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Micro-structuring of thick NdFeB films using high-power plasma etching for magnetic MEMS application

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Abstract
This paper describes the micro-patterning of thick NdFeB magnetic films using a high-power plasma etching method. The effects of RF bias power and gas composition on the selectivity and etching rate are experimentally studied. A maximum etching rate of 60 nm min^{-1} is achieved with an inductively coupled plasma power of 500 W and a RF bias power of 200 W. A maximum selectivity of 0.26 between hard baked AZP4903 photoresist and NdFeB magnetic films is achieved when volumetric Cl_2 concentration is 2.5%. NdFeB micro-magnets as thick as 4.2 μm are achieved by using AZP4903 photoresist. Magnetic film as thick as 10 μm can be patterned by using SU-8 photoresist with a thickness of 100 μm as the mask. The magnetic property of patterned microstructures is characterized using a vibrating sample magnetometer and the magnetic field distribution is measured using a Hall effect sensor IC. The characterization results indicate that the patterned magnetic microstructures have a high magnetic remanance of 1.0 T, which is comparable to that of the non-patterned NdFeB films.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Magnetic materials have various applications in micro-electro-mechanical systems (MEMS), such as electromagnetic sensors, actuators and energy harvesting devices [1–3]. However, it has been a technological challenge to integrate high-performance magnetic structures with MEMS fabrication technologies. Magnetic films such as Co-Pt and NiFe have been fabricated by electroplating techniques for MEMS devices. However, magnetic films formed by electroplating suffer from low magnetic remanance and energy products [4, 5]. For applications such as electromagnetic actuators and energy harvesters, micro-patterning of magnetic films as thick as tens of microns is required to generate sufficient force or electrical power. According to the work of one of our authors, the magnetic property of NdFeB films deposited by magnetron sputtering can catch up with that of commercial sintered NdFeB magnets [6]. The deposition rate is as high as 90 nm min^{-1} and a maximum thickness of 20 μm has been achieved [7]. Though nano-patterning techniques for magnetic materials have been intensively studied for the applications of high-density magnetic recording media and magnetic quantum devices, it is still a challenging work to fabricate magnetic structures as thick as tens of micrometers. Both wet chemical etching and CO/NH_3 gas-based reactive ion etching (RIE) methods have been used to fabricate NdFeB microstructures [8–10]. However, fine patterning cannot be achieved by wet etching method as the isotropic etching method leads to large sidewall etching. Carbon monoxide and ammonia-based RIE is not applicable to multilayered NdFeB/Ta films due to its high selectivity between tantalum and NdFeB. For micro-structuring of NdFeB magnetic films as thick as

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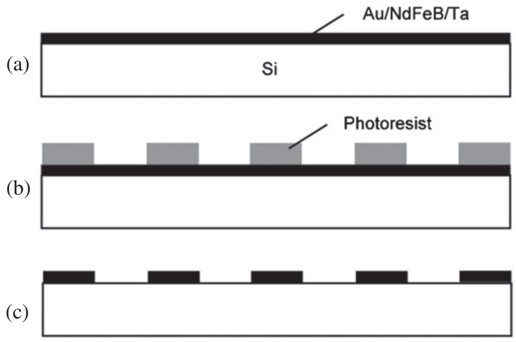

Figure 1. Fabrication process for micro-patterning of NdFeB magnetic films.

Table 1. NdFeB etching conditions.

Cond.	ICP (W)	Bias (W)	Cl_2/Ar flow rate (sccm)	Etching rate (nm min^{-1})	Selectivity
A	500	200	7/21	50	0.13
B	500	100	7/21	26	0.08
C	500	50	7/21	10	0.04
D	500	200	7/0	40	0.1
E	500	200	7/42	44	0.14
F	500	200	7/84	50	0.19
G	500	200	2/48	60	0.26

20 μm, the author adopted a silicon molding process, which includes deposition of magnetic films on a micro-trenched silicon wafer and mechanical polishing processes [7]. This technique has been used in the fabrication of electromagnetic energy harvesters. However, the complexity of this process sets an obstacle for the popularity of its application. In this paper, we report on a high-power plasma etching method using Ar/Cl_2 gases for micro-patterning of high-performance NdFeB magnetic films. The influence of the processing steps on the magnetic properties of the NdFeB films is characterized.

2. Fabrication process and results

2.1. Fabrication process

The fabrication process is shown in figure 1. NdFeB magnetic film is deposited on a silicon substrate using magnetron sputtering with Ta as the adhesive layer and Au as the anti-oxidization layer. A positive photoresist (AZP4903 from AZ Electronic Materials Ltd.) is coated with a thickness of 25 μm and patterned by photolithography. The wafer is baked at 150 °C for 30 min on a hotplate to improve its plasma resistivity. High-power plasma etching of thick NdFeB magnetic films is conducted by varying the gas compositions and electrical conditions as shown in table 1. Finally, the photoresist is removed, and the etching results are characterized.

2.2. Effect of RF bias power

By using the etching conditions (*A*, *B*, *C*) shown in table 1, the effect of RF bias power is evaluated. For a

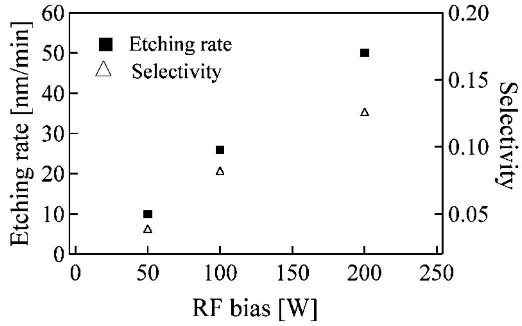

Figure 2. Etching rate and selectivity variation with the RF bias power, where the ICP power is 500 W, the process pressure is 1.5 Pa, and flow rates of Cl_2 and Ar are 7 sccm and 21 sccm, respectively.

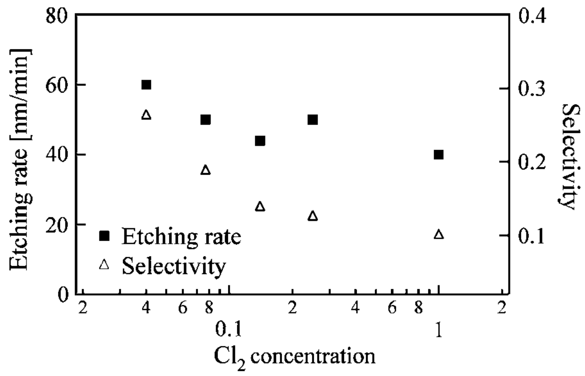

Figure 3. Etching rate and selectivity variation with the Cl_2 concentration, where the ICP power is 500 W, the RF bias power is 200 W, the process pressure is 1.5 Pa.

4 inch substrate, the ICP (inductively coupled plasma) power is 500 W, while the RF bias power varies from 50 to 200 W. The process pressure is set to 1.5 Pa as a constant and chamber temperature is 20 °C. The flow rates of Cl_2 and Ar are 7 sccm and 21 sccm, respectively. The selectivity in etching is defined as the etching rate ratio between NdFeB and hard baked photoresist. As shown in figure 2, both the etching rate of NdFeB films and the selectivity in etching increase with increasing RF bias power. It can be explained that the high RF bias power enhances the ion plasma etching effect. Due to the limitation of our etching system, a RF bias power of 200 W is utilized in the following experiments to evaluate the effect of gas composition on the etching result. The etching rate of NdFeB probably can be further improved by using a higher RF bias power to achieve higher ion energy and sputter yield.

2.3. Effect of gas composition

By comparing the etching results using different conditions (*A*, *D*, *E*, *F*, *G*), the effect of Cl_2 concentration is characterized. In this experiment, the ICP power and bias power are 500 W and 200 W, respectively. The process pressure is 1.5 Pa, and volumetric ratio between Cl_2 and Ar varies from 0 to 1. From the results shown in figure 3, it can be seen

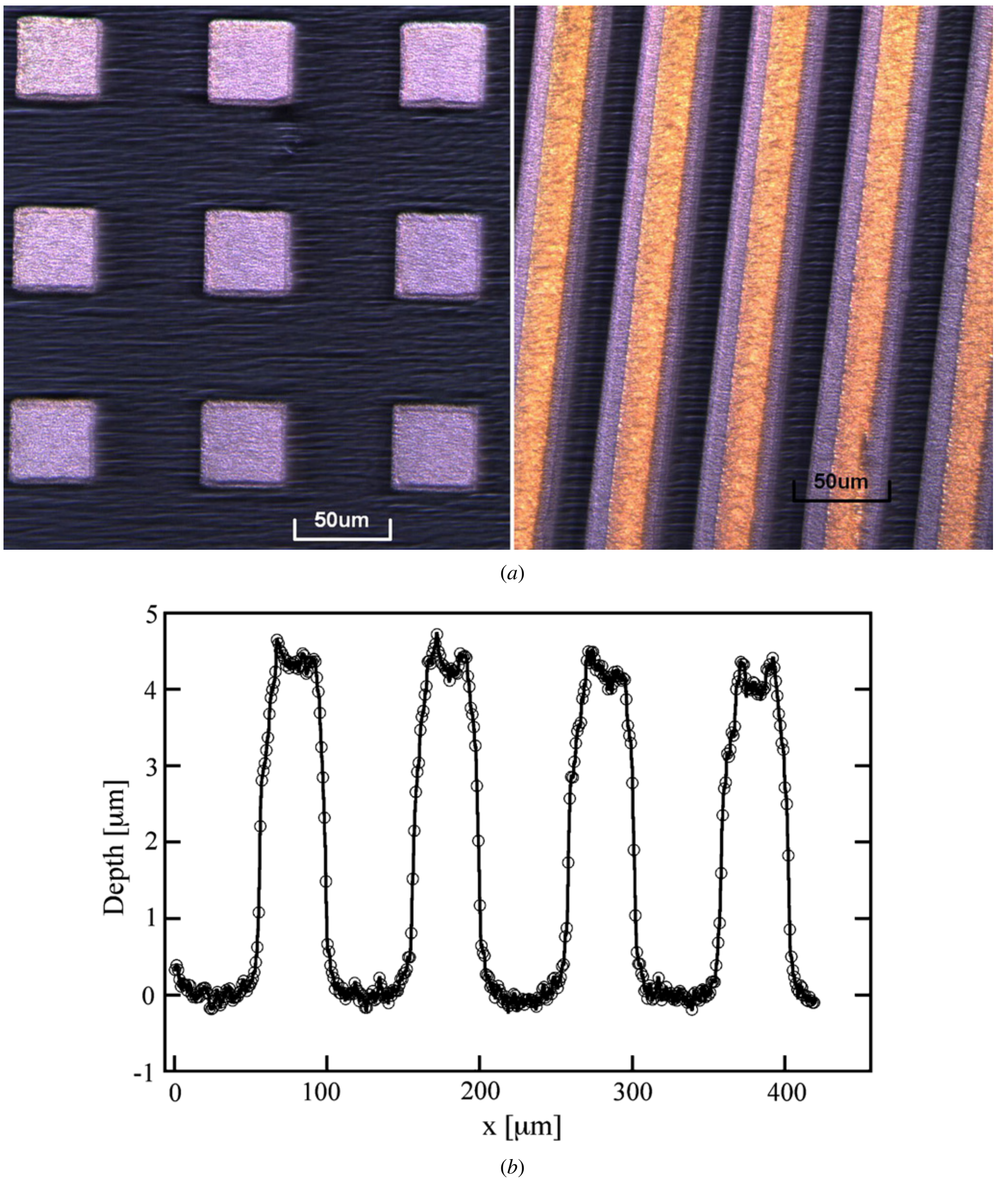

Figure 4. (*a*) Photograph of micro-magnets fabricated by high-power plasma etching using AZP4903 photoresist as the mask. (*b*) The depth profile of the micromagnets shown in figure 4(*a*).

that the etching rate changes from 40 to 60 nm min^{-1} by varying the Cl_2 concentration. However, the selectivity is greatly improved by decreasing the Cl_2 concentration. A maximum selectivity of 0.26 between hard baked AZP4903 and NdFeB film is achieved. Though the etching rate variation has not been clearly understood, it seems that the etching of NdFeB is mainly due to a plasma-based ion milling effect. Furthermore, the etching of photoresist is accelerated by the addition of Cl_2, an effect of RIE. We tried to use pure Ar gas for NdFeB etching to increase the selectivity between the photoresist and the NdFeB materials. However, it was found that the photoresist is carbonized and the pattern of the photoresist is destroyed for plasma etching over 10 min. It probably origins from the heating effect of high-power plasma. The carbonized photoresist can be removed by the RIE effect with a higher Cl_2 concentration. Therefore, chlorine gas is important in NdFeB etching to avoid carbonization of the photoresist.

2.4. Fabrication results

With an optimized etching condition (*G*), the fabrication result of NdFeB magnetic microstructures is illustrated in figure 4 (*a*). Square micro-magnets with a length of 50 μm and thickness of 4.2 μm are successfully fabricated. The depth profile is shown in figure 4 (*b*). In order to fabricate thicker NdFeB microstructures, SU-8 photoresist is employed as the mask for NdFeB plasma etching. Figure 5 illustrates the fabrication results for magnetic films as thick as 5 μm. By using a SU-8 photoresist with a thickness of 100 μm, NdFeB microstructures with a thickness of 10 μm can be fabricated.

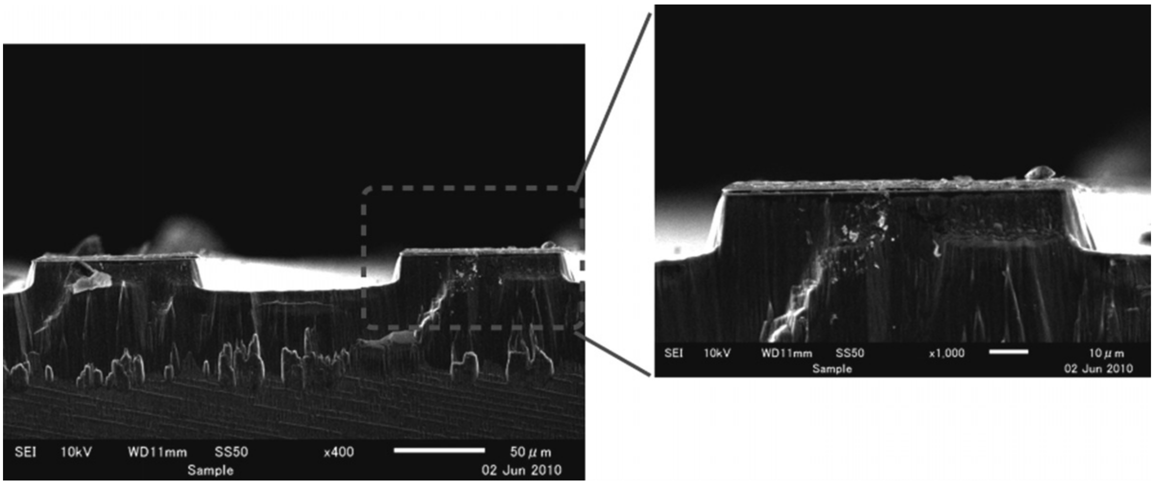

Figure 5. Cross-sectional SEM image of the fabricated NdFeB micro-strips using SU-8 as the mask.

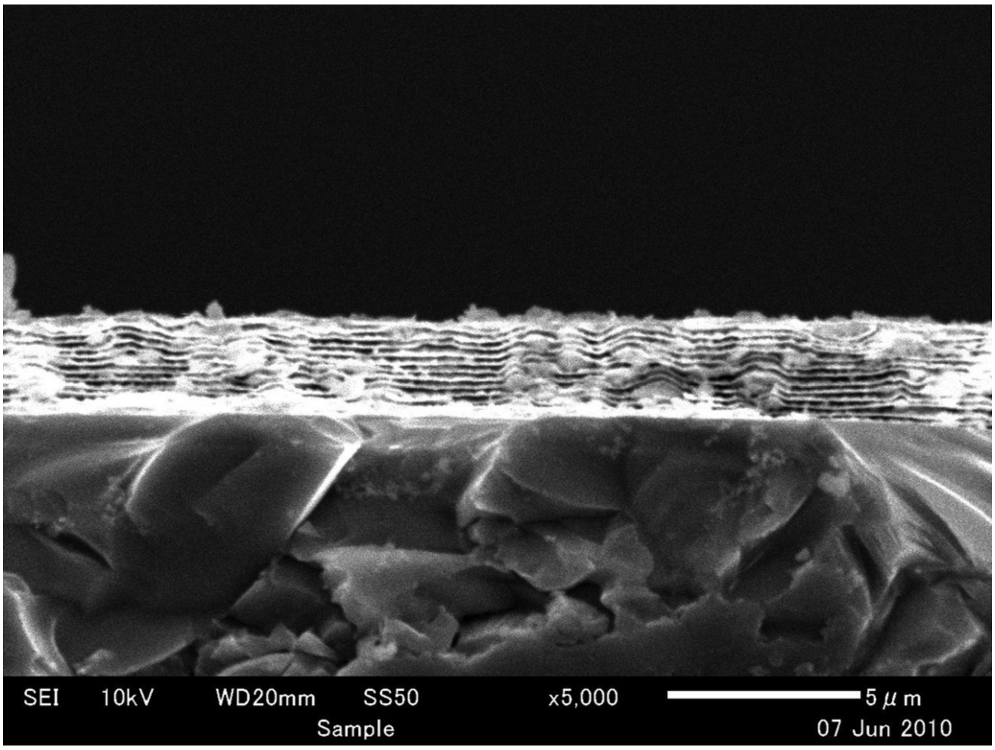

Figure 6. SEM image of the multilayered NdFeB/Ta magnetic films after high-power plasma etching with a thickness of 2.5 μm.

3. Characterization and discussions

3.1. Magnetic property of the patterned NdFeB films

The magnetic property of the magnetic films is measured using a vibrating sample magnetometer (VSM). VSM measurements of multilayered NdFeB/Ta films deposited onto silicon substrates are compared with patterned NdFeB/Ta films. The widths of magnetic strips and space are 80 μm and 120 μm, respectively. The cross-sectional scanning electron microscope (SEM) image of the patterned magnetic line with a thickness of 2.5 μm is illustrated in figure 6. The B–H curves of the non-patterned and patterned multilayered NdFeB/Ta films are plotted in figure 7. After the high-power plasma etching process, the magnetic remanence of the multilayered NdFeB/Ta magnetic film is still larger than 1.0 T. The degradation of magnetic property probably originates from the irreversible flux loss mechanism due to the temperature increase of the substrate in the presence of the high-power plasma [11]. By using an etching system with sufficient substrate cooling or an intermittent etching scheme, degradation of the magnetic property could be avoided.

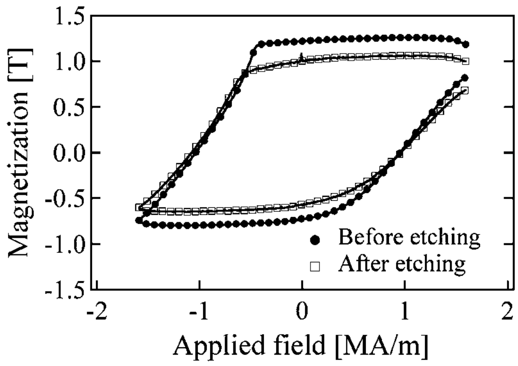

Figure 7. B–H curves of patterned NdFeB/Ta films compared with non-patterned films.

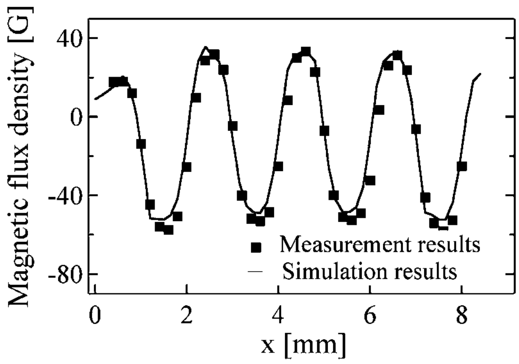

Figure 8. Magnetic field distribution of patterned magnetic micro-strips with a width of 1 mm and a spacing of 1 mm.

3.2. Magnetic field distribution of the NdFeB magnetic microstructures

In order to evaluate further the NdFeB microstructures patterned by the high-power plasma etching method, the magnetic field distribution is measured using a Hall effect sensor IC (A1386 from Allegro MicroSystems, Inc.) with an active area of 200 μm × 200 μm [12]. For NdFeB magnetic strips with a thickness of 10 μm, width of 1 mm, and space of 1 mm, respectively, the measurement and simulation results of magnetic field distribution at a plane that is 300 μm above the surface of the magnetic strips are plotted in figure 8. It can be seen that the measurement result is very close to that of the finite element method (FEM) simulation result, which also suggests that the magnetic structures fabricated by the high-power plasma etching method have a very high magnetic remanence comparable to the magnetic remanence value of 1T in simulation. Higher magnetic flux density can be achieved near the surface of the magnetic microstructures, which can improve the sensitivity of magnetic sensors and power output of magnet-based energy harvesters.

4. Conclusions

In summary, micro-fabrication of high-performance NdFeB micro-magnets using magnetron sputtering and high-power plasma etching techniques was demonstrated. High RF bias power can greatly improve the etching rate. By varying the Cl_2 concentration compared to Ar, it was found that the etching of NdFeB magnetic films is based on a plasma ion milling effect. The addition of Cl_2 can prevent the photoresist from carbonization with a high-power plasma and high substrate temperature. Using an optimized etching condition, a relative high etching rate of 50 nm min^{-1} was realized with a selectivity of 0.26 to the photoresist (AZP4903). The result of VSM measurement indicates that the patterned magnetic microstructures show a good magnetic property that is comparable to that of the non-patterned magnetic films. The measured magnetic field distribution of the magnetic microstructures using a Hall effect sensor IC is very close to the simulation results, which further suggests the good magnetic property of patterned NdFeB microstructures.

Acknowledgments

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