Magneto-Optical Magnetometry of cobalt nano-structures grown by focused electron beam induced deposition

O. Idigoras[1], E. Nikulina[1], P. Vavassori[1,2], A. Chuvilin[1,2], and A. Berger[1]

[1]CIC nanoGUNE Consolider, Tolosa Hiribidea 76, 20018 Donostia-San Sebastian, Spain
[2]Ikerbasque, Basque Foundation for Science, Alameda Urquijo 36-5, 48011 Bilbao, Spain

oidigoras@nanogune.eu

Reduction of ferromagnetic system sizes is a key research area in the field of magnetism and of crucial importance for a wide range of technological applications, such as, high-density hard disk drive storage [1] and spintronics [1,2]. Continuously increasing demands on these technologies are pushing nanofabrication into the extreme nanoscale regime. Even though structuring of nanoscale systems may be achieved by different lithography techniques [3], focused electron beam induced deposition (FEBID) of magnetic materials has recently attracted a very substantial amount of interest [4,5]. One of the most attractive features of this technique is the rapid prototyping, because it is a one-step technique. Moreover, FEBID allows for the fabrication of 3-dimensional complex nanostructures and even lateral dimensions below 1 nm have been demonstrated. In this work, we have fabricated several Co structures by means of EBID, including wires where lateral dimensions were shrunk down to 30 nm and 3 dimensional nano-pillars. Their magnetic properties have been measured by means of a magneto-optical Kerr effect (MOKE) microscope [6], which allows in plane as well as out of plane magnetic property studies. Moreover it is able to characterize individual structures.

FEBID of Co structures have been performed using a commercial Helios NanoLab™ DualBeam™ system (FEI, Netherlands). Figure 1 (a) shows a scanning electron microscopy image of a 30 nm wire, while figure 1 (e) displays an array of pillars that are 80 nm wide and 210 nm high. In order to get the right composition, lateral resolution and desired shape of the structures one needs to find the optimal deposition parameter conditions. In this case, both structures were made at constant values of background pressure (6×10^{-5} Pa), pitch (5 nm) and sample to gas injection system distance (50 µm). While the 30 nm wide wire was produced using a high electron beam energy of 30 kV, an electron beam current of 2.7 nA and 6×10^{-5} Pa precursor gas pressure, the nanopillars were obtained by using an electron beam energy of 2 kV in conjunction with an electron beam current of 86 pA and 8×10^{-4} Pa precursor gas pressure.

The magnetic analysis was carried out with an optical wide-field polarization microscope optimized for Kerr microscopy (Evico Magnetics GmbH, Germany). The microscope is equipped with a high sensitivity CCD camera that is capable of taking magnetic-contrast images of 25x20 µm^2 sample surface areas. Area that is divided in 1024x768 pixels. The key feature of our approach is that we can measure the field dependent local magnetization, either in-plane or out-of-plane, by selecting an arbitrary (shape, size, and position in the field of view) region of interest (ROI) on the CCD camera pixel array, and use this array selection as a conventional light intensity detector. In this way, we can maximize the magneto-optical difference signal $\Delta I/I_0$ for opposite magnetization states, resulting in an increase of the signal-to-noise (S/N) ratio. The advantage of our approach is evident from the measurement reported in Fig. 1(b), where we demonstrate that we are able to record a single shot hysteresis loop with an average S/N of 4.1 per data point for a 20 nm high Co wire that is only 30 nm wide (Fig. 1 (a)) using a ROI of 340 x 8 pixels. Renormalizing this result to the commonly used detection criterion (S/N =2) [7], we conclude that our measurements are sensible to a magnetic moment of only 2×10^{-15} Am^2. By comparing our results to other magnetometry techniques such as the latest generation SQUIDs with their sensitivity in the 10^{-12} - 10^{-13} Am^2 range it becomes obvious that MOKE microscopy based magnetometry allows for true nanoscale magnetic characterizations. Figure 1 (c) shows an average over 9 single shot measurements for the 30 nm wide wire. Here, we find that the S/N has increased by a factor of almost 3. This confirms that we may be able to measure even smaller structures with less than 10 nm width.

Having a look to the 30 nm wide wire magnetization reversal hysteresis loop, one observes a rectangular hysteresis loop with a coercive field of 75 mT (Fig. 1 (c)), i.e. the expected behaviour given that the external field is applied along the wire length, which is the easy axis of magnetization due to shape anisotropy. For wider wires (not shown here) more complex hysteresis loops have been observed were the magnetization reversal is not given anymore by a single switch, but instead double jump inversion is observed.

In the case of hysteresis loops measured in a periodically ordered 20 x 20 nanopillars (Fig. 1 (e)), a center-pinched structure is found with reduced magnetization in remanence state and with a magnetic plateau at low applied fields, i.e. features that arise due to large magnetostatic coupling between adjacent pillars, while exchange coupling is low or absent.

Our results demonstrate that the combination of FEBID and MOKE microscopy makes it possible to explore magnetization reversal properties of individual as well as more complex collective nanostructures and thus opens up a broadly applicable avenue to perform systematic research on nano-scale magnets.

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Figures

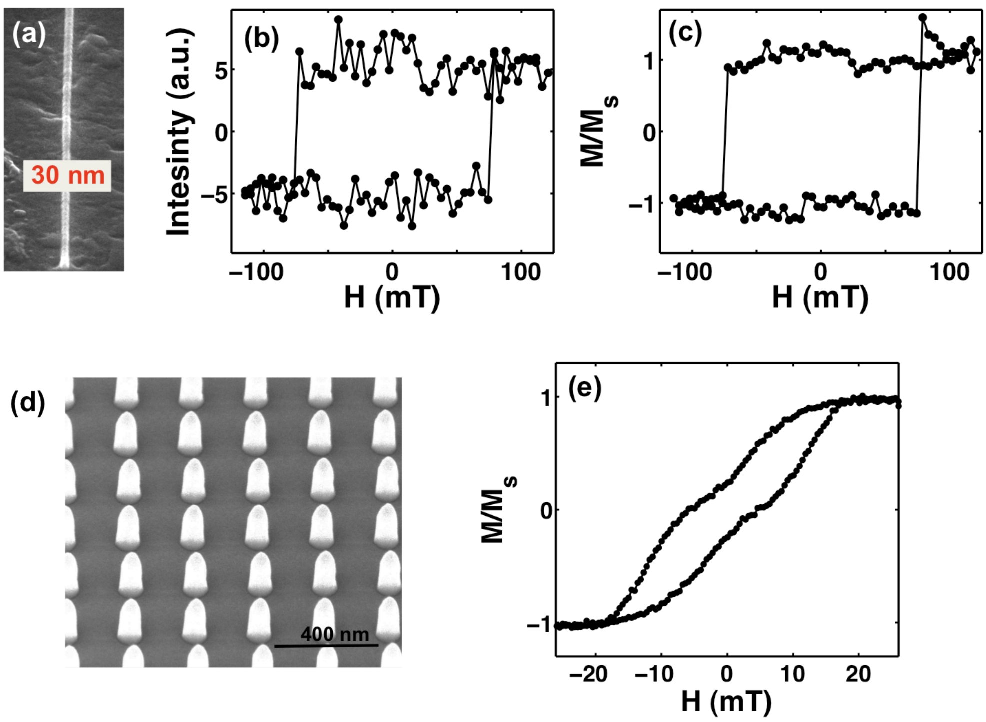

Figure 1: (a) and (d) show scanning electron microscope images respectively of a 30 nm wide Co wire and an array of nanopillars of size 80x210 nm, both of which are fabricated by electron beam induced deposition. (b), (c) and (e) display hysteresis loops measured in these structures by Kerr effect microscopy. While (b) and (c) show hysteresis loop measured in 30 nm wide Co wire ((b) is a single shot measurement and (c) an average of 9 loop cycles), (e) shows hysteresis loop measured in the Co nanopillar array.