



Simulation of Field Coupled Computing Architectures Based on Magnetic Dot Arrays

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Abstract. In this paper, we demonstrate that field-coupled nanomagnets can be used for digital information processing. The operation of logic devices is based on a QCA-like architecture, where information propagates by magnetostatic interaction between individual magnetic dots. Micromagnetic simulations indicate that simple logic gates function properly. Efficient design tools, based on the single-domain approximation are developed.

Keywords: magnetic nanocomputing, QCA, micromagnetic design, SPICE

1. Introduction

Magnetic data storage research is currently exploring the possibilities of storing a single bit of information in a single-domain ferromagnetic particle. Magnetic interaction between these particles might cause the loss of information which, of course, is an undesirable characteristic in a storage device. In this paper, we will show, how one can take advantage of such interactions and how to utilize them for information processing.

The architecture is based on the idea of Field-Coupled Computing, i.e. using electric or magnetic interaction between nanosystems to perform computational tasks. This is similar to the *Quantum-Dot Cellular Automata* (QCA) concept, which was originally proposed for Coulomb-coupled quantum dots (Lent *et al.* 1993). Several nanosystems have been studied as building blocks of QCA: Single-Electron QCA's have already been demonstrated (Snider *et al.* 1999), molecular structures have been proposed, and the feasibility of magnetic QCA was experimentally verified (Cowburn and Welland 2000).

Here, we give the first overview of the design of nanomagnetic logic devices. We will introduce the 'adiabatic control' of magnetic nanostructures, and propose that appropriate external field control can reliably put the nanomagnet system into the desired state. We will present micromagnetic simulations of functioning

devices, and use the single-domain approximation as a design tool.

2. The Classical Theory of Micromagnetics

This well-known theory exhaustively describes the behavior of ferromagnetic materials, if the size and time scale of interest is large enough that quantum-mechanical effects (i.e. the exchange interaction) can be treated quasi-classically. This quasi-classical approach works for spatial dimensions larger than few nanometers, and times longer than picoseconds. The Landau-Lifshitz equation describes, how the magnetization $\mathbf{M}(\mathbf{r}, t)$ changes under the influence of an effective field $\mathbf{H}_{\text{eff}}(\mathbf{r}, t)$:

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

Where γ is the gyromagnetic ratio, α is the damping constant and M_s is the saturation magnetization of the material (Hubert and Schafer 1998). The effective field consists of four parts:

$$\mathbf{H}_{\text{eff}}(\mathbf{r}, t) = \mathbf{H}_{\text{dip}}(\mathbf{r}, t) + \mathbf{H}_{\text{ext}}(\mathbf{r}, t) + \mathbf{H}_{\text{exch}}(\mathbf{r}, t) + \mathbf{H}_{\text{anis}}(\mathbf{r}, t) \quad (2)$$

$\mathbf{H}_{\text{dip}}(\mathbf{r}, t)$ represents the dipole-dipole interactions and $\mathbf{H}_{\text{ext}}(\mathbf{r}, t)$ denotes the external magnetic field. Both are ‘real’ magnetic fields, which result from the solution of Maxwell’s equations. $\mathbf{H}_{\text{exch}}(\mathbf{r}, t)$ models the exchange interactions between the moments, and is proportional to the Laplacian of the magnetization. $\mathbf{H}_{\text{anis}}(\mathbf{r}, t)$ takes into account the anisotropic nature of the material. This system of coupled partial differential equations almost always calls for numerical solutions. There are several software packages available for this task (Donahue and Porter 1999). The steady-state solution for larger (typically micron or bigger) bulk materials is a magnetic-domain structure.

3. Application to Nanomagnets: The Single-Domain Approximation

If the typical size of the nanomagnet is smaller than the single-domain limit, then the exchange field usually overwhelms the dipole field, thus forcing a parallel alignment of magnetic moments inside the particle. The single-domain limit for a cubic permalloy particle is about 50 nm. If this approximation is applicable, then the magnetization of a particle can be represented by a single vector (three scalar numbers), instead of a vector field. This results in a significant simplification for the qualitative understanding of the behavior of the particle, and the numerical simulation of dots becomes much easier. Moreover, the behavior of the single-domain particle becomes much more predictable, unlike the complex switching characteristics of a multi-domain particle with its complicated dependence on the ‘history’ of its magnetization. Single-domain particles have a very simple hysteresis loop, with a well defined switching field.

A nanomagnet logic device consists of a finite number of dots. Denoting the *average* magnetization and effective field of the i -th dot by $\mathbf{M}^{(i)}(t)$ and $\mathbf{H}_{\text{eff}}^{(i)}(t)$ respectively, the magnetization vector obeys the following equation of motion:

$$\frac{d\mathbf{M}^{(i)}(t)}{dt} = -\gamma \mathbf{M}^{(i)}(t) \times \mathbf{H}_{\text{eff}}^{(i)}(t) - \frac{\alpha\gamma}{M_s} [\mathbf{M}^{(i)}(t) \times \mathbf{M}^{(i)}(t) \times \mathbf{H}_{\text{eff}}^{(i)}(t)] \quad (3)$$

These are three ordinary differential equations for each dot. The effective field is given by:

$$\mathbf{H}_{\text{eff}}^{(i)}(t) = \mathbf{H}_{\text{ext}}^{(i)}(t) + \mathbf{N}^{(i)}\mathbf{M}^{(i)}(t) + \sum_{j \in \text{neighbors}} C_{ij}\mathbf{M}^{(j)}(t) \quad (4)$$

It consists of three parts: the first is the external field, the second is the self-demagnetization field which depends on the shape of the nanomagnet, and the third part describes the interaction with neighboring dots. $\mathbf{N}^{(i)}$ is a matrix containing three scalar numbers:

$$\mathbf{N}^{(i)} = \begin{bmatrix} N_x^i & 0 & 0 \\ 0 & N_y^i & 0 \\ 0 & 0 & N_z^i \end{bmatrix} \quad (5)$$

The above system of ODE-s is just one possible form of the single-domain approximation (or the so-called Stoner-Wohlfarth model (Hubert and Schafer 1998)). The matrices \mathbf{N} and \mathbf{C} are given for various approximations, see Hubert and Schafer (1998), Cowburn *et al.* (1999) and Stamps and Hillebrands (1999) for details.

There is still some debate in the literature under what conditions the single-domain approximation is valid, and when it breaks down. We performed most of our simulations both with and without the single-domain approximation, and ‘a posteriori’ verified its validity. Our calculations gave the same results (typically, with less than 10% deviation), however, the single-domain approximation often overestimates the switching fields. All the simulations used the material parameters for permalloy.

4. The Nanomagnet as Bistable Switch

Let us consider now a pillar-shaped single domain nanomagnet, as schematically shown in Fig. 1. Due to the strong shape anisotropy ($N_z < N_x, N_y$), the magnetization of a dot in steady state is always parallel with its longest axis, here pointing upwards or downwards.

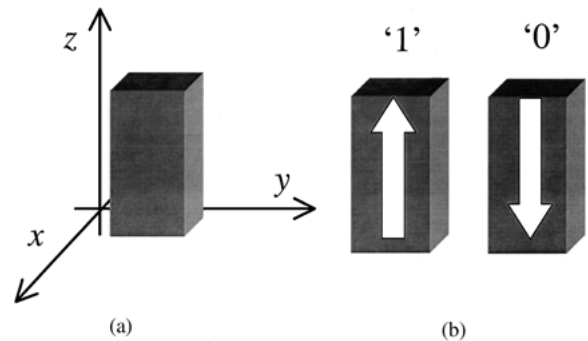


Figure 1. A single nanomagnet pillar (a) and its two stable magnetization states (b).

In logical sense, this dot is a bistable switch, and stores one bit of digital information. We assign the logical value ‘1’ to the magnetization pointing up, and ‘0’ for magnetization pointing down. The miniaturization of the magnets is ultimately restricted by the fact that their switching energies have to be larger than kT , and their switching speed is limited by the precession frequency. These restrictions still yield an impressive integration density of 10^{10} cm^{-2} , and speed in the GHz regime. Storage architectures address all dots individually by a read-write head or metallic wires.

5. Adiabatic Control of Magnetic Nanostructures: The Nanowire

A line of magnetically-coupled permalloy pillars can be thought of a magnetic nanowire.

Let us assume, that the leftmost pillar is pinned, i.e. its magnetization is fixed, and pointing up. We can consider the dipole chain as an inverter-chain in the logical sense (Fig. 2). If we can guarantee that the wire is in its ground state, it transmits binary information from its input to its output, and the state of every dot in the wire is determined by the input. Note that in the physical structure, the input dot is slightly thinner than the other dots, resulting in a higher switching field for this dot.

In order to move the wire from an arbitrary initial state to its ground state, we use adiabatic control by external fields. The details of this process are shown in Fig. 3. In the first phase, an external field is applied which is able to switch every dot, except for the input dot (which has a higher switching field, as discussed above). By the end of the first phase, the ‘memory’ of the structure is erased: the magnetic moments of the

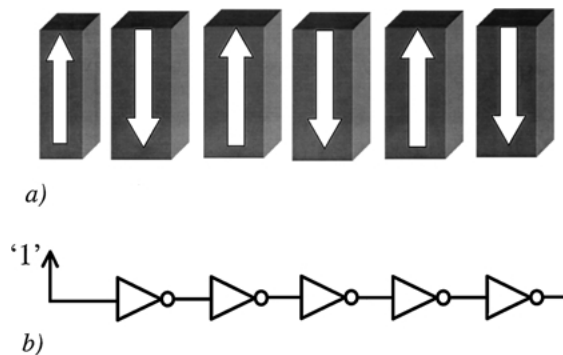


Figure 2. The physical structure of the inverter (a) and its logic equivalent (b).

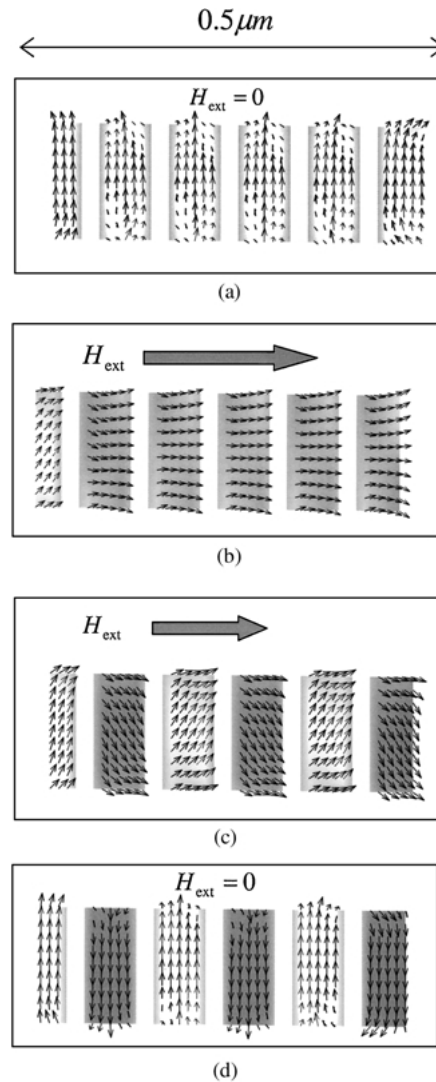


Figure 3. Adiabatic pumping of the nanowire. The initial metastable state (a) eliminated by a strong external field (b). Slowly releasing the field (c), the system relaxes to the zero-field ground state (d).

wire dots are in line with the strong external field, regardless of their previous state. In the second phase, this external field is slowly released. In this phase, the moments order according to the state of the first dot, which retained its magnetization. The term ‘adiabatic control’ is used since the dots always remain close to their ground state during the second phase. As no precession of the magnetization vector occurs, complicated nonlinear dynamics are suppressed. The results of the micromagnetic simulation (shown in Fig. 3) agree well with the qualitative expectations.

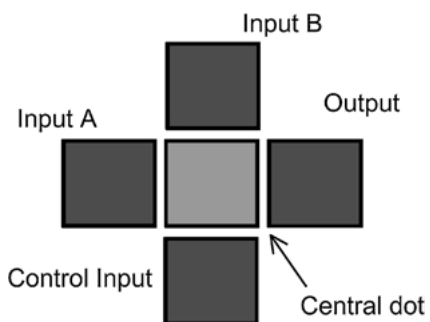


Figure 4. Schematic of the majority gate.

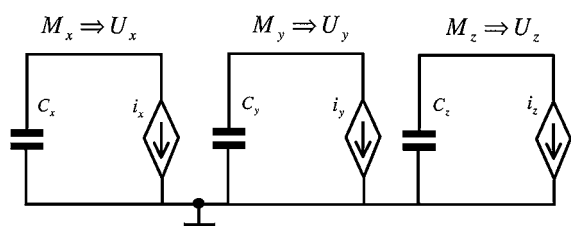


Figure 5. The equivalent-circuit model of a single nanomagnet dot.

The possibility of adiabatic control in magnetic nanostructures is one of the main results of our work. We think that even in large-scale arrays, not only the statistical properties of the system, but the magnetization state of individual dots can be reliably controlled.

6. Toward More Complex Structures: Majority Gate

The majority gate is a three-input, universal logic gate, which can realize basic logic functions, as schematically shown in Fig. 4. An OR gate is realized by setting its control input to ‘1’ and it behaves as an ‘AND’ gate by setting the control input to ‘0’. The majority gate can be operated by the same ‘adiabatic pumping’ scheme as the wire. In the ground state, the central dot is antiparallel with the majority of input dots. Since the interaction between diagonally adjacent dots might have undesired effect on the operation of the device, the design requires more care than for a single wire.

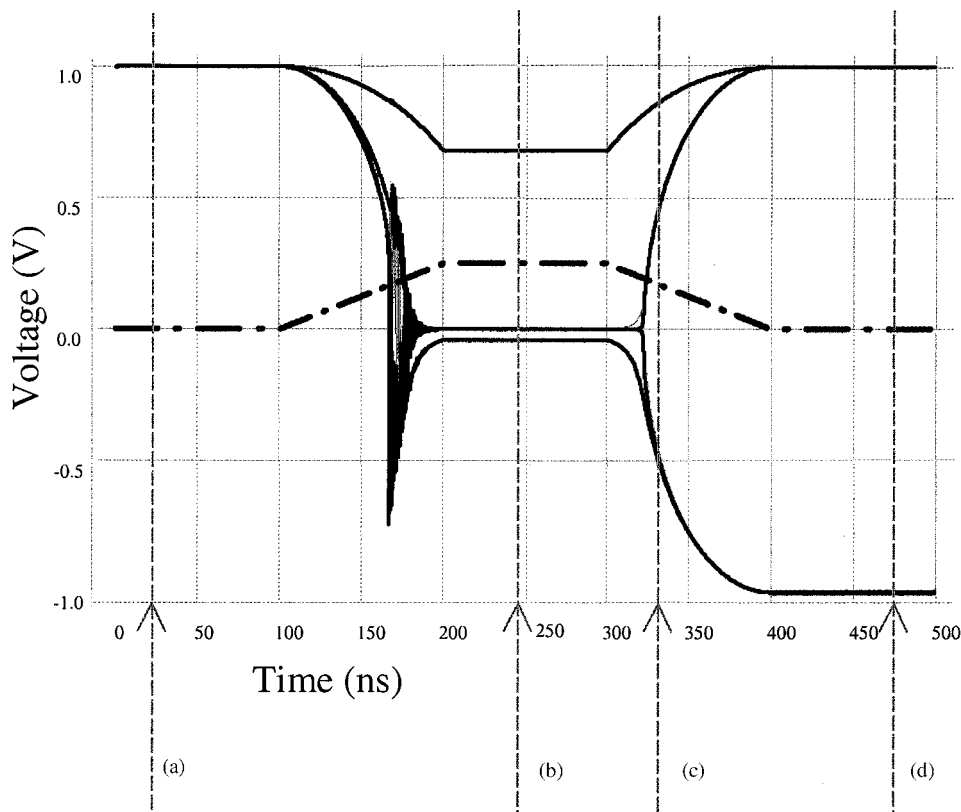


Figure 6. SPICE—simulation: the z-component of magnetization in a nanowire (in M_s units). The phases (a), (b), . . . corresponds to the stages in Fig. 3. The dashed line is the external control field.

The logic blocks presented above (inverting wire, majority gate), in principle, are sufficient for building a logic device of arbitrary complexity. Another degree of freedom is that nanomagnets with different shapes have a different response to external magnetic fields. Therefore, a homogenous external field can ‘target’ specific groups of similarly-shaped nanomagnets in a larger array. Our calculations show that we can take advantage of this fact for clocking the circuit by external fields, and realizing sequential circuits this way.

The realization of basic nanomagnet arrays appears feasible, given the technological base for data storage applications. The maximum possible complexity of nanomagnet networks mostly depends on the error tolerance of the design. Work on this issue is in progress.

7. Design Tools: The Circuit Model of Nanomagnets

An important result of our work is that nanomagnet logic devices can be designed with methods similar to electronic circuits. To fully exploit this analogy, we present a circuit model for nanomagnet dots.

We can identify the magnetization-vector components of each nanomagnet as a formal voltage, which obeys the differential Eqs. (3) and (4). Then, these equations are formally equivalent to the voltage change on a capacitor which is charged by current sources given by the right-hand sides of Eqs. (3) and (4). In this fashion, Eqs. (3) and (4) can formally be represented by a circuit, as schematically shown in Fig. 5.

Now we can use standard circuit-simulation tools, such as SPICE for micromagnetic design. Figure 6 shows the results from a particular nanowire-simulation. We can look at M_z as an electric signal in a real circuit.

8. Summary and Outlook

We proposed coupled ferromagnetic dots as possible building blocks for magnetic QCA-like nanocomputers. Carefully applied external fields make possible the individual, precise control of the state of nanomagnets inside a larger array. Starting from the micromagnetic equations, we have shown operating logic devices, and developed design tools for easily simulating them. Our work suggests that nanomagnets are promising candidates not only for nonvolatile information storage, but also for nanocomputing as well.

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