Nanomagnet Logic (NML)

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Abstract. We describe the background and evolution of our work on magnetic implementations of Quantum-Dot Cellular Automata (QCA), first called Magnetic QCA (MQCA), and now known as Nanomagnet Logic (NML).

Keywords: Nanomagnet logic · Quantum-Dot Cellular Automata · Field-coupled computing · Cellular Automata

1 Introduction

We all are familiar with the fact that magnetic phenomena are widely used for data storage, whereas electronic phenomena are used for information processing. This is based on the fact that *ferromagnetism* is nonvolatile (i.e. magnetization state can be preserved even without power), and that *electrons* and the flow of charge can be effectively controlled to perform logic. However, charge-based logic devices are volatile, which means that a power supply is needed to maintain the logic state and to stop information (electrons) from leaking away.

Presently, there are multiple research efforts underway to harness magnetic phenomena for logic in addition to storage. Motivation for this work is two-fold. First, the amount of static power dissipation in CMOS chips now rivals the levels of dynamic power dissipation. In other words, even if a chip does not perform any computation, stand-by power (i.e., needed to maintain volatile logic state, etc.) is similar to the power dissipated when performing useful work. Anecdotally, in 2004, Bernard Myerson – then chief technologist for IBM's system and technology group – likened the situation to "a car with a 10-gallon gas tank losing 5 gallons while parked with its motor turned off" [2]. The nonvolatile nature of magnetic phenomena means that there is no stand-by power dissipation. Second, the intrinsic switching energy of a magnetic device can be orders of magnitude lower than a charge-based CMOS transistor. While some drive circuitry overhead must be accounted for in magnetic systems, this suggests that magnetic logic could help to minimize dynamic power dissipation as well. Thus, while the multi-decade Moore's Law-based size scaling trends may continue, associated performance scaling trends are threatened by energy-related concerns that magnetic devices could help to alleviate.

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One of the driving forces behind this research is the semiconductor industry itself in the form of the Nanoelectronics Research Initiative (NRI) of the Semiconductor Research Corporation (SRC). The NRI was formed in response to the impending "red brick wall" in the industry's road map, which is primarily the result of the inability to manage dissipation associated with computation with field-effect transistors. In an effort to find alternative, *lower-power* device technologies, the NRI is searching for switches based on state variables other than charge. One possibility is the electron's spin, and associated magnetic phenomena. There now are several research efforts underway to explore switches where the logic state is represented by the magnetization of a nanomagnet. These various approaches have been summarized and reviewed in [3], and our work on nanomagnet logic is one of these efforts.

2 Single-Domain Magnets for NML

Nanomagnet Logic (NML) is based on patterned arrays of elongated nanomagnets that are sufficiently small to contain only a single magnetic domain. The magnetization state of a device – i.e. whether it is magnetized along one direction or another, commonly referred to as "up or down" – can be used to represent binary information in the same way that magnetic islands are used to store information in magnetoresistive random access memory (MRAM). Elongated single-domain magnets are essentially tiny bar magnets with poles on each end, that generate strong stray fields that can be used to couple to other nearby magnets. While such magnetic interactions between neighboring nanomagnets are undesirable for data-storage applications, we have demonstrated that these interactions can be exploited to perform logic operations.

It should be emphasized here that such single-domain behavior is rather special and specific to magnets with certain sizes and shapes. For our work with patterned ferromagnetic thin-film permalloy, these sizes are on the order of hundreds down to tens of nanometers (nm). If the magnet is too large, its magnetization state breaks up into multiple internal domains, and the poles at the end – along with their strong fringing fields – disappear. If the magnet is too small, its magnetization state can be switched by random thermal fluctuations, and it no longer has a stable magnetization state; this is the so-called superparamagnetic limit. As a fascinating side comment, Nature has learned to exploit the stray fields associated with single domain magnets for navigation in the Earth's magnetic field. Specialized, so-called magnetotactic bacteria grow perfectly single-domain nanomagnets, that are specific to a particular animal species [4]. By the way, much of our work on NML uses nanomagnets with sizes and shapes between those characteristic for the pigeon and the tuna.

Figure 1 shows a magnetic force microscope (MFM) image of an array of nanoscale magnets with varying sizes and aspect ratios. The coloring represents magnetic contrast, and dark and light spots indicate magnetic poles. It can be seen that these magnets display single-domain behavior if they are sufficiently small and narrow (left side of image), and these poles generate magnetic flux lines that can interact with external magnetic fields, or couple to neighboring magnets. Otherwise, their magnetization state breaks up into several internal domains (right side of image), and there is

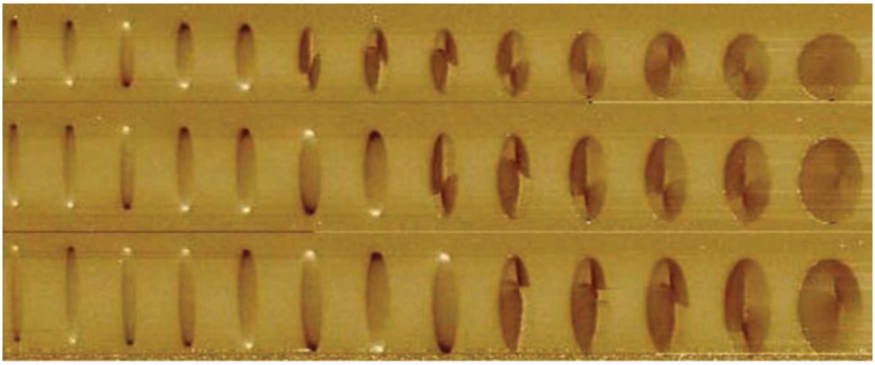

Fig. 1. Nano-scale magnets with varying sizes and aspect ratios. Single-domain behavior is observed if the magnets are sufficiently small and narrow. (Source: A. Imre, Ph.D. dissertation, University of Notre Dame, 2005 [5].)

flux closure inside, without strong coupling to the exterior. Such single-domain magnets, with typical size scales of tens to hundreds of nanometers, form the physical basis for NML.

3 From Quantum-Dot Cellular Automata to Nanomagnet Logic

Our current work on nanomagnet logic grew out of our previous work on Quantum-Dot Cellular Automata (QCA), which was an attempt to base computation on physically-interacting cellular arrays of quantum dots occupied by a few electrons [6]. Instead of wires, neighboring devices interact through direct Coulomb interactions between electrons on neighboring quantum dots. We have shown that such physical interactions in appropriately structured arrays of quantum dots can also be used to realize logic gates. Electronic implementations of QCA proved difficult due to technological limitations of quantum-dot fabrication (such as size variations) and electronic stray charges. For a review of electronic QCA, see Refs. [7, 8].

Nanomagnet logic can be viewed as a magnetic implementation of QCA. (In earlier publications, we used the term magnetic QCA (MQCA), but we now prefer to use NML in order to avoid confusion with quantum dots.) Early theoretical work on magnetic QCA is given in the Ph.D. Dissertation of György Csaba [9]. These simulations demonstrated the feasibility of using field-coupled single-domain nanomagnets for realizing basic logic functionality [10–12]. In subsequent experimental work stimulated by these simulations, and which constituted the Ph.D. Dissertation of Alexandra Imre [5], we first demonstrated magnetic wires formed by chains of near-by magnetic islands. Since the individual dots have elongated shapes, there are two basic types of wire arrangements. In one type, the magnets are lined up side-by-side and, as one’s intuition would tell from two bar magnets next to each other with their long sides, the individual magnets prefer to be magnetized in the opposite direction; we call

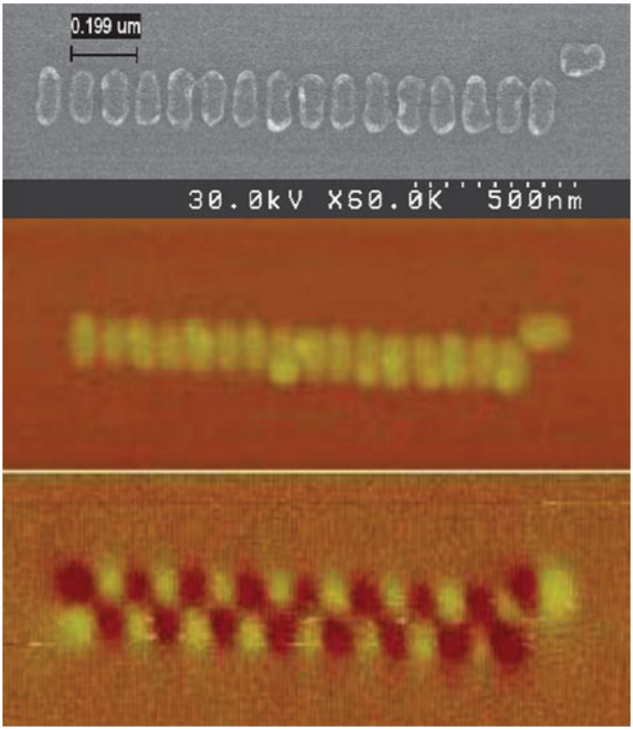

Fig. 2. Demonstration of a magnetically-ordered line of dots. Top panel: SEM, middle panel: AFM, bottom panel: MFM.

this antiferromagnetic coupling. The other type of wire consists of the individual magnets lined up in the same direction, and as one would expect, the individual magnets also prefer to be magnetized in the same direction; we call this ferromagnetic coupling.

Figure 2 shows an example of an antiferromagnetically-coupled wire consisting of a chain of 16 dots. The top portion of the image shows an SEM (scanning electron microscope) image of magnetic islands fabricated from a 30-nm thin film of permalloy using electron beam lithography and standard lift-off techniques. The bottom portion of the figure shows the structural AFM (atomic force microscope) image, and the MFM (magnetic force microscope) image showing the magnetic contrast. The dot on the top right (aligned in the horizontal direction) serves as an input that determines if the wire is aligned up-down-up-down or down-up-down-up.

In these experiments, a magnetic field is required to aid the switching of the array of nanomagnets [12]. When one dot is switched, the fringing fields are not sufficiently strong to switch a neighboring magnet. However, the fringing fields can be used to bias the switching event when an additional switching field is applied. Due to the elongated shape (magnetic shape anisotropy), the dots have very stable magnetization states along the long (magnetic easy) axis. They can be magnetized along the short (magnetic hard) axis by the application of a sufficiently strong magnetic field in that direction. However, when this field is removed, the dots will "snap" back into the preferred "up" or "down" easy-axis direction, and the fringing fields from the neighbors can bias which way they switch. This switching field acts as a magnetic clock.

It turns out that the "native" logic element for NML is a three-input majority-logic gate, just like for the original electronic QCA. As shown schematically below, this gate consists of a cross-shaped arrangement of five dots, where three of the arms (labeled "A," "B," and "C") represent the inputs, the center dot (labeled "M") calculates the majority vote of these inputs, and the fourth arm (labeled "out") represents the output. This arrangement can also be viewed as the intersection between an antiferromagnetic and a ferromagnetic wire segment. Note that the majority vote is "calculated" through magnetic interactions in this physics-driven NML computing scheme (Fig. 3).

It is interesting to note that such a three-input majority gate can be reduced to either a binary AND or OR gate by viewing one of the inputs as a set-input, which selects the functionality of the gate. For example, if we view "C" as the set-input, and "A" and "B" as the data inputs, then a "0" on "C" means that both "A" and "B" have to be "1" in order to have a majority vote of "1" at the output. In other words, setting "C" to "0" reduces the three-input majority gate to an AND gate for the data inputs "A" and "B." Conversely, setting "C" to "1" results in an OR gate since only either "A" or "B" have to be "1" in order to have a majority vote of "1." This programmability offers interesting possibilities from a computer science perspective since the functionality of this gate can be determined by the current state of the computation.

We have experimentally demonstrated functioning majority-logic gates working properly at room temperature [13]. The figure below [from the Science paper] shows the eight possible input combinations for the three-input majority-logic gate. Note that here the different input combinations were realized by different arrangements of the horizontal input dots. However, the shape-dependent switching behavior of such nanoscale magnets [14] can be exploited to individually address specific inputs, thus providing programmability. We have since fabricated gates with input devices of varying aspect ratios, which has allowed a *single gate structure* to be successfully tested with all eight possible input combinations [15] (Fig. 4).

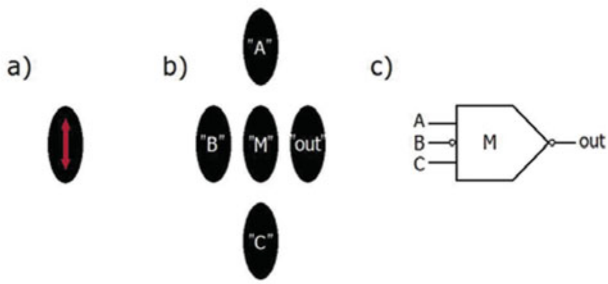

Fig. 3. Schematic of a magnetic three-input majority-logic gate, which consists of a cross-shaped arrangement of five dots. Panel (a) shows the basic dot, (b) the basic logic gate, and (c) the logic-gate symbol.

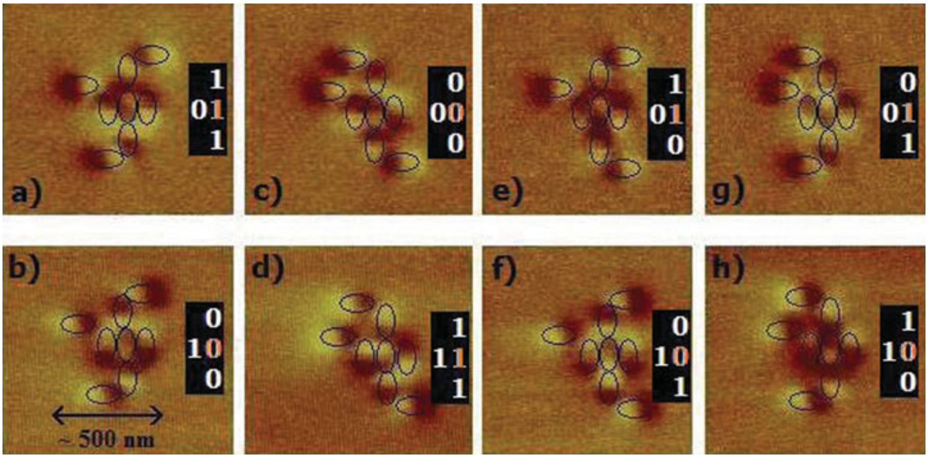

Fig. 4. Experimental demonstration of an NML three-input majority-logic gate. (Source: Imre et al., Ref. [13].)

Thus far [16–18], our work has provided a proof-of-concept demonstration of NML – i.e. the feasibility of performing digital logic with physically-coupled nanomagnets. However, so far we have used MFM to read the state of the dots, and *externally generated* magnetic fields to switch the dots. Of course, this is not practical for real applications. Below, we describe on-going work to develop electronic input and output (I/O) and mechanisms for generating local magnetic fields for "on-chip" clocking.

Before proceeding, we want to emphasize that our experimental proof-of-concept demonstrations satisfy five "tenets" that are considered essential for a digital system: (1) NML devices have non-linear response characteristics due to the magnetic hysteresis loop. (2) NML can deliver a functionally complete logic set enabled by the *3-input* majority gate and the NOT operation naturally achieved by the antiferromagnetic dot-to-dot coupling. (3) Signal amplification/gain greater than 1 has been experimentally demonstrated by showing the feasibility of 1:3 fanout [19], where the energy for the gain is provided by an external clocking field discussed further below. (4) The output of one device can drive another as the fringing fields from individual magnets can bias a neighbor. (5) Unwanted feedback is preventable through clocking.

4 Nanomagnet Logic: Towards System Integration

Recent and ongoing work addresses electronic means for both NML I/O and clocking. Our approach leverages existing MRAM technologies for READ/WRITE operations. After all, setting an input for NML, i.e. setting the state of an input magnet, is similar to writing the state of an MRAM bit. Similarly, reading the state of an NML output dot is just like reading an MRAM bit. These similarities to MRAM suggest that an NML circuit is analogous to a patterned ensemble of the free layers in an MRAM stack.

In this way, NML can leverage much existing technological know-how, and also benefit from future development in MRAM technologies [20].

Under the umbrella of the DARPA Non-Volatile Logic (NVL) program, we worked on approaches to on-chip clocking. As mentioned above, externally supplied switching energy is needed to re-evaluate a magnet ensemble with new inputs. To date, most NML circuits have been "clocked" by an external source. However, it is essential that clock functionality be moved "on-chip." Thus far, the most commonly employed clock is a magnetic field applied along the hard axis of an NML ensemble, which places the magnets into a metastable state such that they are sensitive to the fringing fields from their neighbors. Such magnetic fields can be generated on-chip by current-carrying wires for local control of NML circuits. In recent work, we have fabricated copper wires clad with ferromagnetic material on the sides and bottom (like field-MRAM word and bit lines), and we have demonstrated that NML magnets, interconnect, and logic gates can be switched (i.e. re-evaluated) in this way [21, 22].

Also under the umbrella of the DARPA Non-Volatile Logic (NVL) program, we worked on approaches for integrated electronic I/O. Electronic output can be achieved (similar to MRAM) by a magnetoresistance measurement, where the NML output dot is the free layer in a magnetic tunnel junction (MTJ) stack. Similarly, electronic input can be achieved using the spin-torque transfer (STT) effect, where the NML input dot is the free layer in an STT stack [23, 24].

As is well known from field-MRAM, there is an energy overhead associated with generating local magnetic fields using current-carrying wires. Early on, simulations showed that the overhead associated with such clocking is a major component of the total energy requirement, and that the dissipation associated with the switching of the magnets is rather small [25]. For NML, the clock energy could be amortized over 100,000s of devices as a single clock line could control many parallel ensembles [26]. Clock lines could be placed in series and in multiple planes to minimize driver overhead. Moreover, at cryogenic temperatures, clock lines could be made from superconducting niobium, and I^2R losses could drop to zero. In principle, this opens the door to extremely low energy information processing hardware/memory that could be integrated with RSFQ and SQL logic.

Also inspired by field-MRAM, another approach to lowering the energy overhead associated with clocking is to engineer the dielectric medium between the dots, which influences the coupling strength and thus the switching energy. Specifically, one can enhance the permeability of a dielectric by the controlled inclusion of superparamagnetic particles that increase the dielectric permeability, and thus lower the current required to achieve a certain switching field [27]. Following this approach, we have successfully fabricated such enhanced permeability dielectrics and demonstrated the lowering of switching fields and associated power dissipation [28–30].

Another possible approach to clocking is to exploit the strong local fields associated with a domain wall. We have shown that the motion of domain walls can be controlled [31, 32], and that their local fringing fields can assist in the switching of nearby magnets [33]. This is an interesting approach to NML clocking that deserves further investigation.

Multiferroics, magnetostriction, and spin-torque transfer have also been proposed as potential clocking mechanisms for NML. Multiferroic materials (e.g. BFO) could allow for electric field control of magnetism, which would be highly attractive for NML. Included in this volume is a contribution from the group of Sayeef Salahuddin at UC Berkeley that addresses this interesting possibility [34].

Another important issue for NML is whether or not the magnets that form a circuit ensemble can be switched reliably – or whether or not devices placed into a metastable state by a clock are adversely affected by thermal noise (which could induce premature switching). The group of Jeff Bokor at UC Berkeley has shown that magnets with an extra biaxial anisotropy exhibit superior switching characteristics [35]. Essentially, such an "engineered-in" magnetic anisotropy helps to stabilize the magnets in the "vulnerable" metastable state against random fluctuations. We have shown that shape engineering, i.e. exploiting the influence of geometry on magnetic properties, can be used to not only enhance the reliability of switching, but also to design logic gates with reduced foot print [36, 37].

At Notre Dame, all of our work to date has been based on patterned thin-film permalloy dots, which have in-plane magnetization. An attractive alternative is to use structures with out-of-plane magnetization, such as Co/Pt multi-layer films, where the magnetic properties are due to the Co-Pt interfaces. In collaboration with Doris Schmitt-Landsiedel and her group at the Technical University of Munich (TUM), we are exploring the utility of this material system for NML. It has been shown that such Co/Pt structures can be patterned with a focused ion beam (FIB) instrument, where the ion beam destroys the interfaces, and thus the magnetization at these locations. In this fashion, a film can be patterned into islands, and sufficiently small islands also exhibit single-domain behavior. The TUM group has demonstrated magnetic coupling between neighboring islands [38], and they have shown magnetic ordering in arrays of coupled islands. Moreover, they have realized directional signal propagation in lines, and basic NML logic gates [39], as well as domain-wall assisted switching [40].

All our fabrication work so far has been based on using electron-beam lithography (EBL) to define the NML devices and structures. EBL is a flexible and useful tool for research, but not suitable for large-scale manufacturing. To this end, we collaborate with Paolo Lugli and his group at the TUM to explore the use of nanoimprint lithography and nanotransfer of permalloy structures for the fabrication of large-scale NML arrays [41].

NML represents a technology quite different from CMOS, with its own "pros" and "cons." Undoubtedly, this new technology will likely necessitate new circuit and architecture approaches [42]. Along these lines, we have worked to identify specific application spaces for NML. Our immediate focus is on low energy hardware accelerators for general-purpose multi-core chips, and application spaces that demand information processing hardware that can function with an extremely low energy budget. As an example, we anticipate that NML-based hardware might be used to implement a systolic architecture that can improve the performance of compute-bound applications, provide very high throughput at modest memory bandwidth, and eliminate global signal broadcasts. (Systolic solutions exist for many problems including filtering, polynomial evaluation, discrete Fourier transforms, matrix arithmetic and other non-numeric applications.) Moreover, as devices are non-volatile, information can be stored directly and indefinitely throughout a circuit (e.g. at a gate input) without the need for explicit storage hardware (and the associated area and static/dynamic power dissipation associated with it).

Architectural-level design techniques such as these should allow us to minimize the “cons” of NML (nearest neighbor dataflow and higher latency devices when compared to CMOS FETs) and exploit the “pros” (inherently pipelined logic with no overhead). As a representative example [43], our projections suggest that hardware for finding specific patterns in incoming data streams could be ~60-75X more energy efficient (at iso-performance) than CMOS hardware equivalents. Moreover, these projections include clock energy overheads.

5 Summary and Discussion

In this chapter, we have presented an overview of our work over the years on nanomagnet logic, which can be viewed as a magnetic implementation of the original QCA field-coupled computing idea. We discussed NML basics, as well as approaches and issues related to the realization of integrated systems. This review was Notre-Dame-centric by design, to provide a somewhat historical perspective on the work of our group.

Finally, we would like to mention a couple of other related research efforts that also use nanomagnets to represent logic state, but that employ different mechanisms to couple and switch these magnets. One such effort, the Spin-Wave Bus proposed by a group at UCLA [44], is based on spin waves propagating in a layer underneath the magnets. Since spin waves (plasmons) decay, this scheme requires amplifying elements to restore the signals. Another scheme, the All-Spin Logic proposed by a group at Purdue [45], is based on nanomagnet coupling by spin diffusion in a magnetic layer underneath the magnets. This scheme requires wires to be connected to the magnetic dots in order to inject spin-polarized electrons that then diffuse and provide the coupling mechanism. These approaches are interesting, and further research is warranted. However, in our opinion, it is hard to see how coupling between dots using either spin waves or spin diffusion can be more efficient or lower power than coupling by direct magnetic fringing fields.

We end with a historical note. It was recognized in the very early days of digital computer design that magnetic phenomena are attractive for several reasons [46]: They possess an inherent high reliability; They require in most applications no power other than the power to switch their state; They are potentially able to perform all required operations, i.e., logic, storage and amplification. In fact, some of the very early computers used ferrite cores not only for memory, but also for logic. Ferrite cores were coupled by wires strung in specific ways between them so as to achieve logic functionality. For example, the Elliott 803 computer used germanium transistors and ferrite core logic elements. Of course, this kind of magnetic logic technology based on stringing wires between bulky magnetic cores was not competitive against emerging semiconductor technology. However, with the advent of modern fabrication technology, which allows the fabrication of arrays of nanometer-size single-domain magnets, the old quest for magnetic logic might become a reality.

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