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Fabrication and magnetic characterization of nanometer-sized ellipses of the ferromagnetic insulator EuS

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The magnetic properties of ferromagnetic elements can be tailored by making use of the shape anisotropy of finite-size systems. One material class of particular interest are ferromagnetic insulators, which can be used as spin filters for spintronics applications. Here we present a way to fabricate nanoscale ellipses of the ferromagnetic insulator europium sulfide (EuS) and investigate their magnetic properties. We observe a distinct influence of the magnetic field orientation on the shape of the magnetization curve. This could be used to separately control the individual magnetic elements of a magnetoresistive device using a ferromagnetic insulator.

1. Introduction

The possibility to use the spin of the electron for electronics applications forms the basis of spintronics and is an active field of present research due to both its fundamental insight into electronic transport as well as its important applications [1]. In tunneling devices, a high spin polarization can be created in different ways (for a review see [2] and references therein), either by using highly spin-polarized materials like half-metals [3], by using symmetry filtering in epitaxial MgO tunnel barriers [4], or by using an insulating, but spin-selective tunnel barrier. Europium chalcogenides are known to work as efficient spin filter materials due to their intrinsic exchange field which produces different tunnel barrier heights for spin-up and spin-down electrons [5–8].

Here, we present a study of the magnetic properties of lithographically fabricated nanometer-sized ellipses of the ferromagnetic insulator EuS. In particular, we discuss the effect of aligning the magnetic field in the plane of the film parallel and perpendicular to the long axes of the ellipses in order to provide a route to control the relative orientation of the magnetization of nanoscale EuS ellipses. The data are compared to data obtained for the corresponding EuS films.

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2. Preparation and characterization of EuS thin films

2.1. Preparation of EuS films

The first reports of preparation of EuS thin films date back to the 1970s [9–11]. Kohne et al. [10] mention the need for the substrate to be heated to substrate temperatures $T_S \geq 800$ K to obtain stoichiometric EuS films. Saftić et al. [11] report that epitaxial films were obtained on silicon substrates at $T_S = 900$ °C of different crystal orientations and show that on Si (111) the magnetocrystalline anisotropy of the EuS film is almost zero.

Therefore, we used (111)-oriented, p-doped Si wafers, which were first etched in a buffered HF solution to remove the native oxide prior to the installation of the wafer on the heatable sample stage of a ultra-high vacuum deposition chamber with a base pressure of 5×10^{-9} mbar. The substrate was held at $T_S = 800$ °C during the deposition. The EuS film was grown by thermal evaporation of EuS powder (purity 99.9% by ChemCo GmbH) from an *e*-beam heated tungsten crucible at a rate of ≈ 0.3 A/s [12].

2.2. Structural and magnetic characterization of EuS films

Fig. 1(a) shows a $\theta - 2\theta$ X-ray scan of the resulting EuS film on a semilogarithmic scale (Cu K_α radiation, $\lambda = 1.54$ Å). Red lines indicate the positions of the EuS peaks according to the bulk lattice constant $a_0 = 5.968$ Å [13]. Blue lines indicate reflections from the (111)-oriented Si substrate. The highest intensities are found for EuS(nnn) reflections, despite two peaks with lower intensity indicated as EuS(200) and EuS(400). By comparing the

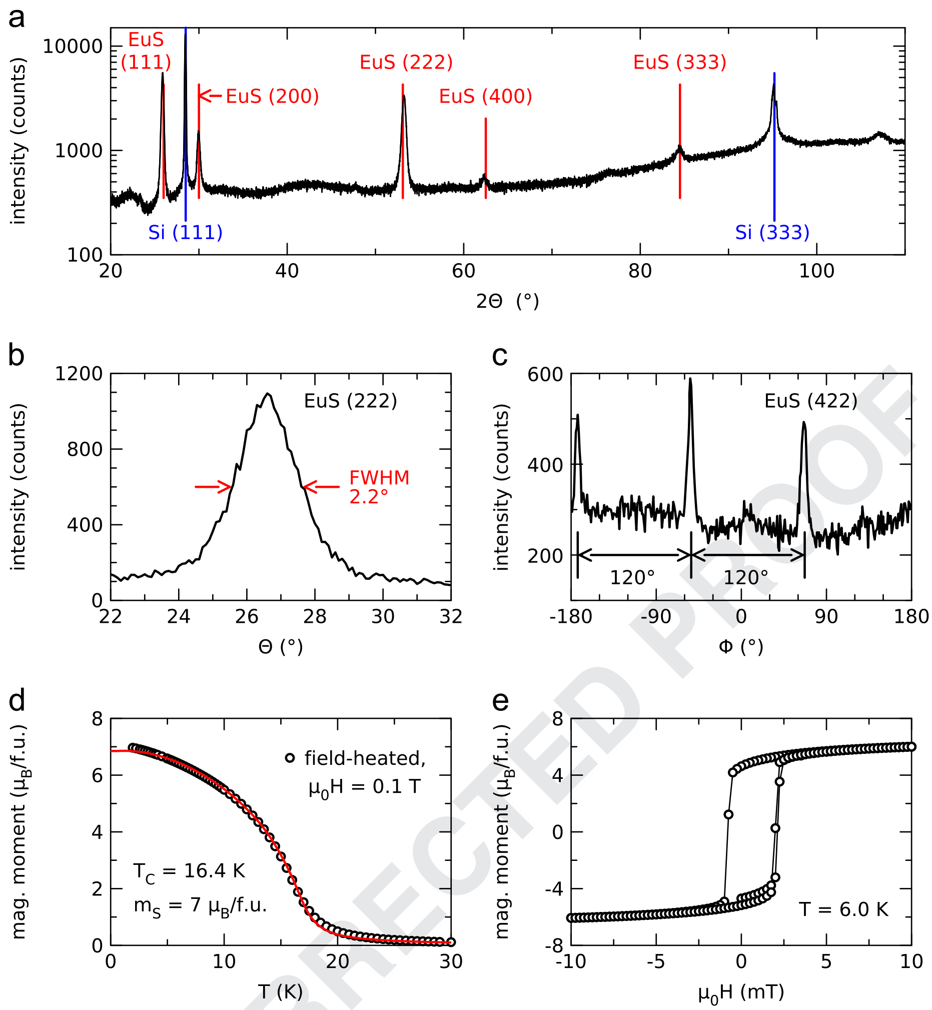

Fig. 1. Structural (a–c) and magnetic (d+e) characterization of a 44 nm thick EuS film (film A). (a) $\theta-2\theta$–Scan. The substrate was tilted by 1° against the symmetric θ–position to suppress the strong Si substrate peaks. (b) Rocking curve across the EuS(222) diffraction peak. (c) Azimuthal scan (ϕ-scan) of the EuS(422) diffraction peak. (d) Temperature dependence of the magnetization M at $\mu_0 H = 0.1$ T in the film plane. (e) Hysteresis curve at $T=6$ K. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

measured intensities of the EuS(111) and EuS(200) reflections to the tabulated reference intensity data for powder samples from the International Center for Diffraction data (ICDD) [14], we estimate the degree of texture along ⟨111⟩ to 90%. The good EuS film quality is also seen in the rocking curve of the EuS(222) peak, shown in Fig. 1(b), where a FWHM of 2.2° is observed.

Furthermore, Fig. 1(c) shows an azimuthal ϕ-scan around the (422) reflection with three pronounced, equally spaced intensity maxima upon rotating the sample by 360° around the film normal as expected for a (111)-oriented NaCl-type crystal structure. For a random in-plane orientation of the grains, no pronounced maxima are expected [15] thus the ϕ-scan identifies an in-plane texture with threefold symmetry of the EuS film.

The magnetization M of the EuS film was measured at low temperatures using a commercial SQUID magnetometer with the applied magnetic field oriented in the plane of the film.

Fig. 1(d) shows the temperature dependence of M. The saturation magnetization and the mean field parameter λ are used for a fit to the data according to the mean-field model [16]

$$\frac{M}{M_S} = B_J(y) \quad \text{and} \quad y = \frac{g_J \mu_B J(B+\lambda M)}{k_B T} \qquad (1)$$

where $\lambda M = B_{mf}$ is the molecular field, M_S is the saturation magnetization and $B_J(y)$ is the Brillouin function for angular momentum J.

We obtain an excellent fit with saturation magnetization $M_S = 7\mu_B$/f.u. and Curie temperature T_C=16.4 K in good agreement with bulk EuS [13] and results from thin films [8,10,12,17].

The hysteresis loop, shown in Fig. 1(e), was measured at T=6 K and exhibits an almost rectangular shape, characteristic for a Heisenberg ferromagnet, and a low coercive field $\mu_0 H_c = 1.7$ mT, comparable with values from Refs. [8,10,17]. Small shifts of the hysteresis curves along the $\mu_0 H$–axis of the order of ≈ 2 mT are due to the remanent field of the superconducting solenoid and are neglected in the discussion.

3. Nanopatterning of EuS ellipses

3.1. Fabrication of nanoscale EuS ellipses

During the course of this project we discovered that thin aluminum films can be used as etch masks due to the durable aluminum oxide passivation layer which is immediately formed once the aluminum film is exposed to air. This was used in the following nanopatterning process. In a first step, the EuS film was covered with a conventional *e*-beam resist (both PMMA-MAA copolymer masks as well as PMMA masks were tested) in which the structures were written by conventional *e*-beam lithography. After development in a MIBK:IPA solution for 25 s, 30 nm of Al