Clocking Schemes for Field Coupled Devices from Magnetic Multilayers

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Abstract—This paper introduces a clocking scheme that can be applied in magnetic field-coupled computing devices made from Co/Pt multilayers. The clocking wires are buried under the magnetic computing layer. Oscillating currents running through these wires generate an easy-axis field in the plane of the magnets. We show that this field can propagate signals between the magnetic dots and prevents frustration and splitting of the dots into multiple domains. We demonstrate our concept on a full micromagnetic simulation of an XOR gate. We argue that large-scale logic devices could be built based on this architecture.

I. INTRODUCTION

Spintronics is a new, quickly developing area of nanoscale electronics with the aim of integrating magnetic materials into solid-state circuits. Our work represents an emerging approach to spintronics, where logic functionalities are performed exclusively using field-interactions between the magnets and without any current flow. This computing paradigm is often referred as ‘magnetic field-coupling’ or (for historical reasons) magnetic quantum-dot cellular automata [1].

The principle of magnetic field-coupling was already demonstrated on domain-wall conductors [2] and permalloy dots [1]. In the latter case, information is represented by the magnetization direction of single-domain nanomagnets and their magnetic ordering (originating from the dipole interactions) is used to evaluate elementary Boolean functions. It was shown that an adiabatic, hard-axis pumping scheme can propagate and amplify magnetic signals with very little dissipation in the magnetic system [3].

Frustration in the magnetic ordering yields to errors in the field-coupled computation and must be avoided. Only nanomagnets with well defined magnetic properties (i.e. narrow switching field distribution) can be used as building blocks of a scalable computing device.

Nanomagnets made from Cobalt - Platinum multilayers offer the possibility to realize such high-quality nanomagnets with tailored magnetic properties. The dots can be defined using Focused Ion Beam (FIB) irradiation and without removing material from the surface. Depending on the dose and the layer composition, dots with desired magnetic characteristics can be fabricated [4] [5]. Partial irradiation of the dots makes it possible to ‘engineer’ their reversal characteristics [6] and the ion dose can be used to set their switching field.

A further benefit of the Co/Pt dots is that the easy axis of the dots is perpendicular to the magnetic film and the binary one (zero) states are represented by the upwards (downwards) pointing magnetization. That allows one to arrange the dots freely in two dimensions, which is advantageous in the design of more complex circuits.

In order to reach their computational (ordered) state, Co/Pt based field-coupled devices should be clocked by external magnetic fields, just as the permalloy-based devices. However, there are important differences between the two material systems and the clocking schemes developed for permalloy-based magnetic computing cannot be directly transferred to Co/Pt based systems. The behavior of permalloy dots can be well understood based on a single-domain approximation, but the reversal mechanism of thin and not extremely small (hundred nanometer - few hundred nanometer size) Co/Pt dots is domain wall nucleation / propagation. Hard-axis fields can easily split the dots into multiple domains. In addition, hard-axis clocking requires strong (several hundred milliteslas) clocking fields, which are difficult to generate on-chip.

For these reasons we developed and simulated a novel clocking scheme suited for Co/Pt based systems. This paper presents a computational study showing how localized, oscillating easy axis fields can reliably drive the dots into their computational ground state. We call this clocking scheme local demagnetization. The field ‘shakes down’ the dots, so they reach their single-domain state which is always antiparallel to the majority of the left neighbors. The local demagnetization also defines nonreciprocal device behavior (i.e. signals propagating from the inputs of a logic gate toward the output and not the other way). We show that such fields can be straightforwardly generated by conductors buried under the magnetic layer.

The paper is organized as follows: in section II the computational model is described. Section III demonstrates the clocking scheme on the example of a wire, and section IV gives a more complex simulation example of an XOR gate, built from three NOR gates. The operation of the XOR gate suggests that the structure is potentially scalable to an arbitrarily complex pipelined logic device. Finally, we give an estimation of device speed.

II. MODELING OF FIELD-COUPLED CO/PT DOTS

As our simulation engine, we used the well-established OOMMF code ([7]), which directly solves the time-dependent
Landau-Lifshitz equations. The three-dimensional solver Oxssii was used but – in order to keep running times manageable – we simulated the films in two dimensions only. The simulation requires three material parameters: the $M_s$ saturation magnetization, the $A_{exch}$ exchange stiffness and the $K_u$ uniaxial anisotropy. The values of these parameters are well known for bulk magnetic materials (such as permalloy, cobalt), but they are different for each particular multilayer composition, layer number, deposition, annealing temperature, etc.

We used hysteresis curves from SQUID and Extraordinary Hall effect measurements [8] to fit the values of material parameters [4]. The magnitude of $M_s$ was estimated by assuming that most of the magnetic moments originates from the cobalt atoms, $A_{exch}$ and $K_u$ was found by selecting the best fit between simulated and measured hysteresys curves. For a Pt$_{5nm}$ $	imes$ [Co$_{0.3nm}$ + Pt$_{0.8nm}$] Pt$_{4.5nm}$ we found $M_s = 7.0 \cdot 10^5 A/m$, $A_{exch} = 1.3 \cdot 10^{-10} J/m$, $K_u = 3.08 \cdot 10^5 J/m^3$ gives the most reasonable fit and is also consistent with [4].

The OOMMF simulator allows one to specify an arbitrary inhomogeneous external magnetic field distribution and apply it for a specified time period. We augmented OOMMF with a magnetic field-calculating module. A simple Matlab-based magnetic field calculator, based on the differential form of Biot-Savart law was used to determine the magnetic field of straight conductors with arbitrary cross section. Then we specified the clocking sequence i.e. the time dependence of the currents applied to the wires. The net magnetic field is calculated as the superposition of the individual wire fields that are written into files. These files are passed to OOMMF, which then calculates the evolution of the magnetization distribution.

III. SIMULATION EXAMPLE: CLOCKED WIRE

We illustrate the concept of local demagnetization on the example of the simplest field coupled device, the nanomagnetic wire. The geometry of the dots with the corresponding 300 nm wide clocking wires is sketched in Figure 1. The dots itself are 160 nm in size, with 20 nm gaps between them. Such geometry can be fabricated with relatively standard FIB technology.

![Fig. 1. The geometry of the investigated structure, side view.](image1)

The magnetization state of the leftmost dot was artificially frozen by assigning a very high anisotropy value to it. This dot preserves its initial magnetization over the entire clocking process and acts as a driver: the ordering of the wires (up/down/up... or down/up/down...) should be dictated by it. In order to demagnetize the wire into its computational ground state an oscillating current with decreasing amplitude was applied to each of the underlying wires sequentially from the leftmost one to the rightmost wire. The time dependence of the current is given in Figure 2a).

![Fig. 2. The time dependence of the current running through the wires. Panel b) shows the magnetic field distribution when current is running in one particular wire.](image2)

Figure 2b) illustrates the magnetic field distribution in the plane of the magnets. As a first approximation the hard axis fields ($B_z$ in the figure) can be ignored. As the amplitude of the oscillating current decreases, dots gradually decouple from the pumping field. Since the $B_z$ field of a wire decreases toward left, at the moment of decoupling each dot already has a fixed-state (already decoupled) left neighbor, which determines its state. The field gradient and the order in which the wires are activated determines the direction of the magnetic signal propagation. Snapshots of the magnetization distribution are shown in Figure 3, clearly showing the propagation of the ordering wave. Numerical experiments suggest that error-free ordering can be achieved for wires with arbitrary length.

For comparison we performed several numerical experiments with nanomagnet wires, but using a homogeneous external field for demagnetization. Frustration-free ordering can be achieved only for relatively small number of dots - ten, or even less.

IV. MICROMAGNETIC SIMULATION OF AN XOR GATE

In order to demonstrate the feasibility of non-trivial computing functions, we designed an XOR gate from coupled nanomagnetic dots. The XOR function can be built from three NOR gates and inverters. Inverters come ‘free’ in magnetic computing as even dot-length wire segments. NOR gates are realized by a majority gates, keeping one of their inputs fixed.
A NOR gate alone is sketched in Figure 4. In ground state the output of the NOR gate is antiparallel to the majority of the inputs. The fix dot constantly points up, biasing the magnetization of the output dot downwards. The output dot points up if and only if both non-fixed inputs are pointing down, realizing the NOR function.

The biasing dot is designed to be smaller than the other (computing) dots. Both inputs of the NOR gate and the bias dot should have an equal vote in determining the output dots state. The field of the bias dot is permanently there, influencing the output, while the inputs are switching several times during the clocking process. To compensate for this mismatch, the biasing dot has to provide less coupling field. Making this dot narrower also eliminates parasitic interactions with the input wire segments. Fabrication of such biasing dots is straightforward: dots, which receive no or very little irradiation will exhibit a high anisotropy and the clocking fields cannot influence their state.

There are six wires running under the XOR gate, 10 nm below the magnetic layer. The cross section of the wires is 300 nm by 150 nm and they are pumped with a high, \( j = 5 \cdot 10^{12} \text{Am}^{-2} \), current density, which gradually decreases to \( j = 2 \cdot 10^{12} \text{Am}^{-2} \) before the next wire is activated.

Simulation results show that the XOR gate can be demagnetized to its computational ground state for all possible input combinations. The alignment of the wires to the dots is not critical. The magnetic information propagates from the left to the right, as the wires are activated in this order. Signals can travel up and down as well, if the dot halfway overlaps with the previous dot in the horizontal direction. Pipelined operation of a larger logic device is straightforward: once the ordering wave traveled sufficiently far (several clocking wires distance), then new inputs can be applied, which do not interfere with the earlier one. Feedback of signals is more difficult to realize in this architecture.

The device operation is insensitive to an abrupt loss of power: the dots preserve their magnetic states and the clocking can be continued after the interruption.

V. SWITCHING SPEED OF CO/Pt DOTS

The switching speed of a nanomagnetic dot is fast, lying in the nanosecond range. Figure 6 illustrates a switching transient for a single dot – the switching occurs in about 1 ns. In this calculation a homogenous external field pulse was applied, just a few milliteslas above the switching field of the dot. Since the coupling fields between nanomagnets also lie in the few millitesla range, we can estimate that dots, which are part of a field-coupled circuit, also operate with this speed.

Clearly, the switching speed of a single nanomagnetic dot is not directly comparable to the circuit speed. The proposed local demagnetization is a slow way to operate the magnetic logic devices, as several clock pulses are required to switch each of the dots to ground state. Our numerical experiments
showed that many-dot logic structures may take ten to hundred clocking cycles to demagnetize, giving an operating frequency in the 10 MHz - 100 MHz range. This result is more promising than the pessimistic estimate of [9], but still quite slow when compared to state of the art electronic circuits.

VI. CONCLUSIONS

We presented a clocking scheme, local demagnetization, which drives Co/Pt based magnetic computing devices into their computational ground state. The wires, which generate the clocking fields can be integrated with the magnetic computing layer in a straightforward way.

This clocking method ensures nonreciprocal signal propagation and prevents the formation of metastable states. It allows to build large, scalable logic devices.

We did not yet invest any effort into optimizing this structure. The current densities required for clocking the dots are very high and device operation is relatively slow. We believe there is a lot of room to improve both figures. Ion-beam irradiation can reduce the switching field of the dots to a few milliteslas, while still maintaining a square hysteresis loop [6] - reducing the switching field proportionally reduces the necessary clocking currents. The cross section of the wires can be optimized and a number of wires can be active simultaneously so their fields are added up. By carefully choosing the value of the pumping current, fewer clocking cycles could be sufficient to relax the dots into their ground state, speeding up device operation. According to our estimations, a two orders magnitude reduction in current densities and a one order of magnitude speedup should be possible with optimized structures.

Magnetic field-coupling devices combine logic functionality with non-volatile storage and they enable very dense device integration [8], [10]. This gives them a promising and unique place among emerging nanoelectronic devices.

ACKNOWLEDGMENT

The authors are highly grateful to Prof. Wolfgang Porod (University of Notre Dame, USA) for his insightful ideas and for initiating their research on magnetic computing devices.

REFERENCES