Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Magnetism and Magnetic Materials 294 (2005) 83–89
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Micromagnetic modeling and analysis of linear array of square nanomagnets

Pooja Wadhwa*, M.B.A. Jalil

Information Storage and Materials Laboratory, Electrical and Computer Engineering Department, 4 Engineering Drive 3, National University of Singapore, Singapore 117576, Singapore

Received 30 March 2004; received in revised form 23 July 2004
Available online 13 January 2005

Abstract

We perform an analytical and a numerical micromagnetic study of the magnetostatic interactions and switching behavior in a linear array of square permalloy ($Ni_{80}Fe_{20}$) elements. The angular anisotropy in the magnetostatic energy of the array is expressed in terms of a shape anisotropy K_s arising from the square geometry of individual elements, and a "chain" anisotropy K_c due to inter-element dipolar interactions. An analytical model of K_c is introduced, which agrees closely with numerical results from the OOMMF micromagnetics package, in the limit of small element separation s. For $s = 5\,\text{nm}$, the energy due to K_c far exceeds that of K_s by a factor of about 20. For larger s, the model is refined to account for the magnetostatic interaction between surface poles on neighboring elements. Based on the refined model, the analytical switching field H_{sw} is derived by assuming coherent rotation. It yields a close correspondence with OOMMF for s larger than $s_0 = 80\,\text{nm}$, but significantly overestimates the numerical value for $s < s_0$. This is due to the onset of sequential reversal at $s = s_0$ brought about by strong dipolar coupling between elements. The critical nucleation and the propagation fields associated with sequential reversal are also investigated as a function of s.

PACS: 75.50.Bb; 75.50.Ss; 85.70.−w; 75.70.Ak; 61.46.+w

Keywords: Micromagnetics; Dipolar interactions; Shape anisotropy; Chain anisotropy; Switching field

1. Introduction

Regular arrays of uniform ("patterned") nanometer-sized magnetic elements have been proposed for use in various applications such as high-density data storage [1] for two-dimensional (2D)

*Corresponding author. Tel.: +65 687 48 309; fax: +65 687 44 264.
E-mail address: g0202800@nus.edu.sg (P. Wadhwa).

0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2004.07.057

arrays, and memory elements [2], magnetic field sensors [3], and logic operation devices [4] for linear (one-dimensional, 1D) arrays. Hence, it is essential to understand the magnetic interactions and reversal process in these arrays from both the fundamental and application aspects. In well-separated elements, magnetization reversal is mostly determined by the properties of individual elements. However, as element separation is reduced to much smaller than the element lateral sizes [5], inter-element interactions become significant. These interactions become increasingly important in patterned storage media, as the bit density approaches 1 Tb/in^2.

In this article, we perform an analytical and a numerical study of the magnetostatic interaction and magnetic switching in a linear array of square Permalloy (Py) elements. The analysis is based on single-domain (SD) configuration. A preliminary micromagnetic simulation is performed to ascertain the extent of SD configuration for different lateral sizes and separations of the elements. For subsequent analyses, the lateral size of the elements is set within the SD regime and subsequently the temperature effects are considered to be negligible.

The chosen magnetic material of the elements, Py, exhibits negligible magnetocrystalline anisotropy. Thus, any residual anisotropy in the free energy of the linear array is due to (i) shape anisotropy arising from intra-element dipolar interactions and (ii) "chain" anisotropy due to inter-element dipolar interactions. Previous work [6] on 1D array of elements considered circular elements which possess no shape anisotropy. Cowburn et al. [7] showed that square elements exhibit finite shape anisotropy, with corresponding four-fold easy axes along the diagonals. However, in Cowburn's study, the inter-element distance is made large enough to render the magnetostatic interactions between elements negligible. In this paper, we consider much smaller inter-element separation, to investigate the relative strengths of shape and chain anisotropies, and how they interact to affect the magnetic reversal of the chain of square elements.

The chain anisotropy expresses the fact that it is favorable for the dipole moment of each element to line up parallel to the chain direction. Thus, the easy axis for chain anisotropy is along the length of the chain (x-axis), while the hard axis is perpendicular to it (y-axis). In assigning easy and hard axes for both the chain and shape anisotropies, we are applying the approximation of Cowburn et al. [8], in which the detailed structure of the demagnetizing field is neglected. Under this approximation, the angular dependence of the magnetostatic energy of square nanomagnets can be expressed as a four-fold symmetric expression. Hence, a four-fold set of easy/hard directions for the shape anisotropy can be defined, corresponding to directions where the energy is at its minimum/maximum. Likewise, for chain anisotropy, a two-fold easy/hard direction can be defined along/perpendicular to the length of the array, which is valid for small element separations. Thus, we introduce an analytical expression of the angular dependence and relative strengths of these two anisotropy terms. From this model, the effective chain anisotropy coefficient K_c is derived and compared with numerical results obtained using a micromagnetic package called OOMMF [9]. The relative strengths of K_c and K_s are also compared in the limit of small separation. Subsequently, a more refined analytical expression for K_c is introduced, which considers the increasing separation s and the interaction between magnetic poles on the vertical edges of the square elements. With this refined expression, we derive the analytical switching field H_{sw} of the linear array of elements and compare it with numerical H_{sw} values obtained by OOMMF simulation for a range of s. Finally, we investigate the excess field required to nucleate a magnetic reversal, compared to the field for propagating the reversal, when s is reduced.

2. Model, results and discussion

In our analysis, we assume that the elements adopt an SD configuration, since it is the most common configuration used in storage and logic applications of patterned nanomagnets. The OOMMF package [10] is used to determine the extent of the SD regime for a linear array of square