Subtractively Prepared Permalloy Nanowires for Spin-Torque Experiments

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Abstract. Physical properties of Permalloy (Ni$_{80}$Fe$_{20}$) can be considerably enhanced by sputtering on substrates heated to temperatures around 300 °C. To enable the use of sputtered Permalloy in micro- and nanostructures for spintronic experiments a subtractive preparation process has to be established, as common lift-off processing is incompatible with high temperatures. Two subtractive fabrication processes for curved Permalloy nanowires are executed: ion-milling and rf-sputter-etching. The results of current-induced domain-wall depinning experiments with these nanowires are compared.

1. Introduction
Permalloy (Ni$_{80}$Fe$_{20}$) is used in many experiments on domain-wall dynamics, spin-torque effects [1, 2, 3], spin valves [4, 5, 6, 7, 8, 9], and dynamics of magnetic vortices and antivortices [10, 11, 12, 13, 14, 15]. We demonstrate that sputtering Permalloy on substrates heated to 300 °C leads to advantageous properties for such experiments [3, 16], e.g. low specific resistances and reasonable depinning fields. Most commonly lift-off processing is employed to prepare micro- and nanostructures. To make use of the advantageous properties of Permalloy sputtered on heated substrates micro- and nanostructures have to be prepared subtractively. Two promising ways on this path are either to ion-mill or by rf-sputter etching Permalloy films sputtered on heated substrates. Both approaches have been studied and will be described and compared.

2. Sample Preparation
Films of Permalloy with thicknesses of 20 or 30 nm are sputtered on Si substrates covered with a 300 nm thick SiO$_2$ layer. During the sputter process the substrates are heated to 280 °C, 300 °C, or 320 °C. The sputter system is a three-target magnetron-sputtering system with a transfer chamber and a base pressure of around 1 × 10$^{-9}$ mbar. Argon pressure and DC power have been optimized for controlling deposition rates and film roughnesses [17]. The Permalloy films studied in this work were sputtered at a rate of 0.11 nm/s, with a DC power of 50 W and an argon pressure of 1 × 10$^{-2}$ mbar.

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Figure 1. (a) Scanning electron micrograph of the sample, including the curved Permalloy nanowire in the middle and the coplanar waveguide made of gold. (b) Blowup of the inner part of (a) with the curved Permalloy nanowire in the middle, contacted by the signal leads. (c) Schematic of the measurement setup.

To subtractively prepare curved Permalloy nanowires for the investigation of domain-wall motion from these films the structures are defined by electron-beam lithography with negative resists. Resists used here are ma-N 2403 by micro-resist in case of the ion-milled wires and ARN 7520 by allresist in case of the rf-sputter-etched wires. After development the desired structure on the sample remains covered by resist while the leftover parts of the metal film that are meant to be removed are uncovered. The uncovered parts of the samples are then removed by ion-milling and rf-sputter-etching, respectively. Both processes are based on physical etching by argon-ion bombardement. In case of ion-milling a power of 18 W at an argon gas flow of 8.9 sccm yield an etching rate of nanometers per second (here 0.22 nm/s). For rf-sputter etching a power of 10 W at an argon-pressure of $1 \times 10^{-2}$ mbar results in an etch rate of nanometers per minute (here 0.02 nm/s, i.e. by a factor of 11 slower than ion-milling).

3. Principle of Measurement

The samples consist of a 30 nm thick (20 nm in case of the sputter etched wires), 200 nm wide curved Permalloy wire with a radius of curvature of 3 μm. It is contacted by two gold leads in coplanar waveguide geometry that are used as voltage probes to measure the resistance as well as to inject the current pulse as visible in Fig. 1. Between the contacts the Permalloy wires show resistances of several hundred Ω depending on the actual geometry. The Permalloy wires and their contacts are prepared on a silicon substrate covered with a thin SiO₂ layer to prevent bypass conductivity. Samples are produced in a two-step process. First the curved Permalloy wire is prepared by subtractive etching from a film that has been sputtered onto the heated substrate; second the larger electrode structures are lithographically defined and then
Figure 2. Scanning electron micrograph of a 200 nm wide and 20 nm thick Permalloy wire subtractively prepared by rf-sputter etching from a film sputtered onto a substrate heated to 300 °C. The white circles at the edge of the wire with diameters of 5, 10, and 15 nm illustrate the roughness of the wire.

deposited by thermal evaporation of 100 nm gold. A schematic of the measurement setup is shown in Fig. 1(c). The resistance of the wire is measured by a dc current of I = 0.1 mA. To induce a head-to-head domain wall in the curved region of the wire a magnetic field of 140 mT is applied under an angle of \( \varphi = 45^\circ \), as shown in Fig. 1. By decreasing the magnetic field the magnetization relaxes along the wire and a domain wall is created in the curved region of the wire [18, 3, 19]. The domain wall is sensed via its contribution to the resistance by the anisotropic magnetoresistance [3]. Subsequently current-induced motion of a domain wall is caused by single current pulses with variable length while an additional magnetic field is applied under an angle of \( \varphi = 180^\circ \). Then the wire resistance is measured again. If the domain wall is depinned by spin-torque transfer and moved out of the region between the taps, the difference in resistance before and after the pulse \( \Delta R \) is increased by about 0.05 Ω - 0.3 Ω.

4. Experimental Results
Permalloy nanowires can be subtractively prepared by ion-milling as well as by rf-sputter etching. A wire prepared by the latter technique is shown in the scanning electron micrograph in Fig. 2. The edge roughness of the wires of 5-15 nm for both fabrication processes are around the limit of accuracy of the lithography system.

Before starting current-induced domain-wall depinning experiments each wire is characterized by applying increasing magnetic fields under various angles between the negative x- and the positive y-direction (see Fig. 1, \( \varphi = 180^\circ - 90^\circ \) in steps of 5° or 10°). By measuring the resistance during the increase of the magnetic field a jump in the measured resistance indicates the field value which is strong enough to depin the domain wall. These measurements are repeated several times to determine the angle with the lowest and most stable depinning fields. For both subtractive fabrication processes low depinning field values, often below 1 mT, are observed. In comparison to that, wires fabricated by thermal evaporation and lift-off processing show depinning fields of 5-10 mT [3, 20].

Measurements on the ion-milled wires with current pulses with a maximum current density of \( j = 1.37 \times 10^{12} \) A/m² revealed several resistance difference levels \( \Delta R \) as shown in Fig. 3. The wire exhibits a resistance of 438 Ω, the magnetic background field was varied between 0 and 3 mT in steps of 0.01 mT, and the current pulse length was varied between 0.2 and 10.2 ns in steps of 0.2 ns. Each combination of magnetic background field and pulse length has been repeated five times, summing up to more than 150,000 measurements of the resistance difference \( \Delta R \) with and without a domain wall. A histogram of all measured \( \Delta R \) is shown in Fig. 3(a).
Figure 3. Experimental results of current-induced domain-wall depinning in an ion-milled Permalloy wire: (a) Histogram of measured resistance differences $\Delta R$ with and without a domain wall, (b) $\Delta R$ vs. background field, and (c) $\Delta R$ vs. pulse duration.

The highest peak at $\Delta R = 0$ corresponds to no change in resistance before and after sending the current pulse through the wire. Thus in these cases the domain wall has not been moved by the current pulse. The four countable positive peaks in the resistance difference can easily be understood as different types of domain walls being depinned by the current pulse. The negative values of $\Delta R$ are more difficult to understand and most probably correspond to changes in the magnetic configuration of the domain wall rather than real depinning events. The negative $\Delta R$ values correspond to a larger resistance of the wire after a current pulse has been sent through the wire, meaning that a larger amount of magnetization is aligned perpendicular to the current flow. This can be interpreted as a change in the domain-wall structure [21] due to the current pulse. This has been observed with imaging techniques like magnetic force microscopy [22] and x-ray microscopy [2]. However, statistical interpretation with a large number of repetitions is not possible with imaging techniques. We deduce that the observed behavior is caused by a specific unknown potential landscape that influences the motion of the domain wall when moving in the negative x-direction. Measurements with a current pulse pushing the domain wall along the wire in the negative y-direction with a background magnetic field assisting the motion of the domain wall in the same direction (not shown) indicate that these domain-wall transformations are reproducible and thus contradict the above speculation. Furthermore similar observations in ion-milled wires have been reported by Hayashi et al. [21] as well as by Malinowski et al. [23]. Figures 3(b) and (c) show the measured values of the resistance change $\Delta R$ versus the magnetic background field and the pulse duration, respectively.

The corresponding data of an experiment on current-induced domain-wall depinning in a
Figure 4. Experimental results of current-induced domain-wall depinning in a rf-sputter etched Permalloy wire: (a) Histogram of measured resistance differences $\Delta R$, (b) $\Delta R$ vs. background field, and (c) $\Delta R$ vs. pulse duration.

A rf-sputter etched Permalloy nanowire is displayed in Fig. 4. This wire exhibits a resistance of 405 $\Omega$, the magnetic background field was varied between 0.5 and 2.1 mT in steps of 0.1 mT and the current pulse length was varied between 0.2 and 10.2 ns in steps of 0.2 ns and had a maximum current density of $j = 1.32 \times 10^{12}$ A/m$^2$. Each combination of magnetic background field and current pulse length has been repeated 30 times, summing up to more than 48,000 measurements of $\Delta R$. In this rf-sputter etched wire only two resistance levels have been observed. The two resistance levels of either zero or 0.05 $\Omega$ shown in Fig. 4(a) indicate three possibilities. Either there was a wall in the wire and it still is there after the current pulse, or the wall got moved out of the wire by the background magnetic field before the current pulse arrived, or there was a wall inside the wire that has been moved out of the wire by the current pulse. The latter corresponds to the resistance difference of $\Delta R = 0.05 \Omega$. However, no dependence of the domain wall depinning probability on current pulse length [3] or current pulse shape [19] could be observed in the rf-sputter etched wires. Note, that the value $\Delta R \approx 0.05 \Omega$ is comparable to the lowest measured positive $\Delta R$ in the ion-milled wire described above. This could imply that the same domain-wall type has been observed in both cases.

5. Summary and Discussion

In summary we are able to subtractively prepare nanostructures from Permalloy films sputtered on heated substrates. This process enables using the advantageous properties of this material which is prevented by additive preparation processes due to two reasons: First, additive sputtering may alter the cross-sectional geometry of the wires and second, lift-off of resists
increasing magnetic roughness
increasing pinning potential depth
(a) (b) (c)

Figure 5. Sketch of pinning potential landscapes. (a) In the ideal case with no magnetic roughness, (b) with moderate magnetic roughness, and (c) with strong magnetic roughness.

heated to 300 °C is impossible. The subtractively prepared Permalloy nanowires feature small edge roughnesses and low depinning fields, independent of the etching process. No influence of the substrate temperature between 280 °C and 320 °C has been observed. The differences in the experimental results on current-induced domain-wall depinning between the ion-milled and the rf sputter-etched wires imply that rf-sputter etching with PMMA resist masks is preferable versus ion-milling with PMMA resist masks as subtractive preparation process for these experiments. This is most probably due to the higher energy of the argon ions penetrating the resist mask and bombarding the Permalloy surface during preparation of the wires. An interesting catchword in this context is magnetic roughness, brought up by Hayashi et al. [18]. Interpreting magnetic roughness as some sort of noise of whatever reason in the pinning potential landscape of the wire it is possible to imagine why it gets more difficult to observe the dependence of the domain wall depinning probability on current pulse length [3] or current pulse shape [19] with decreasing depinning fields. Figure 5 shows a sketch of pinning potential landscapes of different strengths, in the ideal case with no magnetic roughness, with moderate magnetic roughness, and with strong magnetic roughness. The lower the initial pinning potential the more important magnetic roughness becomes. The domain wall in the pinning potential in an ideally magnetic flat landscape as depicted in Fig. 5(a) will exhibit the same dependence on current pulse length as well as on current pulse shape independent of the depth of the pinning potential. Contrary to that in situations as depicted in Fig. 5(b) and (c), when the magnetic roughness and the depinning energy are of the same order of magnitude, this will not be the case. These speculations suggest to further refine the subtractive preparation of nanostructures, which could be obtained by hard masks that protect the magnetic film reasonably during the etching process.

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