Magnetization reversal in single ferromagnetic rectangular nanowires

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Magnetization reversal in single ferromagnetic rectangular nanowires

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Abstract. We report on the magnetoresistance (MR) investigation of the magnetization reversal processes in single rectangular nanowire of Permalloy. A set of nanowires with lengths ranging from 6 to 20 μm, thicknesses fixed in 10 nm, and widths between 250 nm and 1.2 μm, was fabricated by means of AFM local anodic oxidation lithography. Magnetoresistive hysteresis loops show an abrupt jump corresponding to the magnetization reversal that depends on the angle between the wire axis and the applied magnetic field direction. The field value corresponding to the abrupt jump of the MR was associated to the nucleation field deduced from the Brown equations. By the angular dependence of this magnetization reversal field we were able to identify the nucleation mode as the magnetization buckling. We have investigated the temperature dependence of the switching field as well as its stochastic nature as a function of the in-plane angle.

1. Introduction

Nowadays, there have been an increasing number of investigations on the magnetic properties of individual nanoscale ferromagnetic structures such as wires, particles, disks, rings and so on. The interest lies in the emergency of novel magnetic phenomena as well as on the applications of these structures as high-density data-storage devices and as magnetic sensors.[1] Among the various magnetic properties of interest, the magnetization reversal processes that occur in these confined magnetic structures is still an unsolved problem and it has been investigated by many different groups from theoretical point of view as well as from the experimental one.[2-6] It has been known that the reversal mechanisms in confined geometries are difficult to understand in detail because magnetization can assume complex modes that depends on the shape and magnetic properties. Here we report on the experimental and theoretical investigation of magnetization reversal in rectangular nanowires of permalloy. The angular dependence of the magnetization switching field was measured by magnetoresistance as a function of temperature and the data were interpreted by a model that takes into account the buckling mode of reversal.

2. Experimental details

By measuring the magnetoresistive hysteresis loops we were able to investigate the magnetization reversal processes in planar magnetic structures of $Ni_{81}Fe_{19}$ (Permalloy). The investigated structures consist of two rectangular pads measuring 70 x 80 μm that are connected by a 5-20 μm long nanowire, having widths in the range 300-400 nm and thicknesses varying from 3 to 10 nm. Atomic force microscopy (AFM) has been used to fabricate the nanostructures.[7] In order to prevent oxidation a SiO_2 layer of 1 nm thickness is deposited on top of the Py structure. Figure 1 shows an AFM topographical image of the 400 nm wide nanowire including part of the Permalloy pads.

The magnetoresistance (MR) measurements were carried out at room temperature and at 77 K using a direct current (DC) of 200 μA passing through palladium electrodes that are connected to the Permalloy pads. By sweeping the external magnetic field applied in the plane of the sample we were able to obtain MR vs. field for in plane angles varying from 0 to 360^o in steps of 10^o. Figure 2 shows a typical MR data obtained with the external magnetic field applied parallel to the wire axis (0 deg). The magnetic field dependence of the measured resistance is clearly a superposition of a continuous variation corresponding to reversible rotation of the magnetization and discontinuous jumps attributed to irreversible magnetization switching. The magnetic field sweep-up MR data, shown by the solid line in figure 2, exhibits four different regimes of magnetization that occur during the magnetization reversal. In the first regime (-80 Oe < H < -30 Oe) the magnetization is confined parallel to the wire axis and is pointing parallel to the decreasing magnetic field. The second regime (-30 Oe < H < 14 Oe) corresponds to the coherent rotation of the magnetization that occurs in the Permalloy macroscopic pads. As the Py pads exhibit an ease direction perpendicular to the wire axis, the anisotropic magnetoresistance presents a minimum at the zero magnetic field value. The third regime (14 Oe < H < 40 Oe) corresponds to pinning and depinning of the domain walls that appear at the region that separates the nanowire (in which the magnetization still points antiparallel to the field) from the Permalloy pads (in which the magnetization has already switched). The irreversible switching of the nanowire magnetization occurs at a very narrow range of magnetic field (around 40 Oe). This corresponds to the nucleation field value, indicated by the gray arrows in figure 2. For field values above 40 Oe the magnetization of the entire structure is now aligned to the magnetic field.

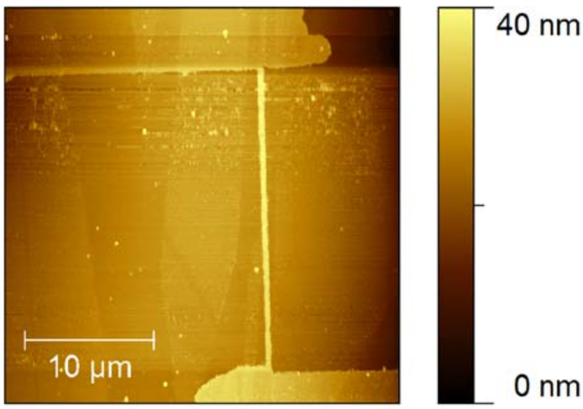

Figure 1. Topographical image obtained by atomic force microscopy (model AFM 5500 Agilent) of a magnetic structure showing the Permalloy pads and nanowire with width of 400 nm, length of 20 μm and thickness of 16 nm.

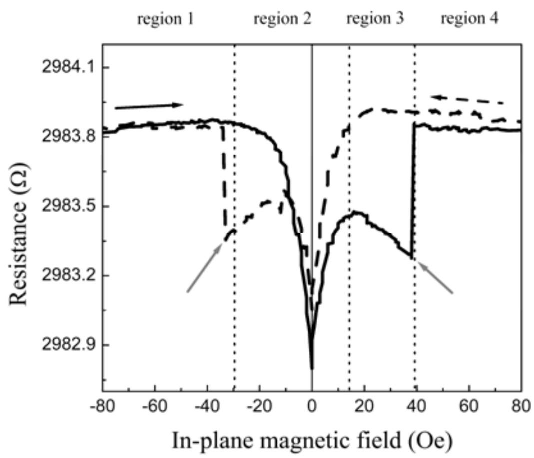

Figure 2. A typical magnetoresistance hysteresis loop for a magnetic structure shown in figure 1 with magnetic field applied parallel to the wire axis. The nucleation field is characterized by the abrupt change occurring at 40 Oe indicated by gray arrows.

3. Results and discussion

By varying the in-plane angle between the applied magnetic field and wire axis (ϕ_H) we were able to measure MR hysteresis loop and nucleation field for different values of ϕ_H. Figure 3 shows the angular dependence of nucleation field at room (circles) and liquid nitrogen (squares) temperature for a Permalloy wire with length l = 20.6 μm, width w = 1.2 μm and thickness t = 16 nm. The dashed lines are a guide to the eyes. We can notice that there is no change on the angular dependence of nucleation field at 77 K and room temperature. This is a clear indication that magnetization nucleation process is dominated by the magnetostatic energy in comparison with thermal energy. The angular dependence of the nucleation field exhibits a U-shape with maximum values at $\phi_H = \pm 90^o$. This dependence can be well explained by applying a model of nucleation in which the magnetization reverses by the buckling mode[4], where the in-plane magnetization just before the switching field exhibits a sinusoidal pattern given by $m_{x'} = A\sin(kz')$ and the nucleation field (H_{nuc}) is given by[4]

$$-k^2C\cos^2\phi_{M,0} - M_S H_{nuc}\cos(\phi_H - \phi_{M,0}) + M_S^2(N_{x'}\sin^2\phi_{M,0} + N_{z'}\cos^2\phi_{M,0}) = 0\,. \quad (1)$$

Here k is the wavenumber associated with the buckling state, ϕ_H and $\phi_{M,0}$ are the field angle and equilibrium angle of the magnetization just before switching, respectively. $N_{x'}$ and $N_{z'}$ are the in-plane demagnetization factors along the x and y direction. The solid line is a fit to the room temperature data obtained by equation (1) using the fitting parameters: M_s = 780 G, C = 10^{-6} erg/cm (exchange constant), $N_{x'} = 4\pi\times0.027$ and the number of oscillations of the static pattern just before switching is around 70.

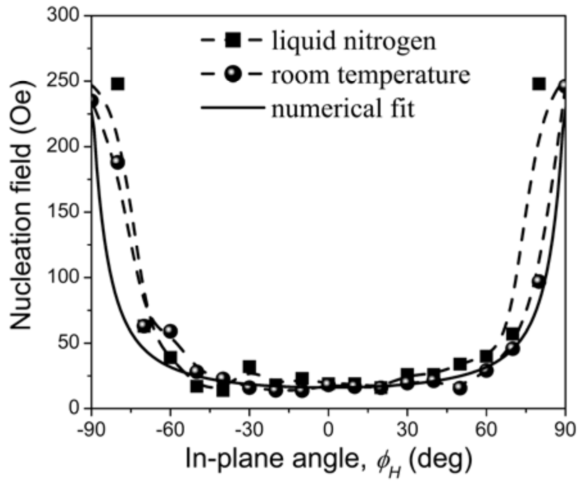

Figure 3. Angular dependence of the nucleation field for room (circles) and liquid nitrogen (squares) temperatures. Solid line is a numerical fit using equation (1).

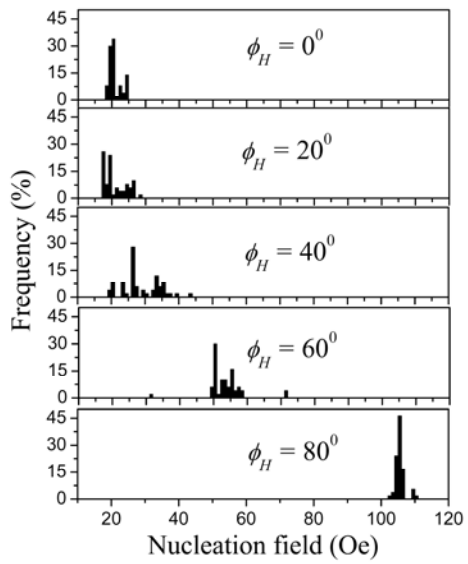

Figure 4. Histograms of the nucleation field values for different applied magnetic field directions (ϕ_H) for a wire of permalloy obtained by repeating the MR curve 25 times.

We also report the experimental statistical analysis of the nucleation field value. In order to perform such an experiment we applied the magnetic field at an angle ϕ_H with the wire axis and measured the MR loop 25 times. For each MR loop there are two nucleation field values, a negative and positive one with a <u>field sweep of around 10 Oe/min</u> Taking into account the absolute values we have create histograms of the nucleation field with 50 values. Figure 4 shows a series of histograms of the nucleation field value for a permalloy nanowire of length l = 22.4 μm, width w = 400 nm and thickness t = 11 nm for different applied magnetic field directions (ϕ_H). In order to avoid Joule heating a small DC electric current of 10 μA was applied during the MR experiments. It can be notice that for low ($\phi_H < 20^0$) and high ($\phi_H > 70^0$) field angles there is a small dispersion of the nucleation field values in comparison with the angles in the middle region ($\phi_H \sim 45^0$). This is most likely caused by the effect of the imperfections along the wire border on the definition of the demagnetizing field. Magnetization reversal switching field somehow depends on the degree of modification introduced by imperfections and roughness on the energy minimization at the magnetization reversal process.

As a summary, we have investigated the angular dependence of the magnetization switching fields in nanowires of Permalloy as a function of temperature. The switching field is identified by an abrupt jump that occurs at the magnetoresistive hysteresis loop, which depends on the angle between the wire axis and the applied magnetic field direction. The U-shape dependence of the switching field can be well explained by the nucleation theory in which the magnetization reverses by buckling instead of curling or coherent rotation. Measurements carried out at room as well as at 77 K showed that the effect of thermal energy is negligible. We have also investigated the stochastic nature of the switching field and constructed histograms from 50 MR curves for each angle, showing that the histograms are wider for angles close to 45^o.

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