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Nanomagnetic Logic Devices Fabrication using Nanoimprint Lithography

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***Abstract*— We present large scale fabrication of nanomagnetic logic devices using nanoimprint lithography. This is a fast and cost-effective way to fabricate nanomagnetic logic devices. Nanoimprint lithography is used for polymer patterning, followed by e-beam evaporation of Supermalloy and liftoff. Scanning electron microscope, atomic force microscope and magnetic force microscope, measurements have been done to verify the eligibility of this method.**

I. Introduction

Nanoimprint lithography (NIL) was first proposed by Chou [1], [2] as a fast and cost-effective method for fabricating nanostructures. Over the past years it has found applications in different fields including electrical, optical and magnetic devices [3–5]. The main role of NIL is to act as a cost-effective, large scale patterning method for nanostructures. Electron beam lithography (EBL) is traditionally used for nanostructure fabrication but it is not suitable for mass manufacturing. Optical lithography is still the main stream fabrication process used by the semiconductor industry but it is very expensive and faces many challenges. NIL promises to be a solution to these problems.

Nanomagnetic logic was demonstrated by A. Imre at the nanomagnet logic group at University of Notre Dame [6]. A lot of work has been done on the simulation and fabrication of NML devices. EBL is used(FIB) for the patterning process that is quite slow. In this paper we demonstrate the use of NIL for NML device fabrications. We will discuss the fabrication process, and review challenges and solutions in the fabrication, and test the results with various tools including Scanning electron microscope (SEM), atomic force microscope (AFM) and magnetic force microscope (MFM). Fabrication

Nanoimprint lithography requires three main components i.e. stamp, substrate and polymer. To fabricate NML devices we focus three types of structures, i.e. magnetic nanowires, majority gates and full adders. Each structure was fabricated on a standalone stamp (stamps were fabricated by IMS Stuttgart, Germany). On each of the stamps, each nanomagnet has a dimension of 60 nm by 90 nm. Ideally, smaller the distance, the coupling will be stronger for magnets. However, the gap between each nanomagnet is 40 nm which is limited by the stamp fabrication technique.

Each stamp is a 1 cm × 1 cm Si substrate with the nanostructures fabricated in the center. The magnetic nanowire stamp has a structured area of 100 µm × 100 µm. Each nanowire consists of 20 units, with a series of nanowires forming columns. Each column is 2 µm wide and 100 µm long. The structures are 100 nm high. Figure 1 shows an SEM image of the stamp of magnet wires.

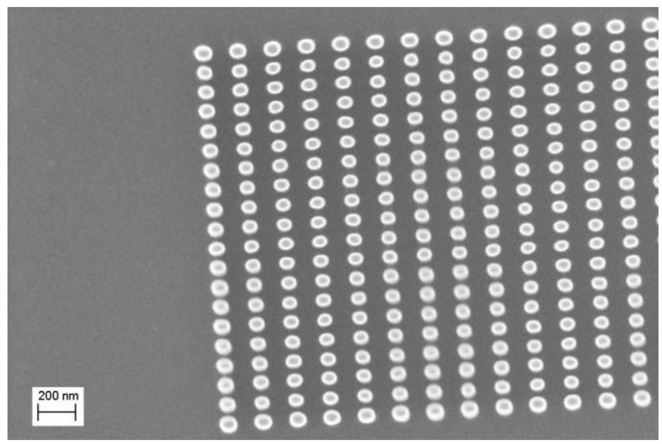

Figure 1. SEM image of magnetic nanowire stamp.

The majority gate stamp has a structures area of 50 µm × 50 µm. Each majority gate consists of three “driver” nanomagnets placed horizontally and five computing nanomagnets. The arrangement of the nanomagnets is shown in Fig. 2. The result of the majority gate is determined by the states of the “driver” magnets. We have four different types of majority gates with “driver” magnets placed in different positions to get all the possible logic operation combinations. The majority gates are arranged in an array of 50 × 50, giving a total of 2500 majority gates. Figure 2 shows an SEM image of the stamp.

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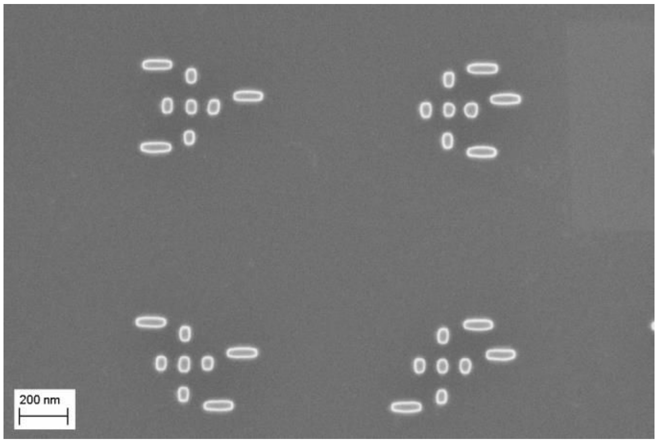


Figure 2. SEM image of majority gate stamp.

The full adder stamp has seven "driver" nanomagnets and forty three computing nanomagnets. The "driver" nanomagnets are of three different lengths in order to input different signals. The full adder has an array of 25 × 25, giving a total of 625 adders on the stamp. Figure 3 shows an SEM image of the stamp.

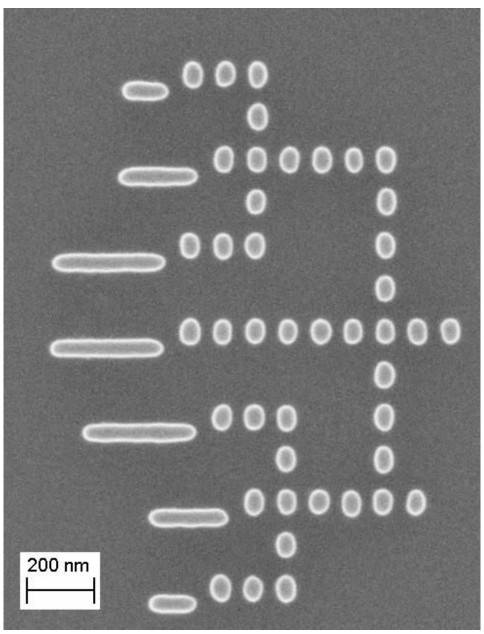


Fig. 3. SEM image of full adder stamp.

The main challenges during the fabrication of the structures include (1) transferring structures from the stamp onto the polymer precisely; (2) liftoff of the evaporated magnetic materials. In the following sections we will discuss how we overcome these challenges

A. *Structure transfer*

We had 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 and resulted in shifted patterns on the polymer. Figure 4 shows an optical microscope image of the shifted majority gate patterns on the polymer. During the structure transfer process, the polymer demolded when the temperature was below the glass transition temperature (T_g). One possible explanation is that during the cooling down process, the stamp moved so that the patterns formed on the polymer also shifted. Once the operating temperature was below T_g, these patterns were formed on the polymer. It is also observed that a shift of 10 nm is enough to spoil the patterns.

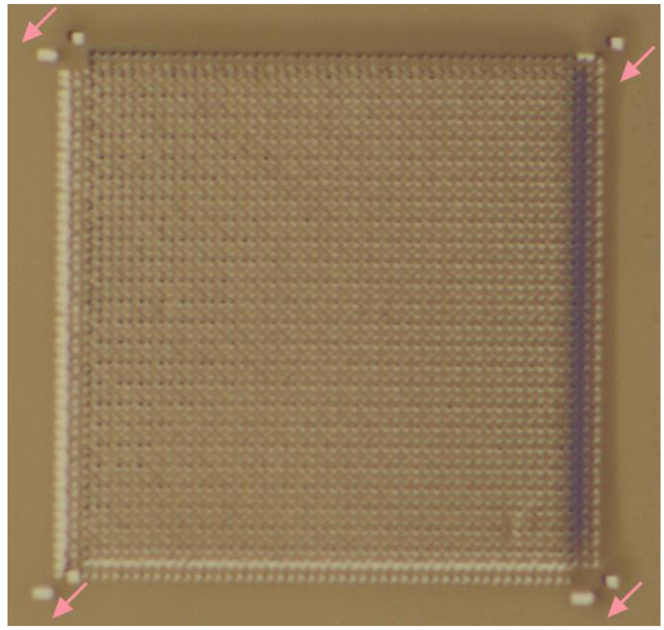
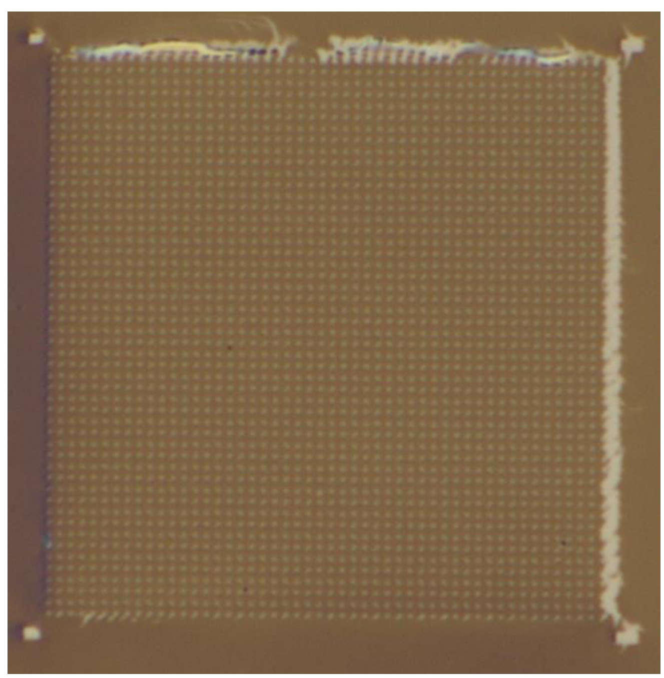


Fig. 4. Optical microscope image of shifted majority gate patterns after imprint. The arrows show the shift direction.

We observed that when we did the demolding step before the temperature went below T_g, the imprinted patterns did not shift. We think that above T_g the polymer is still in its low viscous state, and the polymer is holding the shapes of the nanostructures on the stamp and any shifts of the stamp are not transferred onto the polymer. We changed our recipe and demolded the polymer at a temperature above T_g, and got an improved transfer of the stamp nanostructures into the polymer, as shown in Fig. 5.



Fig, 5. Optical Microscope image of majority gate pattern without any shifts after imprint. There are some defects at the edge of the patterns due to demolding.

B. Liftoff of magnetic material

After the NIL process we evaporated a layer of titanium (~ 6 nm) for adhesion, followed by a layer of Permalloy ($Ni_{79}Fe_{21}$ ~20 nm). The lift-off step was done in a solution of acetone with ultrasonication. The lift-off did not go well for Permalloy, as shown in Fig. 6.

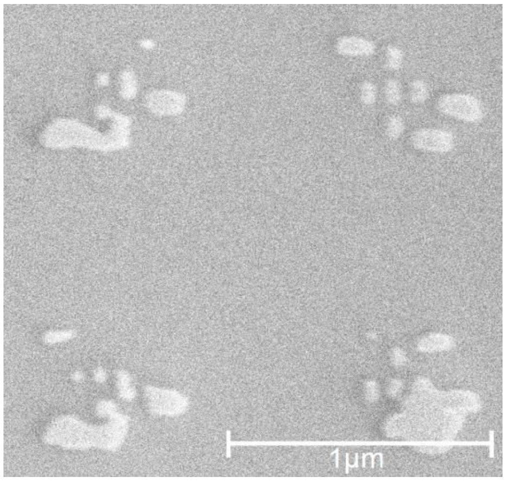


Fig. 6. SEM image of majority gate after lift-off of Ti/Permalloy layers.

Previous publications on the fabrications suggest that most of the magnetic logic devices are made of Supermalloy ($Ni_{79}Fe_{16}Mo_5$) [7-8]. Supermalloy has almost the same magnetic properties as Permalloy but it is much easier for lift-off [9]. So we did the lift-off process of Ti (~6 nm)/Supermalloy (~20 nm) layers with the same condition when we used Permalloy, i.e. in the acetone solution with ultrasonication, and the liftoff worked well. Figure 7 shows an SEM image of majority gates made of Ti/Supermalloy layers.

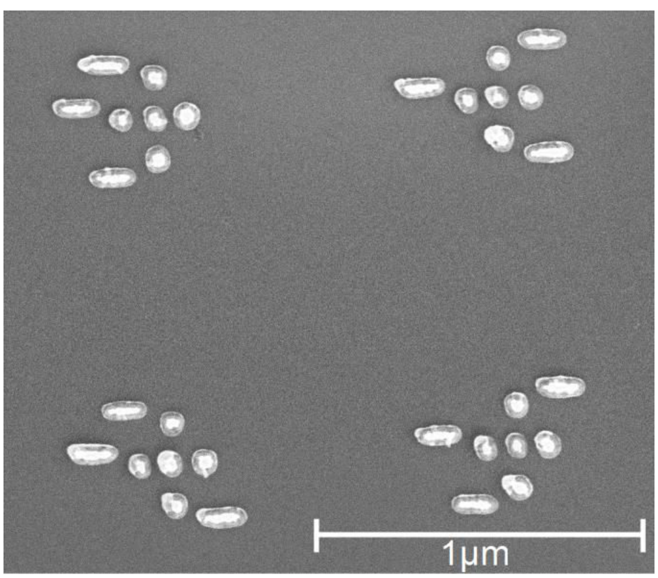


Fig. 7. SEM image of Supermalloy majority gates after lift-off.

II. Results

One of the ways to test magnetic devices is to image them with magnetic force microscope. For nanomagnets that we have fabricated, shape anisotropy is critical for a successful imaging [7], [9]. The longer axis is called the easy axis and the shorter axis is called the hard axis. If there is no external field, a nanomagnet will be polarized along the long axis. For the stamps we have used, the magnets are more olive-shaped than rectangular-shaped, and roundness of the nanomagnets may cause issues in the imaging process. Even so, we are still able to get reasonable images. Figure 8 shows AFM and MFM images of the magnetic nanowire, and anti-ferromagnetic coupling in the magnetic wire is well presented

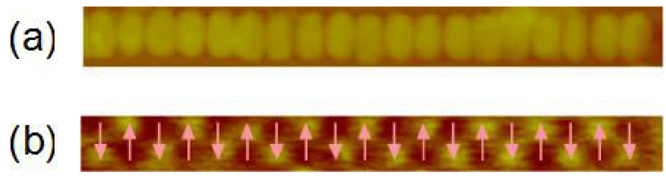


Fig. 8. Anti-ferromagnetically coupled magnet wire (a) AFM image of the magnetic nanowire. (b)MFM image of the nanowire.

However, the majority gates and the fuller adders are much more difficult to image with the MFM technique. The work to understand them with techniques including MFM and magneto-optical Kerr effect microscope is in progress and will discussed in our publications in the future.

III. Conclusion

We propose the use of nanoimprint lithography (NIL) technique in fabricating NML devices. SEM results show that NIL is a promising tool for mass manufacturing of NML devices while some issues are needed to be resolved. Demolding polymer at a temperature above T_g was used to prevent shifting of patterns; Lift-off of Ti/Supermalloy layers produced better-shaped nanomagnets than lift-off of Ti/Permalloy, which is consistent with the previous findings. MFM results show that the magnets are anti-ferromagnetically coupled in the magnetic wires. The majority gate and the full adder were fabricated but they cannot be imaged with the MFM technique. Work to understand their behavior is in progress.

Acknowledgment

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