

# Magnetic domain structure investigation of Bi: YIG-thin films by combination of AFM and cantilever-based aperture SNOM

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**Abstract.** We present the results of magnetic domain structure investigation by combination of atomic force microscopy (AFM) and scanning near-field optical microscopy (SNOM). Special hollow-pyramid AFM cantilevers with aperture was used. This combination allows us use same probe for both topography and domain structure visualization of Bi –substituted ferrite garnet films of micro- and nano-meter thickness. Samples were excited through aperture by tightly focused linearly polarized laser beam. Magneto-optical effect rotates polarization of transmitted light depend on domain orientation. Visualization of magnetic domains was performed by detecting cross polarized component of transmitted light. SNOM allows to obtain high resolution magnetic domain image and prevent sample from any disturbance by magnetic probe. Same area SNOM and MFM images are presented.

## 1. Introduction

A specific place among magnetic thin film materials belongs to bismuth-substituted ferrite garnet (Bi: YIG) films due to their unique optical (high transparency) and magneto-optical (large intrinsic magneto-optical activity) in the visible and near-infrared wavelength region of optical spectrum [1-2]. It determines its efficiency in different areas of applications [3-6]. Investigation of magnetic domain structure and its properties in nano-scale level is important to understand magnetic structure behavior. There are a lot of tools designed to investigate magnetic structure and properties of these objects [7-9]. Atomic force microscopy (AFM) is a powerful tool for study different nanostructures. One of the most popular and widely used methods of AFM is magnetic force microscopy (MFM), enables us to study not only topography but magnetic structure of different kind of samples with high spatial resolution [10,11]. MFM is based on the principle of magnetic interaction between a micromechanical probe (cantilever) and sample surface.

There are a number of factors that negatively affect the quality of the MFM images and limits this technique: electrostatic tip-sample interaction, external magnetic field, cantilever magnetic coating material properties: its rigidity, the thickness of the magnetic coating, and others [12,13]. Meanwhile Kerr and Faraday optical effects are well known for a long time. Special microscopes for magnetic structure visualization were designed based on these effects [14]. Lateral resolution of these method is limited by diffraction limit and typically not exceed 0.5  $\mu\text{m}$ . Sub-wavelength resolution could be achieved by scanning near field optical microscopy (SNOM). The combination of the best sides of



these two methods (AFM and Faraday/Kerr SNOM) could allow us precisely investigate domain structure of thin films in nano-scale level.

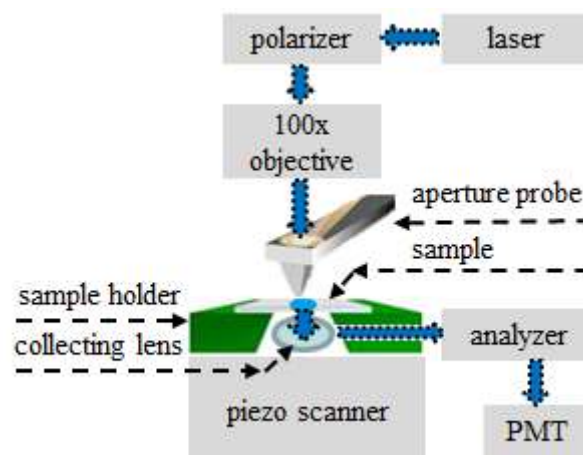
SNOM itself is also well known as a method of magneto-optical visualization of magnetic samples [12-18]. Different types of experimental setup were presented (illumination through the hole [12,13], photon scanning tunneling magneto-optical microscopy [14,15] and apertureless scattering [13,19,21]). The most common SNOM configurations based on fiber probes with metal coating. The weakness of these probes is fragility and complicated behavior in shear-force mode [22]. Combination of AFM and cantilever-based SNOM allows use strongly reproducible silicon cantilevers instead of fibers probes. Feedback system in AFM mode is precise and reliable compare to shear-force feedback system [11,22].

## 2. Experiment

### 2.1. Experiment scheme

Special hollow-pyramid AFM cantilever with aperture was used. Cantilever aperture was performed by focused ion beam etching at the centre of pyramid with diameter of 50 – 150 nm. These probes are designed both for contact and tapping AFM modes. Cantilever probes demonstrate high thermal stability under strong excitation laser power. 20 mW of 473 nm laser beam was tightly focused in to the aperture. No degradation was observed. High durability of probes allows to operate in contact mode for rigid samples. Delicate samples could be measured by tapping mode.

AFM head with build-in 100x, 0.7 NA objective allows tightly focus laser beam and position it on the cantilever aperture. 1064 nm was used in AFM deflection system to avoid interference. Sample was illuminated through cantilever aperture by linearly polarized laser beam in near field. Probe holder was designed with hole at the centre for light transmission from laser to PMT. Sample holder was mounted onto piezo scanner as showed on figure 1.



**Figure 1.** Scheme of AFM and cantilever-based aperture SNOM combination.

Cantilever approaches to the sample surface by step motor. After approaching tip-sample distance is controlled by AFM feedback system. Piezo scanner moves the sample under cantilever line by line (scan area up to 100  $\mu\text{m}$  x 100  $\mu\text{m}$ ). “Objective-cantilever-collecting lens” system position is constant independent on scanner moving.

## 2.2. Samples description

Two types of Bi: YIG films were designed for the measurements.

### 2.2.1. LPE-film.

The films of nominal composition  $(\text{Bi,Gd,Lu,Ca})_3(\text{Fe,Ga,Ge})_5\text{O}_{12}$  and "easy axis" (i.e. normal to the film plane) magnetic anisotropy were synthesized by means of liquid phase epitaxy (LPE) method on surfaces of mono-crystalline gadolinium gallium garnet  $\text{Gd}_3\text{Ga}_5\text{O}_{12}$  substrates (LPE-films) [23]. Crystallographic orientation of all samples was (111); thickness of the films was 4-6  $\mu\text{m}$ . The films characterized by period of equilibrium domain structure of 4  $\mu\text{m}$ , effective uniaxial anisotropy field 2.5 kOe, saturation field  $H_S = 42$  Oe, specific Faraday rotation  $10^\circ/\mu\text{m}$  at wavelength of light 630 nm.

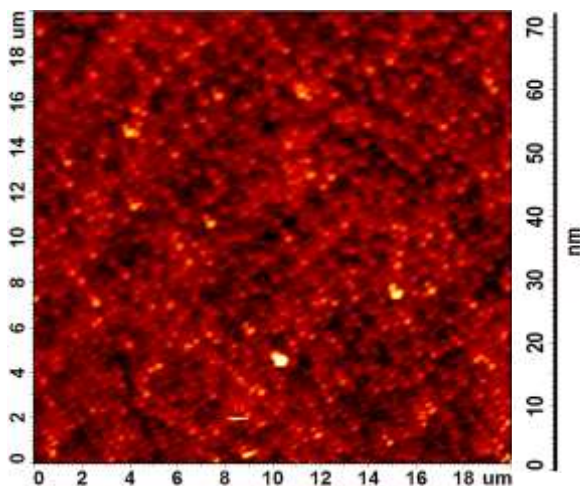
### 2.2.2. RIBS-films.

120 nm thick Bi: YIG films of nominal composition  $\text{Bi}_{2.3}\text{Dy}_{0.7}\text{Fe}_{4.2}\text{Ga}_{0.8}\text{O}_{12}$  were deposited on hot (350 °C) (111) GGG single-crystal substrates by reactive ion-beam sputtering (RIBS) technique in argon–oxygen mixture with following annealing at 680 °C in the air at atmospheric pressure as described earlier (RIBS-films) [9, 24]. To determine the magneto-optical properties of the films (Faraday rotation angle  $\Theta_F$ , coercivity force  $H_c$ , squareness ratio  $K_S$  and others) the Faraday hysteresis loops (FHL) were measured using hand-made computer control magneto-polarimeter at a fixed radiation wavelength of 655 nm.

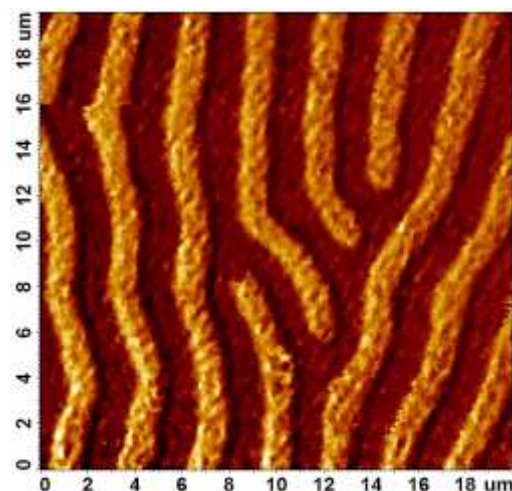
## 2.3. Topography and magneto-optical measurements of LPE-film

Firstly, the topography of Bi:YIG film was obtained by tapping AFM mode, figure 2. Then magneto-optical contrast was obtained by combination of AFM and cantilever-based aperture SNOM, figure 3. Polarization of transmitted light (wavelength – 473 nm) was rotated by magneto-optical effect depend on domain orientation. Visualization of magnetic domains was performed by detecting cross polarized component in transmitted light.

Near-field polarization microscopy allowed to obtain domain structure images with resolution down to  $\sim 100\text{nm}$ . Resolution mostly depends on diameter of aperture, distance between probe and sample. There are several factors which could impact on resolution such as film thickness, domain structure periodicity, mutual orientation of domain walls and light polarization, angle of incidence [14].



**Figure 2.** Topography of LPE-film obtained by semi-contact AFM with aperture cantilever.

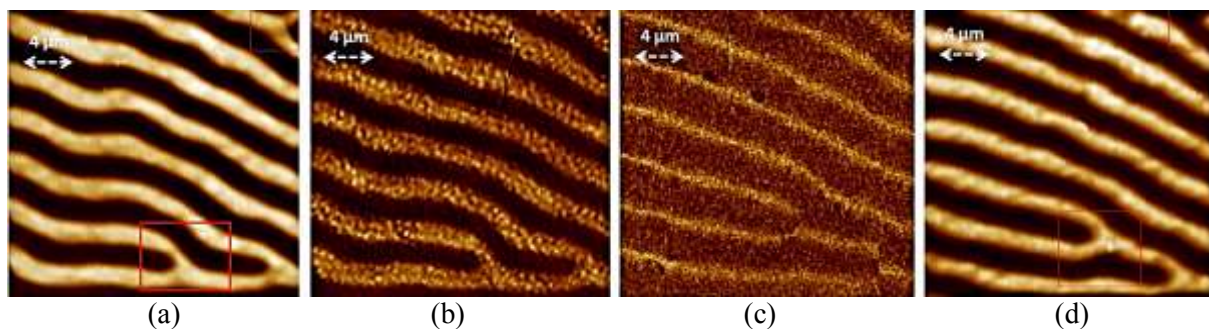


**Figure 3.** Magneto-optical contrast of LPE-film obtained by cantilever-based aperture SNOM simultaneously with topography from the same area.

#### 2.4. Far-field, MFM and cantilever-based SNOM measurements comparison

Far-field and cantilever based SNOM magneto-optical contrast was obtained for LPE-film, figure 4(a) and 4(b) correspondently. Far-field image shows domain structure with standard optical resolution which is limited by diffraction. Then domain structure of the same was measured by conventional two-pass MFM (magnetic force microscopy) mode, figure 4(c). Silicon cantilever with CoCr magnetic coatings was used for MFM.

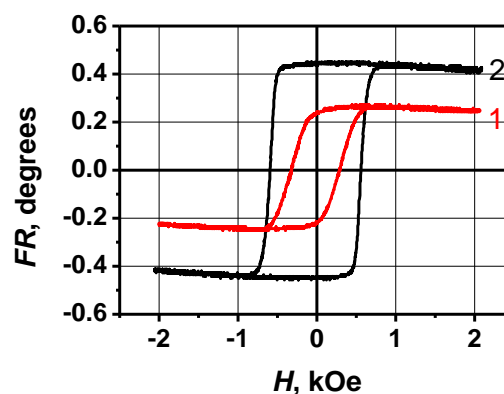
SNOM map of magnetic domains provides direct information of the magnetic domain structure unlike MFM image which provides distribution of magnetic force gradient. Moreover, unlike MFM probe non-magnetic hollow-pyramid probe prevents sample from possible disturbance by internal probe magnetic moment. After all same area was investigated in far-field magneto-optical mode again to show influence of magnetic cantilever on domain structure, figure 4(d).



**Figure 4.** Far-field (a), cantilever based SNOM (b), MFM image (c) of magnetic domain structure of LPE-film. And far-field magneto-optical image (d) after remagnetization of remarkable areas due to magnetic cantilever and sample interaction during MFM measurements.

#### 2.5. Sub-wavelength resolution in cantilever-based aperture SNOM

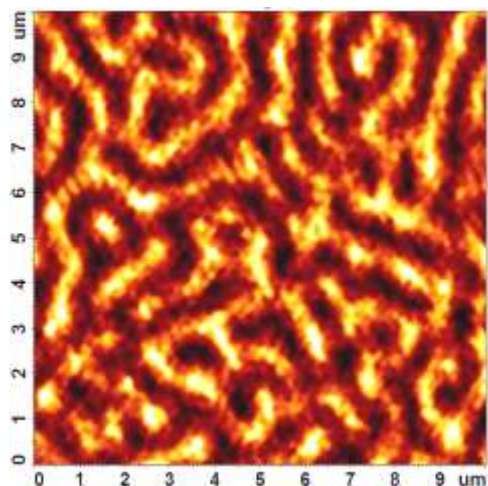
Special RIBS-film was prepared with a low time of crystallization annealing - 1.2min. This sample was created to determine minimal time when garnet phase created and domain structure appeared. Even with such a low annealing time magneto-optical FLH could be measured. Domain structure is also visible. Film parameters:  $\Theta_F = 0.26^\circ$ ,  $H_C = 290$  Oe,  $K_S = 0.96$ , and easy axis magnetic anisotropy showed on figure 5 (curve 1). FHL for another RIBS-film with annealing time 20 min is also showed on figure 5 (curve 2) for comparison.



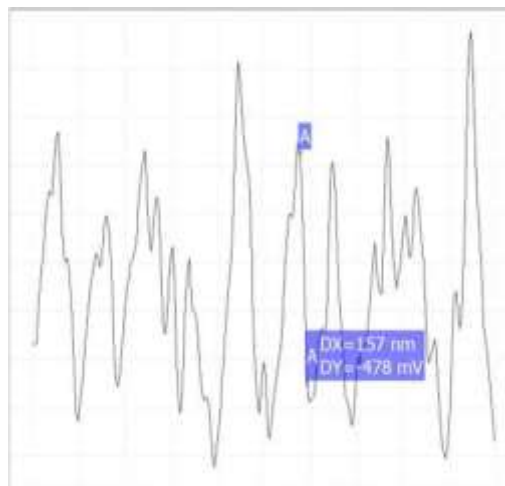
**Figure 5.** Magneto-optical Faraday hysteresis loops of the Bi: YIG RIBS-films annealed at 680 °C during 1.2 (1) and 20 (2) minutes.



Sputtered RIBS-film with a low time of crystallization annealing was investigated. Domain structure is clearly seen with optical resolution  $\sim 150$  nm by the method of AFM and cantilever-based aperture SNOM combination. Domain size is  $\sim 300$  nm. Domain structure and cross section are showed on figure 6 and figure 7 correspondently.



**Figure 6.** Domain structure of RIBS-film with small period obtained by combination of AFM and cantilever based SNOM, scan area  $10 \times 10$   $\mu\text{m}$ ,  $\sim$  optical resolution 150 nm.



**Figure 7.** Cross section of domain structure showed on figure 5.

### 3. Conclusion

Efficiency of combination of AFM and cantilever-based SNOM method is demonstrated. Remagnetization and other disturbances of conventional MFM are eliminated by excluding magnetic coating of cantilever. Fragility of fibre probes in shear force mode in conventional SNOM are also excluded. Resolution of magneto-optical method improved by using near-field illuminating scheme with aperture cantilever. High resolution image of RIBS-film domain structure was obtained with optical resolution  $\sim 150$  nm.

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