Mesoscopic Magnetic/Semiconductor Heterostructures

Yong Bing Xu, Ehsan Ahmad, Yong Xiong Lu, Jill S. Claydon, Ya Zhai, and Gerrit van der Laan

***Abstract*—We report the experimental results of Fe and Fe_3O_4 nanostructures on GaAs(100) surfaces and hybrid Ferromagnetic/Semiconductor/Ferromagnetic (FM/SC/FM) spintronic devices. Element specific x-ray magnetic circular dichroism (XMCD) measurements have shown directly that Fe atoms on the GaAs(100)-4×6 surface are ferromagnetic. Within coverages of 2.5 to 4.8 ML superparamagnetic nanoclusters are formed and exhibiting strong uniaxial anisotropy, of the order of 6.0×10^5 erg/cm^3. The coercivities of epitaxial Fe dot arrays films grown on GaAs(100) were observed to be dependent on the separation and size of the dots indicating that interdot dipolar coupling affects the magnetization processes in these dots. In addition Fe_3O_4 films grown on deformed GaAs(100) substrates have been observed to form nanostripes following the topography of the substrate and magneto-optical Kerr effect (MOKE) measurements showed that these nanostripes have uniaxial magnetic anisotropy with easy axis perpendicular to the length of the nanostripes. Meanwhile the FM/SC/FM vertical device has exhibited a biasing current dependent on MR characteristics, with a maximum change of 12% in the MR observed, indicating for the first time a large room temperature spin injection and detection.**

***Index Terms*—Epitaxial ferromagnetic thin film, ferromagnetic/semiconductor hybrid structures, spintronics.**

I. Introduction

HYBRID ferromagnetic–semiconductor (FM-SC) devices where ferromagnetic materials are used in conjunction with semiconductor materials is emerging as a significant area of research known as "spintronics" with the aim to develop next-generation nonvolatile and fast devices [1]–[4]. In these devices, the electron spin, as well as the charge, will be manipulated for the operation of information processing, and they are expected to be nonvolatile, versatile, fast, and capable of simultaneous data storage and processing while, at the same time, consuming less energy. High-density data storage, microelectronics, sensors, quantum computing, and biomedical applications are among the applications which would benefit from research and development of such devices. The challenge in developing next-generation spintronics devices is the synthesis of high-quality materials with Curie temperature above room temperature and large spin polarization at the Fermi level.

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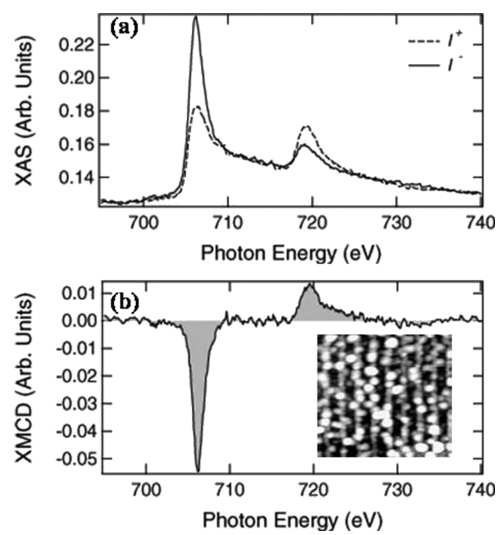

Fig. 1. (a) Normalized (XAS) and (b) corresponding XMCD spectra for Fe thickness of 0.5 ML capped with 9 ML of Co and followed by 7 ML of Cr. The STM micrograph of the 0.5 ML Fe coverage is shown as insert of (b). The dimension of the micrograph is 20×20 nm^2.

In this context, epitaxial ferromagnetic thin films grown on semiconductors like GaAs and InGaAs have already been in the forefront [5], [6]. Very recently, half metallic magnetic oxides such as CrO_2, Fe_3O_4, etc., have drawn considerable attention because of their unique property of producing spin polarization of 100% at the Fermi level [7]. In this paper, we will report our work on: 1) the growth of Fe/GaAs heterostructures, and in particular, the nanoclusters formed at the initial stage and their magnetic properties; 2) patterned single crystal Fe dot arrays on GaAs; 3) magnetite nanostripes on deformed GaAs(100); and 4) magnetoresistance (MR) properties of a FM/SC/FM vertical spintronic device.

II. Sample Fabrication

The Fe films were grown in a molecular beam epitaxy (MBE) system using e-beam evaporators with the pressure below 5×10^{-10} mbar and deposition rates of approximately one monolayer (ML) per minute. To reduce the intermixing of Fe with Ga, In, or As at the interface, the films were grown at room temperature [5]. In order to obtain Fe_3O_4 films, Fe films were grown epitaxially on GaAs(100) substrates and then oxidized in an ultrahigh vacuum (UHV) chamber with an O_2 environment of 5×10^{-5} mbar at 500 K [7]. The Fe dot arrays were fabricated using electron-beam lithography operated at 50 keV followed by ion-beam etching through an intermediate Al-mask prepared by metallization and liftoff process. The FM/SC/FM device was fabricated as follows. A 15 ML film of Co with 20 ML of Cr capping layer was deposited on a 10-mm

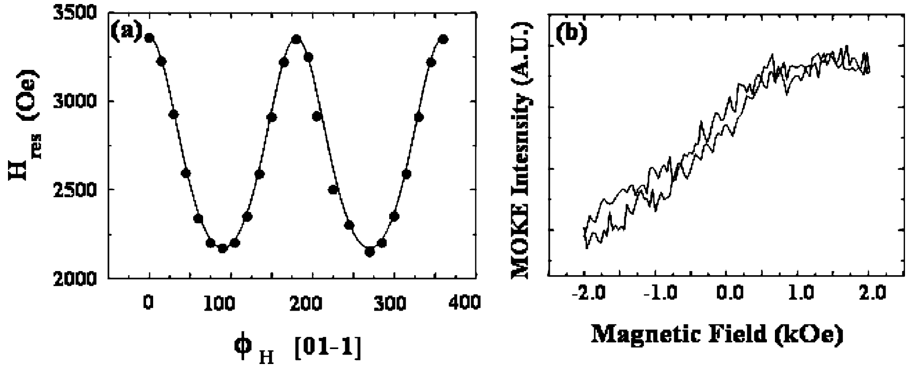

Fig. 2. (a) FMR data of the field H_{res} as function of field orientation angle for a 4.1 ML thick Fe film on GaAs(100). (b) The MOKE loop of a 4 ML Fe film along the [0-11] direction.

$\times$ 10 mm As-desorbed GaAs(100) substrate. The GaAs(100) substrate was of the following structure: As-capping/GaAs (50 nm, n-type, $10^{18}/\mathrm{cm}^3$)/$Al_{0.3}Ga_{0.7}As$ (200 nm, n-type, $10^{18}/\mathrm{cm}^3$)/GaAs(100). Optical lithography was performed on the sample from the backside to open a 200 μm $\times$ 200 μm window. Selective chemical etching was done through the backside window until the AlGaAs layer is reached and then a 30-nm NiFe layer followed by a 10-nm Cr layer was thermally evaporated.

III. Results and Discussion

A. FM/SC Interface and Nanoclusters at the Initial Growth Stages

XMCD measurements were performed on monolayers and sub-ML coverages of Fe on GaAs(100) and on InAs(100). We have found that monolayers of Fe are ferromagnetic at room temperature. In order to gain insight into the Fe/GaAs interface, we have grown submonolayer of Fe films and capped with a 9 ML Co. Fig. 1 represents the normalized x-ray absorption spectra (XAS) taken under opposite applied field directions and the resulting XMCD spectra for 0.5 ML Fe. The XMCD measurements reveal that Fe at the GaAs interface is ferromagnetic as it exhibited a bulk like spin moment of $1.84 \pm 0.21\ \mu_B$ and an enhanced orbital moment of $0.25 \pm 0.05\ \mu_B$. The interface properties, as we know, are an issue for successful spin injection between ferromagnetic layers and semiconductors. In the insert of Fig. 1(b), the STM micrograph of 0.5 ML coverage of Fe shows that Fe atoms form three-dimensional nanoclusters, which are preferably bonded to the Ga dimmer rows of the GaAs(100) surface.

The superparamagnetic phase forms in a narrow thickness range of 3.5–4.8 ML for Fe/GaAs and 2.5–3.8 ML for Fe/InAs, respectively [5], [8]. The exchange interaction within these clusters leads to internal ferromagnetic ordering, thus giving rise to the well-known superparamagnetic phase. Fig. 2(b) shows the superparamagnetic response of the MOKE loop obtain from a 4 ML film. The asymmetry of the MOKE loop might be due to the second order contribution in the MOKE measurement, as discussed in reference [5]. Ferromagnetic resonance (FMR) measurements were carried out to investigate the anisotropy of the nanoclusters. Fig. 2(a) shows the experimental data of FMR field H_{res} as a function of field orientation angle of a 4.1 ML Fe film on GaAs(100) substrate. The measurements show that the nanoclusters have large uniaxial anisotropy with the easy and hard axes parallel to the [0-11] and [011] directions, respectively. Theoretical fitting of the data provides an in-plane uniaxial anisotropy constant as high as 6.0×10^5 erg/cm^3 of for the 4.1 ML sample with zero cubic contribution for the superparamagnetic nanocluster.

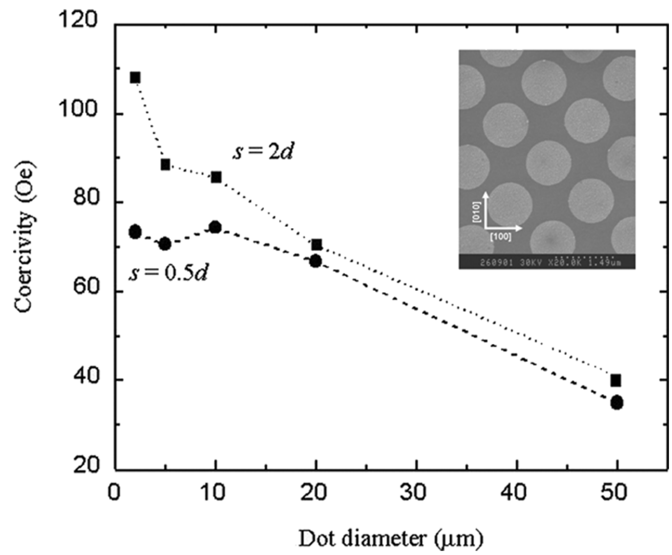

Fig. 3. Effect of interdot separation on coercivity of the Fe dot array with the SEM micrograph as insert. The error bar is comparable with the size of the data points.

B. Patterned Single Crystal Fe Dot Arrays

Patterning an epitaxial film into elements has the advantage of modifying micromagnetic structures via the competing magnetocrystalline anisotropy and dipolar fields [9]. Epitaxial Fe(100) circular dot arrays 30 nm in thickness and of different diameters and separations grown on GaAs(100) have been patterned by e-beam lithography, and studied using magnetic force microscopy and focused magneto-optical Kerr effect. In our study, evidence of the effects of interdot dipole coupling on both the domain structure and the coercivity was found. The coercivity of the dot arrays was found to be dependent on separation s and the diameter d, as shown in Fig. 3 with the SEM micrograph of the

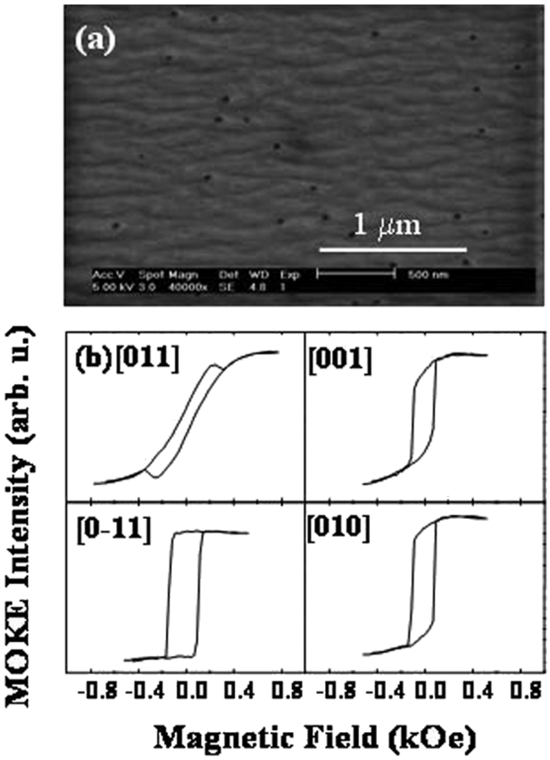

Fig. 4. (a) The SEM micrograph of magnetite nanostripes formed on GaAs(100) substrate. (b) The horizontal axis is parallel to the [011] direction MOKE loops of the Fe nanostripes obtained along four crystallographic directions for a coverage of 4.2 nm.

1-μm dot arrays as insert. The domain structure of the 1-μm-diameter dot arrays also shows the effect of strong interdot coupling when the separation is reduced down to around 100 nm. This provides us with the evidence that interdot dipole coupling affects both the domain structure and the coercivity, illustrating that both the dot diameter and separation are crucial parameters in patterned magnetic data storage media.

C. Magnetite Nanostripes on Deformed GaAs(100)

Half metallic magnetite Fe_3O_4 has recently been attracting great attention as a promising material for spintronics due to its high spin polarization near the Fermi surface and high Curie temperature. We have demonstrated, for the first time, the synthesis of single crystal Fe_3O_4 ultrathin films on GaAs(100) [7]. Here we further show that Fe_3O_4 nanostripes could be formed on deformed GaAs(100) by controlling the substrate processing and postgrowth annealing. Before growth the GaAs substrates were prepared by chemical and thermal treatments with a chevron-featured RHEED pattern observed when the electron beam was along the GaAs(100)[011] direction [10]. Following the growth of Fe this chevron-like pattern becomes less prominent, but it appears again after the oxidation of the Fe into magnetite in 5×10^{-5} mbar oxygen at 500 K for 1200 s. This is due to the formation of the nanoscale magnetite stripes along the [011] direction. The SEM images show that the size of the nano stripes is around 100×600 nm^2 as shown in Fig. 4(a). MOKE measurements reveal that the 4.2-nm sample exhibits uniaxial magnetic anisotropy properties with the easy axis along the [0-11] direction which is perpendicular to the length of the nanostripes. This suggests that the magnetic properties of the nanostripes are controlled by the deformation of the Fe_3O_4 lattice.

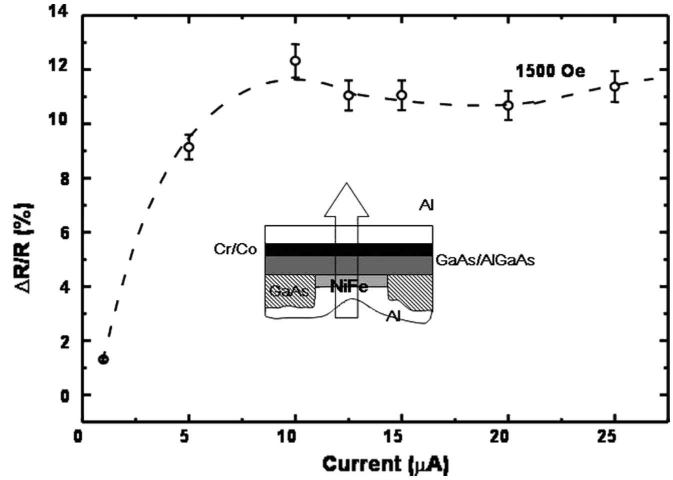

Fig. 5. Magneto-resistance curve of a FM/SC/FM hybrid device. The device structure is shown schematically in the insert. The arrow indicates the direction of current flow.

D. Hybrid Spintronics Devices

The transport measurements were made in a current-perpendicular to plane (CPP) geometry from NiFe to Co layer through the AlGaAs/GaAs layer. The most striking feature is a biasing-dependent MR characteristic, as shown in Fig. 5. At low bias current, the MR is negligible. However, beyond a critical current of 5 μA, the MR increases. A maximum change of about 12% in the MR is observed. This is a large change compared to ordinary anisotropic magnetoresistance (AMR) effects measured at room temperature. As the MR becomes stable beyond a critical current, it rules out the possibility that the MR could be resulting from the Lorentz force. On the contrary, the MR depends on bias current, and as we have a sandwich structure with a SC layer between two FM layers, these direct MR measurements indicate a large room temperature spin injection and detection through the semiconductor layers, as recently suggested by optical spin detection [11].

IV. Conclusions

We have shown the growth of hybrid mesoscopic ferromagnetic/semiconductor structures by conventional lithography and epitaxial mesoscopic growth techniques. These ferromagnetic micro/nano scale structures behaves in different ways depending on the detailed fabrication/growth process and should have potentials to become materials for future spintronics as they are integrated with semiconductors and their sizes could go down to nano/atomic scales. We have also shown that FM/SC/FM vertical spintronic device could produce room temperature MR as high as 12% and could be useful for field sensor applications, for example.

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