EXPERIMENTAL STUDY OF NEW MAGNETIC CIRCUIT ELEMENTS
BUILT FROM NANOMAGNETS FOR MAGNETIC QUANTUM-DOT CELLULAR
AUTOMATA LOGIC APPLICATIONS

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by

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Abstract
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Magnetic quantum-dot cellular automata (MQCA) systems are networks of closely-spaced, dipole-coupled, single-domain nanomagnets designed for digital computation. MQCA offers very low power dissipation with high integration density of functional devices, as QCA implementations do in general. In addition, MQCA can operate over a wide temperature range from sub-Kelvin to the Curie temperature. Information propagation and inversion have previously been demonstrated in MQCA.

In this thesis, we perform a shape study of asymmetric magnets for MQCA gate design, and we demonstrate for the first time room temperature operation of a programmable MQCA majority-logic gate, i.e. the basic majority gate, with different length of the driver magnet.

The samples were fabricated on silicon wafers by using high-resolution electron-beam lithography for patterning of electron beam evaporated ferromagnetic metals. The nanomagnet circuits were imaged by magnetic force microscopy (MFM), with which individual magnetization states were distinguished and mapped. Magnetic switching
behavior was investigated in arrays of magnets with different aspect ratios. Switching fields were determined experimentally by MFM images taken after several independent demagnetizations.

By increasing a magnet’s length along its easy axis, its coercivity increases in that direction. This basic phenomenon was used for the design and fabrication of a programmable majority gate. The majority gate was demonstrated by employing NiFe polycrystalline nanomagnets with 60 nm x 90 nm lateral sizes. Drivers were provided by additional nanomagnets fabricated together with the gate, and the operation was tested by MFM.

The work presented here is an experimental proof of the MQCA concept.
To my husband and my parents
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CHAPTER 1.

INTRODUCTION

Single-domain, lithographically-defined nanomagnets can form circuits in a quantum-dot-cellular-automata-like (QCA) architecture scheme (MQCA). Lines, gates, and inverters have been experimentally realized, and operate at room temperature. It is estimated that if $10^{10}$ magnets switch $10^8$ times/s, the magnets would dissipate ~ 0.1 W. As the energy difference between the two states of the magnetization of the nanomagnets can be large, an external field is needed to re-evaluate a magnet ensemble with new inputs. The external clocking field puts the magnets into a metastable logic state against their preferred anisotropy. When the field is removed, the devices should relax into the correct logical state according to the antiferromagnetically (AF) and ferromagnetically coupled magnets building the magnetic circuit.

Provided that a device’s size/shape remains above the superparamagnetic limit, in the presence of no applied field, each device will retain its state – hence a magnet ensemble can serve as both logic and memory. In this work, we experimentally demonstrate a programmable majority gate – where one driver magnet will retain its state even when an external field is applied.

Previous work with nanomagnets for performing Boolean logic using an MQCA architecture used magnets with a uniform shape. Here, we studied the behavior of
nanomagnets with asymmetric shape. Of particular interest are magnets with one slanted edge. The magnetization dynamics and the response of the magnet to magnetic-field excitations are studied with Object Oriented MicroMagnetic Framework (OOMMF) simulations. It is demonstrated that the slant position, the direction of the applied external magnetic field, and the original state of magnetization of the magnets determine the final magnetization state of the slanted magnets in a controllable fashion.
CHAPTER 2.

INTRODUCTION OF TWO METHODS OF NANOMAGNET FABRICATION

Here we demonstrate two different recipes for the fabrication of nanomagnetic structures, which are adapted to the available procedures in the Notre Dame Nanofabrication Facility (NDNF). Both of these two methods include high resolution electron beam lithography (EBL), magnetic metal deposition and lift-off, and different in applied e-beam resists. We will discuss the advantages and disadvantages for both recipes. The fabrication methods are demonstrated for the realization of the majority gate schematically shown on Fig.1.
2.1. **Lift-off process with single-layer e-beam resist**

The basic lift-off fabrication method for nanoscale magnet implementation was already used by Alexandra Imre in her doctoral thesis. This recipe was modified for the currently available lab equipments in the Center for Nano Science and Technology at Notre Dame.

Poly-methyl-methacrylate (PMMA C2) high contrast, high resolution electron beam sensitive resist was used for the pattern definition. 100 nm PPMA was spun on top of the silicon sample with native oxide on it. The pre-bake was done at 170 °C for 3 minutes on an open air hotplate.

The pattern was defined by EBL (Elionix 7700) on the positive direct write e-beam resist. The pattern was exposed by 400 µC/cm² area dose using a thermal emission tungsten cathode electron gun with 75 kV acceleration voltages. 119 µA emission current
and 41 pA beam current was applied. The distance between the exposed dots was 1.25 nm on the 75 x 75 μm chip with 60,000 x 60,000 dots.

The developing step was done by a solution of methyl-isobuthyl ketone (MIBK), isopropanol (IPA) and methyl-ethyl ketone (MEK)\(^9\), 1 : 3 : 1.5 %, respectively, for a few minutes. The solution was cleaned from the sample by using pure isopropanol.

Reactive ion etching (RIE) was applied to remove the remaining residues after the developing step for 7 seconds. The descum was made with oxygen plasma (100 W RF power).

Ti and supermalloy (Ni : Fe : Mo : Mn, 79 % : 16.7 % : 4 % : 0.3 %) were evaporated onto the sample by electron beam evaporation method, with thickness of 10 and 30 nm, respectively, at a growth rate of 1-2 Angstrom/s. The titanium layer corrects the crystal mismatch in between the silicon substrate and the supermalloy.

The evaporation was followed by the lift-off made in acetone for 10 minutes. The sample was finally cleaned in isopropanol.

2.1.1. Advantages of single layer process

The process introduced above has two main advantages. One of them is due to the RIE descum process. The developing solvent removes the chemically modified, e-beam exposed PMMA resist from the chip to clean the substrate on the well defined areas for the magnets. Due to the small size of these areas, some residues cover a portion of the cleaned areas, which causes problems for the magnets for the lift-off step. The descum step clears the residue with an oxygen plasma, thus providing a good quality substrate for
the nanomagnets. This step improves the number of the magnets successfully fabricated on the substrate. The yield increased significantly and even approached 100%, as almost all magnets were sticking to the surface, improving the result of the lift-off process.

The second advantage is due to the titanium layer. This is an adhesion layer, what sticks well to the native oxide on the silicon substrate. It results in a higher lift-off yield for nanomagnet structures.

With these two extra process steps, the recipe was more effective, and the fabrication yield was improved.

2.1.2. Disadvantages of single layer process

Although this process has advantages, one main disadvantage exists. The fabricated magnets had material accumulations on their top surface. More than 15 nm roughness was measured with atomic force microscope on the magnets in a 60 x 90 nm area. During the lift-off fabrication step, the magnets were covered by residues (metal and organic mixture) from the solution. The residue was not removable either with oxygen plasma or with other chemicals (ALEG-370, acetone, dichloromethane). The extra particles did adversely influence the magnetic measurement of the nanomagnets, and also interfered with the measurement of the switching field as well. In Fig. 2, an SEM image of a majority gate is shown with the process-induced roughness on the top surface. The undesired material accumulation is clearly visible on the magnets.
Figure 2 Scanning electron micrograph of a majority gate with 100,000X magnification.

Figure 3 shows the same majority gate in a tilted position in the SEM. The irregular surface appears more clearly at an 45° angle of the scan. The material accumulations are present only on the top surface, and not on the sides.
2.2. Lift-off process with double-layer e-beam resist

In this fabrication recipe, an MMA EL9 copolymer layer was used in addition to the PMMA C2 to obtain a more sensitive resist structure for pattern definition.

Methyl-methacrylate (MMA) copolymer is spun to a thickness of 400 nm on a native oxide on a silicon sample. The MMA, to be used as an underlayer in a dual-layer resist structure, is exposed to deep UV light at 26.8 mW/cm² to make it more sensitive to the EBL exposure. Pre-bake is done at 170° C for two min on a hotplate. 100 nm poly-methyl-methacrylate (PMMA) is spun over the MMA layer and the pre-bake is repeated.
for the second resist layer. This double-layer resist is intended to provide a deep undercut after developing. The pattern is defined using an Elionix 7700 EBL system with a dose of 640 µC/cm². Development is done by a solution of methyl-isobuthylketone (MIBK), isopropanol (IPA) and methyl-ethyl ketone (MEK), 1:3:1.5%, respectively.

The figure below (Fig. 4) shows the sample with the two resist layers after the developing step. It was covered with a thin, 5 nm chromium layer for the 75 kV SEM scan. The develop solvent washed away the exposed MMA and PMMA areas, causing a deep undercut due to the high sensitivity of the lower copolymer (MMA) layer. This undercut is visible around the magnet patterns. The top PMMA layer kept the shape of the defined pattern.

The developing step is followed by the evaporation and lift-off steps. Due to the high thickness of the resists (400 nm MMA and 100 nm PMMA) and the deep undercut in the MMA layer the probability of forming ‘rabbit-ear’ is small, i.e. the evaporated material cannot accumulate on the side (vertical) wall of the lower, buried resist layer.
Figure 4 SEM of the developed MMA-PMMA layers is shown in this figure. The sample is covered with 5 nm chromium layer for the scan. The MMA undercut is visible around the well defined pattern.
The fabrication steps are summarized in Fig. 5. The left-most part shows the resists profile after the e-beam exposure and developing steps. The central part of the schematic shows evaporated metal on the top surface of the resists. The right –most part shows the sample after the last fabrication step, the lift-off.

Figure 5 Schematic picture summarizes the fabrication process steps. The first step is the resist spinning and e-beam pattern definition, developing (most left); metal evaporation follows the development (center) and the final step is the lift-off (most right).

The lift-off process with double-layer e-beam resist results in a different kind of residue around the pattern, as compared to the single-layer process. The residue is shown in an SEM scan of the fabricated sample right after the fabrication (Fig. 6). The top surface of the magnets is smooth, with no accumulated materials present. But, the majority gate is surrounded by residue from the developing solvent.
In order to remove this residue, oxygen plasma cleaning was applied to clean the surface around the pattern in Tegal etcher for ten minutes on 100 W RF power. The results, the clean area is shown on Fig. 7. The left picture shows the top view of the magnetic structures; here the clean substrate is clearly visible. The right picture is a tilted view of a gate to show the smooth surface of the magnets without any roughness.
2.2.1. Advantages

With this new method, by using double layer resist, we can eliminate the material accumulation on the surface. This improves the quality of the magnetic force micrograph during the test of the gates. The picture below (Fig. 8) shows an array of majority gates fabricated with this recipe, including the cleaning process.

Figure 7 SEM pictures of the majority gates after oxygen plasma cleaning in Tegal etcher.

Figure 8 Scanning electron micrograph of the majority gates fabricated with the ‘double layer’ recipe. The magnets are clean and free of any lift-off legs and residues.
2.2.2. Statistical analysis of the fabricated magnets

In order to demonstrate the reliability of the process protocol, we performed an analysis of fabricated samples to determine what fraction of magnets showed proper magnetization behavior. More specifically, we separately fabricated several batches of samples for this work. Magnets in magnetic wires were fabricated with lift-off using double e-beam resist layers, and studied by MFM to get numerical data on the magnetization state of the sample. The basic structure is shown in the SEM picture (Figure 9). The wires had one input magnet and five wire-magnets. In addition, wire structures were fabricated with 10 and 20 magnets, respectively.

The input magnets are elongated, with a size of 230 nm X 75 nm X 30 nm. The magnets comprising the wire are 110 nm X 70 nm X 30 nm. The separation between the magnets is 15-20 nm.

Figure 9 SEM picture of the wire design for the statistical analysis for the study of the fabrication process.
The samples were magnetized with an electromagnet (Chapter 3) and tested using MFM scan (Chapter 4). The output of the magnetic measurement was used for the analysis. Some magnets were covered with residue stemming from the lift-off solvent. The magnetic signal of these magnets was not measurable. As an example, one wire is shown in Figure 10 with buried magnets on the 6th, 9th and 10th place. Magnets without MFM signals were not counted during the analysis either as working or as defective magnets due to the ‘hidden’, unknown magnetization direction.

![Figure 10 Magnetic measurement picture of one wire from 10 magnets. The 6th, 9th and 10th magnets from the left do not show any magnetic signal.](image)

We studied 3,500 magnets in such wire structures. We found the fabrication yield of our process to be 96.9%, which means that approximately 3,400 magnets displayed magnetic information during the test scans.
CHAPTER 3.

MAGNETIZATION

The nanomagnets were magnetized using two different methods, and then tested by magnetic force microscope scans. The magnetization was performed using a Varian electromagnet, i.e. an external magnetic field was applied to set the magnetization state of the magnetic structures. Two methods of magnetization were used for these experiments. One is called magnetic-field pumping, where the sample was held fixed in the electromagnet, and the external field is ramped up to a certain value, held there, and then decreased back to zero. For the other method, the sample was rotated in the field of the electromagnet during the magnetization cycle, resulting in a rotating field in the frame of the sample.

3.1. Pumping magnetization method

The magnetic field was generated by the electromagnet to set the magnetization of the magnetic sample, which was situated between the two poles. The sample holder was fabricated in the machine shop from nonmagnetic aluminum bars to keep the sample fixed in a certain place in the magnetic field. The generated magnetic field was measured
constantly by a gauss meter to get full control over the applied field strength. The experimental set up, i.e. the electromagnet, the holder and a sample, is shown in the image below (Fig. 11).

Figure 11 Varian electromagnet with the sample holder used for magnetization of the supermalloy samples. The actual field is continuously measured by a tesla meter.

Figure 12 shows the electromagnet-generated field experienced by the sample between the poles during one magnetization cycle. At the beginning, the magnet is off, and then the current is ramped up at 0.5 A/s increments to 9 A, which results in a 150 mT magnetic field. Then, the field is being held constant for several seconds. Finally, the magnetic field is decreased to zero, and then the sample is removed.
3.2. Rotating magnetic field

As an alternative method for magnetizing and demagnetizing the fabricated magnetic circuits, a rotating magnetic field generator was set up. The same electromagnet was used for field generation as for the pumping method, and a rotating motorized stage was designed and fabricated for the experiments. The sample was clipped to the end of a rod between the two poles of the magnet, and this rod was attached to a motor (Figure 13 b). The experimental setup is shown in Figure 13 a.
The motor rotates with 1800 rpm, and as a consequence the magnets experienced a 30 Hz sinusoidal external field. As the magnetic field is increased from 0 mT to 130 mT, and then decreased back to 0 mT, this sinusoidal variation is shown in Figure 14 (at a lower frequency for clarity).
3.3. Magnetization during the experiments

The fabricated structure defines the applied magnetization method. When the external field is parallel with the long, easy axes of the magnets on the sample, the poor alignment available between the poles of the electromagnet is enough. Otherwise, when the applied field is parallel with the hard axes of the magnets, the magnetization alignment is more sensitive.

In general, the magnetic circuits contain driver or input magnets, what define the input of the whole circuit. In our work, these were designed with greater aspect ratio than the other magnets building the circuit, and were magnetized with pumping field along their easy axes. To avoid the issue with the hard axes alignment, rotating field was applied to set the magnets inside the circuit. During the magnetization of such magnetic circuits the pumping and the rotating field was applied in sequence. The pumping, constant high external magnetic field sets the magnetization of the longer magnets, inputs
with greater aspect ratios along the easy axes. The rotating field helps the inside magnets to relax into a logically correct states. This second field had a smaller absolute value compare to the pumping field. The time evolution of the magnetization experienced by the nanomagnets is shown on Fig. 15.

Figure 15 Time evolution of the applied magnetic field experienced by nanomagnet. The 200 mT field sets the magnets with high aspect ratio and the 100 mT field sets the magnets with lower aspect ratios inside the circuit.
CHAPTER 4.

AFM/MFM MEASUREMENT

All of the fabricated samples were magnetized either with the pumping or the rotating field method using the electromagnet to supply the external magnetic field. Then, MFM measurements were done with the Veeco MultiMode SPM microscope (Figure 16), which is a high quality instrument for studying surface properties of materials from the atomic to the micron scale. The measured data was processed with the newest Veeco controller (NanoScope V), which utilizes advanced electronics, including A/D and D/A converters operating at 50 MHz to deliver reliable, high speed data capture. This instrumentation allows us to record and analyze tip-sample interactions that probe nanoscale events. The output of the controller is processed with the corresponding NanoScope software v3.70.

Atomic force microscopy (AFM) was used in tapping mode for topographic information of the magnetic structures with RTESP probe (Rotated Tapping Etched Silicon Probe, Veeco Probes). In this mode we obtained high lateral resolution (around 5 nm) using a vertically oscillating probe.
Magnetic properties of the fabricated pattern were scanned by magnetic force microscopy (MFM) using the magnetostatic interaction between the specimen and a magnetic probe (MESP, Magnetic Etched Silicon Probe) placed at a constant height of tens of nanometers over the specimen surface.

To clarify the direction of the magnetization, arrows were drawn on the MFM images. The head of the arrow always is located on the bright spot (North pole of the nanomagnet), and the tail of the arrow on the dark spot (South pole) of the magnets.
5.1. Design

Two magnetic logic structures have already introduced in previous work\(^4\), namely the majority-logic gate and the magnetic wire built from either antiferromagnetically or ferromagnetically coupled magnets.

There is a great motivation to design new logic structures, i.e. new logic gates and to use more advanced magnetization methods to realize even more complex circuits built from nanoscale magnets. At this point, we have a rather mature and stable fabrication technology, as described in the previous section, and we are able to design and fabricate desired structures with high yield. This enables us to design more advanced structures, and to engineer with the shape and size of such magnets, i.e. with different aspect ratios, magnets with engineered edges, and even more with decreased sizes and separation between the nanomagnets.

Following the basic majority gate structure, we introduce below new structures such as a modified programmable majority gate and shape engineered magnets.
The schematic of the majority gate is shown in Fig. 17. The magnets are named on their function in the logic gate. The driver magnets set the input magnetization of the gate. Note that the driver magnets are perpendicular to the input magnets so that they can be set by an external field without setting the other magnets of the gate. The logic is performed by the computing magnet in the center of the majority gate, which is ferromagnetically coupled to the top and bottom input magnets and antiferromagnetically to the center input. The computing magnet passes the correct logic value to the output magnet, which is antiferromagnetically coupled to it.

![Figure 17 Drawing of the majority gate with the name of the magnets building it](image-url)
5.2. Majority gate with three driver magnets of the same size

The majority gate was fabricated with the previously described fabrication method using single-layer resist. For testing of these structures, an external magnetic field was used to set the drivers. To be able to show all possible input configurations of the gates, we had four different designs. Figure 18 below shows these four configurations in the AFM (left) pictures. The right pictures show the MFM scans, where the orientation of the magnetization of the magnets was imaged.

![AFM and MFM picture pairs showing four majority gate configurations. 150 mT external field applied from right to left by Varian electromagnet.](image)

A strong, 150 mT external pumping field was applied in the right-to-left direction to align the driver (horizontal) magnets, which set the input magnets of the gate. The drivers were magnetized along their easy axes, and the other magnets (input magnets, computing magnet, and output magnet) were forced to magnetize along their hard axes.
As the external field was reduced and no longer strong enough to keep this hard-axis high energy, unstable state, the input magnets, the computing magnet and the output magnet switched into an easy-axis magnetization orientation according to the drivers, i.e. the driver magnets force the vertical magnets to flip into a logically correct state.

5.3. **Magnets with different aspect ratios**

As the energy difference between two states can be large, an external field is needed to re-evaluate a magnet ensemble with new inputs. When the magnetic field is removed, the magnets should relax into a new ordered state in accordance with a new input. Provided that a device’s size/shape keeps it above the superparamagnetic limit, in the presence of no applied field, each device will retain its state – hence a magnet ensemble can serve as both logic and memory.

By increasing a magnet’s length along its easy axis, its coercivity in that direction increases. This is due to the fact that the reversing of atomic dipoles opposes the external field, so a greater field is required to switch more dipoles along the appropriate axis. This is illustrated quantitatively in Fig. 19 via micro-magnetic simulation (using NIST’s OOMMF suite). This simulation is done by Dr Niemier’s group (Computer Science and Engineering, University of Notre Dame).
Fig. 19 shows one-half of an M-H hysteresis curve ($H_y < 0$ A/m) for Permalloy magnets with sizes of $90 \times 60 \times 30$ nm, $120 \times 60 \times 30$ nm, and $180 \times 60 \times 30$ nm. Clearly, as the magnet length increases, higher external fields are required to facilitate a state transition. Thus, if we make one input to the majority gate longer, and the external field applied is sufficient to set the state of the smaller inputs, insufficient to switch the longer input, and sufficient to place the other magnets in the gate into a metastable state, then the longer input can retain its initial magnetization state even after the entire gate switching process is complete. This has been demonstrated in experiment as described below.
We first experimentally determined the magnitude of the field required to set magnets with different aspect ratios. Figure 20 shows an SEM image of 4 rows of 5 supermalloy magnets with lengths of 130, 150, 180 and 240 nm and with 70 nm width, and Fig 21 shows the schematic of an array of rectangular magnets with different sizes and aspect ratios.

Figure 20 SEM image of the magnets with different aspect ratios.

Figure 21 Schematic of the design used for the experiments of the magnets with different aspect ratios.
The fabricated sample was magnetized to the right by an 318 mT external field (positive direction). The resulting magnetization of the array is shown in the MFM picture (Fig. 22 a). The magnets with different aspect ratios were set to the positive direction by this high field. Then, a reverse field was applied to determine the field strength required to reverse the magnetization for the different aspect ratios of the magnets. For a 160 mT reverse field, pointing to the left (negative direction), most of the magnets with 130 and 150 nm length (less than 1:3 aspect ratio) reversed their magnetization, as shown in Fig. 22 b). Not all magnets reversed by the negative field due some uncontrollable fabrication errors.

Figure 22 MFM images of the magnets with different aspect ratios. The magnets were aligned with a +318 mT external field (a) and with a -160 mT external field after (b).

Next, we repeated this experiment, but now with a weaker reverse field. Again, first a high, positive magnetic field was applied, which was then followed by a weaker - 150 mT reverse field. MFM scans (Fig. 23) was taken after each step. Figure 23 b shows that most of the magnets with the lowest aspect ratio are reversed in the first row, but the higher aspect ratio magnets in the other rows kept the magnetization state from the previous magnetization step.
With this experiment we demonstrated that magnets with different aspect ratio have different switching field. We determined this field value for the 150 nm magnets in the second row as 160 mT, and for the 130 nm magnets in the first row as 150 mT.

We have experimentally proven that the switching field of the magnets increases with increasing aspect ratios of the magnet, i.e. we have control over the switching field strength required by changing a magnet’s length.

Figure 23 MFM image of the magnets with different aspect ratios. The magnets were aligned with a +318 mT external field (a) before the -150 mT excitation (b).
5.4. **Programmable majority gate**

After the demonstration of the switching behavior of individual magnets with different sizes and aspect ratios, we show that we can use different external fields to control different driver magnets of a logic gate, thus making the majority gate programmable by the external field strength. Figure 24 shows the design for a majority gate with one long driver magnet. The size of all magnets are $60 \text{ nm} \times 90 \text{ nm} \times 30 \text{ nm}$, except for the long driver which is $60 \text{ nm} \times 150 \text{ nm} \times 30 \text{ nm}$. The separation is 15 - 20 nm between the magnets.

![Figure 24 Design of a majority gate with one long driver magnet. The dimension of the magnets is 60 nm x 90 nm x 30 nm, and for the long magnet 60 nm x 150 nm x 30 nm.](image-url)
Figure 25 shows a tilted SEM picture of the fabricated structures with 90,000 magnification at 30 kV. The designed sizes and the measured dimension of the fabricated magnets are in good correlation. The top surface of the magnets is flat, free from any material accumulations and dirt, what is advantageous for the magnetization behavior, i.e. no strong roughness exist on the surface what would harden the switching process.

The fabricated gates were tested and measured with the atomic and magnetic force microscope. Figure 26 summarizes the results. In part ‘a’ of Fig 26, the clear topography can be seen in this AFM image. Fig. 26 b shows the MFM micrograph after magnetization by an external field, where all the inputs are magnetized to the right (which we could map to a logic ‘1’). After an appropriate reverse field is applied, the two shorter drivers, at upper right and lower left, have switched to logic “0,” but the longest
driver magnet has remained at logic “1”. This switching is shown on Fig. 26 c. With a sufficiently large reversed field, we can switch all the magnets to the left and then choose to switch just the other two inputs back to the right. We have demonstrated that we can arbitrarily choose a fixed “1” or “0” input for the longer driver magnet and independently switch the other drivers. This represents a programmable logic gate – which is especially important when considering how to use this technology at the functional unit level.

Figure 26 AFM (a) and MFM (b and c) pictures of a majority gate with one long driver magnet. All the drivers are pointing into the same direction on the left MFM image (b). An appropriate reverse field can switch the short drivers, and the final configuration is shown in the right MFM picture (c).
The ability to “size engineer” a majority gate driver enables a designer to selectively configure a majority gate to function as either an AND or OR gate (the truth table is shown in Fig. 27). The ability to program a gate post-fabrication will also enable even more sophisticated architectures. More specifically, the programmable gate demonstrated here forms the core of a QCA-based Programmable Logic Array (PLA) design.\textsuperscript{11}

![Majority gate truth table (reduced to AND/OR).](image)

Figure 27 Majority gate truth table (reduced to AND/OR).
5.5. Shape engineering

In this chapter, we illustrate the importance of shape as a design variable when considering circuit elements made from nanomagnets. Careful consideration of the shape of magnetic logic devices could have a significant impact on system level performance benchmarks such as reduced gate delay, smaller circuit areas, and higher system-level throughput. The lithographically-defined nanomagnets that form the basis of this work can be arranged to form circuits in a cellular automata-like architecture scheme – where logical operations and dataflow are accomplished via nearest-neighbor interaction. The wires, gates, and inverters have all been realized with rounded rectangular shape.

In the previous section, we demonstrated a majority gate with one long input, i.e. the clocked majority gate is reduced to a 2-input AND / OR gate. However, majority-gate based logic with rounded-rectangle nanomagnets fails to take into account an important design parameter – magnet shape. Here, we introduce the response of an appropriately-shaped piece of magnetic material to an applied clocking field. To exploit this response of the magnet we can design and fabricate AND and OR logics in further work, what would have a smaller area than a majority-gate based equivalent, and would decrease the gate delay due to the lower number of the building magnets.
5.5.1. Simulation

Simulations were done with the Objected Oriented Micro-Magnetic Framework (OOMMF) developed by NIST. OOMMF uses a Landau-Lifshitz PDE solver to relax 3D spins on a 2D mesh of square cells. OOMMF is widely used, and there is excellent correlation between simulation and experimental results.

We simulated magnets with a “slanted” or “cut” edge, as shown in the insets in Fig. 28. Specifically, we considered three magnets with slanted edges that initially were magnetized to saturation along their hard axes (e.g. $M_x = M_s$ where $M_s$ is the saturation magnetization of supermalloy). If no external field is applied to keep a given magnet in this metastable state (i.e. along the hard axis), and the magnetic material is polycrystalline (e.g. like permalloy or supermalloy), then this magnet will relax into a magnetization state determined by its easy (long) axis due to the strong shape anisotropy. In clocked lines of magnets, the fringing fields from a neighboring device will ideally determine the sign of the final magnetization state. In the presence of no applied bias, which state a magnet with a rounded rectangle shape (like in majority gate shown in Fig. 17) might relax to would essentially be random. However, as magnetic moments tend to align along a magnet’s edge, a slanted edge can give a magnet a preferred y-component of magnetization. Which state a magnet will ultimately relax to is determined by the position of the slant and the initial x-component (direction) of magnetization. This effect is captured quantitatively in Fig. 28, where we consider three magnets with slanted edges. Magnets v1 and v2 have 50 nm X 75 nm X 25 nm size, and magnet v3 has a size of 40 nm X 60 nm X 20 nm. Each device was initialized with both a positive and negative x-component of magnetization, and was allowed to relax with no external clocking field or
Hy bias applied. The placement of the slant and the direction of the initial x-component of magnetization consistently lead to a preferred y-component of magnetization of each magnet – such that $M_y$ is either $\uparrow$(positive) or $\downarrow$(negative).\(^{12}\)

Figure 28 shows the simulation result of the magnets with slanted edges and initially magnetized such that $M_x = M_y$. The magnets relax such that their eventual y-component of magnetization is determined by the position, direction of the slanted edge and the initial x-direction of magnetization.
5.5.2. Magnetic field generated by magnets with different design

The magnetic field generated by magnets with different shapes was studied with the help of an electromagnetic modeling simulator software called Vizimag\textsuperscript{13}. It analyses and simulates the magnetic field lines and flux density of the magnet with a given shape.

The software output graph for a symmetric rectangular shape magnet is shown in Figure 29. The magnet is located at the center of the plot, and this geometry is the input for the software. The magnetic flux lines are drawn around the magnet by the simulator. It is clearly visible that the flux lines are symmetric with respect to the vertical axis of the magnet.

![Magnetic flux lines of the rectangular shape magnet](image)

Figure 29 Magnetic flux lines of the rectangular shape magnet
This symmetry exists only in the case of a symmetric magnet. As we start to
design some magnets with asymmetric shape, we have to take into account the change of
the magnetic field around the new structure. Figure 30 shows various magnets with a cut
on the top left edge. The cuts are at different angles for the different magnets. From a) to
d), the top right edge is more sharp.

Figure 30 Broken symmetry of the magnetic field is shown. The flux lines on the left side
disappear from a) to d) as the cut at the top left corner becomes deeper.

Figure 30 let us compare the flux densities, how the flux decreases with deeper
slant. We see that the symmetry of the flux lines is broken by the cut on the top left edge
of the magnet, i.e. on the side of the slant the number of the flux lines are less than on the
other side. This has to be taken in to account during further implementation of the slant
magnet into different circuits, where the coupling between the neighbours provides the
information propagation. The coupling between the magnets is defined by the magnetic field generated by the nanomagnet, i.e. the density of the flux lines. In the case of symmetric magnets, where the long axes of the magnets parallel or perpendicular to each other, the interaction between the magnets is the ferromagnetic and antiferromagnetic coupling.

The adjacent magnets and the field lines are shown in Fig. 31. The blue and the red magnets are transparent to show the magnetic flux lines of the black magnet. The blue and red magnet flips its magnetization direction according to the direction of the flux coming from the neighbor magnet. The flux is along the easy axes of the blue and red magnets, i.e. along the axes of the low energy, stable state.

Figure 31 The magnetic field of the black magnet is drown on the plot. The blue magnet is parallel with the black magnet and antiferromagnetically coupled. The red magnet is ferromagnetically coupled with the black magnet. The magnets are transparent to show the flux lines of the black magnet.
Figure 32 shows the flux lines of the selected slant design for the fabrication with the asymmetry on the left and right side. The top edge of the magnet has a certain angle (>45°) so that it can be easily fabricated with lift-off. Due to the proximity affect of the electron beam system, the edges got rounded but kept the designed angles.

5.5.3. Energy distribution of the slant magnets

As the OOMMF simulation shows (Chapter 5.5.1), the asymmetric magnet has a preferred direction as it relaxes after magnetized along its hard axes. Due to the energy distribution (shown in Fig. 33 b) it does not need any disturbing field to reach a magnetization directed along its easy axes, the low energy state.

The symmetric magnet has a symmetric energy distribution (shown in Fig. 33 a). After magnetization along the hard axes this magnet needs a small amount of energy to
flip the magnetization to the low energy state (parallel to the easy axes) from the unstable, high energy equilibrium state.

Figure 33 Energy distributions of the rectangular and slant magnets in the presence of an external magnetic field along the hard axes

The relaxed (no external field present) magnetization direction of the slant magnet depends upon the location of the slant and the direction of the excitation magnetic field. Figure 34 summarizes the four possible locations of the slant in the presence of the certain applied field (left to right, parallel to the hard axes of the slant magnet). The energy distribution is showed for all cases. The energy of the magnet, when the external field is on, is marked by a dot on the curves. This always is located on the slope, i.e. the energy state is unstable. As the field disappears, the magnet reaches the 'closest' energy minimum, the magnetization flips parallel to the easy axes. (To reach the farther low energy state it would be necessary to gain more energy.)
Thus we see from the energy distribution, that the position of the slant and the direction of the applied external magnetic field determine the final magnetization state of the slanted magnets.

Figure 34 Energy distribution of the slant magnets are shown in the presence of an external magnetic field parallel to the hard axes of the magnets.
5.5.4. Fabrication and measurement of the slant magnets

As explained in the previous chapter, the slant magnets have particular magnetization properties, which can be exploited for magnetic circuit designs. A schematic of the experimental test structure is shown in Fig. 35. The slant magnets are in the central part of the design with volume smaller than 30 nm X 70 nm X 150 nm. Each column has a slant on a different edge to show all of the magnetization variations shown in Fig. 34. On the left- and right-hand side of the pattern, magnets are located with an easy axis perpendicular to that of the slant magnets. These magnets will be used to show the direction of the applied magnetic field during our experiment. These indicator magnets are in size 30 nm X 75 nm X 150 nm, as shown in the schematic drawing.

![Figure 35 Schematic design of the slant magnet array.](image-url)
Such an array was fabricated with the double-layer resist lift-off method described previously. An SEM image of the completed array is shown in Fig 36. The magnets are rounded at the edges, but the slant still is present and determines the shape behavior of the magnets.

![SEM image of the slant magnet array. The edges of the magnets are rounded but the slant is still visible.](image)

The SEM micrograph in Fig. 37 shows the sizes of the fabricated slant and indicator magnets. The design and measured parameters are in good agreement, indicating the stability of our fabrication process.
An MFM image was taken to test the magnets after an external magnetic field was applied along the top-to-bottom direction. The output of the measurement is shown in the top part of Fig. 38. The bottom image shows again the design to help see the location of the slant on the magnets. The cut edges are not visible on the MFM image due to the spreading flux lines. The indicator magnets show the direction of the applied magnetic field, which was applied along the easy axis of these magnets. The vertical field direction is along the hard axes of the slant magnets, thus forcing them to be in an unstable energy state, as shown in Figure 34. As the external field is removed, the indicator magnets remain in their easy axis state, and the slant magnets relax to the ground state corresponding to their particular slant shape.

Figure 37 The array of the slant magnets with the measured extensions.
Figure 38 MFM image taken after magnetic field applied to the vertical direction. The bottom image shows the design to help to see the location of the slants on the magnets.

In summary, for all slanted magnets, the placement of the slant defines the magnetization direction, and the external field drives them to the corresponding state. We have demonstrated this behavior by simulation and by experimental results as well.
CHAPTER 6.

SUMMARY

Magnetic quantum-dot cellular automata (MQCA) represent networks of field-coupled (ferromagnetically and antiferromagnetically coupled) nanomagnets whose magnetization can be switched between two stable states. The nanomagnets are placed closely in magnetic circuits, so the ground state of the interacting system is ordered. An external time-varying magnetic field is applied to control the magnetic relaxation of the system to the ground state. The relaxation itself is used to propagate and process information and the circuit is capable to store the result. Logical functionality can be achieved at room temperature by certain physical arrangements of the nanomagnets.

In this thesis, we have demonstrated the following results:

- Two different fabrication techniques were investigated for application to MQCA.
- Programmable majority gate featuring field-coupled nanomagnets were demonstrated.
- Asymmetric shape design was studied for future MQCA logic implementations.
CHAPTER 7.

FUTURE WORK

7.1. Simulation work

Part of the follow-on work on this project will be the simulation of the rotating magnetic field to show the simulated time evolution of the magnetization reversal, and to understand more deeply the sinusoidal magnetic field and the domain magnetization interaction.

This would help us to design different magnetic logic structures for this specific excitation method, although the electric circuit implementation of the rotating magnetic field is not solved yet.

Simulations will be done for further symmetric and asymmetric shape studies to demonstrate, how the shape influences the behavior of the magnetic switching, and how it changes to magnetic field generated by the nanomagnet.
7.2. Fabrication

The successful implementation of the programmable majority gate inspire us to design and fabricate a completely programmable majority gate, i.e. gate with three different driver lengths to demonstrate the ability of the separate set of the drivers.

Parallel with the simulation work on the shape studies, fabrication will be done on magnets with symmetric and asymmetric shape such as trapezoidal, triangular etc.

It was shown in Fig. 30, that the slant magnets has asymmetric magnetic field around. We plan to take an advantage of this physical property to design wire from slant magnets to define a certain propagation direction, and avoid any back propagation, i.e. the first magnet next to the input should switch first followed by the second and third etc. The asymmetry of the slant magnet allows to propagate the information only one direction because it does not have enough flux line on the side of the slant edge to switch the neighboring magnet.

Further MQCA implementations are in our plans such as fanout structure, which is a crucial element of the higher level implementation of magnetic logic.
REFERENCES


13 Visualize Magnetic Field software v3.18, www.vizimag.com