Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **Correlating Microstructure with Switching Field Distribution in Nanomagnetic Systems with Transmission Electron Microscopy**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Institute of Standards and Technology,Boulder,CO,80305-3328**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002137. Proceedings of the 2008 IEEE International Conference on Nanotechnology (8th) Held in Arlington, TX on August 18-21, 2008. U.S. Government or Federal Rights License

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**2**	

Correlating Microstructure with Switching Field Distribution in Nanomagnetic Systems with Transmission Electron Microscopy

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Abstract- **We examine how nominally identical nanostructure can exhibit different switching behaviors in two model systems. The first system consists of an array of perpendicularly magnetized Co/Pd multilayer nanodots. We found that the non-uniformity in switching fields among the nanodots in an array is due to a single grain of weak uniaxial anisotropy. In the second system consisting of in-plane magnetized Permalloy nanodot arrays, we found that edge roughness plays an important role in the switching uniformity of the nanodot array.**

I. Introduction

In the information age, we have come to depend heavily on nanomagnets (think mp3 players and laptops), yet it is increasingly difficult to gain useful information on nanomagnetic systems from bulk magnetometry measurements or even from micromagnetic modeling based on bulk parameters. In addition to the signal-to-noise issues associated with small samples, measuring magnetic properties variation due to grain sizes, defects, edges and surfaces, once considered negligible in the bulk, becomes an intractable problem. However, transmission electron microscope (TEM), given its atomic resolution and magnetic sensitivity, have already begun to elucidate the role of nanoscale defects on the switching behavior of patterned nanostructures. In particular, the subject of switching field distribution (SFD) is of intense interest for applications such as MRAM, patterned media, and spintronics, where uniformity among the functional magnetic nanostructures is critical for each technology's success.

II. Experimental

In an array of magnetic nanostructures, the SFD describes not only the magnetic properties and switching characteristics of the array, but is also an indicator of uniformity among the individual elements. The manufacturability of a device consisting of an assembly of magnetic nanostructures will depend critically on the SFD of the ensemble. A large SFD is undesirable; as one can image, it can lead to situations where individual nanostructures either switch far above or below the intended field. There are many documented causes for SFD; e.g., thermal effects [1], edge roughness [2], edge oxidation [3] and choice of seed-layers [4]. In addition, interactions with neighboring dots have been shown to alter SFD [5].

Of the possible causes to a SFD, physical, chemical, and microstructural properties on the nanoscale can be quantified with TEM. We focus on how pieces of the SFD problem have been solved with microscopy methods. Recently, we have identified the presence of large grains with in-plane [100] as an important microstructural origin of switching field distribution (SFD) in Co/Pd multilayer nanodot arrays, consistent with the "nucleation volume" theory [6]. In this study, we patterned an indexed array of 115 nm Co/Pd multilayered nanodots on a silicon nitride membrane. We identified the dots with unusually small and large switching fields using MFM, followed by plan-view TEM analysis of the same dots. Most nanodots with small switching fields have strong (200) spot reflections in their electron diffraction patterns, whereas nanodots with large switching fields lack these spots. Bright-field TEM images reveal an average grain size of 7 nm, but dark-field images of the (200) spots typically reveal 14-nm grains. Crystals with (200) in plane have [001] and [011] as possible out-of-plane axes, both of which have been shown to have weak perpendicular anisotropy in single crystals [7]. The correlation between strong (200) reflections and small reversal fields leads us to conclude that large grains with in-plane [100] orientation are likely weak links responsible for SFD in the Co/Pd multilayer system.

In addition, the effects of edge roughness on vortex nucleation field SFD were measured in Permalloy nanostructured arrays. Teardrop-shaped elements, 250 nm wide and 30nm thick were fabricated using electron beam lithography and lift-off. Roughness variations were created by varying the electron dose during patterning, which was later measured by bright-field TEM images. In the Lorentz mode, nucleation distributions were measured *in situ*, where the external field was provided by the objective lens of the microscope. We measured the population fraction that nucleated at different applied fields. Based on a Gaussian model, we fitted the mean nucleation field and the SFD of the population. In combining the measurements of edge roughness with measurements of nucleation field and the SFD, we showed that edge roughness enhances vortex nucleation, but at the same time, broadens the SFD in Permalloy nanostructured arrays.

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