Simulation of Power Gain and Dissipation in Field-Coupled Nanomagnets

G. Csaba*, P. Lugli*, A. Csurgay** and W. Porod**

*Institute for Nanoelectronics, Technical University of Munich, Arcisstrasse 21, D-80333 Munich, Germany e-mail: {csaba,lugli}@ei.tum.de

**Center for Nano Science and Technology, Electrical Engineering Department, University of Notre Dame, 275 Fitzpatrick Hall, Notre Dame, IN 46556, USA e-mail: {acsurgay,porod}@nd.edu

Field-coupled computing (also known as Quantum Cellular Automata or QCA) is a novel architecture for processing information on the nanoscale. Recently, nanomagnets were proposed and demonstrated as a possible 'hardware' for field-coupled computing [1][2]. In these devices, information is represented by the magnetization state of nanomagnets, while propagation and processing of information is carried out by the magnetic interaction of the dots, as it is illustrated in Figure 1.

We perform a computational study on the power flow and dissipation characteristics of coupled nanomagnets. Magnetization dynamics is calculated by the numerical solution of the Landau-Lifshitz equations. We developed a simple method to determine power flow relations from the simulated time-dependent magnetization and magnetic field distributions. The simulations can be performed either in a full micromagnetic model or using the single-domain approximation.

In field-coupled computing, the result of the computation is represented by the ground state of the physical system (i.e. the ground-state magnetization distribution). An external pumping field is used to control the time-evolution of the system and drive it toward the ground state. We will demonstrate that the pumping field can also be utilized as an energy source to ensure active behavior [3]. As an example, Figure *2a)* illustrates how a nanomagnet-line goes to an antiferromagnetically ordered state when a horizontal pumping field is released. The time-dependence of the vertical magnetization is shown in Figure *2b)*, while the power flowing in the signal path is plotted in Figure *2c)*. Each dot gives more energy to its right neighbor than it receives from its left neighbor, which proves the power-amplifying characteristics.

The pumping field also controls dissipation. If switching takes place quickly (on the nanosecond time scale), then a large energy, corresponding to the barrier separating the steady-states of the magnets) is dissipated. By decreasing the switching (pumping) speed, the dissipation can be reduced to a few kT per bit operation (see Figure 3).

There is a curious analogy between field-coupled nanomagnets and the once well-established ferrite-ring based signal processing devices. We will demonstrate how this analogy can help to understand power flow characteristics of nanomagnetic logic devices.

The fact that field-coupled nanomagnets are active devices and their power dissipation approaches the fundamental lowest limit of information processing makes them attractive candidates for nanoscale computing. We will briefly summarize ongoing experimental work on their realization and proposed further research directions, such as molecule-based spin systems and exchange-coupled magnetic multilayers.

[1] R. P. Cowburn and M. E. Welland, Room Temperature Magnetic Quantum Cellular Automata, *Science*, 287 February 2000

[2] G. Csaba and W. Porod, Simulation of Field-Coupled Computing Architectures Based on Magnetic Dot Arrays, *Journal of Computational Electronics* 1, 87-91 (2002).

[3] G. Csaba, W. Porod, and A. I. Csurgay, "A computing architecture composed of field-coupled single-domain nanomagnets clocked by magnetic fields," *International Journal of Circuit Theory and Applications* 31, 67-82 (2003).

A full journal publication of this work will be published in the Journal of Computational Electronics.

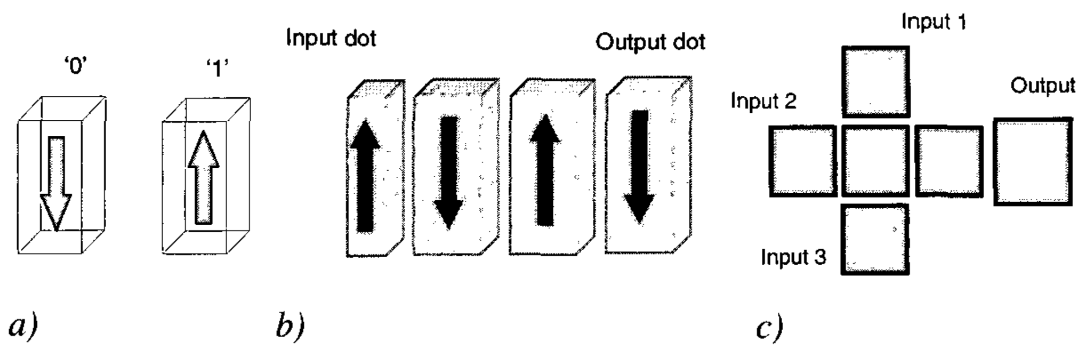

Figure 1. The principle of magnetic field-coupling. Part *a)* shows, how a pillar-shaped nanomagnet can store one bit of binary information. A line of interacting nanomagnets (part *b)*) acts as an inverter and wire, while the three-input majority gate (layout is shown in part *c)*) can be used as a universal logic gate (for AND and OR operations).

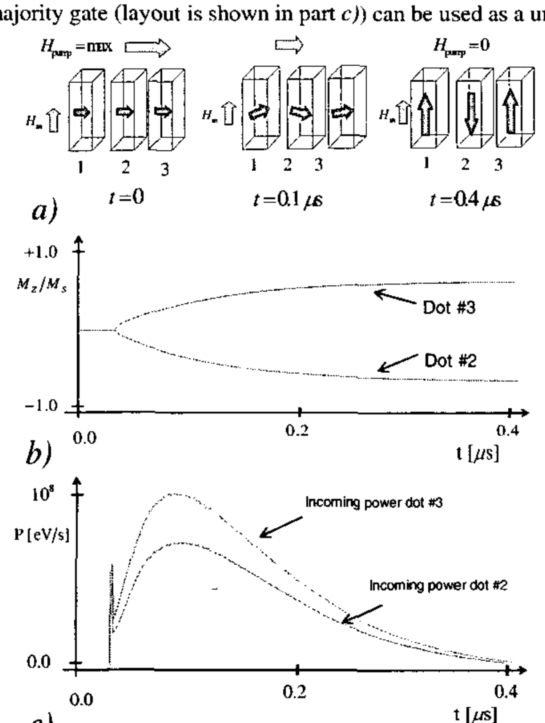

Figure 2. Part *a)* illustrates how a line of dipole-coupled nanomagnets switches to an antiferromagnetically ordered ground state due to an adiabatic pumping field applied along the hard axis. The final magnetization state of the dots is determined by the small and localized H_{in} field. The time dependence of the magnetization is shown in part *b)*. The power arising from the dipolar interaction of magnets is plotted in part *c)*. The increasing power is interpreted as a power gain in the magnetic signal path.

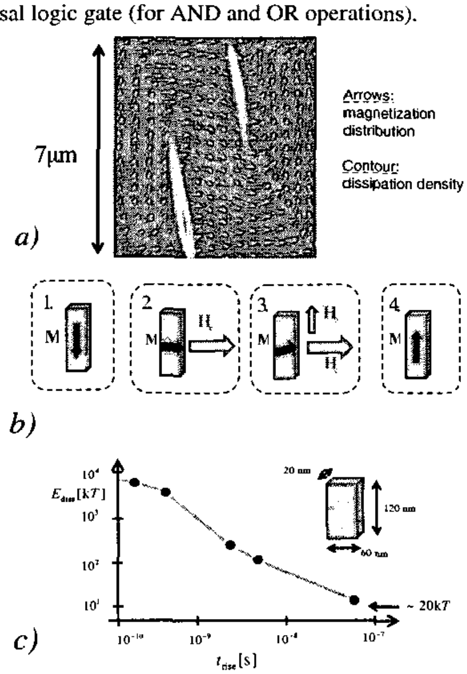

Figure 3. The density of dissipated power in macro-size magnets indicates the energy is dissipated along propagating domain walls (bright areas in part *a)*). Single-domain magnets have no internal domain structure and their dissipation can be reduced by slowly executed adiabatic switching: the process itself is sketched in part *b)*, while the dependence of dissipated power on the pumping speed is shown in part *c)*).

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