

# Bragg magneto-optical investigation on lithographically defined stripe-arrays in epitaxially grown (110) YFe<sub>2</sub> films

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Large-area-micron-sized striped arrays of epitaxial (110) YFe<sub>2</sub> single crystal films are fabricated by photolithography. Bragg magneto-optical Kerr effect (MOKE) measurement is performed to investigate the reversal property of the arrays. Various different shapes of MO Kerr loops with a rich set of additional features are revealed, correlated with an induced shape demagnetizing effect and an intrinsic magnetic switching behavior. In the diffracted loops, the intrinsic switching behavior signifying the domain movement in the vicinity of the coercivity can be replicated or even amplified when the applied field is parallel to the stripes. In particular, when the field is applied perpendicular to the edge of stripes, before a field-aligned saturated state a two-step procedure involving coherent rotation from the center and subsequent magnetization rotation from the edges of the stripes can be clearly distinguished.

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## 1. Introduction

The recent rapid advances of lithographic technology provide a powerful tool to fabricate periodic elements in reduced dimensions with controllable size, shape or spacing [1-3]. The periodic structures such as arrays or dots have received lots of attention due to the potential applications in data storage [4]. From a fundamental point of view, the understanding of the magnetization reversal process of micro-structured magnetic patterned media is of crucial importance to the development of a new magnetic or magneto-optical storage device. Bragg (or diffracted) magneto-optical Kerr effect (MOKE) is most suitable to investigate the magnetization variation of small elements due to its high sensitivity to the magnetic inhomogeneities of local regions [5-6]. This technology can provide not only the information on the mean lateral magnetization distribution [7] but the variation of domain structure during reversal [8] in patterned films with 1D or 2D structures. Also, pronounced different shapes have been observed in the diffracted loops of different orders. This is correlated with the dependence on the order of diffracted beam of the sensitivity to the different order Fourier component of the magnetization distribution as well as the optical interference effects [7-9].

Single crystal rare earth Laves phase intermetallic (RE-Fe<sub>2</sub>) films, epitaxially grown by MBE, have been a hot topic for their potential in a wide range of applications including in permanent magnets, in magnetic data storage media, and in exchange spring magnets *etc.* Very recently we have showed that an uniaxial shape anisotropy can be

effectively induced by the patterning in single-crystal YFe<sub>2</sub> and DyFe<sub>2</sub> (110) films [10]. Moreover, the directions of easy axis and hard axis of YFe<sub>2</sub> films can be tuned by the patterning. In this paper, we further report the MOKE measurements in diffracted geometry performed on large area-micron-sized striped arrays of YFe<sub>2</sub> films defined by UV lithography. A rich set of additional features in various diffracted MO loops is witnessed due to the high sensitivity of Bragg MOKE and can be fully explained in terms of a dominant induced shape demagnetizing effect and an intrinsic magnetic switching behavior.

## 2. Experiment

Single crystal (110) YFe<sub>2</sub> films with a thickness of 400 nm are grown epitaxially on (11-20) sapphire substrates epi-prepared with a 75 Å Nb buffer and a 20 Å Fe seed layer by molecular beam epitaxy (MBE, Balzers UMS 630 UHV facility) as described before [11]. Three typical patterns with a large scale size are fabricated using a laser direct writing system (LSM 150, Zeiss) and wet-etching process. Stripes are patterned along intrinsic easy-axis [-111], intrinsic hard-axis [001] (of 55° with respect to the easy-axis direction) and intermediated [-110], respectively. The patterns are checked with scanning electron microscopes (SEM, LEO 1455VP). As an example in Fig. 1 the SEM shows one striped array patterned along [-110]. Each stripe is 6.5 μm in width and 1 mm in length. The space between two stripes is 13.5 μm. The total size of the patterned region is 1 mm × 1 mm.

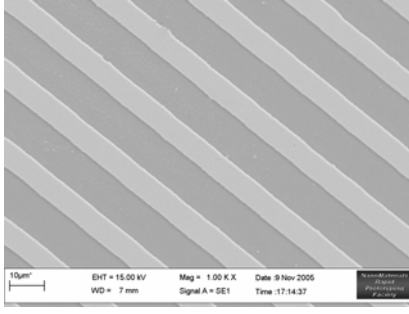


Fig. 1. SEM image of a striped array in a (110)  $\text{YFe}_2$  film. The striped array patterned along  $[-110]$  is exemplified here. Each stripe is  $6.5 \mu\text{m}$  in width and  $1 \text{ mm}$  in length. The space between two stripes is  $13.5 \mu\text{m}$  and the height of the structure is  $400 \text{ nm}$ .

The MOKE measurements on the unpatterned and patterned films are performed in the same setup schematically shown in Fig. 2. A longitudinal configuration using s-polarized light from a He-Ne laser ( $\lambda=633 \text{ nm}$ ) is employed. The incident angle of laser beam is fixed to be around  $15^\circ$  and a focused spot on the sample is achieved to be about  $150 \mu\text{m}$  in diameter. The reflected light from the unpatterned films is measured by a photodiode detector with a built-in amplifier. For the patterned samples, diffracted loops of zeroth (specular reflection), first and second orders are measured individually by positioning a photodiode detector, respectively. The magnetic field is directed in the plane of incidence and parallel to the sample surface. A Hall probe is used to determine the magnitude of the applied field. For each array, two critical perpendicular geometries, i.e., the field applied parallel and perpendicular to the axis of the stripes, are chosen to measure.

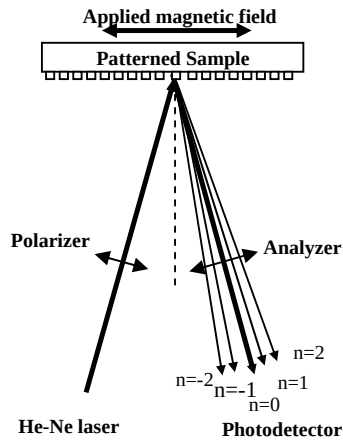


Fig. 2. Schematic diagram of Bragg MOKE setup in the longitudinal configuration. An s-polarized light from a He-Ne laser ( $\lambda=633 \text{ nm}$ ) with an incident angle of about  $15^\circ$  is diffracted by the patterned sample. Diffracted loops of 0th (specular reflection), 1st and 2nd orders are recorded by positioning the photodetector, respectively. Two typical geometries of an external magnetic field, applied parallel and perpendicular to the long axis of stripes, are performed here.

### 3. Results and discussion

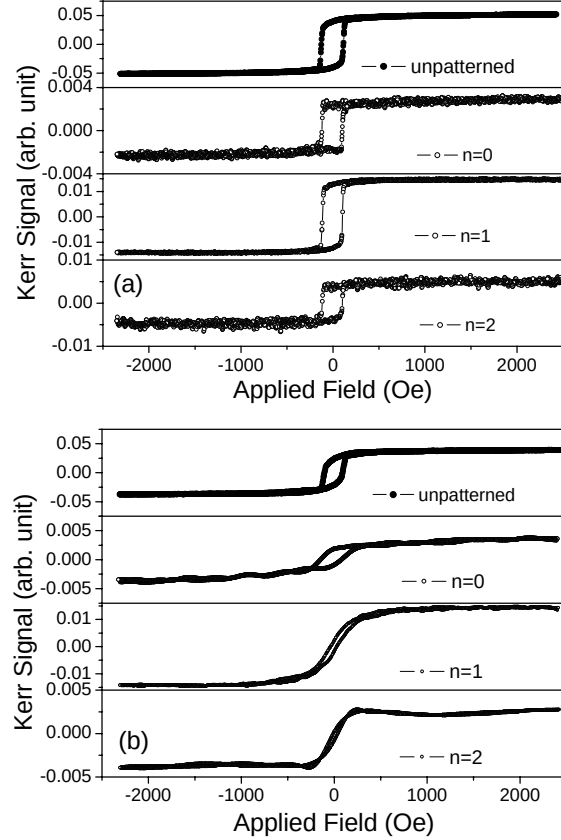


Fig. 3. Bragg-MOKE measurements on the stripe array patterned along  $[-111]$  direction, a) and b) are the measurements carried out with the field applied parallel and perpendicular to the  $[-111]$  directions, respectively. A counterpart loop measured on an unpatterned film with the same thickness serves as a reference.

Fig. 3 is the Bragg-MOKE measurements on the striped array patterned along the intrinsic easy-axis  $[-111]$  direction. Fig. 3a and b show the results of the measurements carried out with the field applied parallel and perpendicular to the edge of stripes, respectively. All the loops in Fig. 3a have a high remnant ratio, indicating an easy magnetic direction. A round turning in the diffraction loop with  $n=1$  is still visible at a field slightly higher than the coercivity. This is in line with the intrinsic switching behavior signifying a domain growth process in the unpatterned sample. The original easy axis direction  $[-111]$  is retained. However, diffracted loops of different shapes in Fig. 3b are obtained when the field is applied along  $[1-12]$  direction, i.e., perpendicular to the edge of stripes. Essentially, all the diffracted loops possess a low remnant ratio, indicating a hard magnetic direction. The diffracted loop of  $n=0$  shows nearly ideal linear behavior, implying the coherent rotation of a typical hard axis measurement. However, a rather different shape in the

diffracted loop of  $n=1$  is demonstrated, characterized by a combination of a slim middle loop and two long symmetric subloops. The subloops, starting at the field of  $\pm 250$  Oe and vanishing at  $\pm 1500$  Oe, can be attributed to the movement of the closure domain formed at the edges of the stripes arising from a large shape demagnetizing effect, which was determined to be of the same order of magnitude of  $10^5$  erg/cm<sup>3</sup> as the intrinsic anisotropy [10]. The closure domain was therefore formed to reduce the total magnetic energy, which was previously revealed by both Kerr microscopy and micromagnetic simulations [12-15]. Simultaneously, overshoots are detected in the diffracted loop with  $n=2$  also at a field of  $\pm 250$  Oe. Similar anomalous loops were previously reported and can be associated with the magnetic domain structure in ferromagnetic dot/antidot arrays, as revealed by Bragg-MOKE method [7-9]. This is in consistent with our results, i.e., the occurrence of the subloop and overshoot after the magnetization reversal of the central part of the stripes. Consequently, the features eventually disappear with the completion of the reversal from the edges, i.e., magnetization saturation at a sufficient field up to 1500 Oe. Two continuous processes are involved during the measurement with the applied field perpendicular to the edge of the stripes, i.e., the initial magnetization rotation process relating to the inner loop and the subsequent reversal process of the edges relating to the subloop or overshoot, as we witnessed in the higher order diffracted loops.

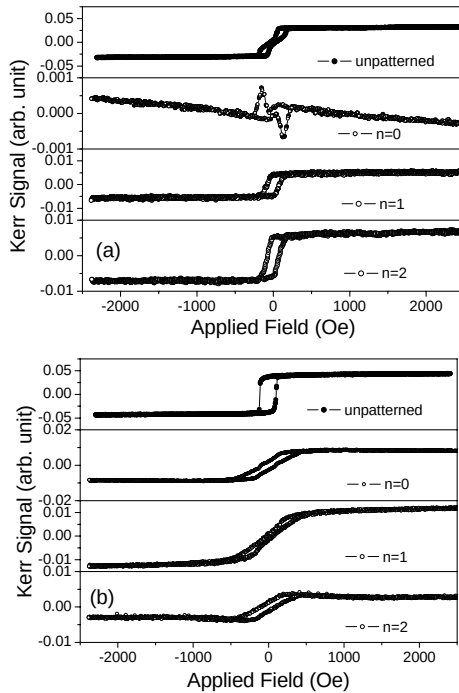


Fig. 4. Bragg-MOKE measurements performed on the film patterned along the [001] direction, a) and b) are the results measured when the field is applied parallel and perpendicular to the [001] direction, respectively.

Fig. 4 shows the Bragg-MOKE measurements performed on the film patterned along the intrinsic hard-axis [001] direction. Fig. 4a and b are the results measured when the field is applied parallel and perpendicular to the [001] direction, respectively. All the diffracted loops measured along the [001] direction are characterized with a high remnant ratio and a large coercivity. This confirms that the uniaxial anisotropy dominates the intrinsic anisotropy. A rather different character is seen in the diffracted loop with  $n=0$ . The two spikes with an considerable amplitude, imposed upon the inner loop with a high remnant ratio but a low intensity, occur at the field of  $\pm 130$  Oe. This combinatory loop reflects a superposition of a uniaxial anisotropy and an intrinsic anisotropy. A dominating uniaxial anisotropy accounts for the high remnant ratio of the inner part in the case that the applied field coincides with the uniaxial anisotropy direction. A strong reduction of two orders of magnitude in the intensity of the Kerr signal in the specular loop, which was earlier observed in Ni-stripe arrays [12], is believed to correlate with a destructive interference effect from the stripe gratings [16,17]. Therefore, the spikes, correlated with the intrinsic switching behavior, are highlighted due to the minimized background signal from the normal loop. This explanation further supported by the fact that spike occurs at the field higher than the coercivity, replicating the switching behavior of an intrinsic hard axis. When the field is applied along the [-110] direction perpendicular to the edge of stripes, all the diffracted loops obtained are slanted in Fig. 4b. A subtle deviation of linear behavior in the first diffraction loops, starting at  $\pm 170$  Oe, is discernible. Again, this nonlinear behavior in the loops indicates the switching of domain at the edge of the stripes. However, the saturation field is now observed only around 500 Oe in the first diffracted loop in Fig. 3b. In our case, the [-110] direction perpendicular to the edge of the stripes, is close to intrinsic easy axis. When the applied field is in this direction, a large intrinsic anisotropy strongly reduces the demagnetizing shape effect. The competition of anisotropy corresponds to a strong reduction in the field required to complete the magnetization movement of domains at the edges of the stripes, as observed experimentally.

Fig. 5 shows the Bragg MOKE measurements performed on the stripe arrays patterned along the [-110] direction. Fig. 5 a and b are the measurements performed with the field applied parallel and perpendicular to the [-110] direction, respectively. In Fig. 5a, all the diffracted loops possess a high remnant ratio. The induced uniaxial anisotropy dominates the intrinsic anisotropy making [-110] an easy magnetic direction. Subloops, superimposed on the normal middle loop, are clearly observed, in the zero and first order loops. These indicate domain growth in the vicinity of the coercivity, reflecting the intrinsic behavior of the unpatterned film. Slanted loops are observed when the field is applied along the [001] direction in Fig. 5b, indicating a hard magnetic direction. Long subloops, corresponding to the movement of the

edge domain, are seen in the diffracted loop of  $n=1$ . These finally disappear when the magnetization reaches saturation at a field around  $\pm 1500$  Oe. Again, a two-step process before a saturated field-aligned state is witnessed.

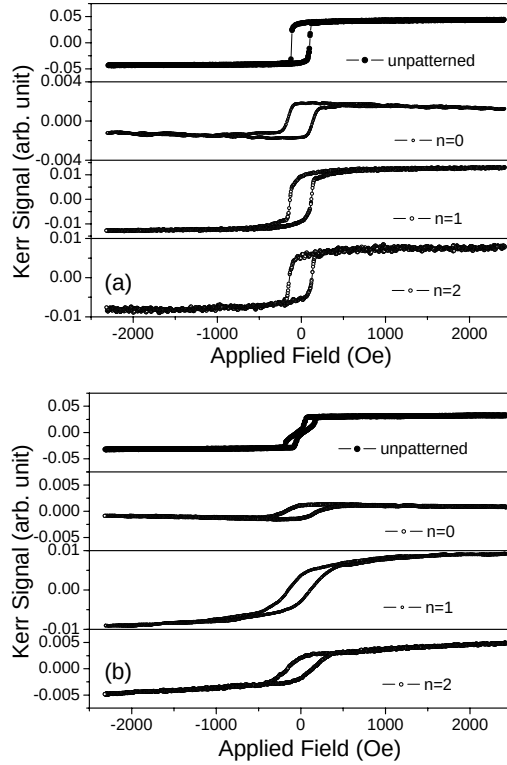


Fig. 5. Bragg-MOKE measurements performed on the stripe arrays patterned along the  $[-110]$  direction, a) and b) are the measurements carried out with the field applied parallel and perpendicular to the  $[-110]$  direction, respectively.

#### 4. Conclusions

In summary, an average switching behavior of the stripes in the arrays are measured by MOKE rig in diffraction geometry. A variety of different shapes of loops including additional features such as overshoot, spike, and subloops, are observed due to a high sensitivity of the diffracted MOKE technology to the higher-order MO effect and the domain structure by effective removal of the background noise in the diffraction geometry. The additional features, associated with the domain movement, can strongly alter the basic shape of the MO loops. Meanwhile, the signal from the movement of the edge domain can be effectively amplified by the Bragg MOKE method. Particularly, in the case when the field is applied perpendicularly to the edge of the stripes, two separated procedures of coherent rotation from the center and edges of the stripes can be well distinguished before a full saturated field-aligned state is obtained.

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