EXPERIMENTAL STUDY OF NOVEL NANOMAGNET LOGIC DEVICES

A Dissertation

Submitted to the Graduate School
of the University of Notre Dame
in Partial Fulfillment of the Requirements
for the Degree of

Doctor of Philosophy

by

Edit Varga

_____________________________
Wolfgang Porod, Director

Graduate Program in Electrical Engineering

Notre Dame, Indiana

April 2013
EXPERIMENTAL STUDY OF NOVEL NANOMAGNET LOGIC DEVICES

Abstract

by

Edit Varga

Today’s omnipresent electronic circuits, chips, and memories are almost entirely based on silicon. Their development closely follows Moore’s law, and many years of further miniaturization and development is foreseen in this technology. However, the limitations of silicon nanotechnology are becoming increasingly clear: high power consumption and the lack of integrable non-volatile memory are two of the key weaknesses. Several recent developments propose and investigate the application of magnetism for future logic and memory devices. Magnets are inherently good memories, and the flipping of spins consumes energy close to the lowest values allowed by thermodynamics. Among the most intensively researched magnetoelectronic devices are the Magnetic Random Access Memory (MRAM), the racetrack memory, as well as the magnetic Quantum-Dot Cellular Automata (MQCA), recently called nanomagnet logic (NML).

The QCA computing paradigm offers a new alternative to build logic and memory devices. Among several realizations, the NML is of interest in this work, which uses nanomagnets as basic building blocks to encode logic bits and switches in the
magnetization state of ferromagnetic materials. An NML device is an array of closely spaced, dipole-coupled, single-domain nanomagnets designed for digital computation. NML offers very low power dissipation with high integration density of functional devices, as well as operates over a wide range of temperature. Basic structures, such as wires, inverters, and majority gate already have been demonstrated.

In this work, we present a detailed fabrication recipe to fabricate nanomagnets with good shape and size control. A complete logic component library is vital for digital logic design. Our ultimate goal is to realize novel logic elements to extend the library of nanomagnet logic circuits. Several building blocks are demonstrated already, such as wires, majority-logic gate, etc. We built new basic magnetic structures such as shape engineered majority gates, AND gate, OR gate, for the first time, and used wires, inverters and gates to construct more complex circuits, such as a fanout, an XOR, and a full adder. We propose NML designs, such as the complex gate, for even more complex structures for future testing. This work goes beyond the original MQCA concept in several ways, such as the building blocks have different aspect ratios and asymmetry to exploit the advantages of the shape engineered nanomagnet behavior.
To Gergő and Benedek
5. NANOMAGNET CHARACTERIZATION TECHNIQUES ........................................ 37
   5.1 Scanning electron microscope ............................................................... 37
   5.2 Atomic force microscope .................................................................... 41
   5.3 Magnetic force microscope ................................................................. 48
   5.4 Spin-scanning electron microscope .................................................... 53
   5.5 Conclusions ....................................................................................... 55

6. SHAPE ENGINEERING OF STANDALONE NANOMAGNETS ..................... 56
   6.1 Magnets with different aspect ratios .................................................. 56
   6.2 Slant edge nanomagnets .................................................................... 59
   6.3 Conclusions ....................................................................................... 60

7. NANOMAGNET WIRES ............................................................................... 61
   7.1 Experimental realization of horizontal and vertical nanomagnet wires ...... 62
   7.2 Nanomagnet wire built from different aspect ratio magnets .................. 64
   7.3 Comparison of the AFC wire with uniform and different aspect ratio magnets ... 66
   7.4 Characterization of the nanomagnet wires with various magnetization methods. 66
       7.4.1 Magnetization methods ................................................................ 67
       7.4.2 Characterization .......................................................................... 67
   7.5 Staircase wires .................................................................................. 69
   7.6 Conclusions ....................................................................................... 74

8. THE DEVELOPMENT OF THE PROGRAMMABLE MAJORITY GATE .......... 75
   8.1 Majority gate with identical magnets .................................................. 77
   8.2 Modified majority gate ...................................................................... 78
   8.3 Programmable majority gate .............................................................. 81
   8.4 Conclusions ....................................................................................... 85

9. NANOMAGNET FANOUT .......................................................................... 86
   9.1 Introduction ....................................................................................... 86
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5</td>
<td>Proposed structure</td>
</tr>
<tr>
<td>15.6</td>
<td>Conclusions</td>
</tr>
<tr>
<td>16.</td>
<td>RADIATION HARDNESS TEST OF NANOMAGNET STRUCTURES</td>
</tr>
<tr>
<td>16.1</td>
<td>The irradiated samples</td>
</tr>
<tr>
<td>16.2</td>
<td>Irradiation</td>
</tr>
<tr>
<td>16.3</td>
<td>Results and Conclusions</td>
</tr>
<tr>
<td>17.</td>
<td>NML RELATED CHALLENGES</td>
</tr>
<tr>
<td>17.1</td>
<td>The domain structure of the nanomagnets</td>
</tr>
<tr>
<td>17.2</td>
<td>Coupling between the nanomagnets</td>
</tr>
<tr>
<td>17.3</td>
<td>Ferromagnetic and antiferromagnetic coupling in the nanomagnet wires</td>
</tr>
<tr>
<td>17.4</td>
<td>Temperature effect in characterization</td>
</tr>
<tr>
<td>17.5</td>
<td>Possible back propagation in horizontal nanomagnet wires</td>
</tr>
<tr>
<td>17.6</td>
<td>Conclusions</td>
</tr>
<tr>
<td>18.</td>
<td>SUMMARY OF THE CONTRIBUTIONS OF THE AUTHOR</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>SPIN-SEM SYSTEM OVERVIEW</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>PUBLICATIONS</td>
</tr>
<tr>
<td>REFERENCES</td>
<td></td>
</tr>
</tbody>
</table>

vi
Fig. 1. Schematic of envisioned structure for NML operation. The nanomagnets are clocked by the current carrying copper wires, and the input is provided by either an MTJ or biasing line(s). The output is an MTJ that converts the magnetic signal to an electrical signal. The information propagates from left to right by a properly set clocking scheme.

Fig. 2. Energy landscape and clocking process of a symmetric, rectangular shape nanomagnet. The thick, blue arrow indicates the strong hard-axis clocking field. As the field is removed, the symmetric nanomagnet relaxes into one of the two energetically equivalent ground states.

Fig. 3. M-H curves ($H_y < 0$ A/m) for magnets with three different aspect ratios (1.5, 2, and 3). As the length increases, coercivity increases.

Fig. 4. Simulated switching field vs. dot length. Thickness and width of nanomagnets are fixed. The monotonically increasing function suggests that the aspect ratio change can be exploited to design separately programmable inputs for the NML circuit.

Fig. 5. Simulation based on the single-domain model result for the slant nanomagnet energy landscape. The energy minima are shifted from the long geometrical axis, i.e., from the 90 deg and 270 deg magnetization directions.

Fig. 6. Energy curves of the slant magnets for different slant locations. The external magnetic field is applied from left to right shown by horizontal, thick, blue arrows. The thin line along the diagonal of the magnet corresponds to the effective easy axis. The energy maximum is perpendicular to this axis.

Fig. 7. Energy diagram of the magnets in different magnetization states. The magnet has low energy while magnetized along its long geometrical axis, and high energy when the magnetization is pointing along its short axis.

Fig. 8. The spin speed versus film thickness curves for PMMA with different solid concentrations (C2, C4, AND C6) [32]. Cx represents x% solids concentration.

Fig. 9. Cross section of the resist profile with the evaporated titanium (Ti) and Permalloy (Py) on top. Single layer resist with ‘rabbit ear’ (a) and double layer resist with the undercut (b) is shown.
Fig. 10. The spin speed versus film thickness curves for MMA with various solid concentrations [32]. ELx refers to x% solids concentration. ........................................... 19

Fig. 11. Double layer resist is exposed by electron beam in oval shapes followed by developing. The deep undercut of the MMA layer shows up as a shadow surrounding the oval shapes. Before the SEM scan, the sample is coated with a thin chromium layer. ............................................................................................. 20

Fig. 12. The beam diameter as a function of the beam current. In our experiments, the smallest, 40 µm aperture is used. As the beam current is 50 pA, the spot size is about 10 nm in diameter [33]. ....................................................................................... 21

Fig. 13. Experimental setup for pumping magnetization method. A sample is held in place by a T-shape aluminum holder between the two pole pieces of the electromagnet. ....................................................................................................... 25

Fig. 14. Time evolution of the magnetic field experienced by the sample during one pumping magnetization cycle. ..................................................................................................................................................... 26

Fig. 15. Pumping process stage with alignment control. The sample sits on the top of a rod. The dial at the bottom end of the aluminum rod enables to adjust the alignment of the sample. ................................................................................... 27

Fig. 16. Experimental setup for shaking magnetization. The electromagnet with the computer controlled stage is shown. ......................................................................................................................... 28

Fig. 17. Shaking stage with the protractor. The sample is fixed by two clips on the end of the stainless steel rod. ................................................................................................................................. 29

Fig. 18. Schematic of our setup to show the x, y, and z axis relative to the pole pieces and to the sample. ..................................................................................................................................................... 30

Fig. 19. The magnetic field experienced by the sample in x direction (green) during a 15° shaking magnetization circle. The field generated by the magnet is overlaid (blue). ........................................................................................................................................... 31

Fig. 20. The magnetic field experienced by the sample in y direction (red) during one 15° shaking magnetization circle. The envelope curves (blue and green) indicate the generated magnetic field. ........................................................................................................................................... 32

Fig. 21. Experimental set up for the rotating magnetization (a). The sample is held between the pole pieces (b). ......................................................................................................................................................... 33

Fig. 22. The rotating magnetic field in x (left) and y (right) direction experienced by the nanomagnets situated between the poles of the electromagnet. .............................................. 34
Fig. 23. The x (red) and y (teal) directional rotating magnetic field overlaid to emphasize the phase shift between the two signals. ............................................................... 34

Fig. 24. Hitachi SEM at the University of Notre Dame4. ................................................. 38

Fig. 25. AFM image of the nanomagnet islands previously exposed by SEM. Top view (a) and tilted, 3D (b) is shown along with the cross section (c). The oval shapes are the nanomagnets and the longer lines are the carbon depositions due to the SEM. ..................................................................................................................... 39

Fig. 26. FEI Magellan, extreme high resolution SEM [38]. ............................................. 41

Fig. 27. Schematic diagram of the optical lever sensor. As the cantilever bends, the position of the laser spot on the detector changes. Small movement of the cantilever causes large change in the position of the laser spot due to the large distance from the cantilever to the detector [41]. ................................................. 42

Fig. 28. Force curve of the AFM probe. The force between the surface and the probe vs. their separation is plotted [42]. .................................................................................... 44

Fig. 29. SEM (top) and schematic image of the probe profile, side view (top schematic and SEM) and front view (bottom schematic [46]).)......................................................... 46

Fig. 30. MultiMode microscope from Veeco is used during the nanomagnet tests [47]. . 47

Fig. 31. MFM Lift Mode principles. The first path allows the system to collect the topographical data. The magnetic information is measured during the second path at a constant height above the sample surface [48]................................. 49

Fig. 32. Stray field of the probe that is perpendicular to the sample surface is shown at 25 nm scan height for different coating thicknesses [49]. .................................................... 50

Fig. 33. Reconstructed axial field component of the MESP probe using Lorentz microscopy [52]. .................................................................................................................... 51

Fig. 34. MFM images of one single magnet magnetized in opposite directions. White arrows are overlaid to make the magnetization direction easily visible. .............. 52

Fig. 35. Schematic of the spin-SEM principle [54]. ............................................................. 54

Fig. 36. Experimental proof of the simulation results shown in Fig. 3. The SEM image of the test structure (a) and the MFM images of the same magnets (b-d) after various magnetization field directions and strengths are shown. ........................................... 57

Fig. 37. Schematic of the test array (a) including horizontally aligned magnets with different positions of the slanted edges as well as vertically aligned indicator magnets. MFM of the slant/indicator magnets (b). A 130 mT top-down field is
applied along the easy axis of the vertical magnets, and along the hard axis of magnets with slanted edges. All magnets are magnetized as expected. .................. 59

Fig. 38. a) SEM image of a 5-nanomagnet-long vertical wire with a horizontally aligned driver magnet. b) MFM image of the same wire for one magnetization state of the driver magnet and c) for the other. The information propagates from the driver magnet toward the bottom of the wire by ferromagnetic coupling....................... 63

Fig. 39. a) SEM image of a 5-nanomagnet-long horizontal wire with a horizontally aligned driver magnet. b) MFM image of the same wire for one magnetization state of the driver magnet and c) for the other. The horizontal driver magnet initializes the entire wire, thereby defining the magnetization state of all of the magnets. The information propagates from left to right, that is, from the region of strongest to weakest influence. ................................................................. 64

Fig. 40. SEM image of the nanomagnet wires with input magnets on the left and different aspect ratios along the line.................................................................................. 65

Fig. 41. Pie chart summary of the error results of different magnetization methods. ..... 68

Fig. 42. Schematic of the NML wire with shifted magnets, i.e., the magnets form a ‘staircase’ instead of being horizontally or vertically aligned.............................. 70

Fig. 43. SEM (a) and MFM (b and c) image of the staircase-like wire. This structure allows us to use arbitrary wire length in the NML circuit design.......................... 71

Fig. 44. The spin polarized SEM image of the staircase wires along the vertical direction. Only one in-plane magnetization state is shown due to the limitation of the instrument. ................................................................................................ 72

Fig. 45. Spin SEM scan of the staircase wires along the horizontal direction. The magnetization of the driver dots is pictured......................................................... 72

Fig. 46. Most of the staircase-like wire magnets failed to flip magnetization after a negative, 100 mT magnetic field is applied.................................................... 74

Fig. 47. Schematic of the majority gate along with the name of the specific magnets (input, driver, computing, and output magnet). ..................................................... 76

Fig. 48. The split truth table of the majority gate. Input A is fixed to set the gate to an AND (left side) and to an OR gate (right side).............................................. 76

Fig. 49. AFM and MFM image pairs show all four majority gate configurations. 150 mT external field is applied from right to left by an electromagnet................. 77
Fig. 50. Majority gate built from uniform magnets including one long driver magnet. Schematic along with the nanomagnet sizes (a), SEM image (b), and MFM images after different magnetization steps (c-e). ................................................................. 80

Fig. 51. Programmable majority gate. The schematic shows the design along with the scale of the magnets. The SEM image shows three fabricated gates............... 83

Fig. 52. MFM images of the programmable majority gate for all input combinations. The black insets show the three input values along the output, majority value......... 84

Fig. 53. Generalized fanout circuit - one input drives multiple (in our case, 3) outputs (a) and schematic of the fanout circuit designed for single-domain magnets (b). ..... 87

Fig. 54. Schematic (a), SEM image (b) and MFM images for both possible driver magnetization states (c and d) of the fanout circuit................................. 89

Fig. 55. SEM (a) and MFM images (b and c) of the nanomagnet fanout circuit with short, two magnet long output wires. The MFM images summarize the correct ordering of all magnets building the structure......................................................... 91

Fig. 56. SEM (a) and MFM images (b and c) of the fanout circuit with three magnet long output wires. The nanomagnets switch into the correct state throughout the entire structure.................................................................................. 92

Fig. 57. SEM (a) and MFM images (b and c) of the fanout circuit with five magnet long output wires. The performance of the fanout is perfect even with these long output wires.................................................................................. 93

Fig. 58. a) An early full adder design constructed from 5 majority gates [60]. b) The smaller full adder design proposed in several publications, e.g., [61]. Only 3 majority voting gates are necessary for the full adder implementation. Since AFC wire is comprised of a series of inverters, depending on the total length of the wire being an even or odd number of magnets, the inverter function is included in the wire length. ......................................................................................... 97

Fig. 59. Schematic of the full adder including three, three-input majority gates, and several high aspect ratio magnets to act as drivers providing the input data (A, B, and Ci) for the circuit. The majority gates are the intersections of horizontal and vertical wires at which the center magnet is influenced by three input magnets (top, left and bottom neighbors) and influence an output magnet (right neighbor). The output is the sum (Sum) and the carry bit (Co). ......................................................................................... 98

Fig. 60. SEM image of the fabricated full adder built from 53 nanomagnets (a) and the MFM image after the magnetization of the structure (b). One single coupling error occurred at the encircled location in the MFM image. ......................... 100
Fig. 61. Schematic (a) and SEM image (b) of a reduced footprint NML full adder. This gate contains 31 magnets. The (*) symbol is explained in the text. .......................... 101

Fig. 62. The MFM image of the reduced footprint full adder design (shown in Fig. 61). Two errors (circled) are present here. The top one is common and it appears in 75% of the gates................................................................. 102

Fig. 63. Our proposed full adder design with different aspect ratio inputs. The number of the magnets is decreased compare to the previous two designs. ..................... 103

Fig. 64. Schematic of the column design. The majority gates (M1, M2, and M3) are located above each other................................................................. 104

Fig. 65. A new circuit diagram for possible column design implementation of the full adder........................................................................................................ 105

Fig. 66. Schematic of the full adder with the column design. This design has two parts. The one on the left provides the sum of the inputs, and the other one on the right provides the carry bit. Four different designs are necessary to demonstrate all possible input combinations. (¬A is a symbol for ‘not A’) ......................... 106

Fig. 67. A reduced footprint design of the full adder. The inputs are provided by the slant magnets. Four different designs are shown (a - d) for testing all possible input combinations......................................................... 107

Fig. 68. SEM images (first column) and the MFM images (second and third column) of the full adders with slant input magnets. All four designs (a – d) are shown. Each line shows two magnetization experiments for two input combinations. The MFM images summarize all possible input combinations. ........................................ 109

Fig. 69. An implementation of the exclusive OR function using QCA cells. This design includes wire crossing as well as an inverter [60]. ........................................ 111

Fig. 70. XOR circuit implementations built from AND and OR gates. These two circuits are chosen for NML implementation..................................................... 112

Fig. 71. Schematics of the NML XOR gates converted from the circuit layouts shown in Fig. 70. One layout includes the staircase-like vertical wire (a), and the other has the regular grid-based structure (b). ........................................................................ 113

Fig. 72. NML exclusive OR gate with a staircase-like vertical wire located on the right side of the gate. The SEM (left) and the MFM (right) images are shown. In the bottom right corner of the MFM image, the corresponding row of the XOR truth table is shown. The central long magnet restricts the function of the majority gates to an OR gate (bottom left) and to an AND gate (top left and bottom right). ........................................................................................................ 115
Fig. 73. NML exclusive OR gate with regular horizontal and vertical wires. SEM (left) and MFM (right) images are shown. The corresponding row of the XOR truth table shown in the bottom right corner. The central long magnet is responsible to set the function of all three majority gates. The top right gate is an OR gate and the other two are AND gates.

Fig. 74. Schematic of a comparator built from three majority gates [50].

Fig. 75. Nanomagnet-based comparator design with two inputs (A and B) and three outputs (Y).

Fig. 76. SEM image of the NML comparator fabricated for the first time. The inputs are A and B, the output is Y.

Fig. 77. Complex gate built from QCA cells [65].

Fig. 78. List of the available functions of the complex gate. Three inputs (e, f, and g) set the functionality of the gate, and the remaining four inputs provide the four variables for the circuit.

Fig. 79. The NML complex gate consisting of three nanomagnet majority gates (wire crossings). A, B, C, and D are the input magnets, and E, F, and G are control magnets.

Fig. 80. Schematic of the logic gate built from one slant magnet and two input magnets.

Fig. 81. Magnetization variations of the slant gate for all input combinations. On the left, the slant is magnetized in the negative direction, and on the right in the positive direction to change the gate from a logic AND to a logic OR, respectively.

Fig. 82. Schematic of the slant gate built from one slant magnet and symmetric input and driver magnets. The driver and the input magnets have the same dimensions.

Fig. 83. SEM images of the slant logic are shown with pairs of MFM figures captured after magnetization with 130 mT horizontal magnetic field to positive and negative direction.

Fig. 84. Schematic of the logic gate consisting of three slant magnets.

Fig. 85. SEM and MFM image pairs of the slant logic devices showing the four possible input combinations. The magnetization is performed by a 200 mT horizontal, positive magnetic field.

Fig. 86. MFM images of the same gates as shown in Fig. 85 after a 100 mT external field is applied from the right to left (opposite direction).
Fig. 87. SEM image of the vertical wires with slanted input magnets and four horizontally aligned indicator magnets (a). MFM images after magnetization with a horizontal field in the positive and negative direction, respectively (b and c). .................... 133

Fig. 88. SEM image of the tested structures. The domain wall conductor on the left has an expanded injector end, and on the right has a slightly rounded end to nucleate the domain wall. The inset is a magnified view of the first magnet next to the DWC with injector to clearly show their separation................................. 137

Fig. 89. MFM image of the structures after a 100 mT magnetic field is applied 10° from the horizontal direction. ................................................................. 138

Fig. 90. MFM image of the structures after applying a 30 mT magnetic field at 45° from the horizontal direction. ...................................................................................... 140

Fig. 91. Snapshots of the DW assisted switching process. The entire structure is shown at B_{nucleation}, right before (a) and after (b) the DWC reverses. The spacing between the DWC and the dots is 10 nm, which is not visible due to the finite image resolution. There are four prematurely switched dots in the structure3. ........... 143

Fig. 92. Enlarged views of the DW area showing the details of the transverse DW. As the DW propagates through the DWC, the nearby magnets switch3. ....................... 144

Fig. 93. Two proposed setups for future experiments to investigate the field generated by the moving domain wall. Standalone nanomagnets are placed on the top of the domain wall conductor. As a reference, several nanomagnets are located farther from the conductor, where the magnetic field of the DW does not effect the magnetization state of these magnets................................. 146

Fig. 94. SEM image of the nanomagnet array used for radiation hardness test. The nanomagnet with the largest footprint is located in the top right corner (300 nm × 300 nm). The width and the length of the nanomagnets decrease from line to line by 5 to 10 nm. ................................................................. 149

Fig. 95. SEM image of four pair of vertical nanomagnet wires with several standalone magnets. This structure is tested against irradiation along with the standalone magnet matrix shown in Fig. 94. ................................................................. 150

Fig. 96. SEM (a) and MFM (b and c) images of one part of the array tested for radiation hardness. MFM scans are performed before (b) and after (c) the irradiation. The contrast lines in (b) between the magnets are image artifacts, they do not influence the outcome of the measurement. ................................................................. 152

Fig. 97. MFM images of before (a) and after (b) irradiation. Even the errors are located at the same locations................................................................. 153
Fig. 98. Phase diagram of a nanomagnet with fixed 20 nm thickness. The contour lines show the energy difference between the single-domain and vortex states. 

Fig. 99. Spin-SEM image of one horizontal magnet and two vertical magnets. The horizontal magnet drives the vertical magnets. The center magnet has a multidomain state indicated by two arrows.

Fig. 100. Spin polarization images of a horizontal staircase wire before (top) and after evaporation (bottom) of a 1.6 nm thick iron layer. The magnetization state of the wire is defined by a horizontal, 100 mT external field. After the iron layer is evaporated, the magnetization of the last magnet in the wire (the most right magnet) switches into the correct state according to its neighbor.

Fig. 101. Simulation results for vertical (top) and horizontal (bottom) magnetic wires. The M vs. H graph shows smooth switching behavior for the vertical line, though not for the horizontal one. Since the external field is reduced from high to low magnitude, the horizontal wire switches after the vertical wire. This difference has to be taken into account during the design of any NML structures.

Fig. 102. Seven nanomagnet long horizontal wires are characterized at room temperature with three different magnetization methods, i.e., rotating, pumping, and shaking fields. Venn diagram summarizes the percentage of the wires working without any errors. The intersections show the percentage of the wires working for more than one magnetization patterns.

Fig. 103. In cold, liquid nitrogen environment, 62 % of the wires have no coupling error after the shaking magnetization.

Fig. 104. The summary of the second magnetization in a cold environment. 66 % of the wires have no coupling error.

Fig. 105. Error count of the first 7 magnet in the short and long nanomagnet wires. 120 identical wires are tested for both lengths after two magnetization cycles (shaking and shaking II). For the long wires (c-d) the null error appears less often, which suggests an influence on the magnetization originating from the end of the wire.

Fig. 106. Spin-SEM system at IBM Zürich.

Fig. 107. Sample holder for sample relocation between the chambers.

Fig. 108. The introduction chamber provides the connection between the UHV and atmospheric environment.

Fig. 109. The forked end of the long rod above the stage in the cross.
Fig. 110. The preparation chamber (a), and the experimental chamber (b) of the spin-SEM system. ......................................................................................................................... 176

Fig. 111. The supporting electronics for the three-chamber system............................. 177
ACKNOWLEDGMENTS

It would not have been possible to write this PhD thesis without the help and support of the many people around me, only some of whom it is possible to give particular mention here.

This thesis would not have been possible without the help, support, and endurance of my advisor, Prof. Wolfgang Porod, not to mention his advice and inspirational discussions.

The good advice, support, and friendship of Prof. Gyorgy Csaba, has been invaluable on both an academic and a personal level, for which I am extremely grateful.

I would like to thank Prof. Gary H. Bernstein and Prof. Alexei Orlov for the continuous support throughout my entire research and for their valuable advice. Many thanks to the professors (Prof. Sharon Hu, Prof. Michael Niemier, Prof. Joe Nahas) and student members of the magnetic group for the continuous help during the presented work.

I really appreciate the help of each member of the Porod-group, especially Pete Krenz for his help in proof-reading some of my documents.

I’m grateful to Rolf Allenspach, who led my research at the IBM Zurich during my internship and allowed me to test some of my samples with his spin-SEM system.
His advice and enormous help made me possible to obtain several results during such a short amount of time.

I thank the help of the collaborating group from the Naval Surface Warfare Center, especially Matt Kay, who kindly assisted at the irradiation of our samples for radiation hardness testing.

I am most grateful to Prof. Arpad I. Csurgay, my undergraduate advisor, who believed in me so much and led me toward graduate studies as well as to Notre Dame.

I thank all of my loving friends at Notre Dame for the continuous support throughout my years here.

I would like to acknowledge the financial, academic and technical support of the University of Notre Dame, and its staff, particularly the staff members of the lab, such as Mike Young, Mike Thomas, Keith Darr, and Mark Richmond. Without their endless help, none of the below mentioned fabrication would be completed. I would like to thank for the generous grants of DARPA, MIND, and SRC-NRI, which allowed me to pursue my work.

Above all, I would like to thank my husband, Gergo, for his personal support and great patience at all time, as well as my son, Benedek, for his everyday contribution and sacrifice to write this thesis. My entire family has given me their unequivocal support throughout, as always, for which my mere expression of thanks likewise does not suffice.
INTRODUCTION

The use of magnetism for information storage processing goes back to the end of the 19th century [1, 2]. At the beginning of the 21st century, as the semiconductor industry faces difficulties for further down-scaling, several applications of magnetism for future logic and memory devices are proposed and investigated, such as the Magnetic Random Access Memory (MRAM) [3], the racetrack memory [4], as well as the magnetic Quantum-Dot Cellular Automata (MQCA) [5] recently referred to as nanomagnet logic (NML). All-magnetic information processing [6, 7] based on nanomagnets may become an attractive alternative to the electronic representation and information processing by naturally providing non-volatility, radiation hardness, high integration density, and very low power dissipation [8]. Energy/performance gains over CMOS are possible as well [9].

NML is based on a new computational paradigm (QCA) invented at Notre Dame [10], and is built from single-domain nanomagnets (nanodots, dots). NML uses stray magnetic fields as a physical coupling mechanism between bistable building blocks, which are assembled into arrays, to perform binary logic functions. Basic NML structures, such as lines, gates, and inverters have been experimentally demonstrated, and function at room temperature [11, 12, and 13].
In the NML devices, the magnets are forced to be in a high-energy state by a magnetic field referred to as the clocking field. As the clocking field is removed, the magnets relax into one of their two stable, low energy states. Standalone magnets relax randomly into one of the two states. As the nanomagnets are placed several nanometers apart, the emanating field from the neighboring magnets defines their final states. The field of the driver magnet is referred to as the *biasing* field.

The main goal of our group is to fabricate a complete NML circuit, such as the one shown in Fig. 1\(^1\). The underlying copper wires are driven by a driver circuitry (not shown in the schematic). Current passing through these wires generates the clocking field for the NML structures, which are built on top of the wires. Although in this case, the required high current density needed to provide the sufficiently strong magnetic fields raises some issues [14]. The clocking is set in such a way that the information propagates from left to right in the magnetic circuit. The envisioned biasing field for the nanomagnet circuit is provided locally either by a magnetic tunnel junction (MTJ) or by a biasing line, which converts an electrical signal to a magnetic signal [15]. At the output of the NML circuit, the MTJ converts the magnetic signal back to an electrical signal for possible further processing. This work focuses mostly on the engineering of the patterned nanomagnet layer.

---

\(^1\) Courtesy of Dr. M. T. Niemier, Computer Science and Engineering, University of Notre Dame
While large NML systems should be clocked with a localized clocking field, throughout this work a homogenous, non-localized, external field is applied to the NML circuits. This method is sufficient to demonstrate novel NML structures, and to extend the possible functionality of the magnetic circuits as well as to build up an NML library.

In our experiments, the external field, generated by a conventional iron core electromagnet, provides the energy needed for switching. This external field plays the role of the clocking field as well as the biasing field for different groups of magnets. The driver magnets have their long geometrical axis (the easy axis) parallel to the externally applied field, which sets the magnetization of these magnets in a well-defined direction, parallel to the field. The single-
domain magnetization of the driver magnet generates a dipole magnetic field, which is the biasing field for the neighboring magnet, and it determines the final state of the ensemble [16]. The externally applied field is the clocking field for the magnets whose short geometrical axis, hard axis is parallel to it. The purpose is to set the magnets in a ‘neutral’ logic state. After the field is removed, the magnets relax to a low energy state dictated by the driver magnet.

After the magnetization process, the nanomagnets are in a single-domain magnetization state that becomes visible by direct observation using a magnetic force microscope (MFM) [17]. An MFM is a modified atomic force microscope (AFM) [18]. MFM measurements in our experiments are performed using a Veeco MultiMode™ microscope with a Magnetic Etched Silicon Probe (MESP). The MFM scan shows the final magnetization state of the NML structures.

We successfully fabricated and characterized for the first time the following structures: fanout, full adder, programmable majority gate, OR gate, AND gate, and XOR gate. Supermalloy (Ni 79.7%, Fe 16.1 %, Mo 4.1 %, Mn 0.1 % [19]) is used in all these structures as a soft magnetic material. Most of the investigated nanomagnets are approximately $60 \times 90 \times 30 \text{ nm}^3$, which is sufficiently small to be single-domain, though sufficiently large to be resistant to thermal fluctuations. The spacing between the nanomagnets is approximately 20 nm. We developed a fabrication recipe using lithography to have control over the size and the shape of the nanoscale magnets.
We introduce an NML design for a complex gate that can perform multiple logic functions by using its seven inputs and one output. The description and the proposed layout are in Chapter 13.

In our experiments, a non-localized magnetic field is used to set the magnetization state of all nanomagnets. This limits the functionality and complexity of our devices. To overcome these limitations, nanomagnet shape engineering is used, i.e., changing the aspect ratio of a magnet by changing its length only (Section 6.1). With this approach, it is possible to set the state of disjunctive groups of nanomagnets.

One critical point of the NML characterization is the externally and globally applied magnetic field. Experimental results are introduced to show a solution for field-localization by using a domain wall generated field (Chapter 15).

Our experiments cannot provide an estimate of the time scale of the device operation. However, simulations [16] and calculations [20] indicate that the magnets switch on the sub-nanosecond time scale. Micromagnetic calculations [8] show that the potential barrier between stable states of nanomagnets has to be larger than several $kT$ (where $k$ is the Boltzmann constant and $T$ is the actual operating temperature). Using the same calculations, the barrier is some hundred electronvolts for our experimental parameters (dot size, operating temperature, etc.). Theoretically, this guarantees stability for decades at room temperature. As an experimental proof, MFM measurements were performed several weeks apart, and the result showed the same pattern, which indicates the stability of the magnetization state.

Currently, the reliability of the NML switching is not well understood, and we do not understand the details of the switching process nor the error formations, although we
make an attempt to define possible error sources (Chapter 17). The error formations could be caused by fabrication defects, or temperature fluctuations, though their roles are unclear yet.

Radiation hard materials are resistant to any damages or malfunctions caused by ionizing irradiation, such as particle radiation. Electronic devices built from these materials could work in a specific environment, such as in outer space, high-altitude flight, around nuclear reactors, particle accelerators, etc. Magnetic materials have been tested already against different irradiations. Several research projects studied the ion irradiation [21] and electron irradiation effect [22] on Permalloy as well as other magnetic materials. Neutron and gamma irradiation is performed on Permalloy to inspect how the hysteresis loop might change in bulk material [23, 24] and in thin films [25, 26]. In our work, we introduce experiments that prove radiation hardness of patterned NML structures (Chapter 16). The radiation hardness property verification would enable space environment applications for nanomagnets.
2.

NANOMAGNET GATE LOGIC DESIGN

The basic unit of NML is the nanomagnet. In previous works, identical nanomagnets were used to build NML structures with simple shapes, such as rectangles and ellipsoids. Some shape studies were performed on standalone magnets [27], and it has been shown that different shapes can have different sensitivity to fabrication variations [37]. In addition to this advantage, shape engineering has other benefits as well. In the following sub chapters, we investigate the magnetic behavioral properties of nanomagnets with various aspect ratios (Section 2.1) and with different shapes (Section 2.2) to show possible programmability for NML gates.

2.1 Symmetrically shaped nanomagnets

It is well known that a symmetrically shaped magnet has an energy barrier between two stable states, as shown in Fig. 2, with the energy (E) vs. magnetization (H) landscape as shown. Consider a symmetric magnet that is subjected to a strong hard-axis field (indicated by the thick blue arrow pointing from left to right in Fig. 2). For a large hard-axis external field, referred to as the “clocking field,” the magnetization is pointing in the direction of the field, and favors neither the up or down direction, a condition
referred to as “nulled.” When the field is removed, the nanomagnet relaxes into one of the two energetically equivalent ground states, i.e., either pointing up or down. Even a small biasing field along the easy axis can influence which magnet ground state the magnetization will select. In Fig. 2, the blue curve shows the potential landscape of the nanomagnet immediately after the removal of the nulling field. The presence of the energy barrier requires that an external field stronger than the nulling field is required to re-evaluate the magnet, i.e., set the magnet so that a new logic value, either up or down, can be written to it. It relaxes into a newly ordered state in accordance with any present biasing field. The magnet retains its new state without an externally applied field, since the size of the magnet is assumed to be larger than the superparamagnetic limit.

Fig. 2. Energy landscape and clocking process of a symmetric, rectangular shape nanomagnet. The thick, blue arrow indicates the strong hard-axis clocking field. As the field is removed, the symmetric nanomagnet relaxes into one of the two energetically equivalent ground states.
A uniform, globally applied magnetic field sets the magnetization state of all on-chip nanomagnets in our experiments. It is essential to find a method to overcome this limitation for independent magnetization of the magnets, which would allow us to set the driver magnets individually. One solution is to change the aspect ratio of the magnets, thereby engineering the corresponding switching field.

Micro-magnetic simulations using NIST’s OOMMF suite [28] are performed to predict the behavioral change of the rounded-edge rectangular shape magnet as the length is increased while keeping the width and thickness constant at 60 nm and 30 nm, respectively. The summary of these simulations is shown in Fig. 3 with M-H hysteresis curves for $H_y < 0$ A/m applied field values for Permalloy magnets with 90 nm, 120 nm, and 180 nm length. One can conclude that by increasing the length of the magnet along its easy axis, its coercivity in that direction increases. Reversing of magnetic moments opposes the externally applied field. Therefore, a larger field is required to switch more dipoles along the appropriate axis.

---

2 Courtesy of Dr Niemier’s group, Computer Science and Engineering, University of Notre Dame
The figure shows clearly that with the increase of the magnet length, higher external fields are required to facilitate a state transition, i.e., setting the longest magnet also sets the shorter ones as well. As a weaker field is applied to set the shorter magnets, the long one retains its previously set state. This has been demonstrated experimentally as described in Section 6.1.

Further simulations show that the aspect ratio cannot be increased indefinitely, since the coercivity starts to saturate at an aspect ratio of about three. A series of simulations were performed to illustrate the coercivity vs. dot length (Fig. 4).
Fig. 4 shows the switching field for different-sized dots. The thicknesses of the dots are 20 and 30 nm, their width is fixed at 60 nm, and the coercivity is plotted as a function of their length. The field is applied at a 45° angle to the long axis of the magnets. Exploiting aspect ratio as a design variable, the driver magnets can be set separately, resulting in a programmable circuit. The relation between the switching field and shape is experimentally demonstrated in Section 6.1.

2.2 Asymmetric nanomagnets

Shape engineering leads us to exploit the magnetic property of asymmetric nanomagnets. Most studies on single-domain magnets focused on symmetric shapes with
two, energetically equivalent ground states pointing along the easy axis (Fig. 2). In this section, slanted-edge magnets are investigated. In Chapter 14, we demonstrate experimentally that this specific shape can be exploited to design NML devices with reduced footprint.

A schematic of the asymmetric magnet having a slanted edge is shown in Fig. 5 on the left side [29]. Simulations based on the single-domain model show that the asymmetry of the magnet shifts the entire energy landscape of the magnet, whereby the energy minima are shifted as well by about 20 deg. The thin line along the diagonal of the magnet in Fig. 5 corresponds to the effective easy axis. The energy maximum is perpendicular to this axis. The horizontally applied field is not precisely in the direction of the energy maximum, so the resulting energy of the magnet is to one side of the maximum, and falls toward the appropriate ground state when the field is removed. As a result of the tilted easy axis, the nanomagnet takes on a preferred magnetization direction, as summarized in Fig. 6. Further theoretical description is published in [30]. Experimental proof of this behavior is introduced in Section 6.2.

The schematic (Fig. 6) lists all possible slant orientations and the corresponding overlaid energy diagrams, energy (E) vs. magnetization (H). The magnets in a) and d) relax into the downward pointing magnetization, and in b) and c) relax into the upward pointing direction. This specific shape can be exploited to reduce device footprint as shown below.
Fig. 5. Simulation based on the single-domain model result for the slant nanomagnet energy landscape. The energy minima are shifted from the long geometrical axis, i.e., from the 90 deg and 270 deg magnetization directions.

Fig. 6. Energy curves of the slant magnets for different slant locations. The external magnetic field is applied from left to right shown by horizontal, thick, blue arrows. The thin line along the diagonal of the magnet corresponds to the effective easy axis. The energy maximum is perpendicular to this axis.
2.3 Nanomagnets in NML devices

The nanomagnets inside the NML devices are aligned on a rectangular grid with their long axis oriented either horizontally or vertically. We apply an external field either along the horizontal or the vertical direction to set the magnetization state of each magnet; therefore, some magnets experience this field along their easy (long geometrical) axis and others along their hard (short geometrical) axis. The energies of these states are summarized in Fig. 7. The easy axis magnetization flips the magnet into a stable and low energy state, and the hard axis magnetization provides an unstable, high-energy state. The energy difference between the two states extends from a few to few hundred electronvolts depending on the size and the shape of the magnet [31].

![Energy diagram of the magnets in different magnetization states.](image)

**Fig. 7.** Energy diagram of the magnets in different magnetization states. The magnet has low energy while magnetized along its long geometrical axis, and high energy when the magnetization is pointing along its short axis.
2.4 Conclusions

The above simulations help to understand the basic switching behavior of standalone magnets. Although symmetrically shaped nanomagnets have been studied already in previous works, the advantages arising from the variation of the aspect ratios were not studied before. Asymmetric nanomagnets provide further opportunities with their unique switching behavior. The simulation results are promising, and we experimentally verify them later in this thesis (Chapter 6). We attempt the exploitation of their switching properties as well, and incorporate these shapes into different NML structures, such as in Chapter 8.
3.

NANOMAGNET FABRICATION

Here a new fabrication recipe is introduced that is used throughout this project. The NML structures are fabricated using high-resolution electron beam lithography (EBL) followed by electron beam evaporation and lift-off. These steps are described in detail in the following sections. The described recipe allows us to fabricate small metallic islands, i.e., 60 nm × 90 nm that are placed approximately 20 nm apart with controllable shape and without any residual material.

3.1 Electron beam lithography

Electron beam lithography requires an electron beam sensitive layer on the sample surface. There are numerous resists available on the market for EBL for different fabrication purposes. In our project, the nanomagnets are designed with small footprint (about 60 nm by 90 nm) and are separated by 15 or 20 nm gap, which leads us to choose the poly-methyl-methacrylate (PMMA) resist. PMMA is a commonly used high resolution and high contrast positive resist for direct write EBL. We used MicroChem 950K PMMA C2 that has a molecular weight of 950,000, and contains 2% solids concentration in chlorobenzene. This resist can be spun as thin as approximately 110 nm,
which is shown in Fig. 8 [32]. At this resist thickness, our structures can be fabricated reliably with 20 or 30 nm thickness without connections between the down-laying structures and the metal on top of the resist layer.

![495PMMA C Resists](image)

**Fig. 8.** The spin speed versus film thickness curves for PMMA with different solid concentrations (C2, C4, AND C6) [32]. Cx represents x% solids concentration.

Although clearance of the PMMA layer during our fabrication is large, some ‘rabbit-ears’ appeared, i.e., some evaporated metal accumulated on the sidewall of the resist (Fig. 9a). To avoid this effect, a copolymer of PMMA, methyl-methacrylate (MMA) is applied underneath to facilitate an undercut in the resist structure after the development (Fig. 9b). MMA is more sensitive to electron beam exposure than PMMA, which results in a wider opening as the exposed area is dissolved in the subsequent development step.
Throughout this project, MicroChem MMA (8.5) MAA EL9 is used with 9% solids concentration in ethyl lactate. The spin speed versus film thickness curve is shown in Fig. 10 [32].
In our fabrication recipe, a thick, 400 nm MMA copolymer layer is spun on the silicon sample with a native oxide to build an underlayer in a dual-layer resist system. Ultraviolet light at 26.8 mW/cm² is applied on the copolymer to increase its sensitivity for the EBL exposure. This is followed by a pre-bake at 170 °C for two minutes on an open-air hotplate.

100 nm 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, as shown in Fig. 11. The oval shape pattern is exposed by the electron beam followed by development process. The MMA opens up more widely than the PMMA, which is indicated by the shadow-like outline surrounding the oval shape openings. For SEM image scanning, this sample is coated with a 2 nm thick chromium layer.

Fig. 10. The spin speed versus film thickness curves for MMA with various solid concentrations [32]. ELx refers to x% solids concentration.
The pattern is defined by an Elionix 7700 EBL system with a dose of 640 µC/cm². A 75 µm × 75 µm area is patterned with 60,000 × 60,000 dot resolution; therefore, the spacing between the exposed spots is 1.25 nm. The electron beam is 75 kV, and the spot size is approximately 10 nm in diameter with a beam current of 50 pA in perfect conditions, i.e., ideally focused beam. Fig. 12 shows the beam diameter as a function of the beam current for three different aperture sizes [33]. Since our structures are small, the smallest aperture is used with 40 µm in diameter. These parameters allow us to pattern islands as small as 90 nm × 60 nm with a separation of about 20 nm.

Fig. 11. Double layer resist is exposed by electron beam in oval shapes followed by developing. The deep undercut of the MMA layer shows up as a shadow surrounding the oval shapes. Before the SEM scan, the sample is coated with a thin chromium layer.
The electron beam treated MMA-PMMA layers are developed in a solution of methyl-isobuthylketone (MIBK): isopropanol (IPA), 1:3 with 1.5% methyl-ethyl ketone (MEK) added by volume [34], for 35 seconds.

3.2 Electron beam evaporation and lift-off

At this point, the sample is coated with two layers of resist featuring several openings with wide undercuts. The next step is to evaporate the appropriate metals to form the nanomagnets on the top surface of the sample. The silicon surface is sufficiently clean in the openings after the developing step, so no cleaning process is necessary. For the metal coating, it has to be taken into account that not all metals have
good adhesion with the native oxide covered silicon. In our case, the magnets are Supermalloy (Ni : Fe : Mo : Mn, 79 % : 16.7 % : 4 % : 0.3 %) islands. This alloy requires a titanium adhesion layer. These metals are electron beam evaporated onto the sample at a slow growth rate of 1-2 Angstrom/s under high vacuum of 2e-6 Torr. The final thickness is 10 nm and 20-30 nm for the titanium and Supermalloy layers, respectively.

The evaporation is followed by the lift-off process. Although dichloromethane provides a clean surface after the removal of the metal coated PMMA-MMA, the industry standard N-Methyl-2-pyrrolidinone M6267 (NMP) leaves an even cleaner surface after lift-off. NMP requires heating to remove all polymers and non-sticking metal flakes from the silicon surface. The dissolution is weak without heating, i.e., the surface remains contaminated after the NMP removal. The ideal heated temperature is approximately 60 °C, and cannot be much higher, since the boiling point of NMP is at 78 – 79 °C, and the flash point is at 91 °C [35]. In our project, dichloromethane is used for the structures with 30 nm thickness, and NMP for thinner, 20 nm nanomagnets.

The fabricated structure is examined with Hitachi S-4500 or FEI Magellan 400 scanning electron microscopes (Section 5.1). After the application of ex-situ magnetic fields (Chapter 4), the magnets are tested with a Veeco MultiMode™ magnetic force microscope (Section 5.3).
3.3 Fabrication issues

Although the above introduced fabrication process enables us to fabricate structures with relatively high yield, some processing issues arise.

Our nanomagnets have an approximately 60 nm × 90 nm footprint with a 20 nm wall-to-wall distance. This size is close to the physical limitation of our EBL system and lift-off process. The shape control of the nanomagnets is feasible at this scale, although not 100% stable. This causes a fabrication variation that leads to the possibility of imperfect performance of our devices.

3.4 Conclusions

The introduced fabrication recipe allowed us to fabricate all NML devices described in this thesis. The recipe proved to be robust and was used many times with good results.
4.

MAGNETIZATION METHODS

After the successful fabrication of any nanomagnet structure, the characterization defines whether the given device operates correctly. For this, the magnetization of the NML gates is necessary. Currently, we do not have any possibility for local magnetic field application; therefore, we perform the magnetization by using a global magnetic field generated by a Varian electromagnet. This means that a homogenous external magnetic field is applied to set the magnetization state of all of the magnetic structures on the entire chip.

Three different methods of magnetization are used: pumping, shaking, and rotating field magnetization. These are introduced in the following sections.

4.1 Pumping magnetic field

Magnetic field pumping is the simplest way to set the magnetization state of the nanomagnets. The sample is held in place by an aluminum sample holder (designed and fabricated by the author) between the poles of the electromagnet, which generates a homogenous magnetic field. This field is continuously monitored during the magnetization process by a gaussmeter. Fig. 13 shows the experimental setup, i.e., the
two flat pole pieces of the electromagnet and the T-shape sample holder with an installed silicon sample.

Fig. 13. Experimental setup for pumping magnetization method. A sample is held in place by a T-shape aluminum holder between the two pole pieces of the electromagnet.

The sample installation, in the absence of a magnetic field, is followed by the sweep of the magnetic field. Fig. 14 shows the generated field experienced by the sample during a single pumping magnetization cycle. As the current is increased from 0 to 9 A, a maximum field of 150 mT is generated between the pole pieces, which are approximately 10 cm apart. The current increment rate is 0.5 A/s, corresponding to a field sweep rate of 8 mT/s. The emanating field of the magnet is perpendicular to the flat
pole pieces with a uniform distribution. The field is held constant for several seconds before decreasing its magnitude to zero.

Fig. 14. Time evolution of the magnetic field experienced by the sample during one pumping magnetization cycle.

This magnetization method is straightforward to carry out without any sophisticated hardware requirements, although great care is necessary with the alignment of the sample to the direction of the applied external field to avoid any error formation in the magnetic state of the nanomagnet devices.

During our work, it turned out that the nanomagnets are sensitive to the alignment between the magnetic field lines and the nanomagnets. The T-shape sample holder does not provide any control over this alignment; therefore, a new stage is designed and assembled by the author (Fig. 15). Here, the sample is placed on the top of a rotatable rod, which provides some alignment control.
It has to be noted that the alignment of these devices is difficult; since the magnetic field lines are invisible as are the nanomagnet devices. The NML structures show increasing alignment sensitivity with increasing complexity according our studies. In the following two sections, two possible magnetization methods are introduced to overcome this difficulty: the shaking and the rotating field methods.
4.2 Shaking magnetic field

During the shaking method, the sample is rotated from its original position parallel to the externally applied field in the clockwise and counterclockwise directions up to a specific angle, e.g., +15° and -15°. To achieve the shaking method, a specific stage is designed and constructed to control the angle and the speed of the moving sample between the pole pieces of the magnet. Fig. 16 shows our setup, which includes the electromagnet, the stage, and the computer controlling the rotation of the stage.

Fig. 16. Experimental setup for shaking magnetization. The electromagnet with the computer controlled stage is shown.
A more detailed bottom view of the stage is shown in Fig. 17. Two non-magnetic copper clips attach the sample to the plastic end of a stainless steel rod. A small needle is installed on the other end of the rod to provide a visible indication of the rotation of the stage. The stage is rotated by a computer controlled stepper motor. The stepper motor is not visible in the image; it is located on the other side of the metal slab that holds the protractor. The stepper motor is driven by a LabView-based software that enables to set the rotation angle and the rotation speed.

Fig. 17. Shaking stage with the protractor. The sample is fixed by two clips on the end of the stainless steel rod.
The sample is moved by the motor in the ‘sample plane’, which is perpendicular to the flat pole pieces of the magnet. To clarify the alignment of our coordinate system, Fig. 18 shows the pole pieces along with x, y, and z directions. The sample plane is the xy plane, and the yz plane is parallel to the pole pieces.

The external field is parallel to the x axis and perpendicular to the pole pieces. During the pumping magnetization, the sample is in a constant position and experiences the magnetic field in only one direction, $B_x$. During the shaking magnetization, the sample is rotated, and experiences field components parallel to its x and y axis ($B_x$ and $B_y$). The magnetic field generated by the electromagnet is swept in exactly the same way as during the pumping method (0 mT – 150 mT – 0 mT). The stepper motor is on throughout the magnetization cycle, i.e., the sample is moved. Fig. 19 shows the x component of the magnetic field (green) experienced by the sample for 15° shaking. The envelope curve (blue) is overlaid, which plots the field generated by the magnet. Fig. 20
shows the y component of the field (red) as experienced by the sample also for 15° shaking. The amplitude of the field in the y direction is smaller than in x direction. The x and y amplitude would be identical only for 180° shaking.

Fig. 19. The magnetic field experienced by the sample in x direction (green) during a 15° shaking magnetization circle. The field generated by the magnet is overlaid (blue).
In this section, we introduce the rotating magnetization, which is equivalent to the shaking method with a shaking angle of 180°. Designs for generating a rotating field on-chip have been suggested in [36]. This method has been used already successfully to demonstrate functioning nanomagnet circuit components in [37]. This clocking scheme is different from the hard-axis clocking (pumping) field described in [8] and parts of [13].

A motorized stage for the sample rotation (360°) has been designed and fabricated. It rotates the sample between the pole pieces of the electromagnet during the magnetization cycle, so the sample experiences a rotating external field. The experimental setup is shown in Fig. 21a, where the complete stage, the motor, and part of

Fig. 20. The magnetic field experienced by the sample in y direction (red) during one 15° shaking magnetization circle. The envelope curves (blue and green) indicate the generated magnetic field.

4.3 Rotating magnetic field

In this section, we introduce the rotating magnetization, which is equivalent to the shaking method with a shaking angle of 180°. Designs for generating a rotating field on-chip have been suggested in [36]. This method has been used already successfully to demonstrate functioning nanomagnet circuit components in [37]. This clocking scheme is different from the hard-axis clocking (pumping) field described in [8] and parts of [13].

A motorized stage for the sample rotation (360°) has been designed and fabricated. It rotates the sample between the pole pieces of the electromagnet during the magnetization cycle, so the sample experiences a rotating external field. The experimental setup is shown in Fig. 21a, where the complete stage, the motor, and part of
the electromagnet is visible. The sample is held by two copper clips at the end of a stainless steel rod between the two poles of the magnet (Fig. 21b). The rod is attached to the motor shaft.

![Image](image.png)

Fig. 21. Experimental set up for the rotating magnetization (a). The sample is held between the pole pieces (b).

The field generated by the electromagnet is increased from 0 mT to 150 mT and then decreased to 0 mT. The sample is rotated by the motor with 1800 rpm, which results in a 30 Hz sinusoidal (x direction) and cosinusoidal (y direction) changing field experienced by the nanomagnets. The time evolution of the field (sinusoidal and cosinusoidal variations) are shown in Fig. 22 at a lower than 30 Hz frequency for clarity. To show the difference between the x and y directional fields, i.e., their phase shift, Fig. 23 shows the overlaid $B_x$ and $B_y$. 

33
Fig. 22. The rotating magnetic field in x (left) and y (right) direction experienced by the nanomagnets situated between the poles of the electromagnet.

Fig. 23. The x (red) and y (teal) directional rotating magnetic field overlaid to emphasize the phase shift between the two signals.
4.4 Magnetization patterns used in our experiments

During the NML device test, various combinations of the above introduced magnetization methods are used to overcome the sample – applied field misalignment issue. The simplest magnetization method is when only the pumping field is used, though sequences, such as pumping – rotating, or pumping – shaking are more efficient for some complex devices.

The applied magnetic field is several tens of mT, sometimes it is even close or above 100 mT. This is a relatively strong field for the nanomagnets, since the coupling field between them is in the range of a few mT. It is clear that for a few degrees of misalignment between the magnetic flux lines and the hard axis of the magnets, the coupling force is overpowered already by the strong external field. In this case, the magnets do not relax into a state defined by the fringing field of a neighbor magnet, though relax into a state defined by the misaligned external field.

The horizontally and vertically aligned magnets inside the NML devices have different sensitivity for misalignment due to the energy level of the magnetization states (Fig. 7). If the external field is parallel to the long geometrical (easy) axis of a (horizontal) magnet, then the magnet is not extremely sensitive to small misalignments of a few degrees due to its preferred low energy state. When the geometrical short (hard) axis is parallel to the externally applied field, the (vertical) magnet is more sensitive to misalignments due to its unstable high energy state. Since most of the NML structures include both horizontally and vertically aligned magnets, the alignment is a constantly present issue.
During the pumping method, the sample has a constant location and position. In this case, there are not any possibilities to compensate for any misalignments. The magnets with their easy axis parallel to the external field lines relax into the correct state; and the magnets with hard axis parallel to the external field, but misaligned by a few degrees, relax into an external field defined state. Since the horizontal magnets relax into the correct state even in the presence of some misalignment, the pumping field is used at the beginning of the magnetization cycle followed by some alignment compensation, such as the shaking or the rotating method. These assist the hard axis aligned magnets to relax into a logically correct state. Experimental results show that the shaking and the rotating field aids the magnets to find an energetically preferred state, although the dynamics of the NML switching behavior is not well understood yet. The shaking and the rotating schemes are successful experimentally. The benefit of the rotating field does allow us to easily test the feasibility of new device layouts and designs.

4.5 Conclusions

The above introduced magnetization procedures help us to overcome the lack of local clocking field. These methods are used for the magnetization of all magnetic circuits described in this thesis and enable a rapid testing of NML circuits without the need to build complex clocking circuitry. These methods will become obsolete once reliable, on-chip clocking becomes possible.
5.

NANOMAGNET CHARACTERIZATION TECHNIQUES

The fabrication and magnetization of the nanomagnet devices is followed by their characterization. To see the exact shape of a single nanomagnet, a high-resolution imaging tool is necessary. Throughout this work, scanning electron microscope (SEM) is used. SEM provides information not only about the size and shape of a magnetic island, but also about the surface smoothness. To gain information about the magnetic state of each nanomagnet, the magnetic force microscope (MFM) is used. MFM is a modified atomic force microscope (AFM), which is made sensitive to any weak magnetic field emanating from the sample surface by a magnetic probe. In some cases, we were able to use the spin-SEM, which is another scanning tool, to obtain more insight into the magnetization state of the NML devices. In the following sections, SEM, AFM, MFM, and spin-SEM are introduced.

5.1 Scanning electron microscope

Throughout our project, the nanomagnet structures are inspected with a scanning electron microscope for detailed surface study and to inspect the cleanliness of the
fabricated structures. In our department, two high-resolution SEM systems are available; the Hitachi S-4500 and the FEI Magellan.

The Hitachi S-4500 SEM (Fig. 24\(^4\)) is a cold cathode field emission microscope. Image resolution better than 2 nm at 30 kV, which is a commonly used acceleration voltage, can be reached. Although this high resolution SEM is straightforward to use, it has relatively high carbon deposition at 30 kV. The deposited carbon can be easily observed with the atomic force microscope. Fig. 25 shows the topography of nanomagnet islands that are imaged with the SEM prior to an AFM scan. The image on

\(^4\) Courtesy of Mike Young, Nanofabrication Specialist, Electrical Engineering, University of Notre Dame
the right (Fig. 25a) shows the topography map of the area exposed by the SEM and the image on the left (Fig. 25b) shows the 3D AFM image. According to the AFM measurement, the deposition thickness can be as high as 17 nm, as shown in the cross section of the AFM image (Fig. 25c). Fortunately, the carbon can be easily removed with oxygen plasma cleaning.

Fig. 25. AFM image of the nanomagnet islands previously exposed by SEM. Top view (a) and tilted, 3D (b) is shown along with the cross section (c). The oval shapes are the nanomagnets and the longer lines are the carbon depositions due to the SEM.
The other system is the recently installed Magellan SEM from FEI Company (Fig. 26. [38]). This microscope has several unique features that make the sample characterization easier and provides more detailed surface information. The available resolution goes beyond the nanometer scale for the entire range of acceleration voltages. The electrons are accelerated by a 1 to 30 kV voltage from the Schottky thermal field emitter. For surface sensitive high resolution imaging, the landing voltage can be as low as 50 V. The beam current ranges from 1 pA up to 22 nA. The system has a through-the-lens detector and an Everhart-Thornley secondary electron detector [39]. A plasma cleaner and a cold trap are installed in the main chamber to ensure cleanliness of the sample, which is mounted onto a 5 axis (x, y, z, tilt, and rotation) piezoceramic stage.
5.2 Atomic force microscope

The atomic force microscope is a high resolution tool for surface characterization, which was invented in 1986 by Binnig, Quate, and Gerber [40]. It is a combination of the principles of the stylus profilometer and the scanning tunneling microscope. The AFM is one of the foremost tools for quantitative high-resolution imaging with great flexibility in the samples that can be studied in ambient conditions.
The AFM records a map of the sample topography by a scanning probe across the sample. The sharp probe (tip radius is about 10 nm) is mounted near the end of a flexible microcantilever. A laser beam is focused onto the end of the cantilever and reflects to the detector as the part of the optical lever system used to track the surface. As the cantilever bends, the position of the laser spot changes on the detector, an array of photodiodes. Since the cantilever and the detector are separated by a large distance, fine topography changes appear as large changes in the laser spot position on the detector, which produces a very high resolution image. Fig. 27 summarizes this basic AFM concept [41].
The probe scans above the sample, across the area of interest, and the force between the probe and the surface is maintained at a set, low level. The force vs. sample-probe distance curve is plotted in Fig. 28 [42]. As the tip approaches the surface from a large distance, where the tip and surface do not interact, it experiences an attractive force toward the sample (attractive regime). Moving the probe even closer causes the total force to weaken as the probe is repulsed by the surface (repulsive regime). These different regions are exploited in various scanning modes. Many variations of the basic technique are commonly used to image surfaces using the AFM. These variations include ‘static’ techniques, such as the contact mode, where the probe remains in constant contact with the sample, or the ‘dynamic’ modes, where the cantilever may oscillate with intermittent or non-contact with the sample [43, 44]. Contact mode imaging is the earliest available mode for topography scanning. It is so called because the probe remains in contact with the sample at all times. As a result, the probe-sample interaction occurs in the repulsive regime as illustrated on the force curve. A drawback to the constant contact mode is that a soft sample might be damaged during the scanning process. In order to overcome the limitation of the contact mode imaging, the intermittent or tapping mode of imaging is developed [45]. Here the cantilever is allowed to oscillate close to its resonant frequency. A piezo stack excites the probe substrate vertically, causing the tip to oscillate up and down. When the oscillations occur close to a sample surface, the probe will repeatedly engage and disengage with the surface. The cantilever is deflected in its encounter with the surface that is monitored by a laser beam reflecting of the cantilever. The reflected laser beam is deflected in a regular pattern over a detector, generating a sinusoidal electronic signal. The signal is
converted to a root mean square (RMS) amplitude value in volts. As the probe interacts with the substrate, the return laser signal reveals information about the vertical height of the sample surface as well as different properties of the sample surface on the nanoscale, e.g., material softness, lateral force, electric force, chemical force, magnetic force, etc.

Throughout this presented work, the AFM is used in intermittent contact (tapping) mode for topographic information using an RTESP Si probe (Rotated Tapping Etched Silicon Probe, Veeco Probes). Using a vertically oscillating probe in this mode, a high lateral resolution of about 5 nm is obtained. The resolution is strongly dependent on the profile of the scanning probe as well as the topography of the sample. In our case, 20 and 30 nm thick metallic islands are scanned, which are separated by approximately 30 nm.

Fig. 28. Force curve of the AFM probe. The force between the surface and the probe vs. their separation is plotted [42].
The SEM image\(^5\) and the schematic [46] of the probe that we used on a regular basis is shown in Fig. 29. The slope of different edges of the probe is provided by the manufacturer (FA=15°, BA=25°, and SA=17°); therefore, one can calculate the critical distance and depth that is still ‘visible’ for the probe during the scan. For example, if 30 nm thick islands are scanned, then the probe can reach the surface inbetween adjacent islands only if their separation is approximately 20 nm. Our fabricated structures have this separation between the magnets; therefore, this probe can reach the substrate.

---

\(^5\) Scan made by the author with FEI Magellan SEM
Fig. 29. SEM (top) and schematic image of the probe profile, side view (top schematic and SEM) and front view (bottom schematic [46]).
Among the several available instruments on the market, we used a MultiMode Scanning Probe Microscope (SPM) from Bruker (former Veeco metrology and earlier Digital Instruments). This system (Fig. 30 [47]) allows us to study surface properties of various materials from the atomic to the micron scale. The measured data is captured with the newest Veeco controller (NanoScope V), which utilizes advanced electronics, including A/D and D/A converters operating at 50 MHz. The output of the controller is processed with the corresponding NanoScope software v3.70.

Fig. 30. MultiMode microscope from Veeco is used during the nanomagnet tests [47].
5.3 Magnetic force microscope

AFM is used many times as an imaging tool, such as a microscope. Furthermore, it has several spectroscopic modes that measure other properties of the sample at the nanometer scale, such as physical, material, and chemical properties. In our project, the magnetization state of the fabricated nanomagnet is the most relevant; therefore, our goal is to gain magnetic information from the sample. For this, we use a modified AFM, a magnetic force microscope. MFM has a magnetic probe that is sensitive to the emanating force from the sample. Since the magnetic forces are long range in nature, they can be separated from the topographical information of the sample by scanning at a certain tip-sample separation of tens of nanometers. This variation of the tapping mode probe is an etched crystal silicon probe with a thin Co/Fe/Cr coating.

Dynamic MFM maps the magnetic force gradient above the sample surface, i.e., the second derivative of the magnetic moment of the sample in the direction perpendicular to the sample surface. As the magnetized probe oscillates within the magnetic fields on or above the sample surface, the oscillation phase and frequency of the cantilever are altered by the magnetic field. During the MFM scan, this frequency or phase shift is measured and are used to produce images of magnetic fields or domains. The phase shift is related to the effective “spring constant” change that is proportional to the gradient of the magnetic field at the tip of the probe, which carries indirect information about the magnetization distribution inside the sample.

In our system, the scan is performed by a two-pass technique called the “Lift Mode” by Veeco. The Lift Mode separately measures the topography during the first pass and another selected property (magnetic force, electric force, etc.) using the topographical
information to track the probe at a previously defined height (lift height) above the sample surface during the second pass as illustrated in Fig. 31 [48]. To avoid problems associated with drift, the lift scan is executed in a line-by-line fashion.

The probe is placed close to the surface and interacts with the stray fields emanating from the sample. The coating of the probe strongly defines the sensitivity of the measurement. In our experiments, Magnetic Etched Silicon Probe (MESP) is used for our MFM scans most of the times. This specific silicon probe is coated with 50 nm Co and Cr alloy; therefore, the magnetic field of this probe is weak enough to not remagnetize the sample. Scanning with a probe (ex., MESP-LM, low magnetic moment) that is coated with only 15-20 nm alloy provides poor contrast on our samples. The MFM image resolution could be increased by a probe with a thicker coating, such as the MESP-HM (high magnetic moment probe) that has an approximately 100 nm thick magnetic layer. The thicker the magnetic film the larger the field because the overall magnetic volume is increased proportionally. According to our experiments, the field of MESP-HM is too strong for our sample and influences the magnetization pattern of our

Fig. 31. MFM Lift Mode principles. The first path allows the system to collect the topographical data. The magnetic information is measured during the second path at a constant height above the sample surface [48].
structures. Fig. 32 shows the stray field of the probe that is perpendicular to the sample surface vs. the coating thickness 25 nm above the sample according to the calculations in [49]. It is clearly visible that the field strongly increases as the thickness is increased. We have to find the balance between the resolution of the measurement and the probe influence on the sample. The advantage of using thin film coated tips is to have a smaller stray field to scan the undisturbed magnetization of the sample; therefore, we selected our tip with 50 nm thick coating.

![Graph showing the stray field of the probe vs. coating thickness](image)

**Fig. 32.** Stray field of the probe that is perpendicular to the sample surface is shown at 25 nm scan height for different coating thicknesses [49].

The approximate value of the magnetic field of the probe can be measured. There have been several approaches that have attempted to measure the stray fields from the MFM tips. Hall effect measurements [50], calibrated MFM measurements [51], Lorentz tomography, and holography have been implemented to measure the field distributions.
from commercially available tips [52]. These measurements show that the axial field of the MESP probe is weak at 50 nm and above. The strongest field of the probe is 40 mT at zero distance, and it drops abruptly by the distance from the tip (Fig. 33).

![Reconstructed axial field component of the MESP probe using Lorentz microscopy](image)

Fig. 33. Reconstructed axial field component of the MESP probe using Lorentz microscopy [52].

The scanning height for the second scan, which collects information about the magnetization pattern of the sample, is set to a user defined height. Typically, distances ranging from 10-100 nm are used, which means that MFM is always operated in non-contact during the second scan. This parameter needs to be set properly for the scan, since if it is too small, then the output will also contain topography information. In case the scan height is set too large, the resolution of the image is reduced, since the magnetic force decreases exponentially with the distance.

The constant height mode is another scanning method for magnetic force scans that does not scan for height information, but rather scans across the sample at a certain
elevation with the height feedback turned off. In this mode, the scan is performed at a certain height from the sample with an oscillating probe. The scanning plane and the surface plane need to be aligned parallel to each other using an electronic tilt correction. This mode is not available in our current system; therefore, Lift Mode is used in all cases. One can find instruments with constant height mode from Attocube [53].

Arrows are drawn in the MFM images to clarify the direction of the magnetization, as shown in Fig. 34. The head of the arrow always is located on the bright spot (North pole of the nanomagnet), while the tail of the arrow is located on the dark spot (South pole of the magnet).

Fig. 34. MFM images of one single magnet magnetized in opposite directions. White arrows are overlaid to make the magnetization direction easily visible.
5.4 Spin-scanning electron microscope

The scanning electron microscope with polarization analysis has developed into a dominant technique to study magnetic domains. Among several magnetic characterization techniques, spin-SEM has almost the highest available resolution, only surpassed by the Lorentz microscope, which is a transmission electron microscope. Due to the ultra high vacuum (UHV, in the range of $10^{-10}$Torr) measurement condition, ultraclean surfaces are essential. Therefore, the sample preparation is a key process, which includes a surface material analysis with Auger spectroscopy and surface cleaning by sputtering ahead of the characterization.

Spin detection, a surface characterization technique for a ferromagnetic sample can be performed by spin SEM with sensitivity down to the atomic layer and a lateral resolution of 20 to 40 nm defined by the diameter of the finely focused electron beam. The spin detector counts the electrons with certain spin polarization at each beam position. The experimental setup is shown in Fig. 35 [54]. Since the scanned sample is ferromagnetic, the generated secondary electrons (SEs) are spin polarized, allowing extraction of magnetic information of the sample surface, i.e., magnitude and direction of surface magnetization. The electrons reach the spin analyzer via the electron optics constructed from electrostatic lenses. Two pairs of detectors count the spin polarized electrons; therefore, two magnetization directions are detected simultaneously. One pair of detectors counts the spin up and spin down electrons in the out-of-plane directions compare to the surface of the sample, and the other pair counts the electrons in one of the

---

6 In this section, the spin-SEM at IBM Zürich is introduced.
in-plane directions. The spin polarization of the emitted secondary electrons is a measure of the surface magnetization.

Along with spin, topographical information is collected by adding the electrons counted in all detectors. None of the typical SEM detectors, i.e., InLens or SE detectors, are used to create the SEM image.

The secondary electrons have a short mean free path, which defines the probing depth of the spin-SEM for thin films as well as bulk materials. The smallest possible beam diameter from the field-emitter source is 5 nm in this system, although the best magnetic resolution is about 40 nm. One drawback to be noted is that even small amounts of contaminants tend to reduce the polarization signal. Therefore, a UHV environment is necessary, which requires a long preparation process preceding the spin-SEM scan. More detailed description of the spin-SEM system is in the appendix.
5.5 Conclusions

The introduced devices enable us to characterize the fabricated nanostructures. Surface information is provided by the SEM and the AFM. The magnetization state of the individual magnet can be scanned with spin-SEM as well as with MFM that is used most of the time throughout this project. All characterization method has trade-offs and limitations and good skills are required to obtain reliable results. For example, careful setting of all parameters is necessary to avoid any influence on the sample from MFM, and special attention is needed to protect the SEM from any magnetic contamination.
The three sources of magnetic anisotropy are related to sample shape, crystal structure, and atomic scale texture. The dominant anisotropy term is the shape anisotropy for Supermalloy, a soft magnetic material that is used throughout our project, which has zero crystalline anisotropy. Using different shapes, one can engineer different types of shape anisotropies that allow NML gates with new functionalities.

Here novel nanomagnet shapes are introduced to experimentally demonstrate that magnetic behavior is primarily governed by shape anisotropy, and to prove the simulation results described in Chapter 2. Experimental results confirm that by varying the aspect ratios of the nanomagnets, the coercivity field can be engineered (Section 6.1). Shape engineering provides us with the capability of changing the energy landscape in slant magnets (Section 6.2).

6.1 Magnets with different aspect ratios

Section 2.1 introduces the simulation results for magnets with different aspect ratios. The promising results for coercivity field engineering encourage us to experimentally prove the described concept.
A set of different aspect ratio magnets is fabricated and tested to progress toward the possible programmability of NML structures. The magnets have a constant thickness and width, 30 nm and 70 nm, respectively. The length is varied: 130, 150, 180, and 240 nm. The SEM image of the standalone magnets is shown in Fig. 36a. During the test of these magnets, our goal is to experimentally determine the magnitude of the field required to switch the magnets individually.

Fig. 36. Experimental proof of the simulation results shown in Fig. 3. The SEM image of the test structure (a) and the MFM images of the same magnets (b-d) after various magnetization field directions and strengths are shown.
The sample is magnetized along the long axis (horizontal direction) of the magnets during each step. First, a 390 mT external field is applied from left-to-right (positive direction). This strong positive field aligns all magnets in the array regardless of their aspect ratios. The resulting magnetization of the magnets is shown in the MFM image of Fig. 36b where all magnets are magnetized uniformly. Subsequently, a reverse field is applied to determine the field strength required to reverse the magnetization for various magnets. A 150 mT field is applied in the negative direction to test the array. This field is only sufficiently strong to flip the magnetization state of the shortest magnet, though it does not affect the other magnets (Fig. 36c). In the third step, a 165 mT magnetic field is applied in the negative direction. This reverses the state of the 150 nm long magnet in the second row (Fig. 36d), but does not influence the magnetization state of any of the longer magnets.

As a conclusion, we experimentally demonstrated the effect of different aspect ratios on the switching field in agreement with the previously shown simulations. The switching field strength is determined for the 130 nm long magnet (first row) as 150 mT, and for the 150 nm long magnet (second row) as 160 mT. We presented the experimental proof to show that the switching field of the magnets increases with increasing aspect ratios, i.e., we have control over the switching field strength by changing a magnet’s length. This magnetic behavior can be exploited to build different NML structures with programmable driver magnets, as shown in Chapter 8.
6.2 Slant edge nanomagnets

Shape engineering provides various opportunities in the nanomagnet design. Here, we introduce the experimental result of the tested slant standalone magnets. The underlying simulations are presented in Section 2.2.

An array of slant nanomagnets are fabricated (Fig. 37a), where the columns of the horizontally aligned, uncoupled magnets have different slant locations (e.g., right top, left top, right bottom, and left bottom). Six vertically aligned magnets surround the array of the slant magnets. These indicator magnets serve to indicate the direction of the externally applied field. All magnets are standalone; their separation is at least 300 nm; therefore, coupling effects should be negligible. The footprint of all of the magnets is approximately 140 nm X 70 nm with a thickness of 30 nm.

![Fig. 37](image-url) Schematic of the test array (a) including horizontally aligned magnets with different positions of the slanted edges as well as vertically aligned indicator magnets. MFM of the slant/indicator magnets (b). A 130 mT top-down field is applied along the easy axis of the vertical magnets, and along the hard axis of magnets with slanted edges. All magnets are magnetized as expected.

An external magnetic field of 130 mT is applied in the vertical direction (from top to down direction) to the sample, i.e., parallel to the easy axis of the indicator magnets and the hard axis of the slant magnets. Each slant magnet is subjected to the same homogenous field; therefore, differences in the behavior have to be attributed only to the
difference in the placement of their slanted edge. The MFM image shows the final magnetization state of the array (Fig. 37b). For all slant magnets, the slant location and the direction of the applied external field determine the magnetization direction as is discussed in Section 2.2. The magnetization of the indicator magnets is parallel to the applied field. As a conclusion in our presented array, each individual magnet behaves as expected.

Due to fabrication variations, the actual shapes of the magnets are slightly different from each other. Nevertheless, their magnetic switching behavior is insensitive to these variations. Fig 37b shows that all magnets in the 6 X 4 array are magnetized in agreement with the simulations discussed in Section 112.2.

We presented the experimental proof of the behavioral change of the asymmetric magnets over the symmetric ones. This magnetic behavior can be exploited to build NML structures with reduced footprint, as shown in Section 10.4.3 and Chapter 14.

6.3 Conclusions

This chapter was devoted to the experimental proof of shape-dependent switching, as predicted by the simulations of Chapter 2. The successful experimental demonstration paves the way toward the exploitation of the switching behavior in NML circuits. The nanomagnets with the introduced shapes are the fundamental building elements for the NML structures described in this thesis.
NANOMAGNET WIRES

NML is a novel nanoscale computing paradigm where circuits are constructed from sub-100 nm, single-domain magnets. Logic signals are propagated in magnetic “wires” built from nanomagnets placed side-by-side. The emanating magnetic field of a magnet provides the interaction. The magnetic circuit is constructed in such a way that the magnets are located on a grid-based array, i.e., they form horizontal and vertical lines on a plane.

The nanomagnet wire is the basic structure of the NML circuit library; therefore, the most often used building block of devices. Nanomagnets comprising NML wires can be coupled in one of two ways. One of these is the vertically aligned wire with ferromagnetically coupled (FC) magnets, and the other is the horizontally aligned wire built from antiferromagnetically coupled (AFC) magnets. These wires have been demonstrated already among the first nanomagnet structures. Here we summarize the experimental result of both types of wires fabricated with decreased, 60 nm × 90 nm footprint uniform nanomagnets (Section 7.1) and with different aspect ratio magnets (Section 7.2). Some characterization and testing methods for the nanomagnet wires along with comparisons are summarized in Section 7.3 and 7.4.
The orientation of the wire can be either horizontal (AFC) or vertical (FC). The FC wires can be as long as it is necessary to fulfill other design requirements, but in the AFC wire, every other magnet inverts the carried information, i.e., the wire length has to be an odd number to have the same bit value at the beginning and at the end of the wire. As the project goal leads us toward complex nanomagnet circuits, where multiple devices are connected, the length restriction of the AFC wire limits the circuit design. To overcome this issue, we introduce a special nanomagnet wire design, where the magnets are side-by-side and form a staircase-like wire. This new structure allows us to connect NML devices located in arbitrary distances. The fabricated structure along with the successful characterization is introduced in Section 7.5.

7.1 Experimental realization of horizontal and vertical nanomagnet wires

The already demonstrated nanomagnet wires have been constructed from rectangular shaped, 100 nm × 150 nm sized magnets. With our fabrication recipe, smaller footprint, shape controllable nanomagnets are possible to fabricate, 60 nm × 90 nm. We build vertical and horizontal wires from five of these magnets. The vertical wire is shown in the SEM image in Fig. 38. The one horizontally aligned magnet on the top is the “driver” magnet; it initializes the entire wire through FC. Its dimensions are 60 nm X 240 nm. All magnets are 30 nm thick, and are separated by 25 nm. The wire is magnetized first by a horizontal pumping field pointing into the positive direction followed by a reverse field. MFM scan is performed after each magnetization to show the magnetization state of the vertical wire (Fig. 38b and Fig. 38c). The nanomagnets
perform correctly and pass the information from the driver magnet through the wire according to the magnetization state of the driver magnet.

![Image of a 5-nanomagnet-long vertical wire with a horizontally aligned driver magnet.](image)

Fig. 38. a) SEM image of a 5-nanomagnet-long vertical wire with a horizontally aligned driver magnet. b) MFM image of the same wire for one magnetization state of the driver magnet and c) for the other. The information propagates from the driver magnet toward the bottom of the wire by ferromagnetic coupling.

One horizontally aligned, five-magnet-long wire is shown in Fig. 39a. Here, the information propagates from the horizontal driver magnet through the antiferromagnetically coupled magnets, i.e., from left to right. Two MFM images (Fig. 39b and Fig. 39c) show the magnetization of the same wire for two possible states of the driver magnet. The same external field is applied here as for the vertical wires.
Although the introduced nanomagnet wires perform without any error during the magnetization reversal, in several cases magnets in identical wires relaxed into wrong states. Since we cannot gain any insights into the dynamical behavior of the switching, it is hard to determine the cause of any error formation.

7.2 Nanomagnet wire built from different aspect ratio magnets

In Section 2.1, the simulations predict that the nanomagnets with various aspect ratios have different switching field values. Here, we introduce a wire constructed from seven different aspect ratio magnets. Our goal is to show experimentally that the
decreased aspect ratio magnets located toward the end of the wire helps the information propagation, i.e., the decreasing aspect ratio delays the switching of the nanomagnets at the end of the wire. We hope that this design change provides better defined direction of the information propagation than in an antiferromagnetically coupled (AFC) wire with uniform magnets. We attempt to compare the switching behavior, i.e., the final state after several magnetization cycles, with the regular AFC wires in Section 7.3.

The SEM image of a short and a long wire is shown in Fig. 40. The driver magnets are 120 nm × 70 nm, the magnets along the wire are 120 nm long, and the width is 35 nm, 40 nm, 45 nm, 50 nm, 55 nm, 60 nm, 65 nm from left to right in the short wire. In the long wire, the first four magnets are 50 nm wide; the width of the next four magnets is 55 nm, then 60 nm, and the last group of four magnets has a width of 65 nm. All magnets have a 20 nm thickness.

Altogether, 130 wires are fabricated and tested from both designs. Each of them is investigated by SEM to confirm that the magnets are present with the correct shapes, with 20 nm separation, and without any defects or residues from the fabrication.

Fig. 40. SEM image of the nanomagnet wires with input magnets on the left and different aspect ratios along the line.
7.3 Comparison of the AFC wire with uniform and different aspect ratio magnets

Per our prediction, the wire with varying aspect ratio magnets has better performance as it relaxes into a stable state following the pumping process. We attempt to prove this statement, and nanomagnet wires are fabricated. Five and ten-magnet-long wires are built from uniform magnets, along with seven and sixteen-long wires from different aspect ratio magnets. The pumping field is applied to both, i.e., positive and negative direction, followed by MFM scans to determine the magnetic state of the wires. The number of errors of the coupling in the wires is counted. Approximately hundred wires are tested, and the result shows only a few percent differences in the number of errors for the wire designs. Although our experiment was not able to prove the difference between the wire performances, it might be worth to design various wires, where the rate of the aspect ratio change is adjusted more precisely.

7.4 Characterization of the nanomagnet wires with various magnetization methods

Nanomagnet wires with different aspect ratio magnets are fabricated for testing of the various magnetization methods, and to attempt to gain some insight into the switching behavior of the nanomagnets. 130 identical wires are tested with the designs shown in Fig. 40. Here, we introduce the applied magnetization cycles as well as discuss the result of the statistical analysis of the MFM images.
7.4.1 Magnetization methods

Three different magnetization patterns are used to set the magnetization state of the nanomagnet wires. Before each magnetization, the nanomagnets are demagnetized by a high, -200 mT field. All wires are magnetized in the same cycle, since they are located on the same sample piece.

The first magnetization pattern involves the pumping method. The sample is magnetized by a 200 mT field into the positive direction generated by a 10.5 A current in the electromagnet. The field is changed in 9.5 mT/s steps.

The second magnetization pattern is a combination of the pumping and the rotating field. The pumping, 200 mT positive field sets the magnetization state of the driver magnets, and a weaker, 40 mT rotating field sets the state of the small magnets in the wire. The field is incremented with 9.5 mT/s steps.

The third magnetization pattern includes the combination of the pumping and the shaking field. Here, like in the previous case, the pumping field (200 mT) sets the magnetization state of the driver magnets. The shaking field is used to help the relaxation of the remainder of the magnets. The angle of the shaking is + and − 15°, which corresponds to 300 steps of the stepper motor.

7.4.2 Characterization

Each magnetization cycle is completed at room temperature and is followed by the MFM scan of all 120 nanomagnet wires. We try to ‘rank’ the various methods by counting the number of coupling errors in each wire. 42 %, 44 %, and 51 % of the wires...
worked perfectly for the pumping, rotating, and shaking field, respectively. Fig. 41 shows the pie chart summary of our analysis, where not only the null error wires are counted, but also the others with one, two, or even three errors. From this testing, we conclude that the *shaking field has the most advantage* to obtain more working wires without any errors. Although we know that the error bar of our testing is unknown at this point, the outcome of the shaking field shows promising improvement in the results compared to the pumping and the rotating methods.

![Pie chart summary of the error results of different magnetization methods.](image)

Fig. 41. Pie chart summary of the error results of different magnetization methods.

Due to the higher performance of the shaking method, the experiment is repeated to gain some information about the repeatability. The results that are compared include the number of perfect wires and the locations of the errors. The number of wires without any error rose to 59 %. The error location changed from one testing to another, which might indicate that the errors are not exclusively generated by fabrication defects. In this case the error would have the same location after each test.
7.5 Staircase wires

The magnetic circuits are constructed from driver magnets with various sizes and from identical magnets that build the inside of the circuit. In an NML circuit, the magnets are arranged in a grid. To design complex and large footprint magnetic structures, the uniformity of the magnets and the grid layout generates a limitation. The AFC wire is a horizontal wire that inverts the carried information if its length is an even number, and does not invert if the length is an odd number. In a circuit where a given distance is interconnected with two AFC wires, there is no possibility to invert information only on one wire and not on the other one. In other words, the inversion of the information is determined by the length of the wire and not by the necessity of it. We introduce here a staircase-like wire as a solution. It allows connecting wires with different length and avoids the above mentioned issue. Fig. 42 shows the schematic of horizontal and vertical wires with shifted magnets. There are two pairs of wires in the group to show opposite magnetization pattern after one single magnetization initialization. Our goal is to prove the functionality of this structure by showing the magnetization pattern after a magnetic field is applied; and to add this structure into the NML library.
The introduced staircase-like structure is fabricated with the already introduced fabrication recipe (Chapter 3). The SEM image is shown in Fig. 43a. The driver magnet has a footprint of 190 nm × 50 nm, and the other magnets have a footprint of 110 nm × 50 nm. The wall-to-wall separation is 20 nm, and the thickness of the magnets is 20 nm. The magnetization is performed with pumping field for functional testing of the structure. Fig. 43b and c show the magnetization state of the wires after positive and negative external field excitation. The wires perform without any errors. This result is promising, and leads us toward complex NML circuit designs.

Fig. 42. Schematic of the NML wire with shifted magnets, i.e., the magnets form a ‘staircase’ instead of being horizontally or vertically aligned.
Another structure with the same design is tested with the non-invasive spin-SEM. Before the scan, the structure has been magnetized in the direction along the driver magnets (horizontal magnets) with a 100 mT positive field generated by an electromagnet in ambient conditions. The spin polarized scan provides information about one direction of the magnetic field in the plane of the sample. To see the magnetization of the horizontally and vertically aligned magnets, two scans are necessary. They are shown in Fig. 44 and Fig. 45. As a conclusion, the magnets inside the wire respond to the bias field arising from the drivers without any errors (Fig. 44). The magnetization of the driver magnets is only shown in Fig. 45.
Fig. 44. The spin polarized SEM image of the staircase wires along the vertical direction. Only one in-plane magnetization state is shown due to the limitation of the instrument.

Fig. 45. Spin SEM scan of the staircase wires along the horizontal direction. The magnetization of the driver dots is pictured.
The MFM as well as the spin-SEM scans prove that the staircase wire performs the function without errors. For a second spin-SEM scan, the sample is magnetized under UHV with an opposite directed (negative) field. Unfortunately, the scan for the same structure shows that the magnets inside the wire fail to switch according to their neighbors, as shown in Fig. 46. In the top part, the magnetization of the driver magnets is shown to follow the direction of the applied field (100 mT), which pointed in the opposite direction compared to the first applied field. The bottom part of Fig. 46 shows the magnetization state of the staircase wires with several errors, which could arise from multiple sources, such as fabrication error (asymmetric magnets, rough surface, and pinned domain structure due to the un-uniformity of the side of the magnets) or other unknown parameters. Further studies are necessary to explore the origin of these errors, and to gain more insight about robustness, as well as, reliability of the structure.
Fig. 46. Most of the staircase-like wire magnets failed to flip magnetization after a negative, 100 mT magnetic field is applied.

7.6 Conclusions

The nanomagnet wires are the basic elements of the NML library. They serve as interconnections in NML circuits and they also constitute the simplest model system for coupled nanomagnets. Since this important role in the NML circuits, possible error formation was studied, and a novel design, the staircase-like wire is introduced.
THE DEVELOPMENT OF THE PROGRAMMABLE MAJORITY GATE

The majority gate is a junction of a horizontal (side-to-side magnets with AFC) and a vertical nanomagnet wire (end-to-end magnets with FC), as the schematic shows in Fig. 47. All of the magnets are named according to their function in the gate, such as driver, input magnet, etc. The driver magnets set the input magnetization of the gate and are aligned perpendicular to the input magnets so that they can be set by an external field separately. The magnet at the center of the cross is the computing magnet that is responsible for the logic function. It receives the input bits from the ferromagnetically coupled inputs (top and bottom) and from the antiferromagnetically coupled center input magnet. The correct logic value is forwarded to the AFC output magnet.

The split truth table of the majority gate is shown in Fig. 48. As one of the input magnets is fixed, the function of the gate is set to an AND gate or to an OR gate.
Fig. 47. Schematic of the majority gate along with the name of the specific magnets (input, driver, computing, and output magnet).

Fig. 48. The split truth table of the majority gate. Input A is fixed to set the gate to an AND (left side) and to an OR gate (right side).
8.1 Majority gate with identical magnets

The majority gate has been fabricated before as the proof of the NML concept [13]. We fabricate the same structure with decreased footprint; i.e., the magnets have a 60 nm × 90 nm area. The introduced recipe has a stable, reproducible fabrication procedure, and provides straight, smooth sidewalls for the dots, as well as a clean top surface.

The fabricated majority gate is shown in Fig. 49. The AFM images (on the left) show the topography of the majority gate with four different designs that are necessary to show all input configurations. The magnets have a 30 nm thickness and a 20 nm wall-to-wall separation.

Fig. 49. AFM and MFM image pairs show all four majority gate configurations. 150 mT external field is applied from right to left by an electromagnet.
To characterize the fabricated structures, 150 mT external magnetic field is applied in the horizontal, right-to-left direction. This field is strong enough to align the magnetization of all magnets horizontally, i.e., the driver magnets along their easy axis and the other magnets (input, computing, and output magnet) are forced to be magnetized along their hard axis. As the external field is reduced, i.e., it is no longer strong enough to maintain the high-energy state of the magnets, the input, the computing, and the output magnets switch into an easy-axis magnetization orientation according to the drivers. The driver magnets provide a bias to the input magnets, which biases the computing magnet and so on. Finally, as the circuit relaxes, the logically correct bit appears in the output magnet, which is demonstrated in Fig. 49, where the MFM images (on the right) show the final magnetization state of the entire majority gate. Arrows are superimposed in the figure to make it easier to visualize the direction of the magnetization of each magnet. The heads and tails of the arrows are placed on the bright and dark spots, respectively.

8.2 Modified majority gate

The majority gate introduced in the previous section has identical nanomagnets; therefore, four different designs are necessary to set all input combinations. To set the driver magnets separately, to program the majority gate, the aspect ratio dependent switching field can be exploited, which we already demonstrated in Section 6.1.

Here, we introduce a majority gate with one controllable driver magnet, thus making one of the inputs individually programmable by a globally applied magnetic field. Fig. 50a shows the new design with one long driver magnet. All magnets have the
same dimensions (60 nm × 90 nm x 30 nm), except for the long driver magnet, which has a length of 150 nm. The wall-to-wall separation is 15 - 20 nm between the magnets.

Fig. 50b shows a tilted SEM image of the fabricated structures imaged with a 30 kV acceleration voltage. The designed sizes and the measured dimensions of the structure are in good correlation. The top surfaces of the magnets are flat and free of any leftover particles from the lift-off step. A clean top surface is important, since any magnetic material residues can affect the magnetization behavior.
The fabricated gate is inspected with magnetic force microscopy after different magnetization steps summarized in Fig. 50c)-e). A strong, horizontal field is applied to set all drivers magnetized in the positive direction (Fig. 50c). An appropriate, oppositely directed field followed to reverse the two short drivers (Fig. 50d). As a result, the magnetization of the two short drivers (top and bottom ones) switched, but the long driver (the center one) has retained its state, i.e., the applied reverse field is not
sufficiently strong to remagnetize it due to its high coercivity. The reverse state of this gate (Fig. 50e) is obtained by the same magnetizations steps, though in the opposite directions.

To find the corresponding row of the truth table to the gates, we define the up and down directions as a logic ’1’ and ’0’, respectively. As the central driver is fixed, so that the central input provides a logic ’1’ for the voting dot (Fig. 50c)-d), the OR function appears on the computing dot. The two short drivers set the inputs to ’1’ in Fig. 50c and so the value of the counting dot is ’1’ as well (1 OR 1=1). The output dot shows a ’0’ value, since it is antiferromagnetically coupled to the central dot, i.e., the output of the OR function is inverted. In Fig. 50d, the short drivers have reversed their directions. This corresponds to the logic ’0’ value of the input magnets, which sets the output bit to ’1’ (not[0 OR 0]). As we change the magnetization direction of the long dot, we change the function of the gate from OR to AND. In Fig. 50e, the two short drivers provide the logic values ’1’ to the AND gate, so the output is a ’0’ as the output dot offers the NAND function.

The possibility to switch a single driver alone without switching the others is demonstrated. Using this method, we define the functionality of the majority gate to be either OR or AND logic.

8.3 Programmable majority gate

Although the majority gate introduced in the previous chapter already has some benefit over the one with uniform driver magnets, all input combinations cannot be tested
on a single device. To be able to do that, all driver magnets have to be programmable individually. In this section, the completely programmable NML majority gate is presented.

To set all driver magnets individually, we exploit the relationship between the length and the coercivity of the magnets further, and so we define different aspect ratios for all three driver magnets. We set the lengths of the drivers according to the simulation shown in Fig. 1 and Fig. 3 and experimental results shown in Fig. 36. The schematic of the new design is presented in Fig. 51 in the inset along with an SEM image of the fabricated structure. The lengths of the driver magnets are 90 nm, 150 nm, and 250 nm. With this design, a single gate can perform the logic with all input variations, unlike the previous majority gate designs, where varying the position of the driver magnets is necessary.
The switching field of the different aspect ratio magnets was already simulated (Section 2.1) as well as experimentally demonstrated (Section 6.1). We set the magnetization state of the gates with a magnetization pattern given that the drivers can retain their distinct initial magnetization state even during and after the magnetization. The applied external field should be sufficient to set the state of a target driver, yet insufficient to switch other (longer) driver(s), and sufficient to place the vertical magnets into a hard-axis biased state.

Fig. 52 shows the MFM images of the gate for all input combinations of the majority-logic operation. The arrows superimposed in the MFM images illustrate the resulting magnetization direction due to the applied external clock fields. The applied
external field directions are indicated above all MFM scans to clarify the magnetization pattern. First, a strong external field sets the magnetic state of all driver magnets into the same direction, as in Fig. 52a and Fig. 52e. For an appropriate reverse field, the two shorter driver magnets switch, though the longest magnet remains in the previously set state (Fig. 52b and Fig. 52f). Finally, to reverse only the shortest driver magnet, a relatively weak field is applied (Fig. 52c and Fig. 52g). Fig. 52d and Fig. 52h show the state of the gate after magnetizing with a strong and followed by a weak field.

The magnetic state of the AFC inputs has the opposite effect on the central magnet as compared with the ferromagnetically coupled inputs, so AFC and FC inputs are assigned the same logical value for opposite magnetizations. Bit value '0' is assigned to down and '1' is assigned to up, as shown in Fig. 52 on the left side. Black insets

Fig. 52. MFM images of the programmable majority gate for all input combinations. The black insets show the three input values along the output, majority value.
shows the corresponding logical values of the input magnets as well as the output magnet. All input combinations are introduced, and the performed logic corresponds to the truth table shown in Fig. 48. Correct NML majority-logic gate functionality is shown for all driver/input combinations for the first time.

In this chapter, we demonstrated the independent programmability of the driver magnets of the majority gate to obtain all logic variations in one physical layout, a completely programmable logic gate. It has been shown that the majority gate can be programmable by shape engineering of the driver magnets, since currently we do not have any options to generate local magnetic fields to set each of the drivers separately.

8.4 Conclusions

The majority gate is the simplest logic gate among all NML devices, and it is the basic logic element for NMLs. In this chapter, we described the development of the gate from the fixed input design to the programmable design. The gate with programmable inputs enables to apply different input combinations to the very same gate. This allows the testing of much more complex gate designs, which will be introduced later in this thesis.
9.
NANOMAGNET FANOUT

9.1 Introduction

The fanout is a crucial element for implementing any binary computers, as it provides a mechanism for signal distribution. In a fanout circuit (Fig. 53a), an input signal is split and passed on as two or more output signals. For a signal to propagate through a fanout circuit, it is essential that the driver element (i.e., nanomagnet in the case of NML, Fig. 53b) dictates the state of the output elements. It has been shown in [55] that a fanout circuit implemented in edge-driven architectures has a high probability of entering into an incorrect (metastable) state. Clocking, in the form of cyclical manipulation of energy barriers (either by means of global external or local electric or magnetic fields) that separate the two binary states of the elements, solves the problem of the unwanted metastable states [56]. The fanout for electronic QCA was recently demonstrated using metal-oxide tunnel junction technology at sub-Kelvin temperatures [57]. One of the most significant advantages of the nanomagnet implementation of the fanout compared to electronic QCA is that it is fully functional at room temperature because of the much larger characteristic (“kink”) energies, which are on the order of hundreds of kT at room temperature for submicron Permalloy magnets easily attainable by modern lithography [58]. Here, we report the experimental realization of a fanout
gate implemented for NML that makes a necessary contribution to the family of the functional magnetic QCA structures.

9.2 Experimental realization of the nanomagnet fanout

The fanout circuit is fabricated with the recipe introduced in Chapter 3 (high resolution EBL, magnetic metal deposition, and lift-off). The nanomagnet fanout design along with the SEM image of the fabricated structure is shown in Fig. 54 a) and b), where the footprint of the driver magnet is 230 nm × 60 nm and for the other magnets 90 nm × 60 nm with a 30 nm thickness. Note that the driver magnet is more elongated than the other magnets composing the circuit in order to achieve different switching behavior for the same external clocking field. The different geometry improves the stability of the driver magnet against an external magnetic field, which sets the magnetization state of the shorter magnets. In our design, the long driver magnet retains its magnetization (set by first applying a large magnetic field) when a weaker external field is applied to switch

Fig. 53. Generalized fanout circuit - one input drives multiple (in our case, 3) outputs (a) and schematic of the fanout circuit designed for single-domain magnets (b).
the shorter magnets. OOMMF simulations as well as experimental results are already shown in Section 2.1 and 6.1, respectively, the magnetization dependence on magnet length. The simulated coercivity values, along the long axis of the magnets, are 130 mT and 70 mT for the long and short magnets, respectively. In our experimental design, the long axis of the driver magnet is perpendicular to the long axis of the rest of the magnets forming the fanout. First, a high (200 mT) external magnetic field is applied parallel to the long axis of the driver magnet and perpendicular to the short axis of the fanout circuit magnets. The field sets the magnetization of the driver magnet and forces the fanout magnets into a metastable state. Next, the external field is reduced to an intermediate level (120 mT), and the sample is rotated at about 1800 rpm as the magnetic field magnitude is reduced to zero during one minute. This rotating field does not influence the magnetization of the driver magnet, since it is weaker than the coercivity of the driver magnet. The driver keeps its initially defined state set by the 200 mT field. During the rotation, the circuit nanomagnets relax into the logically correct ground state driven by the driver magnet.
Fig. 54. Schematic (a), SEM image (b) and MFM images for both possible driver magnetization states (c and d) of the fanout circuit.
The natural non-volatility of NML allows us to scan the structure with MFM after the drivers are set, and the clocking field is removed. Fig. 54 c) and d) shows the MFM images of a single fanout circuit for both possible drivers states that define the final states of the outputs. The experimental proof of the fanout is repeated for different output wire lengths, such as 2, 3 and 5, as shown in Fig. 55, Fig. 56, and Fig. 57, respectively. Each figure shows that the fanout circuit biased by the driver magnets achieved the correct final state. This result is the first demonstration of fanout circuitry functioning in the nanomagnet logic system.
Fig. 55. SEM (a) and MFM images (b and c) of the nanomagnet fanout circuit with short, two magnet long output wires. The MFM images summarize the correct ordering of all magnets building the structure.
Fig. 56. SEM (a) and MFM images (b and c) of the fanout circuit with three magnet long output wires. The nanomagnets switch into the correct state throughout the entire structure.
Fig. 57. SEM (a) and MFM images (b and c) of the fanout circuit with five magnet long output wires. The performance of the fanout is perfect even with these long output wires.
9.3 Conclusions

The nanomagnet fanout structure presented here passes the information from the driver magnet through a vertical FC wire to three horizontal AFC wires. The energy required for signal propagation and fanout is gained from the clocking field, which is applied to drive the nanomagnets from their initial metastable state to their ground state. In previous work, various clocking schemes (hard-axis [59], oscillating field [20]) have been proposed. In the experiments presented here, the oscillating field method is used.

The directionality of propagation, i.e., from the driver magnet through the fanout, is facilitated by holding the magnetization of the driver magnet fixed while the fanout circuit switches in response to the clocking field. This is achieved with a global clocking field, though with different magnet designs in the structure. The difference in switching fields due to magnetic shape anisotropy allows us to apply the same global clocking field, which acts in different ways on the driver and fanout magnets, instead of requiring separate local fields for these different groups of magnets.

In summary, we have demonstrated at room temperature a nanomagnet fanout structure, which is a critical NML circuit element. The implementation of this fanout circuit opens a new path for the design and fabrication of more complicated NML circuit structures. One challenging obstacle on the way toward practical NML circuit implementations is the need for local magnetic fields targeting only particular nanomagnets.
10. ONE BIT NANOMAGNET FULL ADDER

All NML circuits are built from closely spaced nanomagnets that are located on a grid-based array, i.e., they form horizontal and vertical lines in a plane. Various basic structures are necessary to build a complex NML circuit, such as a full adder. NML devices are interconnected by magnetic “wires,” which in the case of NML refers to a line of nanomagnets along which the signal is propagated (Chapter 7). The basic logic element of the currently existing NML library is the majority gate in which one magnet reflects the total magnetic forces of the surrounding magnets (Chapter 8). Signal distribution, i.e., fanout, is performed by splitting the input signal and passing on as three output signals (Chapter 9). Above all, shape engineering helps to design programmable inputs (Chapter 2 and 6) as well as to reduce the overall footprint. All of these components are implemented into the full adder.

10.1 Full adder implementation

The previously published logic structures possess a relatively basic level of complexity; one structure had only one basic function (AND/OR/majority). Prior to this work, the maximum number of inputs was three with one single compute nanomagnet
(majority gate), and the information was passed along a few-magnet-long magnetic wire, or fanned out with a few wires. The total number of magnets was low as well. In the case of the full adder, the basic, most simple circuit design would include multiple logic gates, such as AND and OR gates. Since the fundamental building block of NML is the majority gate upon which the AND and OR gates are based, it is not efficient to restrict the functionality to AND/OR functions since considerable space is wasted with extra inputs and associated magnets. Rather, it is better to find a circuit design constructed from majority gates from which it is straightforward to realize the full adder directly. Such a design of the full adder was proposed in [60] and its operation is proven using five three-input majority gates (Fig. 58a). A smaller design was introduced later in [[61, 62] where the circuit is composed of only three, three-input majority gates (Fig. 58b).
More complicated designs were published requiring one three-input majority gate and one five-input majority gate [63]. Since the three-input nanomagnet majority gate is tested successfully, as shown in Chapter 8, they were selected for the construction of the full adder of Fig. 58b instead of the one majority gate with 5 inputs. Fig. 59 shows a possible nanomagnet-based layout with three, three-input majority gates (the crossing point of the horizontal and the vertical nanomagnet wires). Each input (A, B, and C_i) is applied at multiple positions in the circuits of Fig. 59, making it possible to implement the layout without wire crossings. The adder has two outputs. One of them is the sum (Sum) and the other is the carry bit called C_o.
10.2 Functionality

The long magnets in the left side of the circuit in Fig. 59 are the programmable drivers providing the input data for the adder. A particular applied field $B_{\text{ext}}$ can switch only magnets with a switching field (coercivity) $B_{\text{sw}} < B_{\text{ext}}$. Higher switching fields are required for higher aspect ratio magnets. Therefore, a globally applied magnetic field can switch only magnets smaller than a certain length. We exploit the aspect ratio to set the
driver magnets separately resulting in a programmable circuit. The relation between the switching field and magnet shape is experimentally demonstrated in Section 6.1.

10.3 Realization and characterization

The magnetic structure of Fig. 59 is fabricated using electron-beam lithography, evaporation, and liftoff of Supermalloy as described in Chapter 3. The smaller magnets are 90 nm long and the drivers are 220, 340, 440 nm long with a 60 nm width. The thickness of the Supermalloy magnets is 30 nm. An SEM image of a fabricated structure is shown in Fig. 60a. The device is tested by MFM (Fig. 60b) after the application of external fields.

A homogeneous 200 mT field is applied first to set all of the drivers pointing into the same direction, as shown in Fig. 60b. Here, we do not magnetize the drivers separately; our goal is to test the operation of the entire structure for one set of input bits. The 200 mT magnetization was followed by a rotating field continuously decaying from 40 mT to 0 mT to demagnetize the magnets to their computational ground state. More details about the choice of these field values are given in [4]. The MFM image (Fig. 60b) shows a nearly perfect ordering of the nanomagnets according to their neighbors as required to perform the logic operation. Of the 53 magnets, only a single coupling failed during the testing (circled at the output of the topmost majority gate). This result is encouraging, as 52 of 53 magnets fabricated in this complex geometry are correctly coupled to their neighbors, and all three majority gates functioned correctly. To the best of our knowledge, this circuit is the most complex NML circuit fabricated so far, and the
first one to include multiple logic gates. The error occurred at the circled position (Fig. 60b) for three independent demagnetization events, suggesting that this error is most likely due to a fabrication error (a misshaped or pinned magnet). To achieve truly error-free operation, the design and the fabrication parameters have to be optimized. There are several ways to design more compact NML full adders, as discussed below.

![Image](image.png)

Fig. 60. SEM image of the fabricated full adder built from 53 nanomagnets (a) and the MFM image after the magnetization of the structure (b). One single coupling error occurred at the encircled location in the MFM image.

### 10.4 Simplified full adder designs

The tested full adder structure is fabricated from a large number of magnets, which increases the possibility of error formation during the switching process. One
potential optimization step is the decrease of structure footprint, as well as the number of magnets, as discussed below (Section 10.4.1 and Section 10.4.2). Shape engineering is another solution that can be exploited to achieve successful adder operation (Section 10.4.3).

10.4.1 Small footprint design

The above introduced full adder structure has a 53 nanomagnets. Our goal is here to decrease the number of magnets and therefore, to reduce the footprint of the structure. A novel design with 6 driver magnets and 25 small magnets is shown in Fig. 61a.

The reduced footprint structure is fabricated successfully, as shown in Fig. 61b. However, in this structure the relatively long vertical and horizontal lines reveal a design flaw: the horizontal and vertical magnetic wires relax to their ground state for different external fields (more details in Chapter 4). This relaxation is due to the fact that for a horizontal applied field, the ferromagnetic coupling superposes to the applied field, so...
horizontal (AFC) wires relax at a weaker applied field than vertical (FC) wires. This is why the magnet denoted with a star in Fig. Fig. 61b fails to work correctly in 75% of the cases. An example is shown in Fig. 62. The MFM image clearly displays two errors. The top one is the most common error for this layout.

![Image of MFM image showing two errors](image)

Fig. 62. The MFM image of the reduced footprint full adder design (shown in Fig. 61). Two errors (circled) are present here. The top one is common and it appears in 75% of the gates.

To avoid the above mentioned issues stemming from the different behaviors of the horizontal and vertical wires, we propose a design with a further reduced footprint (Fig. 63). The lengths of the driver magnets are adjusted according to the simulation results shown in Section 2.1.
10.4.2 Column design

The above introduced designs of the full adder are based on the basic circuit model showed in Fig. 58b. In this section, we present another possible implementation. It is clear from the previous layouts that three majority gates are required for the calculation of the sum of the inputs. The most straightforward way to locate them is the “column design” to reduce the lengths of the necessary magnetic wires, i.e., the majority gates are aligned in one column, as shown in Fig. 64. The majority gates are noted as M1, M2, and M3.
To realize this design, the circuit design shown in Fig. 58b has to be modified with Boolean operations to remove the inverter between the M1 and M3 majority gates. The resulting circuit design is shown below (Fig. 65). Here, no information inversion is necessary between the majority gates, which allow us to connect them with a vertical wire. Note, that the column design adder calculates only the sum of the input bits and not the carry bit. The carry can be provided by a majority gate nearby the adder circuit.

Fig. 64. Schematic of the column design. The majority gates (M1, M2, and M3) are located above each other.
Using the new circuit diagram, the direct implementation of the NML-based adder design is straightforward as shown in Fig. 66. The full adder has four different designs for testing all possible input combinations. Our goal is to demonstrate the correct operation of the gate for all logic cases. This can be completed by using fixed inputs (A, B, and C), as shown in Fig. 66, where the inputs are provided by the elongated magnets. The circuit on the left side of each design provides the sum of the inputs (Sum), and the majority gate on the right side provides the carry bit, Cᵢ. This design of the adder is not built nor tested yet.
10.4.3 Full adder with slant magnets

The footprint can be reduced further by using asymmetric, slant magnets as inputs to the adder. The behavior of this magnet shape is summarized in Section 2.2 and 6.2. As previously discussed, the energy of the magnets is not the highest when a device is magnetized along the horizontal direction (Fig. 6), as is the case for the symmetric
magnets (Fig. 2). The design constructed from slant and regular oval shape magnets is shown in Fig. 67. The inputs are provided by the 7 slant magnets, and the number of the rounded edge magnets is only 14 (total of 21 magnets). This full adder requires four different designs (Fig. 67a - Fig. 67d) to test all possible input combinations due to the lack of separate input magnetization. Our goal is to demonstrate the correct operation of the gate for all logic cases, which can be accomplished by using fixed inputs, as shown in Fig. 17 with slant input magnets.

Fig. 67. A reduced footprint design of the full adder. The inputs are provided by the slant magnets. Four different designs are shown (a - d) for testing all possible input combinations.
The full adder with slant magnets is fabricated and tested successfully for each input combination, as shown in Fig. 68. The SEM images of all designs (Fig. 68a – Fig. 68d) are in the first column. The central column summarizes the MFM results after a magnetization performed with a 150 mT horizontal field pointing from left to right. This magnetization sets the drivers of the adder, and provides four out of the eight possible input combinations. A same strength, opposite directed field is applied for testing the other four input combinations. The resulting magnetization state of the adders is shown in the third column. The SEM and MFM images in each row show the exact same gate. The very first row of Fig. 68 are composites as the dashed line indicates.

Each magnet is in the correct magnetization state according to the driver magnets of the circuit. There is no error in any of the presented devices; therefore, the full adder with slant input magnets is successfully demonstrated experimentally.
Fig. 68. SEM images (first column) and the MFM images (second and third column) of the full adders with slant input magnets. All four designs (a – d) are shown. Each line shows two magnetization experiments for two input combinations. The MFM images summarize all possible input combinations.
10.5 Conclusions

In this chapter, we presented the first multi-gate NML circuit, a full adder. To our knowledge, this is the most complex NML design to have been realized.

We introduced several designs and tested one successfully without any errors. Our first adder design contains 53 magnets, and is fabricated and tested with only one coupling error throughout the entire circuit. This is an extremely large circuit. We could not demonstrate error-free operation in this circuit, and we believe that this circuit is too large to operate reliably without multiple clocking zones. However, the small number of errors in this design suggested that a slightly simplified circuit might work.

We redesigned the circuit, reducing the footprint and eliminated the most error-prone parts. The final design consisted of only 18 nanomagnets. The resulting MFM images show reliable, reproducible operation for all possible input combinations.

The NML full adder is demonstrated for the first time.
Here, the NML exclusive OR (XOR) gate is introduced and characterized for the first time. A QCA cell implementation of the XOR was proposed already in [60] with a layout shown in Fig. 69. Unfortunately, the cell-by-cell conversion of this design into an NML structure is not possible because of the wire crossing. In the NML design, crossing of wires is currently not feasible due to the planar implementation. To design the NML XOR gate, the conversion needs to be completed based on a basic circuit diagram.

Fig. 69. An implementation of the exclusive OR function using QCA cells. This design includes wire crossing as well as an inverter [60].
11.1 Realization of the NML XOR gate

There are several possible circuit implementations of the XOR gate. Two that are chosen for our NML designs are shown in Fig. 70. Both implementations include basic gates, such as AND and OR gate as well as inverters.

Fig. 70. XOR circuit implementations built from AND and OR gates. These two circuits are chosen for NML implementation.

The majority gate is the basic logic element for the NML structures; therefore, the conversion of these logic circuits is completed by using fixed input majority gates, i.e., the majority gate is restricted to an AND or OR logic gate. The NML schematics are shown in Fig. 71. Fig. 71a is implemented from the design shown in Fig. 70a, and Fig. 71b is an implementation based on Fig. 70b.
The NML XOR has two regular drivers, A and B, with different aspect ratios to allow possible independent switching. There is one additional long magnet in the center of the circuit that is not a regular driver due to its specific role. It is connected to all three majority gates, and provides a fix input to each to set their function to AND or OR. Because of the shape, this magnet could be set first by a sufficiently high field, followed by the setting of the A and B drivers. The two NML XOR gate designs shown in Fig. 71 differ. The (a) layout has a staircase-like vertical wire (an already introduced structure: Section 7.5) on the right side of the circuit, while the other (b) layout is a regular grid-based design.

In both designs, the magnetization of the longest magnet has to be fixed to set the function of the majority gates. To obtain the XOR function, the magnetization of the long central magnet needs to point from left to right to set the bottom left majority gate of
Fig. 71a and the top right majority gate of Fig. 71b to an OR gate and the other gates to an AND gate.

The NML XOR circuit is fabricated according to the recipe described in Chapter 3. The corresponding SEM images are shown on the left side in Fig. 72 and Fig. 73. The magnetization of the structures is performed by applying a 200 mT pumping field followed by a 60 mT rotating field. The pumping field sets the magnetization of all horizontal magnets, and forces the vertical magnets to be magnetized along their hard axes. The rotating field helps the small footprint magnets to relax to the correct magnetization state dictated by the drivers. After the magnetization, MFM scan is performed and the results are shown on the right side in Fig. 72 and Fig. 73. White arrows are superimposed to visualize the direction of the magnetization of each nanomagnet. The small insets in the bottom right corner of the MFM images summarize the logical value of the A and B input as well as the output dot. The XOR logic is performed correctly by the gate for one input combination in both magnetic circuits.
Fig. 72. NML exclusive OR gate with a staircase-like vertical wire located on the right side of the gate. The SEM (left) and the MFM (right) images are shown. In the bottom right corner of the MFM image, the corresponding row of the XOR truth table is shown. The central long magnet restricts the function of the majority gates to an OR gate (bottom left) and to an AND gate (top left and bottom right).

Fig. 73. NML exclusive OR gate with regular horizontal and vertical wires. SEM (left) and MFM (right) images are shown. The corresponding row of the XOR truth table shown in the bottom right corner. The central long magnet is responsible to set the function of all three majority gates. The top right gate is an OR gate and the other two are AND gates.
11.2 Conclusions

The NML implementation of the exclusive OR function is demonstrated. In our presented designs, the three majority gates along with the interconnections and the drivers are composed of 27 or 34 nanomagnets. The extremely long nanomagnet in the center of each of the circuits sets the function of the nearby majority gates. We introduced the experimental realization of two different designs for one input combination, and demonstrated that the gates provide the correct output for those inputs. Unfortunately, the sizes of the drivers were not properly designed, since the corresponding switching field values are too similar for the fabricated magnets. Consequently, we could not test a single gate for all possible input combinations. As a further step, the length of the driver magnets has to be chosen in such a way that the magnitudes of their nominal switching fields are farther apart than inevitable switching field variations resulting from fabrication errors. These would enable us to set the magnetic state of the driver magnets independently.

This experiment also demonstrates that NML gates with more than 30 dots can be realized in a single clocking zone. Comparing this experiment to the (negative) result of the unoptimized full adder design (53 magnets), we can speculate that a design consisting of 30 magnets is the largest circuit that can be implemented without integrated clocking.
According to the literature, the comparator and the adder have similar significance in arithmetic circuits. However, research-groups mainly focus on QCA-based adder designs and there are a number of proposed structures; far less attention has been devoted to comparator designs. The digital comparator is a device that has two numbers as input in binary form and determines whether one number is greater than, less than or equal to the other number. Comparators are used mainly in central processing units and microcontrollers.

One particular QCA-based comparator (Fig. 74) constructed from majority gates is presented in [64] along with simulations to prove the correct performance of the proposed circuit.
Since the majority gate and the inverter is a well-established building block in the NML library, it is convenient to implement this design by simply substituting all majority gates with the corresponding arrangement of nanomagnets. Fig. 75 shows our NML design, which is the first published nanomagnet-based comparator circuit. Each majority gate has a fixed input as in the exclusive OR gate design in the previous chapter (Chapter 11). The structure has two inputs, A and B, and three outputs, Y.

Fig. 74. Schematic of a comparator built from three majority gates [50].
Fig. 75. Nanomagnet-based comparator design with two inputs (A and B) and three outputs (Y).
The design was fabricated but its magnetic behavior is not tested.

Fig. 76. SEM image of the NML comparator fabricated for the first time. The inputs are A and B, the output is Y.

The design was fabricated but its magnetic behavior is not tested.
This section presents the nanomagnet implementation of the so called complex gate for the first time. This gate has a relatively small footprint; the number of building nanomagnets is small compared to the complexity of the gate functionality.

Although the fundamental NML logic structure is the 3-input majority gate, many of the attempts to implement functional circuitry using these gates begin by restricting them to a subset (AND or OR gate) of their full information content potential. Previously proposed circuits, such as the XOR and the comparator require more than one majority gate; however these are still restricted to implement two-input functions. An alternative to this approach is to use the three-input majority gate without any restrictions as a building block, as introduced in Chapter 10 for the full adder design. One other gate exploiting this alternative approach is the complex gate with multiple control and information inputs.
The QCA-based complex gate has been published in [65]. Fig. 77 shows the schematic, where the gate is constructed from identical cells. The gate has seven inputs (A – G) and one output (out). With three inputs, E, F, and G control cells, the logical functionality of the gate can be configured. The remaining four inputs (A – D) are the real inputs used to implement Boolean functions of four variables. The possible functionalities of this gate for all control input combinations are listed in Fig. 78. Among many functions, the four input AND gate (first row) and the four input OR gate (last row) are present.
The NML implementation of the above introduced QCA design is shown in Fig. 79, where the nanomagnets serve as basic elements of the circuit. Identical, small footprint magnets compose the circuit, and seven long magnets are responsible for the inputs (a – g). The driver magnets have different aspect ratios for possible separate magnetization setting as shown for the majority gate in Section 8.3.

It is possible to use this complex gate to represent more basic functions. For instance, a 3-input AND gate or a 3-input OR gate can be implemented by changing one of the variable inputs into a control input and therefore, increasing the number of control

<table>
<thead>
<tr>
<th>E</th>
<th>F</th>
<th>G</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>A<em>B</em>C*D</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>A<em>B</em>(C+D)</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>A<em>B+C</em>D</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>A*B+C+D</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>(A+B)<em>C</em>D</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>(A+B)*(C+D)</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>A+B+C*D</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>A+B+C+D</td>
</tr>
</tbody>
</table>

Fig. 78. List of the available functions of the complex gate. Three inputs (e, f, and g) set the functionality of the gate, and the remaining four inputs provide the four variables for the circuit.
inputs by one. Therefore, if this gate is available in a circuit, it could also be used in this reduced manner to fulfill computational requirements.

Fig. 79. The NML complex gate consisting of three nanomagnet majority gates (wire crossings). A, B, C, and D are the input magnets, and E, F, and G are control magnets.
NML GATES WITH ASYMMETRIC NANOMAGNETS

The behavior of slant magnets can be exploited to build nanomagnet logic gates with a reduced footprint. NML circuits require several 'biasing dots' – nanomagnets that serve as an input by providing a constant magnetization and a constant coupling field to neighboring dots. The presence of these biasing dots adds to the complexity of the design, for example, the three-input majority gate should normally perform a two-input AND or OR functionality, while the third input converts the majority gate to an AND or OR gate. Fig. 80 shows an example of a non-majority NML logic. The driver magnets are ferromagnetically coupled to the output magnet that is the center magnet. The drivers influence the final state of the center magnet only when both have the same magnetization direction.

Fig. 80. Schematic of the logic gate built from one slant magnet and two input magnets.
All possible magnetization states of the slant gate are listed in Fig. 81. Each gate consisting of two input magnets that are arranged above and below a slant output magnet is uncoupled with the neighboring gates. The input magnets have four different possible magnetization combinations. The two groups in Fig. 81 belong to two possible directions of the external clocking field (indicated by two horizontal arrows at the bottom of the figure) assuming the external clocking field influences only the slant magnets and not the input magnets. It was shown in Section 2.2 that the slant magnet has a preferred magnetization direction. In our case, it points down if the external field is applied in the negative direction (left group in Fig. 81), and it points up if the clocking field is applied in the opposite direction (right part of Fig. 81). By changing the direction of the applied clocking field, the gate functions as a logic AND or a logic OR gate, as shown in Fig. 81 on the left and on the right side, respectively.

![Fig. 81. Magnetization variations of the slant gate for all input combinations. On the left, the slant is magnetized in the negative direction, and on the right in the positive direction to change the gate from a logic AND to a logic OR, respectively.](image)
The slant AND and OR gates are alternatives to the general majority gates, since in most circuits the majority gate has to perform only one of these logic operations.

14.1 Slant gate implementation with regular shape input magnets

We present one possible implementation of the slant gate with symmetric shaped input and driver magnets. The design is sketched in Fig. 82, where the slant magnet is driven by the input magnets that are biased by the driver magnets. In this realization, the external magnetic field can be applied along the long axis of the driver magnets to set their magnetization state. The slant magnet and both input magnets are forced by this field to be magnetized along their hard axis.

Fig. 82. Schematic of the slant gate built from one slant magnet and symmetric input and driver magnets. The driver and the input magnets have the same dimensions.
Images of the fabricated slant logic gate are shown in Fig. 83. The driver magnets serve as 'hard wired' inputs for the gate. Four different locations of the driver magnets are designed to test all four possible input combinations. For each structure, two MFM and one SEM image is shown. A horizontal external field (130 mT) is applied to set the magnetization state of each gate. As the field is removed, the driver magnets keep their set state, since the field was aligned parallel to their easy axis. The input magnets are driven by the drivers, and are antiferromagnetically coupled to the slant magnet. The net magnetic field from the two input magnets – if they point in the same direction – is sufficiently strong to overcome the demagnetizing field of the slant shaped output. If and only if both inputs magnetization point in the same direction, the output magnet is forced to point in the direction of the inputs even if it is against to the slant’s preferred direction. On the left of Fig. 83, the MFM images are shown after the application of a positive external field, and on the right, the MFM images are shown after applying a negative external magnetic field. The final magnetization states of the magnets as well as of the gates are all in agreement with theory, and show the pattern predicted in Fig. 81. The device shows the expected AND/OR logic gate functionality.
14.2 Slant gate implementation with slant input magnet

The slant gate can be implemented using slant magnets as inputs as well; making the driver magnet redundant. The aspect ratio influenced behavior of the magnet can be exploited for this implementation. The input magnets of the logic gate can be set before the output magnet; therefore, the input magnets have larger aspect ratio than the output magnet. The schematic of the logic gate constructed from slant magnets is shown in Fig. 84. Here, the input magnets are not driven by driver magnets; instead the horizontally applied external magnetic field sets the state of the asymmetric input magnets that provide the bias for the center magnet that is the output magnet of this logic gate. Fig. 85 (SEM images) shows the fabricated slant gate with all input combinations, i.e., different slant locations for the slant inputs. The central magnet remains unchanged.

Fig. 83. SEM images of the slant logic are shown with pairs of MFM figures captured after magnetization with 130 mT horizontal magnetic field to positive and negative direction.
A horizontal external clocking field magnetizes all three slant magnets along their hard axes. All of these magnets have a preferred magnetization direction defined by the slant position and the direction of the externally applied field. The coupling is not sufficiently strong to the central computing magnet to define its state when the two input magnets have opposite magnetization states. The central magnet has a preferred direction of magnetization, i.e., always relaxes to the same magnetization state. If the inputs have the same magnetization state, they bias the central magnet, and determine its final state.

Fig. 85 shows the MFM images of the logic gates after a 200 mT clocking field is applied horizontally in the positive direction. The gate performs the logic OR function as summarized on the right part of Fig. 81.
The input magnets have a higher coercivity, which can be exploited to reset the magnetization of central magnets only, and keep the magnetization of the inputs with an appropriately selected small external field. We apply a 100 mT field, which is not strong enough to flip the input magnets, i.e., they point into the same direction as in Fig. 85. It is, however, higher than the coercivity of the center magnets to reset them. The MFM images summarize the state of the gate after this magnetization step in Fig. 86. The gates perform the logic AND function as it is predicted in the left part of Fig. 81. As a conclusion, the function of the logic can be changed while keeping the input magnets in their previously set state.

Fig. 85. SEM and MFM image pairs of the slant logic devices showing the four possible input combinations. The magnetization is performed by a 200 mT horizontal, positive magnetic field.
14.3 Slant magnet as an input to the nanomagnet wire

The above mentioned slant gate has one asymmetric shaped output magnet, although in more complex circuits, the output bit has to be propagated from the gate to other magnetic structures for further computation(s). Magnetic wires have already been demonstrated in previous work with regular, rectangular shaped input magnets. Here the slant magnet is used as an input of a ‘vertical’, FC wire. Since the horizontal wire is more robust and less sensitive to field misalignments, proving this concept only for the vertical wire is sufficient.

In the case of the symmetric shaped magnets, the vertical alignment of the wire requires to place the input magnet perpendicularly aligned to the first magnet of the wire as shown already in Chapter 7. This increases the footprint of the entire structure in both in-plane dimensions. The planar structure of the magnetic circuit already provides a great

Fig. 86. MFM images of the same gates as shown in Fig. 85 after a 100 mT external field is applied from the right to left (opposite direction).
challenge to design compact circuits. A regular vertical wire is shown in Fig. 38 with an input magnet perpendicularly aligned to the wire.

To reduce the footprint of the vertical wire, we replace the horizontal input magnet with a slant magnet, as shown in Fig. 87a along with several horizontally aligned standalone magnets. The two vertical wires have different input magnets, i.e., their slant location vary. This provides us with an opposite input state after a horizontal field excitation is applied, as shown in Fig. 6. The horizontal magnets, on the left side of the array, are indicator magnets to show the direction of the externally applied magnetic field. Fig. 87 b) and c) show the MFM images of the array after positive and negative magnetization directions, respectively. The magnetic moment of the wire-pairs points in opposite directions due to the different biases provided by the slanted magnets that function as inputs.

![Fig. 87. SEM image of the vertical wires with slanted input magnets and four horizontally aligned indicator magnets (a). MFM images after magnetization with a horizontal field in the positive and negative direction, respectively (b and c).](image-url)
This experiment shows that the slant magnet is able to set the magnetization of the entire wire, i.e., the output bit can be propagated away from a slant magnet for further processing. This vertical wire has smaller footprint compared to the regular design shown in Section 7.1.

### 14.4 Conclusions

The asymmetric shaped slant magnets have unique switching behavior because of their tilted energy landscape. Simulations showing the energy corresponding to various magnetization states are shown in Section 2.2. In this chapter, we demonstrated the benefits of these slanted magnets, i.e., nanomagnet logic device can be built by coupling the input to the slant output magnet. Symmetric and asymmetric shaped magnets were introduced for the input implementation. Both structures were fabricated and tested successfully. NML logic devices demonstrated so far had been based on majority gates. This work on slanted magnets allows the direct and compact realization of AND and OR gates.

To prove that the information (i.e., that the output of the gates) can be propagated from a slanted magnet as well, we demonstrated the nanomagnet wire with slanted input magnets. The experiment with the slanted input wires proves that a slanted magnet can drive an entire wire.
Magnetic computing is an emerging technology for future electronics, which may enable robust, low-power operation devices with a natural combination of logic and memory. Magnetic logic operations may be performed either by using interacting single-domain nanomagnets as described in the previous chapters of this thesis or by interacting domain walls (DWs) [12]. It could be fruitful to combine these approaches into devices that exploit the interaction of domain walls and nanomagnets. It was previously demonstrated that single-domain nanomagnets can pin domain walls [66], and work is ongoing to demonstrate the action of domain walls on nanomagnets [67, 68, and 69]. Domain walls act as strong, localized, on-chip sources of magnetic field; such fields are often required for the switching of nanomagnets.

Here we demonstrate that domain walls can be exploited to reduce the (external) field required to switch nanomagnets. We fabricated structures where (1) standalone nanomagnets, (2) nanomagnets coupled to domain wall conductors (DWCs), and (3) nanomagnets coupled to a Permalloy stripe are present. We applied external magnetic fields in appropriate directions and observed the switching of nanomagnets and DWCs by magnetic force microscopy (MFM). The externally applied magnetic field generates a domain wall and biases the nanomagnets. Our experiment demonstrates that
nanomagnets in close proximity to the DWC are switched by fields with a 10 mT lower magnitude than isolated magnets.

15.1 Sample design and fabrication

The domain wall conductor along with the standalone nanomagnets are fabricated with the recipe described in Chapter 3. Fig. 88 shows an SEM image of the fabricated structure with two different DWCs, one with (left) and one without (right) a large-size injector structure. Both DWCs are terminated with a pointed end to prevent the nucleation of a DW at this end. The DW injector is a 2.5 μm diameter disk, which, when exposed to low magnitude magnetic fields, easily splits into multiple domains and can inject a wall into the DWC. A much higher field is required to nucleate a wall in the injector-free Supermalloy stripe.

The nanomagnets are 60 nm ×90 nm rectangles spaced sufficiently far apart to have negligible (<1 mT) coupling with each other. Ten nanomagnets are separated by approximately 15 nm from each DWC. We verified that none of the magnets touch the DWC. The inset of Fig. 88 is a magnified view of the first magnet next to the DWC with injector to clearly show their separation.
Fig. 88. SEM image of the tested structures. The domain wall conductor on the left has an expanded injector end, and on the right has a slightly rounded end to nucleate the domain wall. The inset is a magnified view of the first magnet next to the DWC with injector to clearly show their separation.
15.2 Sample characterization

Before obtaining an MFM image, the sample is first magnetized by a 100 mT field along the 10° direction, as indicated in Fig. 89. This defines the state of the nanomagnets and the DWCs. An MFM image of this initial state, overlaid with interpretative arrows, is shown in Fig. 89.

Fig. 89. MFM image of the structures after a 100 mT magnetic field is applied 10° from the horizontal direction.

Starting from this magnetization state, the sample is magnetized along the 225° angle with fields ranging from 10 mT to 50 mT. This field direction provides a component along the DWC, which creates a domain wall. A field component is also
provided along the easy axis of the nanomagnets, which biases them toward switching. The magnetic fields are applied using a standard two-pole electromagnet using a slow (mT/s) field rise time. MFM images are taken afterwards with no applied field.

We found that fields below 30 mT are insufficient to flip any of the dots or DWCs. Fields between 30 mT and 40 mT switch the DWC with the large injector, as well as the dots adjacent to this DWC, but not the other dots (Fig. 90). Fields above 45 mT flip all nanomagnets. However, this field magnitude is still insufficient to nucleate a wall in the injector-free DWC. The experiments are reproducible with similar results for nominally identical patterns. There is some randomness in the switching patterns due to the switching field distribution (SFD) of the nanomagnets. In some samples approximately 20% of the dots next to the DWC do not switch for a 30 mT field, and approximately 20% of the dots located further from the circular end of the DWC switch prematurely for a 40 mT field. This SFD is consistent with expected shape variations inherent in the sub-100 nm lithography process. We did not observe evidence of the MFM tip influencing the magnets.

The injector-free DWC only switches for externally applied fields with magnitudes greater than 50 mT. The dots next to this DWC behave identically to the dots located farther away from the DWCs.
15.3 Discussion

We interpret the results as domain wall assisted switching. The switching field of standalone nanomagnets along the 45° axis is approximately 40-45 mT. However, for magnets close to the DWC the passing domain wall provides an additional 10 mT; therefore, these magnets switch already with an external field of 30 mT. Dots in the vicinity of the injector-free DWC switch at the same field magnitude as the standalone dots, proving that the domain wall and not the weak static field of the Supermalloy stripe induces the switching.
In this experiment, we cannot observe the dynamics of the domain wall assisted switching and different interpretations of the results are possible. For example, it is possible that the passing of the domain wall generates end-domain states in the dots, which reduce their switching field. Another interpretation might be that the stray field of the wall directly switches the dots.

### 15.4 Simulations

In order to gain more insight into the switching process, micromagnetic simulations are performed using the OOMMF code [28].

The external field is swept in a quasi-static way; each time the magnetization distribution converged to a stationary pattern, the external magnetic field is incremented by 0.1 mT. This is consistent with the fact that the time scale of the field sweep (in the order of seconds) is very slow compared to the nanosecond magnetization dynamics. We used standard parameters for Permalloy (saturation magnetization $M_s=8.6\times10^5$ A/m, exchange stiffness $A_{\text{exch}}=1.3\times10^{-11}$ J/m$^3$, damping constant $\alpha=0.5$). The damping constant in the simulations is much larger than the real value that is approximately $\alpha=0.01$. The overdamping allows the simulation to converge in reasonable time, without significantly changing the results of the quasi-static simulation. Domain wall dynamics (nucleation and propagation times) could be more inaccurate. Temperature fluctuations are not taken into account, which may lead to a slight overestimation of switching fields. We used a relatively crude numerical mesh (5 nm cell size), which allowed the simulation of the entire structure (a 50 hr simulation on a four-core machine). Since the numerical
mesh is misaligned with the dot boundaries, the simulated dots may vary ±10 nm from their nominal 60 nm × 90 nm size. This size variation takes into account, to a first approximation, the switching field variations due to fabrication variations.

Simulation results agree reasonably well with measurements, and confirm that a transverse-type domain wall directly switches the nanomagnets. Simulations indicate a $B_{\text{nucleation}}=25$ mT nucleation field for the domain wall, which is somewhat higher than the measured field strength. The slight disagreement is probably due to the fact that the nucleation field is extremely sensitive to the geometry of the region that connects the DWC to the injector pad. This funnel-like shape is probably inaccurately represented on the simulation mesh. Snapshots from the simulations are shown in Fig. 91 and Fig. 92. Upon reaching $B_{\text{nucleation}}$ the domain wall is injected into the DWC and runs along it (Fig. 91a and Fig. 91b). The nucleation lasts approx. 23 ns, and it takes another 13 ns for the DW to completely propagate through the DWC. As shown in Fig. 91b, the domain wall reverses all adjacent dots.
Fig. 92 shows the DW assisted switching in more detail. The DW is a head to head transverse type wall and its chirality remains constant during propagation. The external field (with an upward-pointing component) also helps to stabilize this chirality. The switching process appears to be very well controlled and the nanomagnets switch deterministically, one by one when exposed to the field of the domain wall.

Fig. 91. Snapshots of the DW assisted switching process. The entire structure is shown at $B_{\text{nucleation}}$, right before (a) and after (b) the DWC reverses. The spacing between the DWC and the dots is 10 nm, which is not visible due to the finite image resolution. There are four prematurely switched dots in the structure.
We do not observe any pinning effect from the dots on the wall. This is explained by the relatively high nucleation field of the DW: once the domain wall is ejected from the injector, the external driving field is more than sufficient to overcome the attraction between the dots and the wall. In this experiment, the injector is engineered for such a large nucleation field to avoid the domain wall to propagate through the DWC before the dots are sufficiently biased. Changing the size and shape of the funnel-shaped pad [70], nucleation fields of a few mT could be achieved [71]. For this configuration, the drag of the dots to the domain wall would become significant [72]. Simulations on the injector-free DWC did not show the DW nucleating for applied fields with magnitude of less than 50 mT, which is in agreement with the experiment.

Fig. 92. Enlarged views of the DW area showing the details of the transverse DW. As the DW propagates through the DWC, the nearby magnets switch.
15.5 Proposed structure

The domain wall generates a complex field distribution with components pointing in all three spatial directions. Above we introduced simulations as well as experiments that exploited only one field component. Here, we propose another experimental design to further take advantage of the moving domain wall generated magnetic field.

Fig. 93 shows the schematic of two possible experiments. Several nanomagnets are placed on the top of the domain wall conductor in both cases. The only difference between the two designs is the orientation of the nanomagnets. In Fig. 93a the long axis of the nanomagnets is perpendicular to the DWC, while in Fig. 93b it is parallel. These two orientations help to experimentally investigate the strength in the x and y directions of the DW generated field. The magnets are separated by several hundreds of nanometers to avoid any magnetic interaction between them and are magnetically isolated from the conductor by a few nm thick Ti layer. Five nanomagnets serve as reference magnets. They are separated from the wire to avoid any influence on their magnetization state by the field of the moving domain wall.
15.6 Conclusions

Domain wall-based devices may become a major component in future mass storage [73, 74]. In this chapter, we explored a novel application for DWs: they could be used for on-chip magnetic field generation and switching of nanomagnets.

We demonstrated experimentally and by means of simulations that the field of a propagating domain wall assists the switching of single-domain nanomagnets.
Simulation results agree remarkably well with the measurements. In the present experiment, the domain wall contributed a 10 mT field. We believe that in optimized geometries this value may be increased significantly [69]. The magnetic field of domain walls can reach the few-hundred mT range, though only within a 10-30 nm distance from the domain wall. This field may penetrate the entire volume of smaller nanomagnets and switch them without the assistance of an external field. It is also possible to generate wider field distributions from larger-size DWCs, however, these DWCs tend to develop vortex-type walls, with more unpredictable stray field distributions.

We believe that DW assisted switching of nanomagnets may find useful applications in spin electronics, especially in NML devices. Propagating a DW requires a field of only a few millitesla, which can easily be generated by on-chip coils or wires. The DWC amplifies the propagating field by orders of magnitude. Incorporating DWs in magnetoelectronic devices may dramatically increase their net power efficiency.
RADIATION HARDNESS TEST OF NANOMAGNET STRUCTURES

NML devices have good potential for high-radiation environment applications. The understanding of their response to ionizing radiation is required. Several material studies are already completed to investigate the effect of neutron radiation on Permalloy [24] and Supermalloy for layers of different thicknesses [23, 25]. The hysteresis loop and the permeability of the material before and after irradiation were measured. As the conclusion of these works, small to little change in the magnetic properties is expected. It is however important to confirm this result for nanomagnet samples in order to establish a reference point for future work.

In our work, we are interested in patterned structures on the nanoscale, i.e., individual nanomagnets as well as nanomagnet structures. Our goal is to show radiation hardness of nanomagnets with sizes ranging from several tens to couple of hundreds of nanometers as well as of NML wires. In our experiment, the magnets are magnetized before the irradiation and scanned with MFM. The irradiation is followed by another MFM scan. We compare the magnetic state of all magnets before and after the irradiation to determine if any magnetization changes were caused by the irradiation.

---

The nanomagnet structures are irradiated by Matt Kay at the Naval Surface Warfare Center.
16.1 The irradiated samples

Two different samples are tested for radiation hardness. One has a matrix of standalone nanomagnets with various aspect ratios. The largest magnet has a 300 nm × 300 nm footprint, and is located in the top right corner of the matrix shown in Fig. 94. Along the two axes of the matrix, the width and the length of the magnets is decreased by 5 to 10 nm from row to row and from column to column, as shown in Fig. 94.

Fig. 94. SEM image of the nanomagnet array used for radiation hardness test. The nanomagnet with the largest footprint is located in the top right corner (300 nm × 300 nm). The width and the length of the nanomagnets decrease from line to line by 5 to 10 nm.
The other tested structure is shown in Fig. 95. It consists of pairs of vertical wires with nearby standalone magnets. The vertical wires have slant input magnets. This structure is already demonstrated in Section 14.3.

![Fig. 95. SEM image of four pair of vertical nanomagnet wires with several standalone magnets. This structure is tested against irradiation along with the standalone magnet matrix shown in Fig. 94.](image)

16.2 **Irradiation**

The samples are exposed using the Cobalt 60 Shepard Irradiator at Naval Surface Warfare Center (NSWC) Crane. Thermoluminescent Dosimetrics (TLDs) are used to calculate the exposure time. The samples are neutron irradiated with 10 Mrad energy. Note that this is an extremely high energy radiation, since 1 rad = 6.24e7 MeV per gram. The test specimens are shipped back Notre Dame for post irradiation characterization.
with MFM. The samples are shipped in a shielding box to avoid any magnetic interaction during the transport.

### 16.3 Results and Conclusions

The nanomagnets are magnetized along the top-down direction with a 200 mT strong external field to define their initial magnetization state before the irradiation. MFM scans are performed following the magnetization and after the irradiation to compare the magnetization state of the nanomagnets pre and post irradiation.

The SEM image of one part of the large nanomagnet array is shown in Fig. 96. The MFM images of the same group of magnets before and after the irradiation are shown in Fig. 96b and Fig. 96c, respectively.
The two MFM images are identical, therefore the irradiation does not have any effect on the magnetization state of the standalone nanomagnets. Other parts of the array are scanned as well with the same conclusion.

The second sample is magnetized along the horizontal direction with 150 mT external field. In this specific structure, two out of the eight vertical wires have one error. They are indicated by white arrows in Fig. 101a. The expected behavior of the slant magnet driven wires are already introduced in Section 14.3. The MFM scans of before and after the irradiation are two identical images.

Fig. 96. SEM (a) and MFM (b and c) images of one part of the array tested for radiation hardness. MFM scans are performed before (b) and after (c) the irradiation. The contrast lines in (b) between the magnets are image artifacts, they do not influence the outcome of the measurement.
We can conclude that the 10 Mrad irradiation does not have any influence on the magnetization state of any standalone magnets nor the NML structures with or without any initial coupling errors. This conclusion is promising and opens the path for possible space environmental NML applications.

Fig. 97. MFM images of before (a) and after (b) irradiation. Even the errors are located at the same locations.
17. NML RELATED CHALLENGES

In this chapter, we introduce several challenges that we faced during our NML research. We studied the nanomagnet domain structure, the coupling between nanomagnets in various NML wires, as well as made an attempt to experimentally show temperature effect on the magnetization of horizontal wires.

17.1 The domain structure of the nanomagnets

Our goal is to build NML devices from single-domain nanomagnets. The smallest fabricated magnets in this work have an approximately 60 nm × 90 nm footprint with a 20 nm thickness. Recent simulations show (Fig. 98) the phase diagram of small magnets, i.e., the magnetic state of the nanomagnets as a function of their size [29]. For nanomagnets with relatively small size and high aspect ratio, the single-domain state is energetically favorable, while for low aspect ratio and large size magnets the vortex state becomes energetically favorable. Fig. 98 shows that there is a range where different magnetization states can coexist, i.e., between the $E_{\text{diff}} = 200 \text{ kT}$ and the $E_{\text{diff}} = -200 \text{ kT}$ contour lines. In this area, neither the flux-closure state nor the single-domain state is preferred during the relaxation of the nanomagnets. Our magnets are close to the 200 kT
line, which suggest that they possibly can relax into a vortex state instead of a single-domain state.

During the MFM characterization of our structures, the nanomagnets show single-domain state in the scan image without any evidence of probe influence on the magnetic state. The scan is performed in two passes (Section 5.3), which means that the probe scans for topography information close by to the surface first and for magnetic information second. During the first pass, the magnetic probe approaches the sample close enough to influence the magnetization state of the sample; therefore, the second pass would measure an already modified magnetic state. Since the vortex and the single-domain state have approximately the same energy levels between their contour lines shown in the simulation, the probe and the bias field of the neighbor magnet might flip a

Fig. 98. Phase diagram of a nanomagnet with fixed 20 nm thickness. The contour lines show the energy difference between the single-domain and vortex states\(^3\).
magnet from a vortex state into a single-domain state. To determine if a magnet is truly in a single-domain state, a non-invasive magnetic information scanning method is necessary. In our case, a spin-SEM is used to provide a high resolution study of the nanomagnet magnetization. Among several scanned magnets, we found one with a multidomain magnetization pattern (Fig. 99). Of the three shown magnets, the central magnet has a horizontally magnetized area in its top most region. We have to note here that this magnetization state will not be visible with any invasive scanning techniques, since the top area of the magnet can be easily magnetized by a weak probing field. The multidomain state is not stable. Fig. 99 proves that the nanomagnet can relax into a multidomain state.

Fig. 99. Spin-SEM image of one horizontal magnets and two vertical magnets. The horizontal magnet drives the vertical magnets. The center magnet has a multidomain state indicated by two arrows.
17.2 Coupling between the nanomagnets

In our NML devices, the nanomagnets are separated by 20 nm. At this distance, the fringing field originating from one magnet is sufficiently strong to interact with its neighbor, and to set its final magnetization state during the magnetization process of the entire structure. This physical effect is used to propagate the information from the driver magnet toward the output of each structure. In this section, an experiment showing weak coupling at the end of a nanomagnet wire is introduced.

Spin-SEM scans are performed on several staircase wires (more details are discussed about this structure in Section 7.5). One of these wires shows one single error in the very last magnet (Fig. 100, top image), i.e., the coupling between the second to the last and the last magnets is not strong enough to influence the magnetization state of the last magnet.

A 1.6 nm thick layer of iron is evaporated from a Knudsen cell under UHV on top of the entire structure to improve the magnetization contrast of the spin-SEM scans. The scan is repeated on the exact same structure, which now shows the correct magnetization state of the last magnet (Fig. 100, bottom image). We presume that the iron layer provided an ‘amplified’ magnetization interaction that is sufficiently strong to flip the magnetization state of the last magnet.

We conclude from this experiment that the coupling might not be sufficiently strong at the end of the wire to set the correct magnetization state of the very last magnet. With the help of the iron layer, this magnet can also reach the lowest energy state, the AFC state.
17.3 Ferromagnetic and antiferromagnetic coupling in the nanomagnet wires

Horizontal and vertical wires have AFC and FC coupling, respectively. Successful experiments are shown already in Section 7.1 for short, five-magnet-long wires. In case of relatively long AFC and FC lines, it has to be taken into account that the magnets of same dimensions in the horizontal and vertical wires relax to their ground state for different external field magnitudes. This happens because the ferromagnetic
coupling adds to the horizontally applied field. This is why the marked magnet in Fig. 61b fails to work correctly with high percentage as shown later in Section 17.5.

OOMMF simulations are performed to understand the different wire behaviors. The results are shown in Fig. 101. As the external field is decreased from 300 mT, the long horizontal wires start to switch to their antiferromagnetically ordered ground state at around 60 mT field, while the vertical wires start to order at around 200 mT. The horizontal (AFC) wires relax at a later time than the vertical (FC) wires. This is a significant difference and may cause information to propagate in the wrong direction along the wire. If a long horizontal wire precedes a long vertical wire segment in the signal flow, then the dots of the vertical segment may fall to a random magnetization state before the effect of the drivers can reach them via the horizontal wire.
Fig. 101. Simulation results for vertical (top) and horizontal (bottom) magnetic wires. The $M$ vs. $H$ graph shows smooth switching behavior for the vertical line, though not for the horizontal one. Since the external field is reduced from high to low magnitude, the horizontal wire switches after the vertical wire. This difference has to be taken into account during the design of any NML structures.
17.4 Temperature effect in characterization

All of the experiments described above are performed at room temperature. Thermal fluctuations randomize the state of the magnetic moments, i.e., the spins of the material are never perfectly at rest in the ground state at non-zero temperature. One consequence of this is that the nanomagnets cannot be arbitrarily small since in that case the temperature fluctuations could flip their magnetization state and destroy stored information. The switching frequency \( f_{\text{switching}} \) of a standalone magnet depends exponentially on the energy barrier \( \Delta E \) and the temperature \( T \), as it is summarized in the equation below,

\[
\begin{align*}
f_{\text{switching}} &= f_0 \times \exp\left(-\frac{\Delta E}{kT}\right), \\
\end{align*}
\]

where \( f_0 \) is the attempt frequency with an approximate value between 0.1 GHz and 10 GHz [75]; and \( k \) is the Boltzmann constant. It is calculated that the coupling is about 150 room temperature \( kT \) between nanomagnets with footprint about 60 nm × 90 nm × 20 nm. Our equation shows that this value is sufficiently strong to result in robust, room temperature operation, and to preserve the stored information for several decades. Further calculations show that “sub-100 nm size dots are sufficiently stable against temperature fluctuations, but thermal noise imposes design constraints for structures with long signal paths” [76]. According to this calculation, experimental results of [77] show that 40 \( kT \) barrier is sufficient to preserve magnetic information for a decade.

The number of nanomagnets in a circuit increases the number of metastable states. The magnetization process switches the magnets from one low energy state to another one. During clocking, the energy barrier between two stable states is lowered;
and thermal fluctuations can easily turn the magnetization around and have a strong influence on the final magnetization state of the magnet. Magnets that are stable at their ground state can still be susceptible to thermal fluctuations during switching.

Here we attempt to compare experimental results done at room temperature and at liquid nitrogen cooled temperature.

At room temperature, we tested the seven nanomagnet long horizontal wires already characterized in Section 7.4. The magnetization procedure is repeated several times with different magnetization methods. We study here the state that does not show any ordering errors. Our interest is to determine whether a certain wire has any errors after various magnetization scenarios. The result is summarized in Fig. 102. The Venn diagram shows that 25% of the studied wires work perfectly for each and every magnetization method; 15% has no error for either of the pumping and for the rotating field methods, but show some errors after the shaking magnetization is performed; and 23% of the wires work perfectly only after shaking magnetization, but fail for any other magnetization method.

As a conclusion, every 4th wire works without any errors for any magnetization pattern at room temperature. Since no other evidence is clear from this analysis, we conclude that this kind of statistic does not provide much insight in the error formation mechanisms of nanomagnet wires.
We repeat the shaking magnetization pattern in liquid nitrogen environment to determine if the ambient temperature has any effect on the coupling error rate. We use the same magnetization parameters as in the previous section to obtain a true comparison. The room temperature test had an outcome with 51% (Fig. 41). The cold environment result is shown in Fig. 103 with 62%. This means that 62% of the wires have no error. Since repeated magnetizations with the same method also give an approx. 5% variability, the 10% difference between the room temperature and liquid nitrogen-temperature magnetization tests are statistically small. Using MFM image analysis it is difficult to
obtain a significantly larger data set and it would be useful to develop new characterization techniques to deepen understand temperature effects.

The experiment in cold environment is repeated using ten times slower sweep rate for the externally applied magnetic field. This experiment takes longer to complete, and the magnets experience a smoother increase and decrease of the field magnitude during the shaking process. The result is summarized in Fig. 104. Although the outcome (66%) is better than in the previous case (62%), the difference is small.

Based on the equation shown above cooling of the magnets to a nitrogen temperature is expected to cause exponentially strong reduction of thermal errors. The observed reduction of errors is instead very insignificant suggesting a different (not thermal) mechanism of error formation.

Fig. 103. In cold, liquid nitrogen environment, 62% of the wires have no coupling error after the shaking magnetization.
17.5 Possible back propagation in horizontal nanomagnet wires

In the nanomagnet wire, the information propagates from the driver magnet toward the end of the wire. The propagation is provided by the interaction of the fringing fields of neighboring magnets for both AFC and FC coupled wires, i.e., horizontally and vertically aligned wires. The clocking field defines the input bit, as well as forces the remaining magnets into a metastable state. As these magnets relax into a stable state, the driver magnet biases the first magnet of the wire, which in turn biases the second magnet, and so on. As our structures are characterized with MFM, we cannot study the dynamics of the switching process. The acquired images show only the ‘before’ and ‘after’ magnetization state of the structures, although we can gain some insight to the magnetization process using micromagnetic simulation (OOMMF tool). Even if the
simulation outcome shows the dynamics of the nanomagnet ordering according to our expectations at room temperature, it cannot take into account all fabrication and crystal structure defects.

In several cases, the output of the characterization clearly shows some errors in the magnetic ordering of the wires or other structures. We attempt to investigate the error formations, and define whether the end of the wire could have any influence on the final state of the entire wire, i.e., information back propagation might be present. To answer this question, 7 and 16 magnet long horizontal NML wires are fabricated; 120 identical wires are fabricated for both lengths. Shaking magnetization is used to avoid any errors caused by field misalignments. The magnetization process is repeated twice: shaking I and shaking II. We count the errors in each wire after each magnetization. One error is defined as a coupling failure between two neighboring magnets. To see the end-effect present, the last 9 magnets of the 16-magnet-long wire is neglected, and only the first 7 magnets are investigated for any errors. Fig. 105 summarizes the results. Fig. 105 a) and b) shows the number of errors in the short, 7-magnet-long wires. A little more than half of the wire performs perfectly. Fig. 105 c) and d) shows the number of errors in the first 7 magnets of the 16-magnet-long wires. Here, significantly fewer than the half of the wires performed without any coupling errors.

The charts for the 7-magnet-long wires and for the first seven magnets of the longer wires show a significant difference between the numbers of errors. We speculate that the difference might stem from the fact that the second part of the long wire influences the first part, i.e., backward propagation of information in long wires. This
experiment illustrates the shortcomings of the globally applied magnetic field for clocking. A localized clocking field could improve these devices.

Further studies are necessary to gain more information on the propagation, and error formation in the NML wires (both horizontal and vertical ones).

17.6 Conclusions

Understanding error formation in NML circuits is one of the most important challenges of future NML research. Most of our studies turned out to be inconclusive,
since the present experimental setup is not appropriate for this purpose. MFM studies are relatively slow, and reliable, in-situ magnetization of the sample is not possible. A priority of future research is to develop new methods for the reliable statistical characterization of NML gates.
Finally, we would like to summarize the original contributions to the research on nanomagnet logic devices.

1. We have developed a new fabrication recipe that is capable to build NML devices from closely spaced, small footprint nanomagnets with sufficiently good cleanliness and shape control.

2. We have shown the potential of shape engineering for NML applications via both simulations and experiments for different aspect ratio magnets and for slant magnets.

3. We have experimentally realized novel NML device components, such as the staircase-like wire, the programmable majority gate, and the fanout structure, as well as the AND and OR gates with slant magnets.

4. We have demonstrated for the first time several multi-gate NML circuit designs, such as the comparator and the complex gate, furthermore an operating full adder and the XOR gate was experimentally realized.

5. We have experimentally demonstrated that the magnetic field of the propagating domain wall is able to influence the magnetization of nearby nanomagnets.

6. We have performed radiation hardness test on standalone nanomagnets as well as on NML wires.

7. We have recognized a number of NML related fabrication issues, characterization limitations, and some poorly understood magnetic behaviors, and have proposed possible solutions for them.
The spin-SEM signal is formed in the top few nm of the sample; therefore, extremely clean surface is necessary. Sputter cleaning is a widely used physical cleaning method for solid samples under vacuum, which removes the top atomic layer of the sample by bombardment. This method is used for the first time in 1955 by Farnsworth, Schlier, George, and Burger to prepare ultra-clean surfaces in UHV for low-energy electron-diffraction (LEED) studies [78]. Since sputter cleaning can re-contaminate the surface continually during the process, it is important to use clean plasma. Re-deposition of sputtered material on the substrate can also cause problems, especially at high sputtering pressures. Sputtering of the surface of a compound or alloy material can result in the change of the surface composition. In the system that we used at IBM Zurich [79], a noble gas, neon, is introduced, which allows us to keep the number of implanted atoms at a negligibly low level. Neon has a comparable mass with oxygen and carbon, both of which should be removed during the sputtering process. The sputtering occurs in the chamber, where the neon is introduced at a pressure of 1.2e-5 mbar. A filament with 10 mA emission current at 3.5 keV source energy is used for the sputtering process. An

---

8 The author was an intern at IBM Zurich, where all spin-SEM related work is completed.
ion pump is used to maintain the UHV pressure. During the cleaning process it is switched off and a turbo pump is used to provide the sputtering pressure in the $10^{-7}$ mbar range ($1 \text{ Torr} = 1.33 \text{ mbar}$), while pumping away the generated particles along with the neon atoms. For alignment, an electron emission image of the sample is displayed on a screen. This system is calibrated in such a way that 1 nm material is sputtered away in 10 minutes. The goal is to remove the native oxide, the carbon contamination, and the cap layer from the surface.

The surface is analyzed with Auger spectroscopy before and after the sputter cleaning to compare the material composition of the surface and to determine any further necessity of cleaning. Auger spectroscopy is a powerful tool for surface analysis of almost any solid, non insulating sample. The sampling depth is shallow, and information is provided about the material composition only from the top few monolayers of the surface to determine the cleanliness of the sample. During the data acquisition, the sample is aligned perpendicular to the 2 kV energy beam. The measurement is supported by a lock-in amplifier, which is powered by a channeltron or channel electron multiplier (2.86 kV). The output is given to an x-y recorder where the spectrum is displayed on a mm scaled sheet.

The typical scanning beam energy ranges between 2 and 10 keV, while the beam current scales from 0.1 to 1 nA. The unpolarized electron beam scatters from the sample surface primarily by inelastic scattering, i.e., the beam electrons partially lose energy and excite low-energy secondary electrons (SE). SEs travel back to the surface, and escape into the vacuum, where different detectors are located, e.g., InLens, SE detector, and spin detector. The typical SEM detectors (InLens and SE detectors) count the number of
electrons received at each scanning position of the beam, which yields the surface
topography map.

The operating principle of the various spin detectors is based on the same physical
principles, such as the use of the spin-orbit interaction as a means of transforming a spin
asymmetry into a spatial asymmetry. The Mott detector, in which the electrons are
accelerated to high energies and scattered by a high-atomic number target like Au foil, is
widely used. Since different spins have different scattering planes, two pairs of detectors
are located at the angle of the maximum scattering asymmetry. The spin polarizations of
the electrons are antiparallel to the magnetization vector in ferromagnetic materials. The
polarization (P) is defined as $P = \frac{N \uparrow - N \downarrow}{N \uparrow + N \downarrow}$, where the $N\uparrow$ and $N\downarrow$ are the
number of electrons with antiparallel and parallel spins. P is a normalized quantity,
which makes the measurement independent of changes in the total number of emitted
electrons, i.e., the fluctuation of the incoming beam is cancelled out from the
measurement.

An overview image of the entire spin-SEM system is shown in Fig. 106
(chambers with several detectors, viewports, as well as various evaporators). As shown
in the figure, multiple chambers, such as the introduction, the preparation, and the
experimental chambers, are required due to the necessity of UHV. Limited space inside
the chambers requires us to install a sample with a maximum diameter of 10 mm. The
sample is affixed to a sample holder, shown in Fig. 107, with silver paint and a forked rod
is used to move the sample between chambers with various vacuum levels and functions.
Fig. 106. Spin-SEM system at IBM Zürich.

Fig. 107. Sample holder for sample relocation between the chambers.
The introduction chamber, shown in Fig. 108, provides the interface between the UHV system and the atmospheric pressure environment. It has several parts including two small chambers, the exchange chamber, and the cross (the two sample navigation axes are crossing each other here). The sample is moved with a short rod between these chambers. The sample is attached to the rod at atmospheric pressure and mounted in the exchange chamber, where a turbo pump maintains the vacuum level around $10^{-6}$ Torr. The next vacuum level is in the cross ($10^{-9}$ Torr), which is maintained by an ion pump. Here, a stage supports the sample while it is unmounted from the short rod and mounted on the long one (Fig. 109). This stage can move the sample in the z-direction (up-down).

Fig. 108. The introduction chamber provides the connection between the UHV and atmospheric environment.
From this point on, the sample is under UHV. The next step is to move it to the preparation chamber (Fig. 110a), where the cleaning and surface analysis of the sample is conducted by neon sputtering and Auger spectroscopy, respectively. Small chambers provide the instrumentation for sample preparation, such as a neon source with a filament for sputtering, detectors, a 2 kV filament for Auger spectroscopy, evaporators for in situ film growth, etc.

The prepared sample is moved through a valve to the experimental chamber (Fig. 110b) for high resolution SEM and spin-SEM scanning. The extension on the right of the experimental chamber is the detector system, which consists of the electron optics and a Mott spin-polarization analyzer operated at 100 keV.

Fig. 109. The forked end of the long rod above the stage in the cross.
The electronic parts are not shown in the previous figure due to their extended size. Fig. 111 summarizes the different parts. The electronics supporting the Auger scan and the sputtering process are shown on the left side, while the spin-SEM electronics are shown on the right side.

The introduced chamber system provides everything that is required for the spin-SEM characterization of a magnetic sample under UHV, i.e., cleaning, surface analysis, SEM scanning for localization, and spin detection.
Fig. 111. The supporting electronics for the three-chamber system.
APPENDIX B:

PUBLICATIONS

Results of the research that is presented in this dissertation are published in journal articles and conference manuscripts that are listed below:

JOURNAL PUBLICATIONS


PATENTS


CONFERENCES


E. Varga, A. Imre, L. Ji, and W. Porod, „Simulation of magnetization reversal and domainwall trapping in submicron NiFe wires with different wire geometries,” the poster is presented on the 11th International Workshop on Computational Electronics (IWCE-11), Vienna, Austria, 2006.


L. Ji, E. Varga, A.Wolf, A. Imre, G.H. Bernstein, A. Orlov and W. Porod, „Investigation of different wire geometries for magnetization reversal and domain-wall trapping in submicron permalloy wires,” the poster is
REFERENCES


[33] Elionix 7700 EBL Manual


