Supplementary material: Quantitative magneto-optical investigation of superconductor/ferromagnet hybrid structures

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I. THE MAGNETO-OPTICAL IMAGING SETUP

Magneto-optical imaging (MOI) is based on the Faraday effect, the rotation of the direction of polarization of a light beam proportional to the local magnetic field. Figure 1 shows a schematic representation of the MOI setup at the University of Liège. The polarization microscope is a commercial Olympus modular system. The core of the microscope is the modular Olympus BX-RLA2 illuminator. Light beam produced by a 100 W Hg arc burner lamp (USH 103 D) is passed through a green filter (U-25IF550 at 550 nm), then crosses a linear polarizer (U-PO3), and is then directed to the Faraday active indicator through the objective by a beam splitter. As discussed in the manuscript, the indicator we use throughout this work is a 3 μm thick Bi-doped yttrium iron garnet (Bi:YIG) epitaxially grown on a 450 μm thick $Gd_3Ga_5O_{12}$ (GGG) transparent substrate. The Bi:YIG Faraday-active layer of the indicator has a Verdet constant $V = 0.018 \pm 0.005$ $\mu m^{-1} mT^{-1}$ at 10 K. Typical values of the out-of-plane saturation field for indicators similar to ours are $\mu_0 H \sim 100$ mT. A 100 nm thick Al mirror was deposited on the optically active layer side in order to ensure sufficient reflection of the incident light beam. The linearly polarized light crosses the GGG substrate of the indicator and the Bi:YIG layer, where its polarization direction is rotated proportionally to the local magnetic field. It is then reflected by the mirror and crosses the indicator and the objective once again. It then passes through an analyzer (AN-360), whose polarization direction is oriented close to 90° with respect to the polarizer. The orientation of the analyzer can be adjusted with a precision of 0.1°. The analyzer absorbs the component of light polarized in the original direction, so only the light whose polarization has been rotated in the indicator passes through. The rotation of the polarization is proportional to the component of the magnetic moment along the direction of light propagation. Light finally enters a high resolution RETIGA-4000R CCD-camera mounted on top of the microscope unit. The captor consists of 4.2 mega pixels and each pixel is 7.4 μm × 7.4 μm large. The camera captures light intensity on a 12-bit gray-scale and records 2048 × 2048 px^2 images where intensity values range from 0 to 4095. With a 5× objective (LMPLFLN 5BD) this represents a field of view of approximately 3 × 3 mm^2, i.e., each pixel in the images corresponds to an area of 1.468 × 1.468 μm^2. We thus obtain a light intensity map representative of the magnetic field texture at the indicator's plane, where dark areas correspond to low magnetic fields and bright regions represent high fields. Magnetic fields in the range ±12.5 mT are applied by feeding a cylindrical copper coil with a dc current. The sample is installed on an oxygen free copper cold finger enclosed by a radiation shield, in a closed-cycle He cryostat (Montana Cryostation). The whole microscope and the cryostat are mounted on an actively damped non-magnetic optical table. Details on different possible MOI configurations can be found in Refs 1–4.

II. PREPARATION OF CO BARS

The arrays of Co bars are defined by electron beam lithography on a Si/SiO_2 (300 nm) substrate covered by a resist mask (double layered, MMA/PMMA, 200 nm

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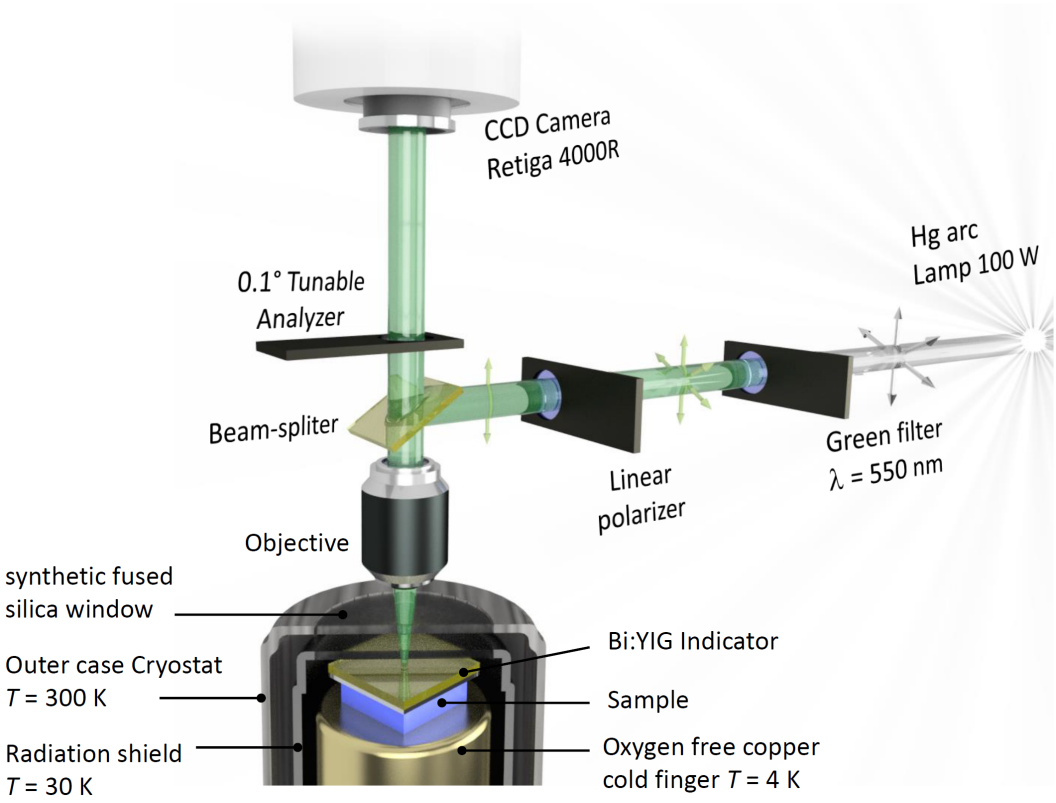

FIG. 1. Schematic of the MOI setup (cf. text for details).

+ 100 nm), using a nanofabrication system from Raith GmbH. After development in methyl isobutyl ketone : isopropanol (1:1) followed by an isopropanol rinse, a 30 nm thick Co layer is evaporated by molecular beam epitaxy (operation pressure $P \leq 4 \times 10^{-9}$ mbar) with a rate of 0.04 Å/s. A 20 nm thick Au layer is subsequently evaporated at a rate of 0.23 Å/s. After lift-off in acetone using a sonic bath, a 5 nm thick layer of Ti and a 45 nm thick Au layer are deposited (at rates of 0.4 Å/s and 0.23 Å/s respectively) on top of the structure to prevent further oxidation of the Co over the course of the experiments. All the arrays used in this study are fabricated on the same substrate. This ensures their observation under similar experimental conditions.

[1]M. Koblischka and R. Wijngaarden, "Magneto-optical investigations of superconductors," Superconductor Science and Technology **8**, 199 (1995).
[2]P. E. Goa, H. Hauglin, M. Baziljevich, E. Il'yashenko, P. L. Gammel, and T. H. Johansen, "Real-time magneto-optical imaging of vortices in superconducting nbse2," Superconductor Science and Technology **14**, 729 (2001).
[3]R. J. Wijngaarden, K. Heeck, M. Welling, R. Limburg, M. Pannetier, K. van Zetten, V. L. G. Roorda, and A. R. Voorwinden, "Fast imaging polarimeter for magneto-optical investigations," Review of Scientific Instruments **72**, 2661 (2001).
[4]P. Mandal, D. Chowdhury, S. Banerjee, and T. Tamegai, "High sensitivity differential magneto-optical imaging with a compact faraday-modulator," Review of Scientific Instruments **83**, 123906 (2012).