1 0] and the hard axis along [1 1 0]. It should be noted that previously [3], the orientation of the uniaxial easy axis was erroneously given following an earlier report by Krebs et al. [2], instead of a direct determination from the GaAs surface reconstruction.

A fit to w_m(\phi) by Eq. (2),

\[ w_m(\phi) = -\frac{K_1^{\text{eff}}}{4} \sin^2(2\phi) + K_\theta^{\text{eff}} \sin^2 \phi, \]  

where \( \phi \) is measured from [1 1 0], yields the effective anisotropy constants, \( K_1^{\text{eff}} \) and \( K_\theta^{\text{eff}} \). A more economic

![Fig. 1. Scanning tunneling micrograph (200 × 200 nm²) of a GaAs(0 0 1) surface after UHV annealing and Ar⁺ ion etching as described in the text. The image displays five different terrace levels, separated by steps with a height of half the GaAs lattice constant. The stripe pattern corresponds to a surface reconstruction with the 6-fold periodicity of the primitive surface lattice of GaAs(0 0 1) along the [1 1 0]-direction.](Image)

![Fig. 2. Polar plot of the magnetizing energy, w_m, for 73 ML Fe(0 0 1) on GaAs(0 0 1) as determined by integration of magnetization curves (see text).](Image)
Fig. 3. Effective components $K_i^{\text{eff}}$ (full symbols) and $K_{\gamma}^{\text{eff}}$ (open symbols) of the inplane magnetic anisotropy as a function of Fe layer thickness for a stair step patterned film (circles; MOKE data) and for single thickness films (squares; AGM data). Triangles represent FMR-data from Ref. [1]. The solid and dashed line represent fits to the MOKE data for $N_{Fe} = 8$–34 ML according to Eq. (3).

$K_{U/1}^{\text{eff}} = K_{U/1}^{\gamma} + (K_{U/GaAs}^{Fe} + K_{U/Fe}^{Fe})/t_{Fe}$  

It is assumed that the effective anisotropy constants are the superposition of contributions from the volume and from both interfaces of the Fe film.

The data points for $K^{\text{eff}}$ are well fitted by Eq. (3). The volume term, $K_{\gamma}^{\gamma} = (4.3 \pm 0.2) \times 10^6 \text{erg/cm}^2$, is very close to the cubic anisotropy constant of bulk Fe. The sum of both interface contributions, $-(4.6 \pm 0.2) \times 10^{-2} \text{erg/cm}^2$, is obtained from the fit. By using $K_{U/Fe}^{Fe} = -(2.5 \pm 0.2) \times 10^{-2} \text{erg/cm}^2$ from a recent study of Fe films grown on Au(0 0 1) [9], the Fe/GaAs interface contributes the value $K_{U/GaAs}^{Fe} = -(2.1 \pm 0.2) \times 10^{-2} \text{erg/cm}^2$. The negative sign of both interface anisotropy energies causes a rotation of the fourfold easy and hard axes below a critical film thickness of about 7 ML.

This reorientation transition is directly seen from the shape of the hysteresis loops of the thinnest films [3]. For the uniaxial anisotropy, the fit gives $K_{U}^{\gamma} = 0$, i.e. it is a pure interface term. The fact that the data points for $t_{Fe} < 7$ ML fall below the fitting curve is attributed to structural imperfections related to the coalescence around 4 ML.

A previous investigation of Fe films grown on Au(0 0 1) did not indicate a uniaxial anisotropy of comparable strength [9], therefore we assume $K_{U/Fe}^{Fe} \approx 0$. Hence, quite a large anisotropy energy constant is obtained for the Fe/GaAs(0 0 1) interface: $K_{U/GaAs}^{Fe} = (1.2 \pm 0.2) \times 10^{-1} \text{erg/cm}^2$.

The relatively large scatter of the data for $K^{\text{eff}}$ in single thickness films has been reported before [2,4]. In comparison, the data measured on the step patterned sample (Fig. 3, filled circles) are much more regular. This confirms the earlier interpretation [4] that the uniaxial anisotropy originating from the Fe/GaAs interface is strongly affected by the surface properties of the individual substrate. In particular, local variations of chemical composition and related surface reconstruction seem to have a large influence. A more detailed study of the atomic arrangement at the Fe/GaAs interface and the correlation with the observed uniaxial magnetic anisotropy is expected to give more insight into the microscopic origin of this anisotropy, which because of its strength – an in-plane anisotropy field up to 2 kOe can be achieved – is also of great technological interest.

References