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Pseudo exchange bias due to rotational anisotropy

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ABSTRACT

Ferromagnetic nanostructure arrays with particle dimensions between 160 nm and 400 nm were created by electron-beam lithography. The permalloy structures consist of rectangular-shaped walls around a square open space. While measuring their magnetic properties using the Magneto-Optical Kerr Effect (MOKE), in some angular regions an exchange bias (EB) seemed to appear. This paper gives an overview of possible reasons for this "pseudo exchange bias" and shows experimentally and by means of micromagnetic simulations that this effect can be attributed to unintentionally measuring minor loops.

1. Introduction

Magnetic nanostructures are promising candidates for novel data storage media or magnetic sensors [1–3]. In nanostructures, the shape anisotropy dominates over magneto-crystalline and magneto-elastic anisotropies, allowing to tailor anisotropies and other magnetic properties by tailoring the magnetic particle's shape [4].

One possibility to create systems with interesting magnetic properties is based on "square rings", i.e. magnetic rectangular-shaped walls around a square open space. As could be shown theoretically, this form can result in hysteresis loops with steps on both sides of the loop which can be attributed to stable intermediate states, depending on material and dimensions [5,6]. On the other hand, experimental investigations of this system created from permalloy (Py) have shown the quantitatively and qualitatively changed angular-dependences of the coercive fields with different lateral dimensions and wall thicknesses, resulting from varying magnetization reversal processes [7]. This special shape is thus of interest not only for understanding magnetization reversal processes in nanostructures, but also for designing new magnetic storage media with increased storage density due to the possibility to safe two bits in one storage position [5].

However, Magneto-Optical Kerr Effect (MOKE) measurements on these samples have revealed an additional unexpected effect. All samples showed a horizontal shift of the hysteresis loop in most angular regions. Such a shift along the field axis is usually attributed to an exchange bias (EB). This unidirectional anisotropy can occur when a ferromagnetic layer in contact with an antiferromagnetic one is cooled in an external field through the Néel temperature of the antiferromagnet [8,9]. It is known from thin layer systems [10] as well as from core/shell nanoparticles [11].

In a system which is structured of pure permalloy, however, no such effect should occur. This article describes different approaches to explain this surprising finding.

2. Experimental

The permalloy nanostructures were prepared in the Karlsruhe Nano Micro Facility (KNMF) using a lift-off process. After spin-coating a 4″ silicon (100) wafer with a double layer resist of PMMA600k and PMMA950k on top, the desired structure was exposed by the E-beam tool VB6UHR-EWF (Raith) with energy 100 keV. The exposure dose was varied between 500 $\mu C/cm^2$ and 700 $\mu C/cm^2$, using the Proximity Effect Correction (PEC). The

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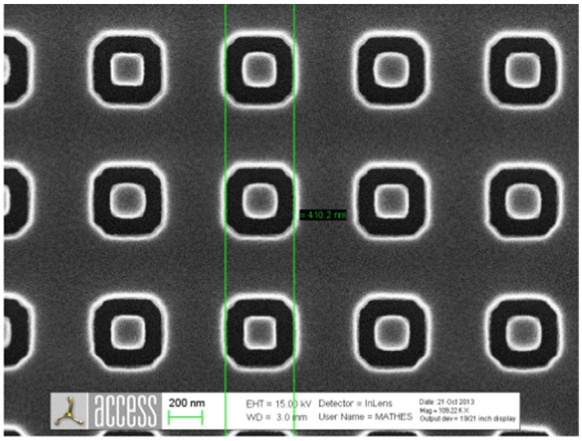

Fig. 1. Array of nanostructured particles with edge length 400 nm and the maximum wall width.

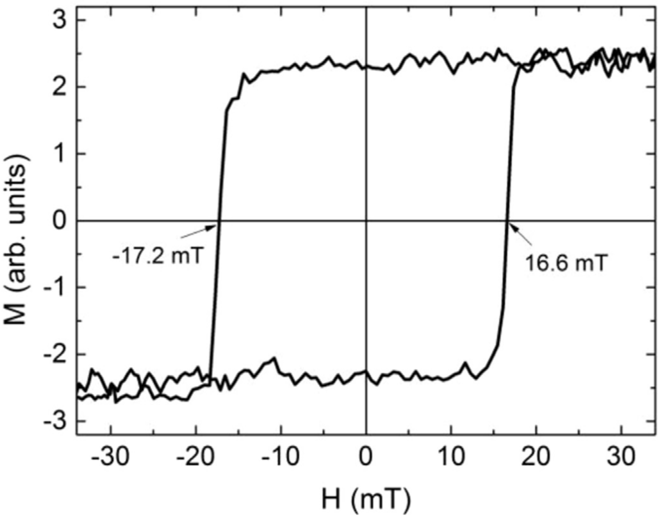

Fig. 2. Hysteresis loop, measured on a sample with edge length 200 nm and maximum wall width in a sample orientation of 35°.

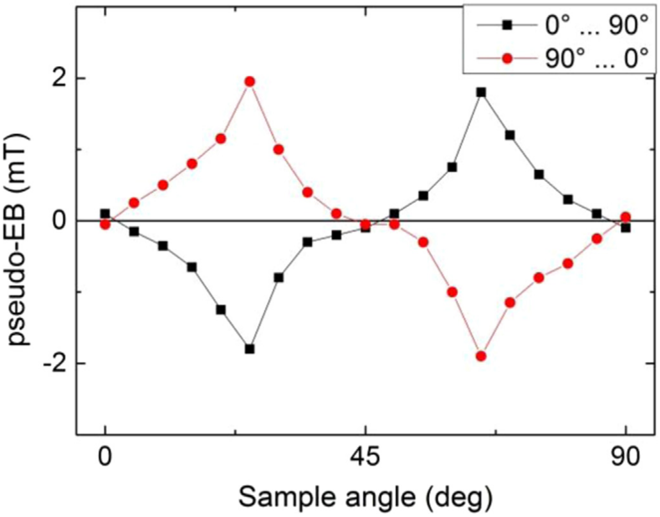

Fig. 3. Results of measurements from 0° to 90° and back from 90° to 0°, depicting the horizontal hysteresis loop shift described as pseudo-EB.

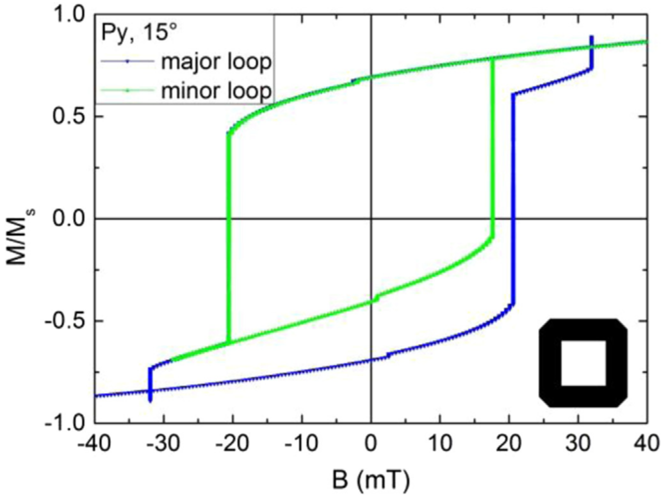

Fig. 4. Major and minor loop, simulated for a sample orientation of 15° with respect to the external magnetic field. The sample is modeled similar to the shape visible in the SEM images (cf. inset and Fig. 1).

samples were developed using a spraying tool with a solution of MIBK:IPA (1:3). Metalizing the samples included a titan layer (5 nm) as an adhesion promoter, a 15 nm permalloy layer and finally a 1–2 nm titan cap layer.

The samples are shaped as described above (cf. Fig. 1), with lateral dimensions between 160 nm and 400 nm and identical distances between the single particles. The wall widths were nominally equal to ¼ of the wall lengths and changed with the applied radiation doses.

MOKE measurements were performed in a longitudinal setup at room temperature, using a CW diode laser with wavelength 532 nm. The light intensity was reduced to max. 5 mW on the sample surface in a laser spot of approximately 30 μm diameter to avoid heating of the nanostructures. This means that in all measurements an ensemble of magnetic particles is examined; measurements average over approximately 5000 magnetic particles in case of samples with particle edge length 200 nm. Former calculations of clusters of up to 4 × 4 particles using OOMMF have shown that the influence of neighboring particles is small for particle sizes between 100 nm and 400 nm. In the recent paper, dealing with asymmetries of hysteresis loops, a symmetric environment of these small influences can be neglected.

For the results shown here, a sample of edge length 200 nm and maximum wall width was used. However, it should be mentioned that the horizontal shift of the hysteresis loop was visible in all of the samples, independent of dimensions and wall widths. For the measurements, the sample was rotated with respect to the external magnetic field with an angular accuracy of ± 0.5°. Signals were detected by a photodiode-bridge technique, [12] allowing for exact measurements of longitudinal magnetization components. The magnetic field was swept between ± 40 mT which is significantly higher than the highest coercive fields and seemed to be sufficient to reach a saturated state, as shown in Fig. 2. The error of the magnetic field is max. 0.5 mT.

3. Results and discussion

Since the small horizontal shift which is visible in Fig. 2 can be found in nearly all measurements, it was examined more in detail.

One possible explanation for this finding is an erroneously shifted adjustment of zero field of the Hall probe. However, this idea could be excluded by measuring diverse sample orientations and finding horizontal shifts of the hysteresis loops to the positive as well as to the negative side.

Another possibility would be the existence of polar and/or transverse components which can, depending on the polarization