Structuring of Permalloy by means of Electron-beam Lithography and Focused Ion Beam Milling

S. Getlawi[1], M. R. Koblischka[1], F. Soldera[2], and U. Hartmann[1]

[1]Institute of Experimental Physics, Saarland University, P.O.Box 151150, D-66041 Saarbrücken, Germany
[2]Institute of Functional Materials, Saarland University, P.O.Box 151150, D-66041 Saarbrücken, Germany

Focused-ion-beam (FIB) milling has been employed to structure magnetic nanoelements from 20 nm thick films of permalloy ($Ni_{81}Fe_{19}$). As permalloy is a soft magnetic material, the magnetic properties are controlled by structural engineering on the nanoscale and novel magnetic phenomena may be exhibited on the nanoscale [1,2]. However, the fabrication of nanostructures in magnetic systems is hampered by the sensitivity of magnetic materials to the resulting structure of the sample edges which plays an important role for the formation of magnetic domains. However, for magnetically soft materials, such as those used in the emerging technology of magneto-electronic devices, the degree to which the magnetic properties of the structured devices suffer due to FIB milling remains unclear. Ion implantation, the introduction of magnetic pinning defects, and nanometer-scale displacements are all ion-induced mechanisms which have recently been shown to strongly influence soft magnetic properties. Therefore, permalloy structures are commonly prepared using electron-beam lithography (EBL), while FIB milling is described in the literature to produce irregular sample edges [3,4].

As test structures, rectangles are patterned into permalloy thin films grown on Si substrates firstly by means of electron-beam lithography as a prestructure and finally, by means of FIB milling structures down to the 100 nm range are created. For these structures, we have chosen rectangles, circles and ellipses, which are characterized by specific magnetic domain patterns. In this study, we analyze the effect of the FIB milling parameters (ion current, dose) on the resulting magnetic domain structures. The ion currents have been varied between 10 pA and 20000 pA; the dose of the ion beam used for milling was varied in order to achieve the best definition for the milled areas. The resulting edges of the permalloy structures are characterized by means of atomic force microscopy (AFM), and the magnetic domains structures are imaged using magnetic force microscopy (MFM).

Figure (1) represents a SEM image of a structured permalloy sample (20 nm thickness, on Si substrate). The outer rectangle (5×5 µm^2) was created by means of EBL and a lift-off procedure, the two crosses cutting into the substrate were created by means of FIB milling. Figure (2) shows a topography and MFM image of the resulting small rectangles (2×2 µm^2 and finally, 500×500 nm^2); the marker is 2 µm long. The MFM image reveals that in each rectangle, a Landau pattern is formed without disturbation along the edges. This sample was cut using a ion current of 100 pA (corresponding dose of 0.03 nCµm^{-2}), while the sample shown in image (3) was prepared with an ion current of 10000 pA (dose of 2.5 nCµm^{-2}). The MFM image clearly reveals the damage caused by the ion beam on the small rectangles, while the larger rectangles are still magnetically intact. Finally, figure (4) presents a toography image of a permalloy ellipse, and (5) the corresponding MFM image. On the right side of (5), one can see the effect of a not perfectly cut edge on the resulting magnetic structure, which is otherwise homogeneous in the other ellipses. The dose for the

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FIB milling was kept low at 0.03 nCμm^{-2} (ion current of 100 pA) in order to ensure no significant damage caused by the ion milling. With this result, it becomes possible to create permalloy nanostructures using FIB milling. We find that small ion doses (= small ion currents) do not affect the resulting magnetic domain patterns in the nanostructures, so FIB milling can be applied to create high-quality permalloy nanostructures [5].

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