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Stray fields above artificial magnetic in-plane domains

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ABSTRACT

The out-of-plane component of the magnetic stray field over a magnetically patterned exchange biased layer system was quantitatively determined by scanning μ-Hall measurements. These were performed over a $Cu^{50\ nm}/Ir_{17}Mn_{83}{}^{10\ nm}/Co_{70}Fe_{30}{}^{5\ nm}/Au^{8\ nm}$ layer system patterned by light-ion bombardment induced magnetic patterning. The system consists of artificial 5 μm wide magnetic parallel-stripe domains with head-to-head/tail-to-tail magnetizations in adjacent domains. The experimental data were taken within a height range relevant for magnetic micro-particle transport (0.75–2.65 μm). We fit the experimental results by two different simulation approaches and discuss the feasibility of extrapolating the simulations to even closer surface distances. The models are used to extract stray field data as they would be measured by an ideal point-like probe.

1. Introduction

Magnetic field landscapes (MFLs) emerging from micron or submicron sized magnetic domains or from topographic micromagnets are suitable to efficiently position [1] and transport magnetic micro- and nano-objects in liquids, and therewith provide a versatile potential for a manifold of lab-on-a-chip applications [2–8]. For designing such devices, however, quantitative knowledge of the emerging MFLs very close to the surface is indispensable, since they determine the forces on the transported magnetic objects. The experimental quantification of the MFLs as a function of lateral position and height above a magnetic surface is difficult at small distances because size, positioning accuracy and spatial resolution of the field sensor must match the length scale of the magnetic field's alteration. For magnetic patterns suitable for micro- or nano-object transport these constraints require a sensor with positioning accuracy and resolution at the submicron level which implies a sensor sensitive area of about 1 μm^2 or less. At the same time the sensor must provide a sufficiently high magnetic response to measure at least one component of the MFL, which is expected to be well below one mT at the distances of interest. As this study should quantify magnetic fields for possible applications at room temperature, techniques requiring cryogenic temperatures like SQUID measurements are excluded. Methods fulfilling these conditions are quantitative magnetic force microscopy (qMFM) [9], nitrogen vacancy (NV) center magnetometry [10,11], scanning magnetoresistive microscopy [12] and μ-Hall probe microscopy [13]. Here we present a quantitative determination of the stray field *z*-component (perpendicular to the sample surface) strength as a function of lateral position and height over the surface by μ-Hall probe microscopy. The measurements were performed in planes parallel to the sample surface at distances between 0.75 μm and 2.65 μm.

The intentionally engineered domain pattern is a topographically flat layer system consisting of 5 μm wide parallel-stripes with head-to-head/tail-to-tail magnetization perpendicular to the domain walls in adjacent domains [Fig. 1(a)]. These samples were fabricated by light-ion bombardment induced magnetic patterning (IBMP) in exchange biased (EB) layer systems [14,15]. This technology is extremely promising for the design of MFLs as the domain geometries and their in-plane magnetizations can be set independently, thus enabling the tailoring of the magnetic charges close to the corresponding Néel walls [16]. Several sophisticated methods for the modelling of magnetic stray fields are

Abbreviations: MFL, Magnetic field landscapes; IBMP, ion bombardment induced magnetic patterning; EB, exchange biased; ub, unbombarded; b, bombarded

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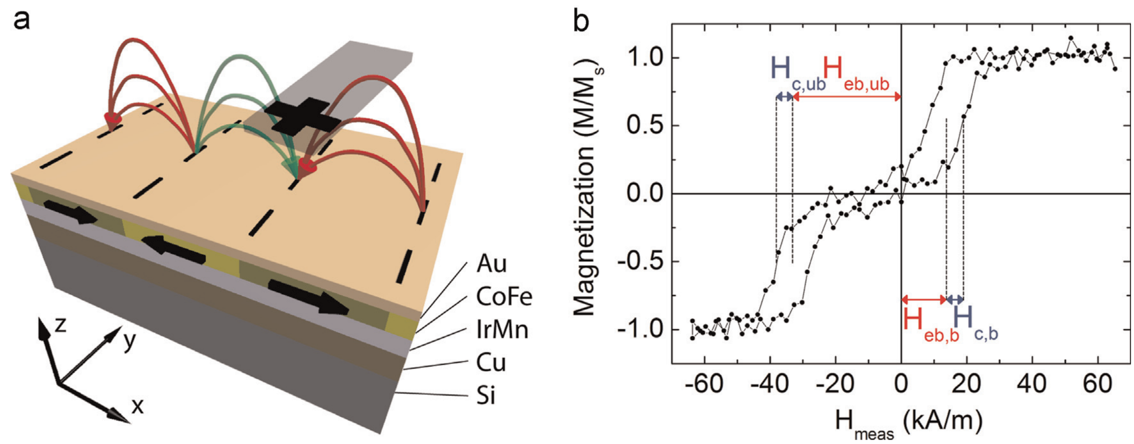

Fig. 1. Scheme of the used sample and measurement of its magnetic properties. (a) Schematic view of the exchange biased (EB) layer system (IrMn: antiferromagnetic; CoFe ferromagnetic), its artificial remanent magnetic domain pattern and the magnetic stray fields above the sample surface. Additionally, a sketch of the microscopic Hall sensor and its orientation is shown. (b) Magnetic hysteresis curve for this EB system measured using vibrating sample magnetometry. The measuring field H_{meas} is oriented parallel to the *x*-axis, $H_{eb,ub}$ and $H_{eb,b}$ indicate the exchange bias fields of the unbombarded (ub) and bombarded (b) areas, while $H_{c,ub}$ and $H_{c,b}$ denote the corresponding coercive fields.

currently available [17,18], some with the limitation, however, that they can only be applied to particular material systems [19]. In the present work, the experimental data will be used to evaluate two different, more general modelling methods: the finite element toolbox *CST*-studio and an analytic model [20,21].

2. Methods

The EB thin film system $Cu^{50\ nm}/Ir_{17}Mn_{83}{}^{10\ nm}/Co_{70}Fe_{30}{}^{5\ nm}/Au^{8\ nm}$ was fabricated by rf sputter deposition (*Leybold-Hereaus Z400*) at a base pressure of 10^{-6} mbar on a naturally oxidized square shaped silicon substrate, with an edge length of about 10 mm. The exchange bias effect was initialized by field cooling with a temperature plateau of 300 °C for 1 h, followed by cooling down to room temperature at a rate of 4 °C/min. This leads to an in-plane exchange bias field of $H_{eb,ub} = (-32.6 \pm 2.4)$ kA/m and a coercive field of $H_{c,ub} = (5.6 \pm 1.6)$ kA/m. Then, an approx. 750 nm thick photo resist (AZ-1505 from *MicroChemicals*®) was spin coated and irradiated by UV radiation (Hg lamp) through a shadow mask. After development of the resist in a 0.9% KOH solution a parallel-stripe structure results, consisting of 5 μm wide resist-covered and 5 μm wide resist-free stripes both having their long axes perpendicular to the initial EB field direction. The thickness of the resist was chosen to prevent 10 keV He^+ ions to reach the sample surface in the subsequent bombardment step [14,15,22–24]. The ion bombardment was performed through the resist mask using a home-built plasma source [25]. During bombardment an in-plane magnetic field of about 72 kA/m antiparallel to the initial EB field direction was applied, changing the in-plane magnetization to the opposite direction in the resist-free areas. This field is thus imprinted and leads to a magnetic stripe pattern with head-to-head and tail-to-tail orientation of the remanent magnetizations in adjacent domains [see Fig. 1(a)]. Finally, the photo resist was removed by sonication in 3% KOH solution and rinsing with acetone, isopropanol and water. The end result is a flat sample surface with a magnetic pattern and stray fields above the sample surface as shown in Fig. 1(a). The magnetization reversal of the complete magnetically patterned layer system was characterized by vibrating sample magnetometry [Fig. 1(b)], showing a double hysteresis loop where the right loop (IBMP modified areas) has an EB field of $H_{eb,b} = (12.7 \pm 2.4)$ kA/m and a coercive field of $H_{c,b} = (4.8 \pm 1.6)$ kA/m, while the left loop (unbombarded areas) stays stable.

Scanning μ-Hall probe microscopy was carried out with a RT-SHPM from *NanoMagnetics Instruments Ltd.*® in Lift-off mode. The sensitive area of the GaAs/AlGaAs Hall sensor measured about 1×1 μm^2 and was contacted by gold electrodes. The sensor was oriented approximately parallel to the sample surface [Fig. 1(a)] with a slight tilt of 2°. It is therefore mainly sensitive to the *z*-component of the magnetic stray field. Due to the size of the probe all data displayed represent stray field values that are laterally averaged over 1 μm² [26]. The influence of the geometric details of the μ-Hall sensor, like its exact shape and its charge depletion from the rounding of the edges [27], was taken into account by reducing its physical size to its effective size, following Refs. [26,28]. The response of the sensor is assumed to be linear over the size of this reduced active area [26]. The measured magnetic field strength is also averaged over the effective thickness of the active layer (about 10 nm) [29]. Exploratory simulations showed, however, that averaging over this intrinsic height range can be neglected in the investigated system.

The Hall probe was calibrated using an external magnetic coil producing a well-defined variable magnetic field at the position of the sensor. The distance of the Hall sensor above the sample surface was accurately determined by an STM tip, which was attached to the probe. In order to guarantee that the STM tip was closest to the surface, the whole sensor head, consisting of both the STM tip and the Hall probe, was tilted by 2° with respect to the sample surface. From the distance between STM tip and Hall sensor (14.3 μm) and the tilt of the unit a minimum distance between the Hall sensor head to the sample surface was determined to be 500 nm. The active layer of the sensor is buried 150 nm deep below its surface. Additionally, in order to avoid tunnel currents during the Hall measurements the tip was 100 nm retracted after approach of the STM tip to the surface (detecting a tunneling current of 0.5 nA at 1.5 V). Such currents would influence the detected Hall voltage introducing unacceptable systematic errors. In summary, using this set up magnetic stray fields can be determined down to a minimum distance of 0.75 μm from the surface. 2D microscopy scans were thus performed within different planes of constant height (varied between 0.75 μm and 2.65 μm) above the surface (Fig. 2). The 2D scanning was performed in lateral steps of 60 nm in *x*- and *y*-direction. Each measurement at a defined height consisted of 5 consecutive quantitative measurements of the *z*-component of the MFL, which were then averaged.