Journal of Physics: Conference Series

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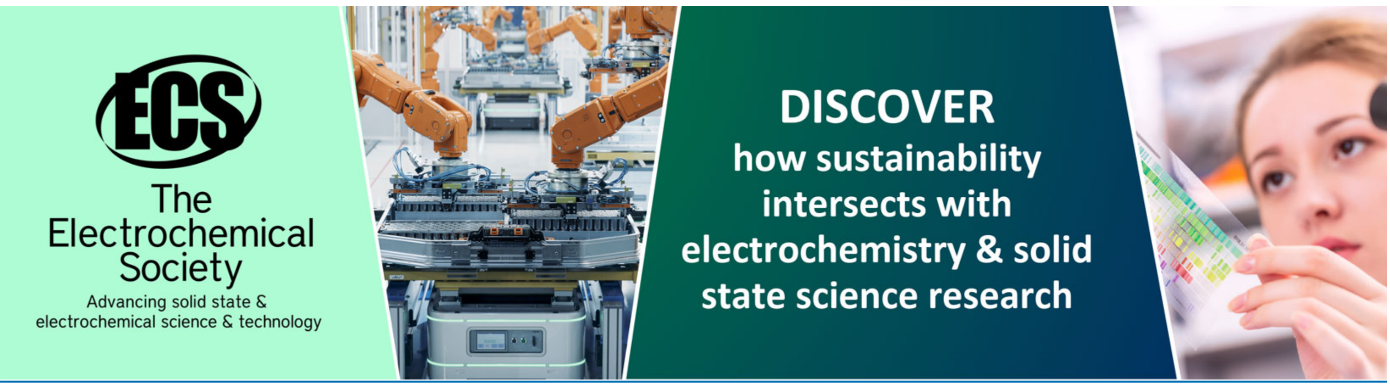

IOP Conf. Series: Journal of Physics: Conf. Series **903** (2017) 012052 doi:10.1088/1742-6596/903/1/012052

Micromagnetic simulation of nanomagnets with geometry-tuned domain wall nucleation

W. Kaiser, M. Kiechle, G. Žiemys, D. Schmitt-Landsiedel and S. Breitkreutz-v. Gamm

Institute for Technical Electronics, Technical University of Munich, 80333 Munich, Germany

E-mail: waldemar.kaiser@tum.de

Abstract. In this work we show the feasibility of tuning the domain wall nucleation by changing the geometry of nanomagnets using shadowing effects. Therefore, micromagnetic simulations based on a three-dimensional model of the nanomagnetic structures have been performed. Atomic force microscopy and anisotropy measurements on fabricated Co/Pt-nanomagnets are used to calibrate the model. It is shown that an increasing gradient due to shadowing effects decreases the switching field of the nanomagnets. By varying the nanomagnet geometry, the switching field can be further decreased and the spot of nucleation can be controlled making these technique feasible for the use in nanomagnetic logic circuitry.
Index terms— Nanomagnetic Logic, Domain wall nucleation, Micromagnetic simulation, Shadowing effects, Artificial nucleation center

1. Introduction

Perpendicular Nanomagnetic Logic (pNML) is a promising beyond-CMOS emerging technology exploiting three-dimensional magnetic field coupling between nanostructured Co/Pt-multilayers [1, 2]. The switching process is based on domain wall (DW) nucleation in the weakest spot followed by DW propagation through the entire magnet [3]. The switching energy is provided by an alternating perpendicular magnetic clocking field [4]. Controlled DW nucleation is ensured by creating an artificial nucleation center (ANC) with local focused ion beam (FIB) irradiation [3, 5], which however causes large fabrication variations, requires an additional process step and is difficult to implement on wafer processes [6, 7]. Kimling shows in [8] the local reduction of the perpendicular magnetic anisotropy (PMA) due to shadowing effects during sputter deposition of the multilayers, generating an anisotropy gradient at the edges of the magnetic structures. Hence, the nucleation field can be tuned by changing the geometry of the magnetic wire ends [8, 9]. The origin of the effects occurring due to the shadowing process is determined by a simulation model in [8]. We improve this model by including the gradient, measured by atomic foce microscopy (AFM), to all sides of the nanomagnets, as naturally observed during fabrication. Multilayer films with scaled thicknesses are measured to obtain the scaling of the anisotropy at the gradient. A three-dimensional model of the nanomagnets is designed using the experimental data. Simulations including different gradients and geometries of the nanomagnets are performed using OOMMF [10] to obtain the switching field and the spot of domain wall nucleation.

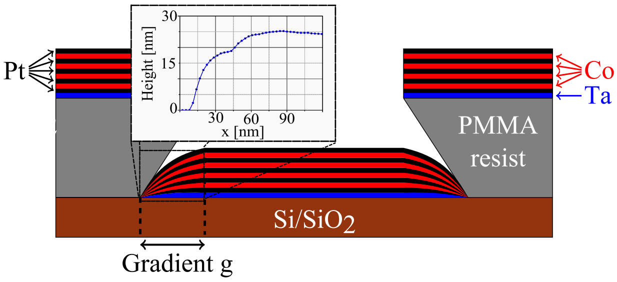

Figure 1. Illustration of the shadowing process and the gradient measured by AFM.

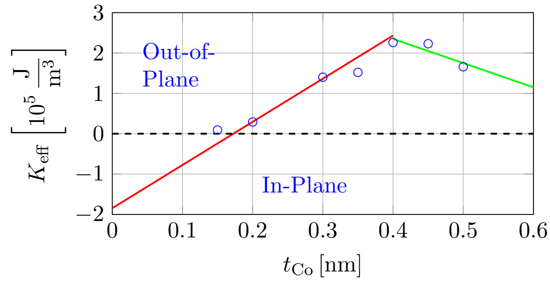

Figure 2. Effective anisotropy of scaled Co/Pt-multilayers.

2. Experimental measurements of the Co/Pt-multilayers

Co/Pt-multilayers and magnetic structures have been fabricated and characterized to feed the micromagnetic model with realistic geometry and magnetic properties resulting from shadowing effects. The different magnetic characteristics of this geometry need to be considered in the switching behavior of the nanomagnets. In Fig. 1 the cross-sectional view of the shadowing effect illustrates the lowered height of the individual layers at the edges due to the lift-off process [8]. To measure the magnetic anisotropy of the changed geometry a series of Co/Pt-multilayer stacks with a composition of $\mathrm{Si/(SiO_2)/Ta_{3nm}/Pt_{x\cdot 5.0nm}/4\times[Co_{x\cdot 0.5nm}+Pt_{x\cdot 2.0nm}]/Pt_{1nm}}$ has been fabricated under variation of the scaling factor $0 < x < 1$. Realistic dimensions of process-related lift-off edges of fabricated nanomagnets are investigated by AFM as highlighted in Fig. 1. Anisotropy measurements based on extraordinary Hall voltage measurement [11] show a significantly lowered anisotropy for samples with an individual cobalt layer thickness t_{Co} below 0.4 nm, as depicted in Fig. 2. The decreasing anisotropy for thinner layers origins from a lower density of the magnetic material. Since the layer thickness is in the range of the diameter of a single Co atom, the deposited magnetic material generates atomic islands instead of complete layers [12]. The anisotropy drop above $t_{\mathrm{Co}} = 0.4$ nm has its nature in the volume contribution of the effective anisotropy dominating in thicker layers [12].

3. Micromagnetic Modeling and Simulation

We investigate the DW nucleation behavior of tip nanomagnets with a tip opening angle Θ of 20° to 150°, shown in Fig. 3a. As fabrication results of tip nanomagnets showed an uncontrolled rounding of the tip, it is more beneficial to investigate nanomagnets with flat ends, as shown in Fig. 3b. Hereby, the width w is varied between 10 nm and 100 nm at constant length. We perform non-thermal simulations using OOMMF [10] to extract the induced shadowing effects. Magnetic field pulses of 10 ns length and a rise time of 2 ns are applied. In our 3D-model, a gradient is added to all sides of the nanomagnets, as observed by AFM measurements, which is depicted in Fig. 4. The net saturation magnetization is kept constant at $M_{\mathrm{S,net}} = 7.23\times10^5$ A/m for each cell. The effective anisotropy is scaled according to Fig. 2. Fig. 5 shows the simulation results for the nucleation field B_{nuc} of the magnets in dependency of Θ. The nucleation field is strongly decreasing for increasing gradients g, as the anisotropy energy slope from the edge to the center of the magnet is reduced. At a constant gradient, B_{nuc} decreases for lower angles, passes a minimum and increases slightly for low angles. For small tip opening angles the amount of magnetic material with in-plane easy axis increases, thus the anisotropy step increases and DW nucleation requires more energy. The DW nucleates for all angles at the desired ANC. A similar behavior is obtained for the simulated nanomagnets with flat tips. For decreasing widths the nucleation field is lowered. The geometries of the flat magnets with DW nucleation at undesired spots are marked by the shaded region in Fig. 5b. For geometries in the unshaded region, we observe a DW nucleation at the desired ANC, like shown in the inset of Fig. 5b. Thus,

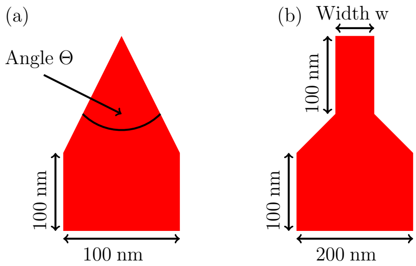

Figure 3. Top view of simulated magnets: (a) Tip magnets, (b) Flat end magnets.

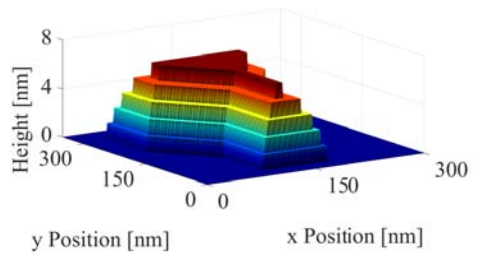

Figure 4. Model of a flat end magnet (gradient $g = 40\,$nm, width $w = 90\,$nm).

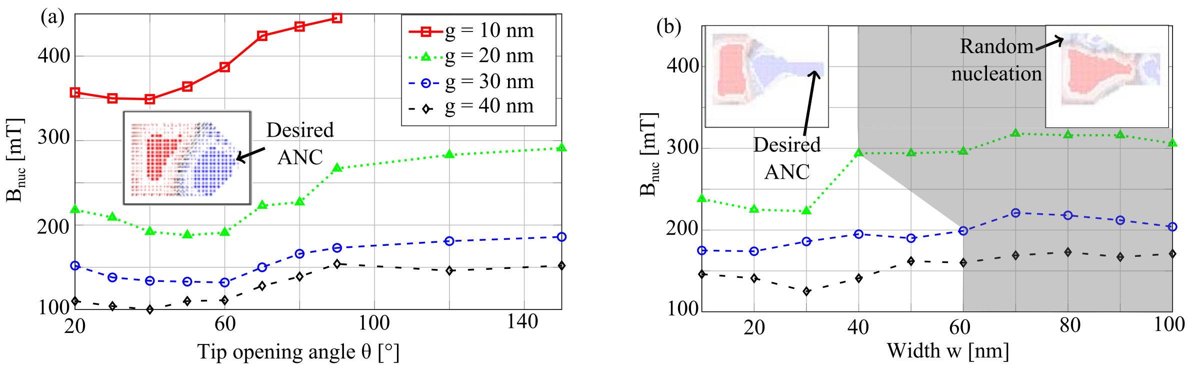

Figure 5. DW nucleation field of (a) tip magnets and (b) flat end magnets. The shaded area marks the geometries undesired DW nucleation occurs.

for application in pNML circuitry nanomagnets geometry and gradient need to be controlled to ensure signal flow directionality.

4. Conclusion

In this work, a study on the DW nucleation of geometry-tuned nanomagnets has been performed using 3D simulations based on fabrication results. It is shown, that including a gradient at a tip using shadowing effects lowers the anisotropy and creates an ANC working as required in pNML devices. This shows the potential of substituting the ANC creation by the use of shadowing during the sputtering process, instead of an additional FIB irradiation step.

Acknowledgments

The authors thank M. Becherer (TUM) and G. Csaba (ND) for their fruitful support.

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