Fabrication of nanomagnetic logic components via nanoimprint lithography

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This theis is dedicated to my mother Yasmin Intaar and my father Muhammad Intaar.
Abstract

Nanomagnetic Logic (NML) is a promising new method for performing logic operations, offering an alternative to silicon based logic technology with advantages of low power consumption and robustness. In this thesis we use nanoinprint lithography (NIL) for the fabrication of NML. Using this fabrication technique we exploit advantages of low cost and mass production. We devise three different techniques for using NIL i.e. (1) nanotransfer printing, (2) electrodeposition and (3) Lift-Off. We look into the different challenges in fabrication and demonstrate the utilization NIL for NML. We fabricate a magnetic nanowire, majority gate and full adder. Scanning Electron Microscope (SEM), atomic force microscope (AFM) and magnetic force microscope (MFM) results of the fabricated nano structures are presented.
Acknowledgements

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Chapter 1

Introduction

Technological advancement requires the identification of limits of state of the art and devising a plausible strategy to go beyond the limits. This needs a thorough look into the current technologies and a realistic look into the perceivable future of that particular filed of research. In this thesis, we look into the fabrication methods of nanostructures. We discuss the state of the art. We shall deconstruct it, looking into the limits and then talk about a plausible strategy of going beyond the limits.

Nanoimprint Lithography (NIL) has been used to make Nanomagnetic Logic (NML) in the course of this PhD thesis. NML has already been demonstrated by [1] as a working logic operation entity which promises very low power consumption and robustness in harsh environments. Electron Beam Lithography (EBL) is traditionally used to make the nano structures required for NML but EBL is a very slow fabrication process and is not feasible for large scale production. NIL is a non-conventional fabrication technique which is not only low cost but is also a fast fabrication technique for nano structures. In this thesis we fabricate NML using NIL, which has not been demonstrated before. The whole idea is to have a fabrication process which is suitable for large scale production for NML which is gaining rapid popularity ever since its conception.

The arrangement of the chapters is as follows:

In chapter 2 we discusses details of NIL starting from the first experiments and the moving towards its modern day use. We will also talk about NML, the vocabulary
1. INTRODUCTION

associate with it and some working description.

In chapter 3 we talk about the first applications for which we used NIL for fabricating nanomagnetic structures. We talk about electrodeposition and how NIL is used to do electrodeposition of magnetic structures.

In chapter 4 we will discuss the second application of NIL for fabricating nanomagnetic structures, and this time for NML. Some of the problems faced will be looked into and then the approach to solving these problems will be explained.

In chapter 5 we go into the third application of NIL as a process for fabricating nanomagnetic structures. Nanotransfer printing is a variation of NIL and is a single step fabrication process.

Chapter 6 presents an overall conclusion to the whole thesis and also looks into some future work that can be done.
Chapter 2

Nanoimprint Lithography and Nanomagnetic Logic

This chapter will be an introduction to the basic concepts of NIL and NML. The first part of this chapter will cover an introduction to nanoimprint lithography, where its basic concepts and its different types will be discussed. The second part will talk about nanomagnetic logic and its basic concepts. But first, we shall talk about the driving force for research in the semiconductor industry, i.e. Moore’s law.

2.1 Moore’s Law

Moore[2] gave a statistical projection of how the number of components per Integrated Function will increase. Over the years this statistical prediction has become a self-fulfilling prophecy for the semiconductor industry. In 1968 Moore co-founded Intel and his influence over the semiconductor industry was increased. The term ”‘Moore’s Law’” was coined by a professor in Caltech in 1970 and has ever since been used as a road map for the development and research of the semiconductor industry. Figure 2.1 is a graph showing Moore’s projection [2].

To keep up with Moore’s Law, miniaturization is the key driving force. To fit more components on the same wafer, the size of the transistor has to be reduced. But this has to be done in a way that the costs are kept low, the process is accurate, and the throughput is also high. Optical lithography was a candidate which fulfilled the requirements of the day and was adopted as the commercial process. But as the years
2. NANOIMPRINT LITHOGRAPHY AND NANOMAGNETIC LOGIC

![Figure 2.1: Moore's Law](image)

went by, miniaturization started to become a problem for optical lithography because of physical limitations. We will look into these limitations in the next topic.

With further research, people are now talking about what is called “More than Moore’s law”. This is said to be achievable with technologies alternate to silicon, e.g. spintronics and single nanowire transistors.

2.2 Nanoimprint Lithography?

Here we shall look into what are the limitations of the technology currently in use and how nanoimprint lithography can be used as an alternate fabrication technique.

2.2.1 Optical Lithography

Optical Lithography has been the industrial process of manufacturing semiconductor devices. It consists of shaping multiple structures on top of each other. The process consists of the following components:

1. A substrate on which the structures are shaped. Examples are Si/SiO₂ wafers
2. A photoresist which is coated on top of the substrate. The photoresist acts as the intermediate layer which transfers the desired structures to the substrate. The
2.2 Nanoimprint Lithography?

photoresist is light sensitive and changes its physical properties when illuminated by a light source. Depending on the type of the photoresist, either the shadowed area in case of positive-photoresist or the illuminated area in case of negative-photoresist, becomes insoluble to etching.

3. A source of light to illuminate the mask. The wavelength of the light source plays an important role in determining the size of the structures formed.

4. A mask which is the template of the structures to be transferred to the substrate. The shapes are in the form of slits on the mask. Light from the light source is casted by the mask and it is this casted light which illuminates the substrate.

When the photoresist has been exposed and structured, these structures are then etched into the substrate. To keep up with the Moore’s Law, miniaturization is the path to follow. For miniaturization in optical lithography, two steps are taken.

- Making the mask slits smaller
- Reducing the wavelength of the light source

These miniaturization steps have some inherent physical limitations. Making masks with smaller slits is an expensive procedure. One mask can cost millions of euros and there is no space for an error. Making these masks is also a challenge.

For making smaller structures, the wavelength of the light source should be comparable to the size of the structure. Such light sources are very expensive and are not economically feasible. With smaller slits in the masks and smaller wavelength, optical properties of light such as diffraction and beam scattering become pronounced, creating problems in making precise structures.

Many work around have been formulated to keep Optical Lithography in the commercial business, like Deep-UV light sources, immersing the substrate in a liquid to use the refractive index of the liquid to help in reducing the wavelength. All of this is becoming more and more expensive to make. Phase-Shifting masks, published by [3], reduces the effects of diffraction, and is being used to increase fabrication resolution.

Nanoimprint Lithography can be used as a versatile fabrication technique for simple processes consisting of one to two layers. It does not provide a solution to the problems faced in optical lithography but an alternate technique with many applications.
Figure 2.2: This figure shows the basic steps of optical lithography. The substrate with photoresist on top. The mask has the desired structure shape etched into it. The photoresist is exposed to UV light through the mask. The exposed area is removed and the photoresist provides a mask to further etch the substrate.
2.2 Nanoimprint Lithography?  

2.2.2 Nanoimprint Lithography explained  

It is interesting how every now and then old technologies come back into modern times to take their place as the state of the art. Alois Senefelder, an actor and playwright and the father of modern printing lithography, writes in his book “The Invention of Lithography”, “...I could press this into a soft material, transfer the impression to a board covered with soft sealing-wax, and reproduce the relief plate thus obtained in stereotype form.”

Malloy [4] mentions how NIL fulfills the requirements of the International Technology Roadmap for Semiconductors for 22 nm node flash memory devices. Nanoimprint Lithography (NIL), first introduced by Chou et al.[5, 6, 7], was developed as a low-cost, high-throughput manufacturing process for nanostructures. Over the years, NIL has been used for making nanostructures for different applications [8, 9]. NIL cannot be used as a complete replacement to optical lithography because the technology can be used mainly for single layer fabrication. Doing more than one layer still has some challenges, which will be discussed during the course of the thesis.

Guo[10] defines Nanoimprint Lithography as:

“Nanoimprint lithography (NIL) is a non-conventional lithographic technique for high-throughput patterning of polymer nanostructures at great precision and at low costs.”

This definition highlights the three main goals of any fabrication process.

- **High-Throughput**: For making a process feasible for commercial use, this is one of the most important parameters. Other non-conventional lithography techniques like Electron Beam Lithography and Atomic Force Microscope Lithography are limited in this aspect.

- **Great Precision**: Combined with high-throughput, great precision at sub-micron levels is also of great significance.

- **Low Cost**: This is one of the main reasons why NIL is being pursued, as will be discussed later.

Miniaturization and low cost is the main driving force in the International Technology Roadmap for Semiconductors. Lets explore the reason of this driving force behind the miniaturization race.
2. NANOIMPRINT LITHOGRAPHY AND NANOMAGNETIC LOGIC

2.2.3 Details of Nanoimprint Lithography (NIL)

Nanoimprint Lithography (NIL) is a process of forming structures at the nano scale. These structures have applications in semiconductor electronics, optics, micro fluidics etc. The main attraction of NIL is its simplicity of concept. It was first demonstrated by Chou[11].

The main idea of NIL is the transfer of structures from an imprint mold to a resist on top of a substrate. The concept is based on the centuries old method of embossing in which there is an imprint mold and then heat and pressure is used to transfer the patterns of the mold. In case of NIL, the same idea of an imprint mold is used but here the embossing is done on an imprint resist. So the idea is old but its application is new.

NIL has some equivalence to Optical Lithography. They are as follows:

- Light Source ⇒ Heat and Pressure Source
- Mask ⇒ Imprint Mold
- Photoresist ⇒ Imprint Resist
- Substrate ⇒ Substrate

The imprint mold landscape consists of structures in the nanometer dimensions, instead of slits in a Optical Lithography mask. Heat and pressure is used to press this imprint mold on top of the Imprint Resist to transfer the structures of the imprint mold to the imprint resist. So, here the expensive light source and expensive mask is replaced by a simple heat and pressure source and a simple imprint mold. The imprint mold is a bit expensive to get manufactured but compared to the light source and mask, it is very cheap.

As simple as it may sound, NIL also has some challenges associated with it. We will now discuss the different aspects of NIL and also look into the challenges they pose.

2.3 Types of NIL

The type of NIL is mainly determined by the type of imprint resist being used. Following are the types.
2.3 Types of NIL

Figure 2.3: Nanoimprint Lithography
2. NANOIMPRINT LITHOGRAPHY AND NANOMAGNETIC LOGIC

2.3.1 Thermal NIL

This is the same as the first proposal made for NIL. In this case the resist makes a
transition from glass to liquid when heated beyond the glass transition temperature
($T_g$), explained in section 2.3.3.3. This is done so that the resist is liquid enough to
fill in the trenches of the mold structures. After application of heat and pressure for a
time duration determined by the mold landscape, the temperature is decreased below
the $T_g$ before demolding. This process is explained in Figure 2.3

2.3.2 UV-NIL

In this type of NIL, the resist is sensitive to UV light and becomes rigid when exposed
to it. The mold used in this case is transparent, usually made of Quartz. As shown in
the Figure 2.4, the first few steps are the same as Thermal NIL, but after application
of heat and pressure, the sample is exposed to UV light. Since the mold is transparent,
the resist is exposed to UV light and it becomes rigid before demolding is done.

UV-NIL has the advantage of operating near room temperature since the $T_g$ in
this case is low. It is also more appropriate for alignment purposes since the mold is
transparent and optical alignment methods can be used.

2.3.3 Important Parameters for NIL

Following are some parameters which play an important role in the NIL process.

2.3.3.1 Imprint Mold

The imprint mold is made out of Silicon or Nickel in case of Thermal NIL. In case of
UV-NIL, the imprint mold is made of a transparent material such as quartz. Quartz
mold can also be used for Thermal NIL.

Proper designing of the mold landscape is very important. Firstly it should be in the
center of the mold to spread the applied pressure evenly all over the mold structures.
It is also useful to have dummy structures around the active structures. This helps
in getting good imprints after demolding. The different kind of molds/stamp that we
used will be mentioned with the corresponding experiment in the coming chapters.
2.3 Types of NIL

Figure 2.4: Basic steps of UV-NIL. Step 1 shows all the main constituents of the NIL process. The transparent stamp, the substrate covered with UV imprint polymer. Step 2 shows the imprinting process itself. As indicated, the temperature should be more than $T_g$. In step 3, the stamp is exposed to UV light and the polymer goes into its glass state. In step 4, the stamp is demolded. For this step the temperature does is usually above $T_g$. Residual layer is left in the structured pattern. In step 5, the residual layer and substrate is etched using RIE. This is one of the many things that can be done to the substrate through the polymer mask. Evaporation of a metal in step 5 will fabricate nanostructures.
2. NANOIMPRINT LITHOGRAPHY AND NANOMAGNETIC LOGIC

2.3.3.2 Imprint Resist

This is the main component which serves to transfer the topology of the mold to the substrate. How the imprint mold structures are transferred to the imprint resist mainly depend on the below mentioned parameters.

2.3.3.3 Glass Transition Temperature

This is the temperature at which a non-crystalline material changes its state from glass to viscous. In the glass state the material is hard and brittle and in the viscous state it is like a liquid. On a molecular level, in the glass state the molecules of the material are frozen at their places and cannot move while in case of the viscous state the molecules are mobile.

For NIL, the glass transition temperature, $T_g$, is very important. NIL is always performed after heating the resist beyond its $T_g$. The viscosity of the resist decreases and is able to go into the trenches and between the structures of the imprint mold. Beyond the $T_g$, the resist can be easily transported and displaced by the imprint mold. Before the imprint mold is released from the substrate, the temperature is first decreased below the $T_g$ of the resist so that it maintains the shape of the imprint mold landscape.

For thermal-NIL, the $T_g$ is quite high, typically around 190°C. For UV-NIL the $T_g$ is around room temperature. For TUV-NIL, it is around 60°C.

2.3.3.4 Adhesive Forces

The adhesive forces between and the substrate and the resist and between the resist and the mold are of great importance when demolding. The adhesive forces between the substrate and the resist should be stronger than the adhesive forces between the resist and the mold to get the imprinted resist to stay on the substrate and not to come off and damage the imprinted structures. Adhesive forces play an important role in nanotransfer transfer as well.

To reduce the adhesive forces between the resist and mold, an anti-sticking layer is coated over the mold, making the mold surface hydrophobic. Or the material of the mold is such that it poses very little adhesive forces to the resist. The surface treatment of substrates [12, 13, 14, 15, 16] plays an important role during the imprint process.
2.4 Nanotransfer printing

2.3.4 Residual Layer

When a NIL process is finished, some polymer thickness is left between the imprint mold and the substrate. This is called the residual layer. This residual layer cannot be completely removed even if the resist thickness is less than the imprint mold structure heights. This is because of a liquid to glass transition of liquid in a confined space [17]. This residual layer is a minimum of 5nm-10nm [18].

This residual layer has to be removed for further etching processes. The thickness and uniformity of this layer is very important. But sometimes because of improper imprint mold and substrate placement, the thickness becomes non-uniform.

2.4 Nanotransfer printing

This is a modified version of NIL where the species of metal thin film is directly coated on the stamp with nanostructures. The thin film is structured in this process according to the structures on that stamp. This stamp is then pressed at high temperature and high pressure on a substrate and the structured thin film is transferred on top of the substrate. We shall talk about this process in detail in chapter 5.

2.5 Nanomagnetic Logic

Nanomagnetic logic (NML) is an derivative of what started as Magnetic Quantum-Dot Cellular Automata (MQCA). A lot of work has been done on the simulation [19, 20, 21] and fabrication [1, 22, 23] of NML, which has advantages of power efficiency, and can incorporate both memory and logic. In the coming sections we will be focusing on the different aspects related to NML. Details can be found in the PhD work done by Csaba [24] on simulations and Imre [25] on fabrication but using EBL.

2.5.1 NML Explained

In this section we will try to explain the working principle of NML. The working force behind it is magnetic interaction. We know from basic physics that like poles repel each other and unlike poles attract each other. Now consider two bar magnets. If we place the two of them close to each other in such a way that the north of both points upwards, as shown in part (a) of figure 2.5, where both the magnets will repel each
other. This is called an unstable state. If we turn one of them in such a way that one magnet has a north pointing upwards and the other has its north pointing downwards, then the two magnets will attract each other. This is called a stable state. In this state the nanomagnets are said to be anti-ferromagnetically coupled, as shown in part (c) of figure 2.5. For the logical operations we preform, it is important that all the magnets are in their stable state. If they are not in their stable state then we apply an external magnetic field, place them into a metastable state, to bring them to a stable state. Figure shown what the metastable looks like.

Figure 2.5: This figure shows the different stages of how a pair of nanomagnets go from (a) ferromagnetic coupling to (c) anti-ferromagnetic coupling. By applying an external magnetic field the nanomagnets are placed in a metastable state. When the external magnetic field is removed the nanomagnets move into a state of lower energy, which is the state of anti-ferromagnetic coupling.

Now if we place more than two magnets in close proximity to one another, such that their magnetic fields effect each other, we will have what we call a magnetic nanowire. In this case the magnetic nanowires are in a stable state when all of the magnets are pointing in an opposite direction their neighbors. They are said to be anti-ferromagnetically coupled. Figure 2.6 shows an example of a anti-ferromagnetically coupled.
coupled magnetic nanowire. If one nanomagnet is placed horizontally at one end of the nanowire, this magnet can act as an input magnet and help the other nanomagnets arrange in an anti-ferromagnetically coupled orientation, without the presence of an external magnetic field.

![Input magnet](image1.png)

Figure 2.6: An anti-ferromagnetic coupled magnetic nanowire is shown with an input magnet at one end. The input magnet help the magnetic nanowire to settle into a desired state.

Now we place the nanomagnets in an orientation as shown in figure 2.7. This particular structure has three input magnets, which are horizontal, and five computing magnets, which are vertical. This structure acts as a majority gate in its functionality. The center magnet is effected by the surrounding three magnets which have input magnets. Depending on the dominant effect the center magnet will set its orientation. Similarly there is a composition of nanomagnets which acts as a full adder. It consists of a few majority gates and nanowires arranged in a specific placement order. We shall discuss this in the coming chapters.

### 2.5.2 Magnetic Material

There are two types of magnetizations that can be used for doing logical operations. One is called in place magnetization and the other is called out of plane magnetization. The materials for both kind of magnetizations are different. For in plane magnetization we use Permalloy (80% Ni, 20% Fe) or Supermalloy (79% Ni, 16% Fe, 5% Mn). For out of plane magnetization a CoPt multilayer stack is used. The work in this thesis is based on inplane magnitzation materials. We use Permalloy for electrodeposition and Supermalloy for Liftoff. Detials are given in the coming sections.
2. NANOIMPRINT LITHOGRAPHY AND NANOMAGNETIC LOGIC

Figure 2.7: A majority gate works with the dominant magnetic orientation deciding the output.

2.5.3 Magnetic Domains

Thin film magnetic materials (10 nm to 30 nm) have different areas with different magnetization directions. An area in which all the atoms have the same magnetization direction is called magnetic domain. Such a thin film is called a multi domain magnetic material. When the area of the thin film is made small enough (smaller than 100 nm x 100 nm), all the atoms of this small area are pointing in the same direction. Such an area size structure is called a single domain magnet.

2.5.4 Anisotropy

In plane magnetic materials have a shape anisotropy. This means the shape of the magnet will decide the direction of magnetization. In case of Permalloy and Supermalloy, the shape needs to be asymmetric. The longer length is called the easy axis and the shorter length is called the hard axis. The hard axis needs a stronger external magnetic filed to magnetize compared to the easy axis.
2.5 Nanomagnetic Logic

2.5.5 Switching of Magnets

Nanomagnetic logic devices are operated using an oscillating external magnetic field. The external magnetic field helps in driving the coupled nanomagnets from their initial state, which is a metastable state, to ground state, which is a relaxed state. The coupled nanomagnets have a magnetostatic energy between them and fig 2.8 shows a simulated calculation of it. The nanomagnet on the right is fixed and the one on the left can rotate at an angle of theta. The corresponding magnetostatic change is plotted in the figure. We see that there are two minima in the graph, depicting states of low energy. The one at 0 degrees is the metastable state and the one at 180 degrees is the ground state. The figure is taken from the PhD work done by György Csaba [24].

![Diagram of magnetostatic energy](image)

Figure 2.8: Magnetostatic energy diagram of two coupled nanomagnets. The energy state of two anti-ferromagnetically coupled nanomagnets is lower than that of two ferromagnetically coupled nanomagnets. Thus the anti-ferromagnetically coupled nanomagnets are more stable.
2. NANOIMPRINT LITHOGRAPHY AND NANOMAGNETIC LOGIC
Chapter 3

Nanoimprint Lithography and Electrodeposition

In this chapter we present a novel fabrication process for the growth of metal nanostructures that combines nanoimprint lithography and electrodeposition, both of which are suitable for large-scale industrial fabrication. Gold nanostructures fabricated by nanoimprint lithography on a highly doped, p-type, Si wafer act as a seed layer for metal electrodeposition. This novel process has wide applications in Nanomagnet Logic and surface-enhanced electrochemistry. We fabricate magnetic nanowires and nanodots using this process. The resulting nanostructures are analyzed with atomic force microscopy and scanning electron microscopy. The composition of the electrodeposited nanostructures are analyzed by energy-dispersive X-ray spectroscopy. The magnetic properties are measured with magnetic force microscopy.

3.1 Introduction

NIL is discussed in detail in chapter Nanoimprint Lithography and Nanomagnetic Logic.

Electrodeposition has been extensively used for depositing thin films for data storage in the hard drive disk (HDD) industry [22, 26, 27] and microelectromechanical systems (MEMS) [28, 29, 30, 31]. Electrodeposition has already been used for growing nano-magnetic structures in conjunction with electron beam lithography (EBL) [6, 26, 27], which proves to be a bottleneck for large scale fabrication. Getlawi et al. [32] used EBL and focused ion beam (FIB) cutting for the realization of magnetic structures.
3. NANOIMPRINT LITHOGRAPHY AND ELECTRODEPOSITION

We demonstrate the use of nanoimprinting and electrodeposition as a fabrication process for nanomagnets. This combined technique provides sufficient precision for many applications, and is much faster and cost-effective compared to EBL, and as such is suitable as a high-throughput, scalable and commercial process.

This fabrication technique can be used for any process where metal nanostructures with small spacing are required. One such application is Permalloy nanostructure fabrication for Nanomagnetic Logic (NML). Permalloy has already been studied for magnetic properties [32, 33, 34, 35, 36]. Much work has already been done on the simulation [19, 20, 21] and fabrication [1, 22, 23] of NML, which has the potential to be power-efficient, and can incorporate both memory and logic.

The mentioned fabrication process starts with a highly doped p-type Si substrate, and uses NIL and lift-off to make gold nanostructures that act as a seed layer for electrodeposition, and then selectively electrodeposit magnetic material on the gold nanodots and nanowires using the substrate as the electrical contact to the gold cathodes. Since the fabricated nanowires are too long to be observed in a single magnetic force microscope (MFM) scan, we use focused ion beam (FIB) to cut nanorectangles out of the nanowires in order to observe both magnetic ends within a single scan frame.

EBL, which is the most common method for fabricating nanomagnets, is slow and costly, and is therefore not suitable for industrial applications. Our fabrication process can provide a conducting substrate for other nanostructures used for surface enhancement in electrochemical processes [37, 38, 39].

3.2 Fabrication Process

Our fabrication process is a combination of NIL followed by evaporation and electrodeposition. Figure 3.1 shows a schematic diagram of all the steps involved in the fabrication process. First of all we take a highly doped p-type Si 2 inch substrate and clean it with acetone and isopropanol. We spincoat the substrate with a thermal imprint resist. We use mrI-8010r thermal imprint resist (Microresist, Berlin, Germany). Then we do NIL. Since some residual layer is left after NIL we do RIE and open the imprinted structures to the substrate surface. The electrodeposition process needs a seeding layer and for this Ti and Au is evaporated. We talk about this more in the coming sections. After evaporation of Au we do a liftoff process to remove the Au on
3.2 Fabrication Process

the thermal resist. Once all the resist is removed it takes with it the Au in between in the imprinted nanostructures thus leaving only the Au nanostructures. Now the sample is ready for electrodeposition.

Figure 3.1: Process steps for magnetic material electrodeposition. Step 1, highly doped p-Type wafer spin-coated with thermal resist. Step 2, nanoimprint lithography is done. Step 3, demolding of stamp from resist. Step 4, reactive ion etching (RIE) to remove residual layer. Step 5, Ti is evaporated. Step 6, gold is evaporated. Step 7, Lift-off is done. Step 8, electrodeposition of magnetic material.
3. NANOIMPRINT LITHOGRAPHY AND ELECTRODEPOSITION

3.2.1 Nanoimprint Lithography

The three important components for an NIL process are the stamp, the imprint resist, and the substrate. We use two Si stamps, each with a different structure. One stamp consists of dots with 60 nm diameter on a 240 nm pitch covering an area of 8 mm x 8 mm. The other stamp consists of lines with 60 nm width on a 240 nm pitch covering an area of 12 mm x 6 mm. Figure 3.2 shows SEM images of the dot stamp and the line stamp (fabricated by IMS Stuttgart, Germany). A two-inch, highly doped, p-type, Si wafer (boron-doped to 1018 cm$^3$) is used as the substrate. We discuss the advantages of using a highly doped wafer below. The commercially available Obducat 2.5” Nanoimprinter (Obducat, Sweden) is used to perform the nanoimprinting process. The fabrication process is explained in Figure 3.1.

![Figure 3.2: SEM image of stamps (a) dots with 60 nm dia. and 240 nm pitch and (b) lines with 60 nm width and 240 nm pitch.](image)

Using this fabrication process, we fabricated gold nanodots and nanowires. Using
AFM we measured the nanodots to be 20 nm high and nanowires to be 23 nm high.

### 3.2.2 Electrodeposition

A two-electrode system is used for electrodeposition. Figure 3.3 shows a schematic of the setup. In order to electrodeposit Permalloy, we use a commercially available Nickel (Ni) electrolyte (Conrad), and mix it with FeSO$_4$ and saccharine. The electrolyte is stirred for 24 hours for a proper mix. Preliminary experiments of Permalloy electrodeposition showed that adding saccharine improved the homogeneity and adhesion of the electrodeposited Permalloy film on the Au seed layer [40]. Details of Permalloy electrodeposition can be found in [41, 42].

A 5 cm x 5 cm Platinum (Pt) wire mesh is used as the anode. The gold (Au) nanostructures on the wafer act as the cathode. In our setup, the highly doped, p-type, Si substrate has a deficiency of electrons, and the gold nanostructures on the p-type Si has an excess of electrons, therefore, metal is electrodeposited only on the
Au nanostructures. The Pt mesh (anode) and the gold nanostructures on the p-type Si (cathode) are connected to a Keithley 2602 current source that provides 6 mA for about 7 min to electrodeposit.

First we will have a look at the nanostructures on which electrodeposition was done. Figure 3.4 shows AFM images of the gold nanodots. The pillar stamp was used to make an imprint for these structures. Following the fabrication steps in 3.1 a liftoff of Au was done to get the nanostructures. AFM measurements were done to make sure the fabricated nanostructures came out as expected. From the cross-section measurements we can see that the nanodots are 20 nm high. A 2D image of the nanodots is shown in the small figure in the cross-section.

![AFM of Au dots after liftoff and before electrodeposition. The initial height is 20 nm.](image)

Gold nanolines were fabricated using the same process for electrodeposition. Figure 3.5 shows AFM images of the gold nanolines after liftoff. From the cross-section measurements we see that the nanolines are 23 nm high. 2D measurements show that the lines were straight as expected. Some slight defects are observed in the nanodots and nanolines. These are because of some residual resist left after the liftoff process. But as we will show later on, there were many parts where there were no defects and the nanostructures came out to be very nice after the electrodeposition process.

Now we will look into the nanostructures after they have been electrodeposited. In case of both the nanodots and nanolines we took SEM images to have a better top view and we did AFM images to get a better measurement of the height of the structures. Let’s look at the nanodots first. Figures 3.6 shows an SEM image of the nanodots and figure 3.7 shows an AFM image. From the SEM image we see that the nanodots are more than 200 nm wide in diameter and they are fairly uniform in size.
Figure 3.5: AFM of Au lines after liftoff and before electrodeposition. The initial height is 23 nm.

Figure 3.6: SEM image of electrodeposited nanodots.
3. NANOIMPRINT LITHOGRAPHY AND ELECTRODEPOSITION

The AFM cross-section in figure 3.7 shows that the nanodots are 89 nm high. There was 20 nm of Ti/Au before the electrodeposition process thus 69 nm of permalloy is electrodeposited. AFM measurements are mainly good for height measurements and not for x-y measurements because of artifacts introduced by the AFM tip.

![AFM of Permalloy dots after electrodeposition. The height is 89 nm.](image)

Figure 3.7: AFM of Permalloy dots after electrodeposition. The height is 89 nm.

Now we look at the nanoline. From the SEM image in figure 3.8 we can see that the nanolines are around 140 nm wide. Again they look fairly uniform. Each of the nanolines is 32 µm long with a gap between every corresponding line. The SEM image is take at one such gap.

![SEM image of electrodeposited nanowires.](image)

Figure 3.8: SEM image of electrodeposited nanowires.

The AFM cross-section in figure 3.9 shows that the nanolines are 40 nm high. There was 20 nm of Ti/Au before the electrodeposition process thus 17 nm of permalloy after electrodeposition. Later we will see that the nanostructures clearly shows magnetic
3.2 Fabrication Process

contrast and showing that the metal electrodeposited is definitely magnetic in nature.

![AFM Image](image)

Figure 3.9: AFM of Permalloy dots after electrodeposition. The height is 40 nm.

3.2.2.1 Electrodeposition of nanotransferred nanodots

Now that we had done out electrodeposition process on nanostructures made by NIL, we wanted to see if this process works for nanostructures fabricated by a different process. Nanotransfer printing is a single step process for fabricating nanostructures and we explain more about it in 5.2.2. We took some samples made by using nanotransfer printing and did electrodeposition on them. The nanostructures we used were nanodots fabricated on a highly doped p-Type Si wafer. Figure 3.10 shows an SEM image of the electrodeposited nanodots. It is observed that they are not as uniform as the electrodeposited nanodots made by NIL. One explanation is that in nanotransfer printing the nanostructures do not have as good of a bonding to the substrate as compared to evaporated metal.

Figure 3.11 shows an AFM image of the electrodeposited nanodots. They have a sort of a donut shape to them and they are around 55 nm high, compared to the original Ti/Au height, which was 39 nm. The donut shape can also be due to the bad contact the Ti/Au nanodots have with the Si substrate, which provided a path of the current to reach the nanodots for the electrodeposition process.

Figure 3.12 shows a 3D image of the electrodeposited nanodots. This gives a more detailed view of the topography of the electrodeposited nanodots. The donut shape is much more evident and some of the nanodots are slightly larger than the other.
3. NANOIMPRINT LITHOGRAPHY AND ELECTRODEPOSITION

Figure 3.10: SEM image of electrodeposited nanodots done by nanotransfer.

Figure 3.11: AFM image showing heights of electrodeposited nanodots done by nanotransfer.
3.2 Fabrication Process

![Image of electrodeposited nanodots fabricated by nanotransfer.](image)

Figure 3.12: 3D image of electrodeposited nanodots fabricated by nanotransfer.

### 3.2.3 Further Analysis

We also carried out an energy-dispersive X-ray spectroscopy (EDX) to measure the composition of the electrodeposited metal. An FIE Magellan was used for this purpose. Figure 3.13 shows the EDX spectrum. Ni and Fe are present, along with Si from the substrate. The composition percentages are 70% of Ni and 30% of Fe, which is close to the commercially available Permalloy with 80% of Ni and 20% of Fe.

One of the main advantages of our electrodeposition process is the ability to overgrow the nanostructures to decrease the distances between them. Figure 3.14 shows a conventional electrodeposition compared to our electrodeposition process.

In a conventional electrodeposition of nanostructures, a resist is patterned using photolithography or EBL, and the electrodeposited metal is grown through it. The distance between two consecutive structures is determined by the resolution of the lithography process. In our process, the gold nanostructures on a highly doped, p-type, Si wafer are the seeding points and are electrically connected via the highly doped, p-type, Si wafer. As explained above, only the gold nanostructures will have metal deposited on them. As there is no resist between the gold nanostructures, the metal is free to overgrow, and by controlling the necessary parameters, the metal can be overgrown for minimum spacing that is difficult to achieve with a conventional lithography methods. This has applications in NML. Figure 3.15 shows overgrown nanodots with a spacing of 27 nm between them.
3. NANOIMPRINT LITHOGRAPHY AND ELECTRODEPOSITION

Figure 3.13: EDX spectrum of electrodeposited permalloy.

Figure 3.14: (a) Conventional electrodeposition through resist. (b) Electro-deposition on Au nanostructures on a highly doped p-type Si wafer.
3.3 Results and Discussion

The fabrication process described here has been used in surface-enhanced electrochemical processes [37, 38, 39]. Hydrogen evolution reaction (HER) and hydrogen oxidation reaction (HOR) activity enhance on Pt catalyst monolayers and submonolayers on Au supports have been observed. The catalytic activity increases with decreasing amounts of Pt. Electrochemical deposition on plain Au films yields randomly distributed Pt nanoparticles with varying sizes and spacings. A study of arrays of Pt nanoparticles on defined Au nanostructures around 100 nm has been done. The supporting Au nanostructures are fabricated using NIL on a highly doped, p-type, Si wafer in a method similar to that described here.

![SEM image showing overgrowth of nanodots.](image)

Finding the optimum parameters for electrodeposition of nanostructures is a challenge because firstly the area they cover is very small, and secondly, there is always some stray area left around the nanostructured area after the RIE process performed for removing the residual layer. Some of the surrounding resist is also etched away due to inhomogeneities in the resist thickness, and gold is deposited in those areas during the evaporation process.

3.3 Results and Discussion

Permalloy thin films exhibit an in-plane magnetization that depends on the shape of the thin film. Generally, the remanent state of elongated magnets is along the long, or
3. NANOIMPRINT LITHOGRAPHY AND ELECTRODEPOSITION

easy axis. We used a Veeco MFM to do the magnetic measurements discussed below. Both the nanodots and nanowires were subjected to a magnetic field and imaged using the MFM to observe magnetic poles. Since the nanodots have both axes of the same length, no magnetic poles were observed in the nanodots. The ends of the nanowires did exhibit magnetic poles, but an individual nanowire was too long to be captured in a single image. In order to image both poles in a single image, we cut the nanowires using FIB, as discussed below.

3.3.1 FIB Cutting

In order to image the end poles of the nanowires in a single scan field, they were cut into nanorectangles using a Zeiss NVision Gemini focused ion beam. When cutting the nanowires with the FIB, the main challenge was to cut completely through the nanowires without leaving any residue that might link the lines through exchange interactions, meanwhile keeping the cut width small in order to observe magnetic coupling between the structures. The beam sweep time was varied for a current of 10 pA and a length of 50 µm. We did a series of FIB cuts for 30 s, 60 s, 90 s and 120 s, leaving cut widths of 42 nm, 52 nm, 63 nm and 82 nm, respectively, as shown in figure 3.16. There was some residual interconnect material at 30 s, but for the other variations, there was none. Therefore, the cut made at 60 s (52 nm) was optimum.

Using the optimum parameters, four FIB cuts were made at 90 degrees to the nanowires, producing three sets of nanorectangles across a length of 50 µm with lengths of less than 340 nm. Figure 3.17 shows the resultant nanorectangles. The nanorectangles were placed in a magnetic field oriented parallel to the long axis of the nanowires.

A magnetic field of 350 mT was applied for a few seconds along the long axis. In Figure 3.18 the MFM image of the nanorectangles clearly shows end poles on the nanorectangles in a single image. All of the poles are aligned in one direction. With this we demonstrated that the electrodeposited material is indeed magnetic in nature.

3.4 Summary

We have demonstrated a fabrication process for the growth of magnetic nanostructures using nanoimprinting and electrodeposition on a highly doped Si wafer that served as the cathode contact. The fabrication process is scalable and suitable for large-scale
3.4 Summary

Figure 3.16: Each line was FIB cut 50\(\mu\)m long at 10 pA for (a) 30 s, (b) 60 s, (c) 90 s and (d) 120 s. The lines are 42 nm, 52 nm, 63 nm and 82 nm respectively.

Figure 3.17: SEM image of FIB cut nanorectangles. The lengths of the rectangles are 236 nm, 330 nm and 337 nm.
Figure 3.18: MFM image of FIB-cut nanorectangles.
industrial fabrication. SEM images show the dimensions to be less than 350 nm, and MFM images show magnetic poles in the nanorectangles formed by FIB. Having the seeding layer nanostructured on a highly doped, p-type, Si wafer allows overgrowth of the electrodeposited nanostructures. This overgrowth decreases the distance between the magnetic nanostructures, which is crucial in NML. The process can also be used for surface-enhanced electrochemistry. Future work will include optimization of the electrodeposition process for controlling the dimensions of the nanostructures. We will pursue the same process for working on NML structures.
3. NANOIMPRINT LITHOGRAPHY AND ELECTRODEPOSITION
Chapter 4

Nanoimprint Lithography and Liftoff for NML

Large scale fabrication of nanomagnetic logic devices using nanoimprint lithography is presented. It is a fast and cost effective way to fabricate nanomagnetic logic. Nanoimprint lithography is used for polymer patterning and liftoff of Permalloy and Supermalloy is done for nanostructure fabrication. SEM, AFM and MFM measurements are shown.

4.1 Introduction

NIL was first proposed by Chou [5, 6, 7] as a fast and cost effective fabrication method for nanostructures. Over the years, it has found applications in different fields [8, 9, 22]. The main goal of NIL is to have a cost effective large scale fabrication process for nanostructures. EBL is traditionally used for precise nanostructure fabrication but it is not at all suitable for large scale production because of being slow and relatively expensive. Optical lithography is still the main stream fabrication process used by the industry but it is very expensive. NIL promises to be a solution to these problems.

NML was demonstrated by Imre [1]. A lot of work has been done on the simulation and fabrication of NML. People use either EBL or focused ion beam (FIB) for fabrication. But both processes are very slow. In this paper we demonstrate the use of NIL for NML fabrication. We will discuss the fabrication process and discuss some of the challenges in fabrication and discuss their solutions.
4. NANOIMPRINT LITHOGRAPHY AND LIFTOFF FOR NML

4.2 Fabrication Process

Nanoimprint lithography requires three main components i.e. stamp, substrate and polymer. To demonstrate NML we used three different type of structures, i.e. magnetic nanowire, majority gate and full adder. Every type of structure was fabricated on a different stamp (stamps fabricated by IMS Stuttgart, Germany). On each of the stamps the nanomagnets are around 60 nm by 90 nm. The distance between each nanomagnet is 40 nm. This was the minimum achievable size by the company. Ideally, smaller the distance, better it is for coupling.

Each stamp is a 1 cm x 1 cm piece of Si with the nanostructures fabricated in the middle. The magnetic nanowire stamp has a structured area of $100 \mu m \times 100 \mu m$. Each consist rows of 20 nanomagnets forming one magnetic nanowire, with a series of nanowires forming columns. Each column is 2$\mu m$ wide and 100$\mu m$ long. The structures are 100 nm high. Figure 4.1 shows SEM images of the nanomagnetic wire.

![SEM image of magnetic nanowire stamp.](image)

The majority gate stamp has a structured area of $50 \mu m \times 50 \mu m$. Each majority gate comprises three input nanomagnets placed horizontally and five computing nanomagnets. The arrangement of the nanomagnets is shown in Fig 2. The operation of the majority gate is determined by the positioning of the input magnets. We have four different types of majority gates with input magnets placed in different positions to get all the possible logic combinations. The majority gates are arranged in an array of 50 x 50, giving a total of 2500 majority gates. Figure 4.2 shows SEM images of the stamps.

![Figure 4.2: SEM images of the stamps.](image)
4.2 Fabrication Process

The full adder stamp has seven input nanomagnets and forty three computing nanomagnets. The input nanomagnets are of three different lengths in order to clock them in different directions. The full adder has an array of 25 x 25 giving a total of 625 on the stamp. Figure 4.3 shows an SEM image of the stamp.

Two main challenges were faced when fabricating the structures. One was to get a faithful transfer of the structures from the stamp into the polymer. The second was the liftoff of the evaporated magnetic material. In the next sections we will discuss these challenges in detail.

4.2.1 Structure transfer in polymer

It was observed that during some of the NIL processes, the structures are not properly transferred into the polymer. In our results, during the imprint process, the stamp shifted which formed a shifted pattern in the polymer. Figure 4.4 shows a microscopic image of the shifted majority gate pattern.

Figure 4.5 shows an AFM image of the shifted nanowire pattern. According to the recipe, the stamp was demolded after the imprint temperature was below the glass transition temperature $T_g$. Our understanding is that during the cooling down phase, the stamp shifted and the patterns formed in the polymer were also shifted. Once the operating temperature was below $T_g$, these patterns were fused in the polymer. One
Figure 4.3: SEM image of majority gate stamp.
4.2 Fabrication Process

Figure 4.4: Microscopic image of shifter majority gate pattern after imprint. The arrows show the shift direction.

The reason for the shifting effect could be some air trapped between the stamp and the substrate. Even a shift of sub 10 nm is enough to spoil the pattern.

Figure 4.5: AFM image of a shifted nanowire pattern.

Through repeated experiments it was found that demolding before the temperature goes below $T_g$ avoids shifting of pattern. This means that the polymer is still in its low
viscous state and the polymer is still holding the shape of the nanostructures on the stamp and any effect of shifting of the stamp is not yet fused into the polymer. When we demold above $T_g$, we get a faithful transfer of the nanostructures into the polymer, as shown in figure 4.6.

![Image of majority gate pattern](image)

Figure 4.6: Microscopic image of majority gate pattern without any shift after imprint. There are some defects because of demolding.

Figure 4.7 shows an AFM image of the nanowire pattern without the shifting effect. We observed that not only were the patterns transferred without any shift but the penetration of the nanostructures into the polymer was good. A depth of more than 40 nm by nanostructures of 100 nm in height is measured. The shallow depth is due to artifacts introduced in measurement by the AFM tip. This is because the AFM tip is not sharp enough to go into the nanostructures and does not touch the bottom.

Imprints using the stamp with majority gates was done as well. Figure 4.8 shows an AFM image of a majority gate faithfully imprinted into thermal imprint polymer. This imprint was also done with demolding above $T_g$. Again the exact depth cannot be determined due to AFM tip artifacts.

Figure 4.9 shows a close up 3D image of the four majority gate set. All four type of majority gates are very nicely made with good separation between neighboring nanomagnets.
4.2 Fabrication Process

Figure 4.7: AFM image of nanowire pattern without shift.

Figure 4.8: AFM image of imprinted majority gate.
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4.2.2 Liftoff of magnetic material

Two different kind of magnetic materials were evaporated, one is Permalloy (80% Ni and 20% Fe) and Supermalloy (79% Ni, 16% Fe and 5% Mn). We will discuss why we shifted from Permalloy to Supermalloy.

4.2.2.1 Permalloy Liftoff

After the NIL process we do a reactive ion etching (RIE) of the imprinted polymer. Figure 4.10 shows an AFM of the nanowires after RIE. The remaining polymer is around 30 nm high.

After the RIE process, first a film of titanium (4 nm to 8 nm) and then a film of Permalloy (15 nm to 30 nm) was evaporated. Figure 4.11 shows the stack of metal on the substrate. Ti acts as a gluing layer between Permalloy and the substrate. If Ti is not there then the Permalloy is removed during the liftoff process.

Once the evaporating is done, we need to remove the unwanted metal on the polymer and keep the metal which went through the fabricated nanostructures and into the substrate. For this we do a liftoff process. Liftoff in done by placing the sample in a solvent like acetone. After placing the sample in an acetone beaker, we place the beaker in an ultrasonic bath to speed up and aggravate the liftoff process. In our experiments the liftoff was not working very well for Permalloy. Figure 4.12 shows a microscopic image of the nanowires structures after the fist 10 min of ultrasonic bath in acetone.
Figure 4.10: AFM image of nanowires after RIE. The height is around 30 nm.

Figure 4.11: Stack of metal evaporated on the sample.
Metal is removed the columns of nanowires but there is still metal left on the nanowires. This observation is made by the presence of shining metal on the nanowires.

![Figure 4.12](image1.jpg)

Figure 4.12: Microscope image of nanowires after 10 min in hot acetone.

Then we placed the sample in warm acetone for 10 min and afterwards used a cotton-bud to mechanically wipe the metal off. Figure 4.13 shows the result. It is better than before with more metal removed.

![Figure 4.13](image2.jpg)

Figure 4.13: Microscope image of nanowires after 10 min in hot acetone and wiping with a cotton-bud.

Finally, we placed the sample in ultrasonic bath for 5 min and then used the cotton-bud for wiping and the result we got is shown in figure 4.14. It is a great improvement from what we started with and we used it for further analysis. There are some areas left with some metal and we find a better solution to this problem by changing the metal species from Permalloy to Supermalloy.

For a detailed view for the nanostructures we used a SEM. Figure 4.15 shows SEM images of the nanowires where most of the permalloy is removed after liftoff. The
4.2 Fabrication Process

Figure 4.14: Microscope image of nanowires after 5 min in ultra sonic bath and wiping with a cotton-bud.

Nanomagnets are nicely formed into oval shapes and the separation between them is clearly visible.

Figure 4.15: SEM image of the magnetic nanowires after liftoff.

Now we will have a closer look at the nanomagnets. Figure 4.16 shows the nanomagnets of the nanowires. Again the shape and spacing is very nice. The structures are 92 nm wide and 120 nm long. The spacing between them is around 8 nm.

As we said previously, in some part the metal was not completely removed and figure 4.17 shows an SEM image of a part of the nanowire columns where the Permalloy did not properly liftoff. This metal present in between the nanomagnets is not desired as it will not allow the nanomagnets to behavior properly.
4. NANOIMPRINT LITHOGRAPHY AND LIFTOFF FOR NML

Figure 4.16: Close-up SEM image of the nanomagnets of the magnetic nanowire.

Figure 4.17: SEM of a column of nanowires where the Permalloy did not properly liftoff.
4.2 Fabrication Process

By looking at the nanostructures at a tilt, one gets an idea about the height profile. This is what we did in figure 4.18. There are some areas which still have some metal left in between.

![Figure 4.18: Tilted SEM image of a permalloy magnetic nanowires.](image)

In figure 4.19 we look closer at the tilted nanomagnets. Again we see the oval shape of the nanomagnets and the spacing between them. When we took MFM images of these nanomagnets we could clearly see a magnetic contrast, showing that the nanomagnets are actually separated.

![Figure 4.19: Close-up tilted SEM image of a permalloy magnetic nanowires.](image)

We did the same procedure of liftoff with a sample having majority gate nanostruc-
NANOIMPRINT LITHOGRAPHY AND LIFTOFF FOR NML

structures imprinted into a polymer. But with the majority gate structures we had some issues in the beginning. Figure 4.20 shows SEM images if the majority gates where the Permalloy layer was removed for some of the nanostructures and titanium remained after liftoff.

Figure 4.20: SEM of a permalloy majority gate liftoff. Two of the input magnets have been removed during the liftoff process.

Figure 4.21 shows an AFM image of the four kinds of majority gates we have on our stamp. The titanium layer is visible with the evaporated Permalloy.

Figure 4.21: This is an AFM image of the four kind of majority gates. Permalloy is removed from some of the nanostructures and this is visible from the height contrast.

In figure 4.22 we see a zoom in of one of the majority gates. Here we see very clearly...
the Ti and Permalloy from the height difference. In the SEM image above the Ti is not very visible. Figure 4.23 shows height measurements. The titanium is around 7 nm high and the permalloy is around 35 nm high. This shows that the liftoff process sort of worked but Permalloy did not stick properly to the Ti.

Figure 4.22: This is a closeup AFM of one of the majority gate.

![Image of AFM closeup](image)

Figure 4.23: Height measurements show the height differences.

![Height Measurements](image)

Figure 4.24 show AFM and MFM images of one of the majority gates. The nano-
magnets show magnetic contrast but they are not properly anti-ferromagnetically coupled. The main reason being the presence of unwanted metal between the nanomagnets.

![Image](image_url)

Figure 4.24: These are (a) AFM and (b) MFM images of the permalloy majority gate. As can be seen from the images, the titanium nanostructures show no magnetic contrast whereas the permalloy nanostructures do.

We tried to increase the imprint time in order to make the nanostructures go deeper into the polymer and thus giving a thicker layer for liftoff but still we had the same issues. Later we figured that it was a problem with the material we were using. We talk more about it in the coming section.

### 4.2.2.2 Liftoff of Supermalloy

The solution to this issue was to use Supermalloy instead of Permalloy. Magnetically speaking, it behaves the same as Permalloy. We repeated the same process of NIL and RIE etching for making the nanostructures into polymer. When we tried a liftoff with Supermalloy nanostructures, the liftoff worked perfectly. Figure 4.25 shows an SEM image of majority gates fabricated with Supermalloy.

### 4.3 Results and Discussion

We demagnetized the nanomagnets by placing them in an external magnetic field of 3.5 mT applied in one direction. Figure 4.26 shows (a) AFM and (b) MFM images of these magnetic nanowire and all of them are aligned in one direction.

Then we demagnetized the nanomagnets by placing them in an external magnetic field of 3.5 mT of decreasing oscillation. Figure 4.27 shows a large AFM and MFM
4.3 Results and Discussion

Figure 4.25: Supermalloy majority gate liftoff.

Figure 4.26: (a) shows topography of the magnetic nanowire and (b) the MFM image. A unidirectional external magnetic was applied and all the nanomagnets are aligned in one direction.
view of such magnetic nanowires. The checker board pattern can be seen which mean there is anti-ferromagnetic coupling between the nanomagnets. The places where the checker board pattern is not present are places where there was a problem in the liftoff process and some metal is still left.

Figure 4.27: This figure shows the (a) AFM and the (b) MFM image of the Nanowires on a large scale. A checker board pattern can be seen in the MFM image. The places where the checker board pattern is not present are places which had a problem with liftoff and some metal is still there.

Figure 4.28 shows a cropped version of the AFM and MFM images of the same sample. Here the shape of the nanomagnets came out to be much better and thus we were able to observe and anti-ferromagnetic coupling. These images clearly demonstrate the usability of NIL for making magnetic nanowires which show anti-ferromagnetic coupling.
4.3 Results and Discussion

Figure 4.28: Anti-ferromagnetically coupled nanomagnets. (a) shows topography of the magnetic nanowire. (b) shows the MFM image.

Once we had confidence in our fabrication process, we proceeded to more complicated nanostructures. We looked into the majority gate and the full adder structures made of nanomagnets. One of the issues we had was with the shape anisotropy. Both Permalloy and Supermalloy have shape anisotropy, meaning that the polar behavior depends on the shape of the nanomagnet. The longer axis is called the easy axis and the shorter axis is called the hard axis. A nanomagnet is easier to magnetize along the easy axis compared to the hard axis. For the stamps we had, the shape of the structures was not very asymmetric. Instead of ovals we had more of a circular shape, which spoils the shape anisotropy and we are not able to see a polar behavior under the MFM.

For the majority gate the computing nanomagnets were not ovalish enough and were more circular in shape. Thus we had no shape anisotropy and we saw more of a vortex behavior, typical for symmetric shapes, as shown in Figure 4.29.

Figure 4.29: (a) shows topography of the majority gate. (b) shows the MFM image. The input magnets are magnetized but the computing magnets are in vortex state.
The full adder had more circular shaped nanomagnets compared to oval shaped nanomagnets and we observed a vortex behavior in most of the magnets, as shown in figure 4.30.

Figure 4.30: (a) shows topography of the majority gate. (b) shows the MFM image. The input magnets are magnetized but the computing magnets do not show proper contrast.

The issues of shape can be solved by having nanomagnets with more asymmetry and lesser distances between them. We are working on getting new stamps fabricated and will be using them for getting better results.

4.4 Summary

We have shown the NIL can be used to making NML. We were facing issues of getting a faithful transfer of patterns in the polymer, which we solved by demolding above $T_g$. The issue with liftoff was solved by using Supermalloy instead of Permalloy. Nanomagnetic wires show anti-ferromagnetic behavior. The majority gate and the full adder
were fabricated but because of slight defects in the stamp the shape anisotropy was not observed.
Chapter 5

Nanotransfer Printing

5.1 Introduction

We have discussed about the conventional use of NIL in chapter 3 and 4. In this chapter we introduce a new convention of using the nanoimprint concept. According to figure 2.3, NIL conventionally consists of a stamp pressed on top of a polymer and embossing the polymer with nanostructures. After evaporation of metal thin films the nanostructures are formed after liftoff. In this chapter we will discuss a different convention of using the nanoimprinting machine for nanostructure fabrication.

5.2 Concepts and applications

Working of Nanotransfer printing is analogous to that of an ink pad and stamp. It consists of two processes, namely inking and stamping. First we need stamps with nanostructures on them. In our case we had stamps with nanodots and nanolines. Then we do the inking process. During the inking process, metal thin film is evaporated directly on top of the stamp. The metal thin film is structured according to the profile of the stamp. This means that the metal is deposited on top of the nanostructures, forming thin film nanodots and nanolines in their respective cases. The rest of the metal goes into the trenches around the nanostructures. In the stamping process, the stamp is pressed on a substrate at high temperature and pressure. During the nanotransfer process, the adhesive forces between the different surface play a very important role. Figure 5.1 shows the main steps involved in nanotransfer printing.
Figure 5.1: These are the different steps of nanotransfer printing. Step 1 shows the stamp already inked with different metals. In step the stamp is pressed on top of a substrate at high temperature and high pressure. In step three the stamp is demolded and the metal on top of the structures is transferred on the substrate.
This is one fine detail that is very important, the pre-treatment of the stamp surface before metal evaporation and the substrate surface before being pressed on. The adhesive force between the stamp and the thin film needs to be very small so that the metal thin film comes off of the stamp very easily. For this the stamp surface is treated with an anti-sticking layer. After this when the stamp is pressed on top of the substrate, the metal film should stick well onto the substrate. For this the adhesive force between the metal thin film and the substrate should be strong so as to keep the metal film on top of the substrate. This is done by treating the substrate surface with $O_2$ plasma. This contrast in adhesion is necessary for a successful transfer for the structured thin film from the stamp to the substrate. Adhesive treatments are used for other experiments as well [43, 44, 45, 46] and the knowledge from their work is used for helping the nanotransfer process. Nanotransfer printing is a dry process and does not require any etching during the fabrication of the nanostructures. We used two main species of metals for nanotransfer printing, namely Permalloy and Gold.

5.2.1 Stamps with Permalloy

Figure 5.2 shows the stack of metals evaporated on the stamp. To further help the metal stick to the substrate surface, we use a 4nm layer of Ti as an adhesive layer of the stack to the Si substrate. As our magnetic metal species, we evaporated 10 nm of Permalloy. In order to further facilitate the metal to come off from the stamp a 10 nm thick layer of Au is used as a sacrificial layer. During the transfer process, the Au acts as a weak contact between the stamp and the metal.

<table>
<thead>
<tr>
<th>Ti = 4 nm</th>
<th>Py = 10 nm</th>
<th>Au = 10 nm</th>
<th>Si</th>
</tr>
</thead>
</table>

Figure 5.2: The schematic shows the stack of metals evaporated on the stamp.
5. NANOTRANSFER PRINTING

After evaporating the metal stack we took a look at the stamp using an SEM to understand better what was happening on the stamp surface. Figure 5.4 is a cross-sectional SEM images of the stamp before being used for nanotransfer. The metal stack sits on top of the nanopillars on the stamp and the remaining is between the trenches. Permalloy was evaporated at different evaporation rates. Later on it will be explained how the different evaporation rate of the metal play a very big role in making the nanotransfer process work.

Figure 5.3: Pillar stamp with Permalloy evaporated at 15 Å/s. The total thickness of the Ti and Py is 33 nm.

During the cleaving process of the Si stamp, the break went through some of the nanopillars and literally chopping the nanopillar into half. This gave an amazing insight into how the metal sits on top of the nanopillar. Figure 5.4 shows the metal sitting on top of the nanopillar.

5.2.2 Stamps with Gold

We repeated the evaporation process of metal thin films but this time we evaporated only Ti and Au. As pre-treatment the nanopillar stamp was first treated with an anti-sticking layer. Figure 5.5 shows the stack of metal evaporate on the stamp. It consists of 20 nm of Au and 4 nm of Ti.

Here we look at the pillar stamp with evaporated 4 nm Ti and 20 nm Au. Again the stamp was cleaved and we had a look at the cross-section of the stamp. Figure 5.6
Figure 5.4: While cleaving the stamp, the crack went through one of the pillars and this showing a cross-section of the pillar itself.

Figure 5.5: Metal stack evaporated on Si pillar stamp. It consists of 20 nm of Au and 4 nm of Ti.
5. NANOTRANSFER PRINTING

shows the cleaved edge of a pillar stamp with metal on top.

Figure 5.6: Cleaved edge of nanopillar stamp with Ti and Au evaporated.

Figure 5.7 shows an SEM image of some pillars where the metal caps are removed due to cleaving. Figure 5.8 shows a close-up of the pillars without the metal caps. The height of the pillar without the metal cap is 95 nm and with the metal cap is 122 nm. This gives the thickness of the evaporated metal stack to be 27 nm, which is near to the thickness read from the evaporation machine.

Figure 5.7: SEM image of pillars without caps.
5.3 Results and Discussion

After preparing the stamps with the evaporated metal stack, we do the nanotransfer. The process is very similar to a NIL where the stamp is pressed on top of a substrate coated with polymer. In this case, the surface of the substrate is pre-treated to be sticking and then the stamp with the metal stack is pressed on top of it, at high pressure and temperature for a certain length of time. Once it is done, the stamp demolded.

We will first discuss Au because we have an optimized recipe for it where almost 100% of the nanodots are transferred. We had some issues with Permalloy in the beginning. We will discuss the faced issues and the solutions we found to them.

5.3.1 Gold Transfer Printing

Using the metal stack for Au, as shown in figure 5.5, the nanotransfer process was done. Figure 5.9 is a large area SEM image of the transferred Au nanodots. The nanodots are transferred over the whole area of the structured area. There were some slight defects in the nanodots where it seemed as if a slight edge of the nanodot was not properly transferred.

Figure 5.10 shows a close-up of one of the nanodots. It clearly looks that some part of the nanodot did not get transferred. As stated before, the SEM does not give any
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Figure 5.9: SEM image of the transferred Au nanodots.

information of the profile, so we did AFM images to find more about the transferred nanodot.

Figure 5.10: Close-up SEM image of one of the nanodots.

Figure 5.11 is an AFM image of the transferred Au nanodots and it gives us additional information of what is actually happening. The profile measurements of the nanodots show a difference in height. In case of the figure, the ones the left shows a height of 25 nm, which match the amount of metal evaporated on the stamp. But the nanodots on the right shows a height of 49 nm, which is actually more than what was evaporated. Most of the nanodots are like the one on the right, with a height more
5.3 Results and Discussion

than that of the evaporated metal thickness. We needed a bit more of information.

![AFM image of the transferred Au nanodots](image)

**Figure 5.11: AFM image of the transferred Au nanodots**

For this we look at the 3D image that we can get from the height profile. Figure 5.12 shows a 3D AFM image and we can see that the nanodots which are measuring 25 nm in height are flat and the other are slightly raised in the middle. Now, the metal height cannot be different for the nanopillars, as we see from the previous SEM images of the stamp that they look all the same. So, there is only one possible explanation for this issue.

We think that during demolding of the nanotransfer, the top Au is being pulled and bending upwards. This is illustrated in figure 5.13. This can explain why many nanodots are measuring taller than others.

Although Au is not the metal species we are interested in but it gives a reference to start with for working on the nanotransfer of Permalloy. After repeated experiments we found out that Permalloy actually behaves completely different from Au and needed some extra attention to detail for making the process work for it.

### 5.3.2 Permalloy Transfer Printing

In this section, we will discuss how in case of Permalloy we found out that the evaporation rate has a big effect on the nanotransfer process. We discovered that a faster
Figure 5.12: 3D AFM image of the transferred Au nanodots.

Figure 5.13: Au bending upwards after demolding of stamp.
5.3 Results and Discussion

Evaporation rate produces better results. In case of Permalloy, we used nanodots, nanolines and NML structures for nanotransfer.

5.3.2.1 Transferred Nanodots

Nanodots were the first nanostructures that were tried for the nanotransfer process. For evaporating thin films, thickness and evaporation rate are the two parameters that we can set. We were always setting the thickness but we never paid much attention to the evaporation rates. The evaporation of Permalloy was always done at a rate of around 5 Å/s. The evaporated metal stack is shown in Figure 5.14.

| Ti = 4 nm | Py = 20 nm | Au = 25 nm | Si |

Figure 5.14: Stack of evaporated metals on stamp before transfer. Au is 25 nm and acts as the sacrificial layer. Permalloy is 20 nm and then Ti is 4 nm.

From our experiments we observed that the transfer was taking place only around the edges of the structured area. Figure 5.15 shows an SEM image of a nanotransfer where the evaporation of Permalloy was done at 5 Å/s. As it is clear, the transfer is done only around the edges.

Figure 5.16 shows a large area SEM image of the transferred nanodots. Apparently the areas where the nanotransfer worked, it worked very well with the nanodots well formed and well spaced. But the overall yield of the nanotransfer was not high.

Figure 5.17 shows a close-up tilted image of the nanodots. Again, the nanodots look very nice and the tilted image give an impression of it overall form.

We compared Au and Permalloy transfer printing by preparing two stamps, one with Au and the other with Permalloy, and putting them through the exact same
5. NANOTRANSFER PRINTING

Figure 5.15: Large area SEM image of transferred nanodots. The evaporation was done at 5 Å/s. Only some nanodots are transferred around the edges.

Figure 5.16: Large area SEM image of transferred nanodots. The evaporation was done at 5 Å/s. These nanodots were transferred only around the edges but the transfer at the edges works quite good.
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Figure 5.17: Close-up of the transferred nanodots. Each dot is around 116 nm in diameter, with a spacing of around 40 nm.

The process of preparation and printing. Figure 5.18 shows microscopic images of (a) Au and (b) Permalloy transfer printed side by side and we observed that the parameters that work for Au did not work for Permalloy. This made it very clear that the recipe that worked for Au did not necessarily work for Permalloy. We had to start looking into other parameters.

The evaporation rate was one parameter that we did not play around with yet. So, we decided to change it to see its effects. We had always used 5 Å/s as the evaporation rate. We increased it to 10 Å/s and noticed a significant change in the yield. Figure 5.19 shows the transfer printing of nanodots where Permalloy was evaporated at 10 Å/s. There is metal on the edges but in the middle as well.

This result gave us a new direction to explore. To further improve the transfer yield we increased the evaporation rate to 15 Å/s and the metal thickness was reduced. As expected, we observed further improvement with the transfer yield jumping to almost 100%.

Figure 5.20 shows a close-up of the transferred nanodots. It is clear that the nanodots were transferred almost perfectly. We observed the nanodots transferred over the whole area and we found some differences.

When we look at the nanodots at the corners, we observe that they are slightly shifted. Figure 5.21 shows a close-up of all four corners. The arrows indicate the
Figure 5.18: Comparison of Au and Permalloy transfer printing. The transfer printing recipe is different for different metals.

Figure 5.19: Large area microscopic image of transferred nanodots. The evaporation was done at 10 Å/s. Nanodots are transferred around the edges and some in the middle as well.
5.3 Results and Discussion

Figure 5.20: Close-up SEM image of transferred nanodots.

direction of shift. The nanodots around the edges were experiencing not just a vertical force coming from the top but some horizontal force as well coming from the side. This made them slightly shift. One explanation is that the stamp bends while being pressed and created lateral forces on the edges, thus producing the shifts. The bending of Si has has been studied by Namazu [47]. To have a better understanding of what is happening, we needed to look at the AFM images.

Figure 5.22 shows a close-up 3D AFM image of one of the shifted nanodots at the edge. We can actually see how the nanodot is shifted, where some residue is left and a small trail is left. It really seems as if the nanodots are smeared.

To get any sort of magnetic contrast out of MFM measurements for Permalloy, the shape has to be asymmetric. But still we did some MFM measurements. Figure 5.23 shows (a) AFM and (b) MFM images of transferred nanodots. As expected the nanodots being symmetric in shape are not showing any magnetic contrast. Some contract is visible. This is because some of the nanodots got skewed during transfer and because of this had a slight asymmetric shape and thus showing some contrast.

5.3.2.2 Transferred Nanolines

With nanolines we experienced the same results of having nanotransfer only at the edges. Figure 5.24 shows an SEM image of the whole area. The shiny part is where the nanotransferred metal is.
Figure 5.21: Close-up SEM image the four corners of the transferred nanodots square. (a) is the top-left corner, (b) is the top-right corner, (c) is the bottom-left corner and (d) is the bottom-right corner of the rectangle. The arrows indicate the direction of shift.
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Figure 5.22: AFM image of a shifted Permalloy nanodot the edge.

Figure 5.23: (a) AFM and (b) MFM images of transferred nanodots.
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Figure 5.24: Large area SEM image of transferred nanolines. These nanolines were transferred only around the edges but the transfer at the edges works quite good.

Figure 5.25 shows a close-up of the nanolines. The nanolines are around 80 nm wide, with a spacing of around 70 nm.

Figure 5.26 shows (a) AFM and (b) MFM image of the transferred nanolines. Since the line is too long to be scanned by the MFM end to end, we see only one end of it.

Figure 5.27 shows one nanoline which got broken while transfer and here one can
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Figure 5.26: (a) AFM and (b) MFM image of the transferred nanolines.

In this section we have shown how a lower evaporation rate produces a bad transfer yield in case of both nanodots and nanolines. For the nanodots we increased the evaporation rate and it had given the expected results. Using what we had learned from these basic structures, we applied the recipe on more complicated structures, in our case NML.

5.3.2.3 Transferred Nanomagnets

We had three different kind of NML stamps. Magnetic nanowires, majority gate and full adder. In all the cases we tried to apply the same recipe to do the nanotransfer. We first tried the nanowire stamp. The process did not work very well for it. Figure 5.28 shows SEM image of the transferred nanomagnets. This is a very small section of the whole transfer. The nanomagnets of the magnetic nanowire were completely smeared and shifted.

Figure 5.29 shows (a) AFM and (b) MFM images of Permalloy nanomagnets. Magnetic contrast can be seen as the transferred still had an asymmetric shape. But since
5. NANOTRANSFER PRINTING

Figure 5.28: SEM images of nanowires done with nanotransfer printing.

The transfer is not very good, the nanomagnets are not properly aligned.

Figure 5.29: (a) AFM and (b) MFM images of Permalloy nanomagnets done by nanotransfer printing.

5.3.2.4 Transferred majority gate and full adder

The we did an attempt to transfer print majority gates and full adders but gain the nanostructures came out smeared and the permalloy nanostructures did not stick to the substrate. Figure 4.2 shows the majority gate stamp. This is the classic three input majority gate made up of nanomagnets. Figure 5.30 is an SEM image of nanotransfer of the majority gate. None of the nanomagnets are at their expected position. It seems as if the stamp moved a lot during the transfer process resulting in a very bad transfer.

Figure 4.3 shows full adder stamp. This is a combination of majority gates and nanowires. The transfer results were the same as that of the majority gate. Figure 5.31
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Figure 5.30: SEM image of majority gate transfer attempt. Mainly the input nanomagnets are there but the rest did not get transferred.

is a SEM image of a full adder. Again, all the nanomagnets are moved and shifted.

Figure 5.31: SEM image of full adder transfer attempt. Mainly the input nanomagnets are there but the rest did not get transferred.

Since we had only once stamp of each NML structure for nanotransfer, we could not repeat the process to optimize it. One explanation of the NML transfers not working is that the structured area on all the NML stamps was very small and thus the stamp did not have enough friction to stay put and shifted while high pressure was applied.
5.4 Summary

It is shown that the nanotransfer printing process had issues of transfer yield in the beginning. A slower evaporation rate was used and the metal stack was thicker. This allowed the metal to move to the edges of the nanostructures on the stamp and hindered the transfer printing process. When the evaporation rate was increased, a significant increase in transfer yield was observed. By increasing the evaporation rate even further to 15 Å/s and decreasing the metal stack thickness, a near 100% transfer yield was demonstrated. These recipes were applied for other kind of nanostructures as well. For NML we observed issues of the stamp moving during the transfer printing process and thus disrupting the transferred nanostructures. One improvement would be to use more dummy structures to increase the contact area and prevent the stamp from moving.
Chapter 6

Conclusion and outlook

NIL has the great advantage of low cost and high throughput while keeping an acceptable precision during the fabrication process. The idea of the thesis was to exploit these advantages for the fabrication of NML. In this thesis it was explored how NIL can be used in different ways to make magnetic nanostructures for NML. The three ways were electrodeposition, NIL and nanotransfer printing. The aim of the thesis was to make these magnetic nanostructures specifically for NML. It has been shown that using all three methods, magnetic nanostructures can be fabricated. Out of the three, NIL proved to be the best method. Using NIL, magnetic nanowires were fabricated and their anti-ferromagnetic behavior was demonstrated. Majority gate and full adder structures for NML were also fabricated but due to some issues in the stamp fabrication, the shape anisotropy was not prominent and thus we had issues in observing magnetic contrast.

Electrodeposition and nanotransfer printing too can be used for NML fabrication and the identified challenges are very well solvable. Within the given duration of this thesis these problems could not be looked into. For electrodeposition a two electrode system was used. During nanotransfer printing, the main issue was the shifting of the structures during the nanotransfer printing. Having dummy structures placed strategically around the main structured area can help in reducing the shifting as the stamp will have more area to get in contact with and will be much more steadier on the substrate. Moreover, it will also help prevent any kind of bending of that stamp during the transfer process.

With advantages of low power consumption and robustness, NML has great potential in becoming the main technology for logic computation. Combined with NIL, the
cost of fabrication can be reduced and amount of throughput can be increased significantly. In this thesis it has been shown how the two can be very well combined and presented results demonstrate that NIL can become the industrial fabrication process for NML.

More work can be done on improving the electrodeposition process by using a potentiostat which gives much better voltage control. We have shown how NIL and liftoff works for NML. Using stamps with more precisely shaped rectangles for nanomagnets can help improve the shape of the fabricated nanomagnets in NML structures. This will result in improved functionality of the NML structures. In case of nanotransfer printing, as mentioned before, the use of dummy structures around the NML structures can help in removing the shifting problem. This requires the better understanding of designing stamps. Simulation work on nanotransfer printing can help reduce the cost of experimental testing as each stamp fabrication is costly and time consuming.
Chapter 7

Acronyms

EBL   Electron Beam Lithography
NIL   Nanoimprint Lithography
NML   Nanomagnetic Logic
AFM   Atomic Forced Microscope
SEM   Scanning Electron Microscope
MQCA  Magnetic Quantum-Dot Cellular Automata
UV    Ultra Violet
MFM   Magnetic Forced Microscope
HER   Hydrogen evolution reaction
HOR   Hydrogen oxidation reaction
EDX   X-ray spectroscopy
FIB   Focused ion beam
RIE   Reactive ion etching
Chapter 8

Publications, presentations and posters

Publications


8. PUBLICATIONS, PRESENTATIONS AND POSTERS

Presentations

- “Nanomagnet fabrication using nanoimprinting.”, IAS Kickoff Meeting, October 2009
- “Fabrication of magnetic nanostructures via nanoimprinting”, International Symposium on Advances in Nanoelectronics
- “Single domain nanomagnet fabrication using electrodeposition, nanoimprinting and focused ion beam cutting”, 4th TUM-Nanomagnetic Workshop, Feb. 3rd 2012

Posters

- “Nanotransfer and nanoimprinting techniques”, IGSSE Forum Raitenhaslach June 2010
- “Nanomagnet fabrication for nanomagnetic logic (NML)”, IGSSE Forum 2012
- “Nanoimprinting for nanomagnets”, 5th joint meeting for the nanocenters in the EuroTech Universities Alliance, Friday June 1st 2012
- “Embedded permalloy nano-oval fabrication using nanoimprinting and liftoff for Magnetic Quantum-Dot Cellular Automata”, Nanoimprint and Nanoprint Technology (NNT) Symposium ,Napa California, October 24-26, 2012
Chapter 9

Appendix

9.1 Nanowire Stamp Design

Figure 9.1 shows the placement of the nanomagnets that make up the magnetic nanowire. Figure 4.1 shows the SEM image of the nanowire after fabrication.

Figure 9.1: Nanowire nanomagnet placement.
9. APPENDIX

9.2 Majority Gate Stamp Design

Following are the details about the majority gate stamp. Figure 4.2 shows SEM images of the stamp after fabrication. Figure 9.4 shows how the support structures are arranged around the structured area. The support structures are useful in preventing the stamp from moving during a NIL process.

- Horizontal Oval: 60nm x 120nm
- Vertical Oval: 60nm x 90nm
- Horizontal Spacing: 20nm
- Vertical Spacing: 20nm
- Spacing between horizontal and vertical oval: 20nm
- Rows: 50
- Columns: 50

The grey patch depicts the area covered by the whole structure. This patch is repeated as many times as mentioned.

9.3 Full Adder Stamp Design

Following are the details about the full adder stamp. Figure 4.3 shows SEM images of the stamp after fabrication. This stamp has similar support structures as showed in figure 9.4.

- Horizontal Oval: 60nm x 120nm
- Vertical Oval: 60nm x 90nm
- Horizontal Spacing: 20nm
- Vertical Spacing: 20nm
- Spacing between horizontal and vertical oval: 20nm
9.3 Full Adder Stamp Design

Figure 9.2: A single majority gate.
9. APPENDIX

Figure 9.3: Majority gate placements.

- Rows: 25
- Columns: 25

The grey patch depicts the area covered by the whole structure. This patch is repeated as many times as mentioned.

9.4 Pressure calculations for nanotransfer printing

The pressure experienced by the nanodots during nanotransfer printing was calculated. Figure 9.7 shows the schematic used to calculate total surface area of the nanopillar tops. Figure 9.8 shows a schematic of the stamp indicating the two area used for calculating the pressure using the pressure-area equality. For the calculations, the bending of the stamp was not taken into consideration.

As shown in figure 9.7, ’a’ is the diameter of the nanopillar and ’b’ is the spacing between two pillars. In order to calculate the total number of pillars along the x-axis,
9.4 Pressure calculations for nanotransfer printing

Figure 9.4: Support structures around the structures. They are used for holding the stamp in its place during imprinting.
Figure 9.5: A single full adder.
9.4 Pressure calculations for nanotransfer printing

Figure 9.6: Full adder placements.
APPENDIX

(nx), and the total number of pillars along the y-axis, we use the following formulas:

\[
\begin{align*}
nx &= \frac{Tx}{(a+b)} \\
ny &= \frac{Ty}{(a+b)}
\end{align*}
\]

To calculate the total number of nanodots we do the following:

\[
nd = nx \times ny
\]

Now to calculate the total contact area of the nanopillars, we do the following:

Area of dots = \( nd \times (\pi \times (a/2)^2) \)

We use the following pressure-area equality to calculate the pressure experienced by the nanopillars:

\[
P_2 = P_1 \times \frac{A_1}{A_2}
\]

According to Figure 9.8, the area of the dots is \( A_2 \). The area of the stamp experiencing the pressure from the NIL machine is \( A_1 \).

From the above formulas we can calculate the pressure experienced by the nanopillars. Below we will discuss one example.

\[
\begin{align*}
a &= 100 \text{ nm} \\
b &= 200 \text{ nm} \\
Tx &= 600 \mu m \\
Ty &= 600 \mu m \\
nx &= \frac{600 \mu m}{(100nm + 200nm)} = 2000 \\
ny &= \frac{600 \mu m}{(100nm + 200nm)} = 2000 \\
nd &= 4000000
\end{align*}
\]

Area of dots = \( 4000000 \times (\pi \times (50nm)^2) = 31.7 cm^2 \)
Figure 9.7: Structured patch area calculation. 'Tx' is the total x-axis length. 'Ty' is the total y-axis length. 'a' is the diameter of the nanopillar and 'b' is the space between two pillars. The whole arrangement is used to calculate the total surface area of the structured patch.
Figure 9.8: Surface area indication. A1 is the area on the back on the stamp where the pressure is applied by the nanoimprinting machine. A2 is the surface area of the nanostructures on the stamp.
9.4 Pressure calculations for nanotransfer printing

\[ P_1 = 50 \text{ bar} \]
\[ A_1 = 1cm^2 \]
\[ A_2 = 31.7cm^2 \]
\[ P_2 = 159.2 \text{ kbar} \]

This a very large amount of pressure and the nanopillars should break. But since the stamp bends during transfer printing, the total contact area, \( A_2 \), is much larger and the corresponding pressure, \( P_2 \), is smaller. Figure 9.9 shows a table for the mentioned calculations. These calculations were some in collaboration with Tobias.
Figure 9.9: Table with pressure calculations for the above mentioned parameters.
References


REFERENCES


REFERENCES


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