Signal Processing with Coupled Ferromagnetic Dots

G. Csaba[1], A. Imre[1], G. H. Bernstein[1], W. Porod[1] and V. Metlushko[2]

[1] *Center for Nano Science and Technology, Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556 USA*
[2] *Department of Electrical Engineering and Computer Science, University of Illinois, Chicago, IL 60607 USA*

Abstract — This paper demonstrates how magnetically-coupled nanometer-size ferromagnetic dots can be used for information processing. A hierarchy of modeling tools is utilized for efficient simulation and design of these nanomagnet circuits. Based on these tools, we show how the shape and placement of dots can be designed to perform desired logic functions. Experimental investigations of such closely-packed nanomagnet arrays are promising.

I. Introduction

Nowadays information processing technology is almost entirely based on manipulation of electric currents in semiconductor devices, while the data storage industry is dominated by magnetic technologies. Recently, the boundary between the two disciplines has become more diffuse. Magnetic random access memory (MRAM) devices embed magnetic nanoelements within semiconductor memory-like architectures, and novel spintronic devices integrate magnetic materials with semiconductor devices in order to manipulate the spin polarization of currents [1]. However, all these structures access nanomagnets *individually* by electric currents. This requires frequent conversion of magnetic fields to electric currents and vice versa.

It has been recently demonstrated that magnetic excitations (domain walls, solitons) propagating in magnetic nanostructures might be utilized for propagating and processing digital information [2]. We would like to explore this concept in the framework of Field-Coupled Computing (FCC), which was originally proposed for Coulomb-coupled quantum dots in the quantum-dot cellular automata paradigm [3]. In these devices the bits are represented by the magnetization state of nanomagnets. Magnetic interactions between neighboring nanomagnets naturally provide the interconnection between the dots, eliminating the need for additional wiring circuits. This concept is schematically illustrated in Fig. 1. The input and output of the FCC array is realized in a very similar fashion to an MRAM, but the vast majority of the dots (the interior of the array) are influenced only by their neighbor's fields.

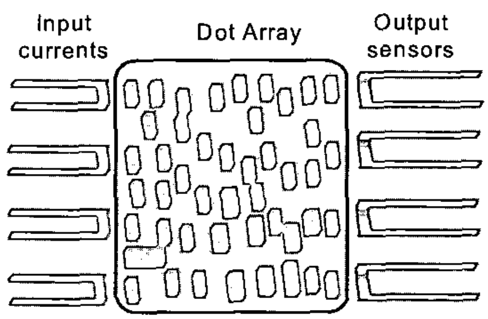

Fig. 1. Illustration of a magnetic computing array. The information flows from the inputs toward the outputs through magnetic interactions.

Technologies for realizing arrays of nanomagnets (like the one shown in Fig. 1) are currently under development for ultra-high density hard disk drives. The devices we envision can be built on this existing technological basis.

Obviously, the geometry of the array must be carefully designed in order to exhibit the desired functionality. We will review the physical theory behind this design in Section II, and also introduce our design tools.

Based on these tools, operating logic devices will be designed and simulated in Section III. While our more complex device structures have not been realized yet, the proof-of-concept will be confirmed experimentally in Section IV.

II. Modeling of Coupled Ferromagnetic Dots

In this chapter, we will present a hierarchy of nanomagnet-modeling. Starting from the mathematically complex and computationally intensive micromagnetic equations, we will show simple and intuitive models for the simulation of coupled nanomagnets.

0-7803-7538-6/02/$17.00©2002 IEEE

A) Micromagnetics of Small Ferromagnetic Particles

The theory of micromagnetics was originally developed for understanding the domain structure of bulk ferromagnetic materials. The material is characterized by a classical vector field $\mathbf{M}(\mathbf{r},t)$, which when subjected to an effective field $\mathbf{H}_{\text{eff}}(\mathbf{r},t)$, evolves in time according to the Landau-Lifshitz equation [4]:

$$\frac{\partial \mathbf{M}(\mathbf{r},t)}{\partial t} = -\gamma \mathbf{M}(\mathbf{r},t) \times \mathbf{H}_{\text{eff}}(\mathbf{r},t) - \frac{\alpha\gamma}{M_s}[\mathbf{M}(\mathbf{r},t) \times \mathbf{M}(\mathbf{r},t) \times \mathbf{H}_{\text{eff}}(\mathbf{r},t)] \quad (1)$$

Here γ is the gyromagnetic ratio, M_s is the saturation magnetization of the material, and α is a phenomenological damping constant. The effective field depends on the magnetization in a very complex way: partly through Maxwell's equations, and partly through phenomenological forces, which take into account quantum-mechanical effects quasi-classically. The steady state solutions are usually complex domain patterns for larger size bulk materials. Apart from some very special cases, (1) must be treated numerically, and for larger structures (>5-10 μm) this becomes increasingly time consuming.

For small (below 100 nm) materials the Single Domain Approximation (SDA) provides an intuitive, computationally efficient method for the understanding and designing coupled nanomagnet arrays. The domain wall of a single-domain particle is simply its physical border, and the magnetization is a single vector for each dot, rather than a vector field. The SDA leads to a system of coupled ordinary differential equations, which formally resemble the dynamical equations describing electric circuit behavior [5]. Using this analogy, one can then use a circuit simulator, such as SPICE, to understand the behavior of "magnetic signals" in the nanomagnet circuit, which will be demonstrated in Section III.

B) Energetics of Coupled Nanomagnets

In the absence of external excitations, physical systems will occupy their ground state. In a first approximation, the operation of FCC devices can be understood based on this principle, as will be shown in the following.

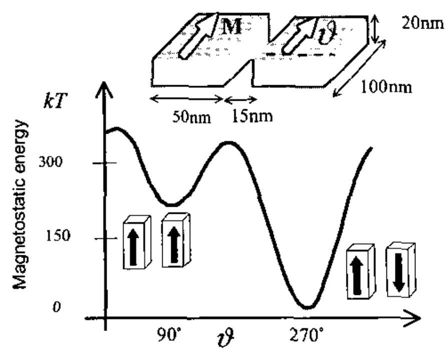

Fig. 2. Energy diagram of two coupled nanomagnets.

Figure 2 shows the total magnetostatic energy of a system of two coupled single-domain permalloy nanomagnet pillars, as a function of the magnetization of the right dot. The magnetization of the left magnet was kept fixed. The energy is dominated by the shape-anisotropy term, resulting in two deep energy minima for magnetization directions parallel to the easy axis (for $\vartheta = 90^\circ$ and $\vartheta = 270^\circ$). The ground state is found for $\vartheta = 270^\circ$ due to the dipolar coupling between dots, which favors their antiparallel alignment. Note that the energy of the ground state is $150kT$ lower then the excited state, consequently the ground state is perfectly stable at room temperature. Even for a more complicated arrangement of dots, the ground state of a given dot will be uniquely determined by its neighbors. After assigning logic values to the magnetization component along the easy axis (say '1' if it is pointing up, and '0' if down), digital information can be represented and processed in such structures. In the next section, we will show how this can be accomplished.

III. Logic Devices Built From Nanomagnets

Our simplest device is the nanomagnet wire, a one-dimensional structure which orders according to the state of the input dot. Figure 3 presents plots of micromagnetic simulations, showing how an external pump field is applied at different instances in time to drive the dots from an initial metastable state to the antiferromagnetically-aligned ground state. The input dot is designed to have a larger switching field than the other dots, which assures that it does not switch under the effect of the external pumping field.

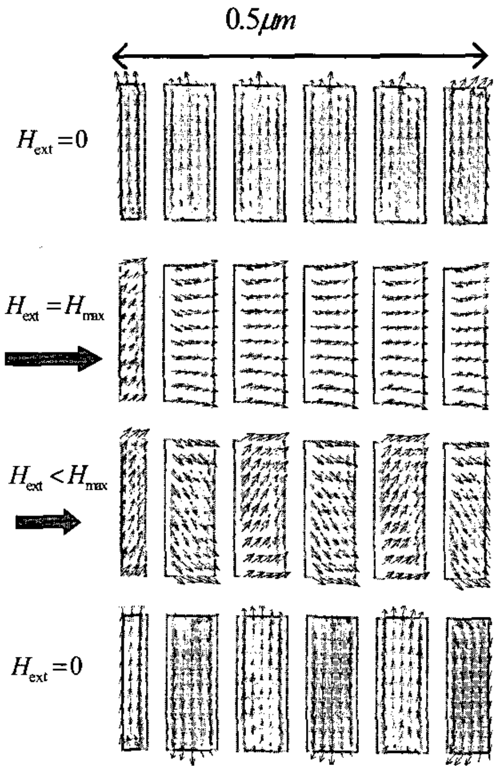

Fig. 3. Micromagnetic simulation of the switching of the nanowire. The four snapshots are different phases of the pumping cycle. The red and blue colors denote magnetization pointing up and down, respectively.

Since metastable states represent deep local minima on the energy landscape of such an array, the external pumping field is always required to drive the system out of a metastable state. The pumping field first erases the 'memory' of the structure, as all dots move to their highest energy, but logically neutral state. The external field pumping also ensures the local activity and signal restoration property of the nanoelements.

One can think about the nanowire as an inverter chain: even-dot-length wires simply transmit the state of the input; odd numbers of dots operate as an inverter.

The magnetic majority gate is the universal logic gate of nanomagnet devices. The layout of a magnetic majority gate built from permalloy pillars with output wire segments is sketched in Fig. 4. The inputs are determined directly by driving-currents. In the ground state, dot '1' will be antiparallel with the majority of its neighbors. If one of the input dots is in the logical '1' state, the dot realizes a logical NOR function between the other two inputs and the output, and if one input is in the logical '0' state, then the gate computes the NAND function.

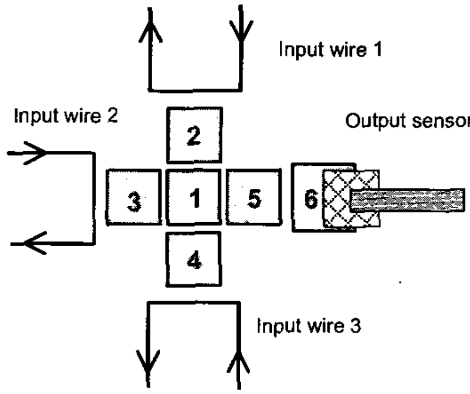

Fig. 4. Layout of the magnetic majority gate. The longest axis of the pillar-shaped dots is perpendicular to the plane of the paper.

The single-domain time-dependent SPICE simulation of the majority gate for a particular input combination is shown in Fig. 5. Note that the geometry parameters of dot '6' are different from the other dots in the structure. It assures that this dot is the first to make the transition to the neutral logic state, and the last to switch back to a definite logic value. This fact determines the direction of signal propagation and defines dot '6' as the output of the structure.

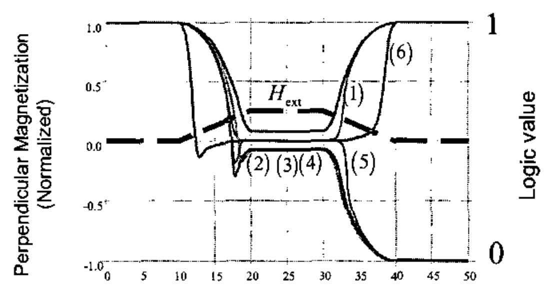

Fig. 5. Single-domain SPICE simulation of a magnetic majority gate. The numbers denote the waveforms of the corresponding dot in Fig. 4, and the dashed line represents the external pump field.

In theory, these two logic devices are sufficient to realize any arbitrary logic function between the inputs and outputs of the structure shown in Fig. 1. Moreover, since the switching behavior of dots depends on their geometry parameters, a homogeneous external field can be designed to target specific dots in a larger array. This fact can be utilized for building sequential circuits as well [5].

IV. Experimental Investigation of Nanomagnet Arrays

Several techniques can be employed for the fabrication of planar or 3D magnetic nanostructures. To validate our models, we manufactured nanowire-like arrangements of planar permalloy and Cobalt dots. A comparison between experimental and simulation results is shown in Fig. 6. The line geometry determined by atomic force microscopy (AFM) is shown in part (a), and part (b) shows the micromagnetic simulations using the OOMMF code [6]. Parts (c) and (d) show magnetic force microscopy (MFM) images, both as expected from simulations of the field gradients (c), and the experimental MFM image (d) which clearly exhibits the expected coupling in the wire.

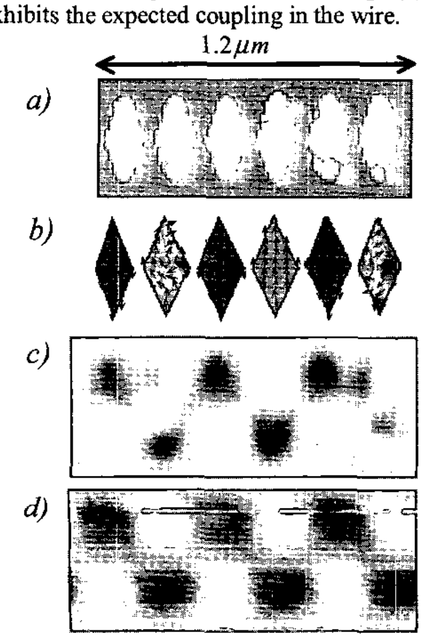

Fig. 6. *a)* AFM topographic picture of a Cobalt nanostructure, *b)* magnetization distribution *(c)* MFM image as expected from simulations, and *d)* recorded MFM image.

Switching-field variations, which arise from the imperfect shape or rough surface of the dots, will introduce faults in longer lines, and we find a typical correlation length of about 5-10 dots. This result is consistent with the observation of other groups [7], and suggests that design for fault-tolerance is a crucial issue in nanomagnetic networks. A simple example of fault-tolerant design is non-reciprocal structures, which show much less sensitivity against defects than the ones lacking definite signal propagation direction.

V. Benefits of Magnetic Nanocomputing

This paper demonstrated that it is in principle possible to construct a family of logic devices from coupled ferromagnetic dots using electric circuits only as the interfaces of the computing array. The magnetic devices are characterized by low power dissipation (a few ten or hundred kT per bit operation, as estimated from Fig. 2.) and relatively high speed (on the order of a hundred MHz, as estimated from time-dependent simulations). These magnetic structures take advantage of the technological base developed by the magnetic data storage industry. The computing architecture naturally incorporates memory elements in the logic circuit, which might be very well suited for certain applications. We are currently working on the experimental realization of the proposed devices. While the realization of complex circuits might pose formidable difficulties, we do not see any fundamental obstacle of building a magnetic logic device of high complexity.

Acknowledgement

The authors would like to acknowledge fruitful discussions with Prof. A. Csurgay. This work was supported in part by the Office of Naval Research and the W. M. Keck Foundation.

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