Journal of Magnetism and Magnetic Materials 394 (2015) 391–396

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Micromagnetic simulation of exploratory magnetic logic device with missing corner defect

Xiaokuo Yang*, Li Cai, Bin Zhang, Huanqing Cui, Mingliang Zhang

Science College, Air Force Engineering University, Xi'an 710051, China

ARTICLE INFO

Article history:
Received 14 November 2014
Received in revised form
16 May 2015
Accepted 25 June 2015
Available online 8 July 2015

Keywords:
Quantum-dot cellular automata (QCA)
Nanomagnet logic (NML)
Aspect ratio
Clock field
Missing corner

ABSTRACT

Magnetic film nanostructures are attractive components of nonvolatile magnetoresistive memories and nanomagnet logic circuits. Recently, we studied switching properties (i.e., null logic preserving) of rectangle shape nanomagnet subjected to fabrication imperfections. Specifically, we presented typical missing corner material-related imperfections and adopted an isosceles triangle to model this defect for nanomagnets. Micromagnetic simulation shows that this kind of imperfections modeling method agrees well with previous experimental observations. Using the proposed defect modeling scheme, we investigate in detail the switching characteristics of different defective stand-alone and coupled nanomagnets. The results suggest that the state transition of defective nanomagnet element highly depends on defect type and device's aspect ratio, and the defect type B_d needs the largest coercive field, while the defect type D requires the largest null field for switching. These findings can provide key technical parameters and guides for nanomagnet logic circuit design.

1. Introduction

Nanomagnet Logic (NML, originally termed magnetic quantum cellular automata [1]) device is a variant of emerging electronic quantum-dot cellular automata (QCA) architecture [2], which has gained much interest from researchers due to its substantial advantages of radiation harden, room temperature operation, potentially low power and nonvolatility [3–8]. The basic element of NML is sub-200 nm size single-domain magnet (see Fig. 1a), where the dimension along z axis direction depicts the thickness of nanomagnet. Usually, the in-plane magnetization orientations along y axis are used to encode binary logic states '1' and '0', respectively, while the in-plane magnetization along x axis (hard axis) denotes 'null' logic [4]. Dipole coupling interaction between neighboring nanomagnets is responsible for NML data (logic state) transmission.

To date, there are some candidate fabrication methods to realize NML devices [4,9]. However, although the advanced technologies are used in the NML manufacturing, defects are still likely to occur at such small nanoscale size [10], one representative fabrication imperfection is the major irregular corner defect in the NML (see Fig. 1b the red circle, the scanning electron microscopy image of defective nanomagnet is from Ref. [7]). This common defect mainly arises from deposition process phase. In the fabrication of NML devices or circuits, when the deposited material clumps, the followed lift-off might remove a large chunk from one side of the magnet [7], which results in so-called missing corner materials defect.

From previous studies [11], it is known that error-free logic state switching or transition in the NML array relies on planar shape and size of nanomagnet, but how the typical missing corner defect affect the switching of individual NML device is not well known. However, in order to construct large scale robust NML circuits, one must understand the switching properties of basic NML elements, also various defective nanomagnets. To this end, this work studies the switching characteristics of different defective shape NML devices. Specifically, we herein employ a triangle to describe the missing corner materials region (see Fig. 1c), where $\alpha = 45°$, d_V represents side length of the triangle. Using the approximation treatment, the simulation model of nanomagnet with missing corner materials has been established, and all the possible missing corner defect types are taken into account in the paper, which includes

- Type A—nanomagnet with single missing corner defect.
- Type B_s—nanomagnet with two missing corner defects in one same side (B_1–B_4).
- Type B_d—nanomagnet with two missing corner defects in a diagonal direction (B_5, B_6).
- Type C—nanomagnet with four missing corner defects.
- Type D—nanomagnet with three missing corner defects.

* Corresponding author.
E-mail address: yangxk0123@163.com (X. Yang).

http://dx.doi.org/10.1016/j.jmmm.2015.06.068
0304-8853/

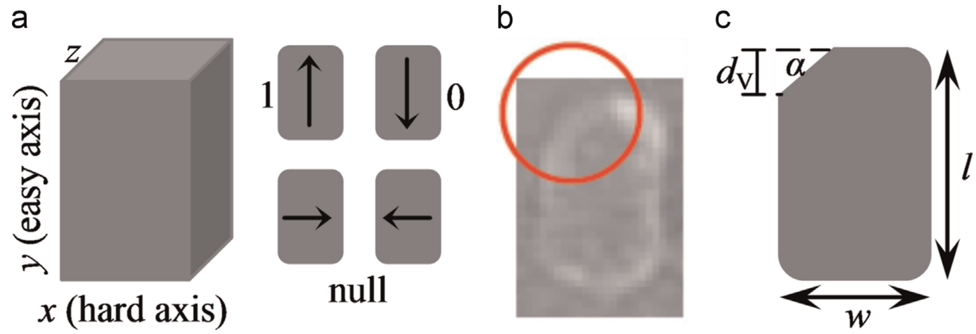

Fig. 1. NML device and missing corner materials defect modeling. (a) The three dimension schematic of NML device and its magnetic logic states; (b) the scanning electron microscopy image of defective nanomagnet [7]; (c) the planar size of nanomagnet device and its missing corner defect model. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

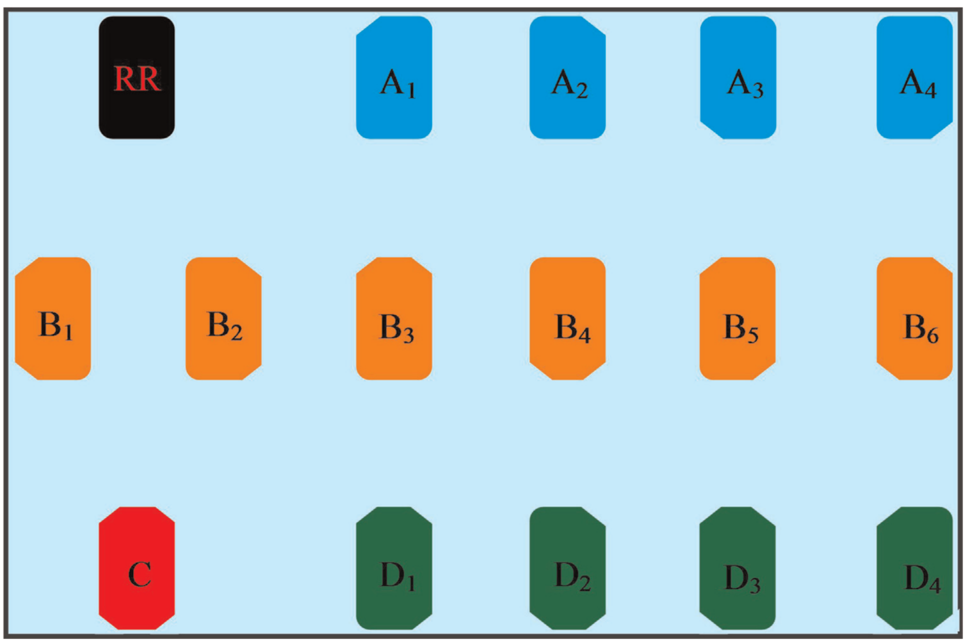

Fig. 2. A set of NML devices with missing corner(s). Note that 'RR' denotes defect-free rounded rectangle nanomagnet, 'C' denotes nanomagnet with four missing corner defects.

The schematic of above-mentioned five types of missing corner defects are shown in Fig. 2. It should be pointed out that single missing corner defect (equals to Type A) of NML device had been succinctly explored in Refs. [12,13]. These works are helpful to realize corner defect issue of nanomagnet logic. However, no previous study considers with a thorough analysis the impact of the variation of defect type and device shape, as (1) the multi-missing corners defect devices, (2) the size (aspect ratio) effect of defective devices, and (3) the coercive field and null field required for switching defective nanomagnets of different type.

In the remainder of this paper, we present a detailed study of 'clock field removal' and 'aspect ratio (AR)' effects for defective NML devices using micromagnetic simulation. Then two devices switching characteristics parameters, namely the device's coercive field and null field, which are significant for NML applications, will be deeply investigated. In order to complete logic state reversal or transmission in the NML computing, an external magnetic field is required to align all of the devices' magnetization along their hard axis (null logic), this external field is usually called clock field, which would be used in the following work.

2. Simulation of irregular shape NML devices

2.1. Simulation setup

The study throughout the paper considers NML devices in a supermalloy material implementation. Each element is $50(w) \times 100(l) \times 20\ \text{nm}^3$, $d_V = 10$ nm (a moderate defect according with modern advanced technologies [8]), and a thermal stability ratio K_uV/k_BT (room temperature 300 K) of 10 [14] is included. That is to say, we introduce the magnetocrystalline anisotropy constant K_u of 25 KJ/m^3 to lower spontaneous magnetization flipping. The Object Oriented MicroMagnetic Framework (OOMMF) [15] is chosen to simulate the switching behavior of nanomagnet with corner defects, a damping constant of 0.5 and 2-D periodic boundary conditions are used. Specifically, in order to accurately capture the characteristics and dynamics of corner-defect devices, a mesh discretization of $1 \times 1 \times 5\ \text{nm}^3$ (1 nm is far smaller than the characteristic exchange length 5.2 nm of supermalloy [15]) is used since the defect zone is relatively small.

2.2. Clock field removal effect of defective NML device switching

There are several switching properties for missing corner shape nanomagnets, such as null logic preserving ability after shutting