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Inductively Coupled Plasma Etching of Ta, Co, Fe, NiFe, NiFeCo, and MnNi with Cl_2/Ar Discharges

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Abstract−Dry etching of the magnetic thin films such as Ta, Fe, Co, NiFe, NiFeCo, and MnNi was carried out in inductively coupled plasmas of Cl_2/Ar mixture. All the magnetic materials went through a maximum etch rate at 25% Cl_2. The effects of the ICP source power and the rf chuck power on the etch rate and the surface roughness were quite dependent of the materials. An ion-enhanced chemical etch mechanism was important for the magnetic films. The surface roughness of the etched samples was relatively constant of the rf chuck power up to 200 W, but a rougher surface at a higher rf power was obtained. Post-etch cleaning of the etched samples in de-ionized water reduced the chlorine residues substantially.

Key words: Magnetic Thin Films, Inductively Coupled Plasma Etching, MRAM, Post-etch Treatment

INTRODUCTION

Magnetic random access memory (MRAM) is known to possess many good intrinsic characteristics as a memory cell, some of which include non-volatility, high density, high speed, low power consumption, thermal stability and unlimited read/write operations. From the practical point of view, it is important to realize the high density, among many others, in order for the MRAM to compete with other existing technologies [Zhu et al., 2000; Tehrani et al., 1999; Gallagher et al., 1997].

Magnetic thin films are utilized as device materials of the MRAMs. To increase the storage amount in the MRAM device, the development of methods for producing various geometrical structures is required. Therefore, both development of new magnetic materials and optimization of patterning process are required for MRAM application. Specially, the etching technique must be guaranteed in order to accomplish the sub-micron pattering [Vasile and Mogab, 1986].

There are several etching techniques such as ion milling [Gokan and Esho, 1981], lift-off [Gallagher et al., 1997; Gokan and Esho, 1981], reactive ion etching (RIE) [Vasile and Mogab, 1986] and high-density plasma etching [Jung et al., 1999; Hong et al., 1999; Hahn and Pearton, 1999]. The ion milling method using physical sputtering has problems such as low etch rate, low mask selectivity, and re-deposition of etch products on the sidewall. The problems of the RIE and the lift-off are thermal instability due to high processing temperature and low yield, respectively. By contrast, the high-density plasma etching technique promises a relatively high etch rate, low plasma-induced damage, and easy control of processing [Hahn et al., 1999, 2002; Jung et al., 1999].

In this work, to elucidate the etch characteristics of the magnetic films of Ta, Fe, Co, NiFe, NiFeCo, and MnNi, a parametric study of inductively coupled plasma (ICP) etching with Cl_2/Ar discharges has been carried out. We investigated etch rate, surface morphology, and etch profile as a function of the processing parameters such as ICP source power, rf chuck power, operating pressure, and etch gas concentration. We also examined a post-etch cleaning with de-ionized water to remove chlorinated residues on the etched surface.

EXPERIMENTAL

Magnetic thin films of Ta, Fe, Co, NiFe, NiFeCo, and MnNi were deposited on Si(100) substrates by radio frequency (rf) magnetron sputtering from composite targets. As a hard mask material, SiO_2 film of about 6,500 Å thickness was deposited on the magnetic films by PECVD (plasma enhanced chemical vapor deposition). All the samples were lithographically patterned with AZ6612 photoresist. After the etching, the samples were rinsed with de-ionized (DI) water to remove the chlorine residues.

Etching was performed in a planar type inductively coupled plasma (ICP) system (Vacuum Science ICP etcher, VSICP-1250A), in which the samples were placed on an rf powered (13.56 MHz), helium backside-cooled electrode. This rf chuck power controls the incident ion energy, while the plasma ion density is controlled by the applied ICP source power (13.56 MHz). The Cl_2/Ar mixture with total gas flow rate of 20 standard cubic centimeters per minute (sccm) was injected into the reactor through mass flow controllers. Etch depths of the etched sample were obtained from stylus profilometry measurements after removal of SiO_2. Surface morphology and etch profile were examined with an atomic force microscope (AFM) operated in a tapping mode with Si tip and scanning electron microscope (SEM), respectively.

RESULTS AND DISCUSSION

Fig. 1 shows the effect of the operating pressure on the etch rate

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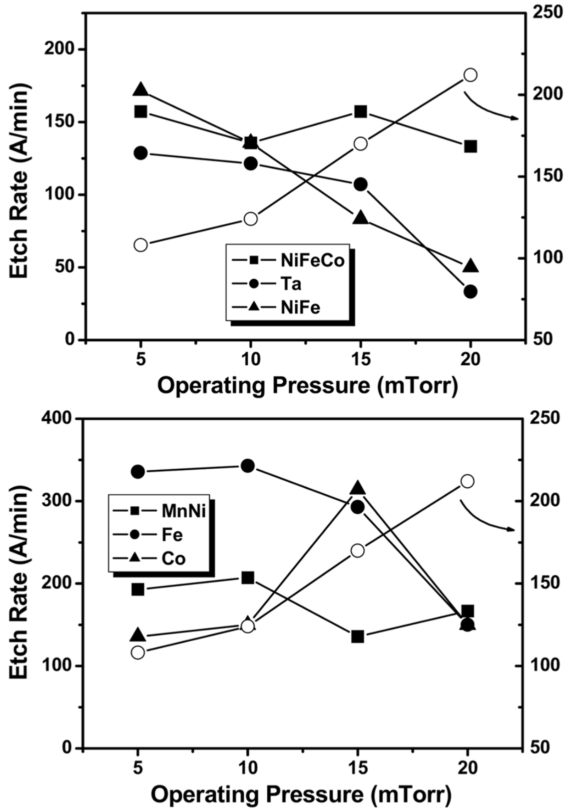


Fig. 1. Effect of operating pressure on etch rate and dc bias voltage at 700 W ICP, 150 W rf, and 50% Cl_2.

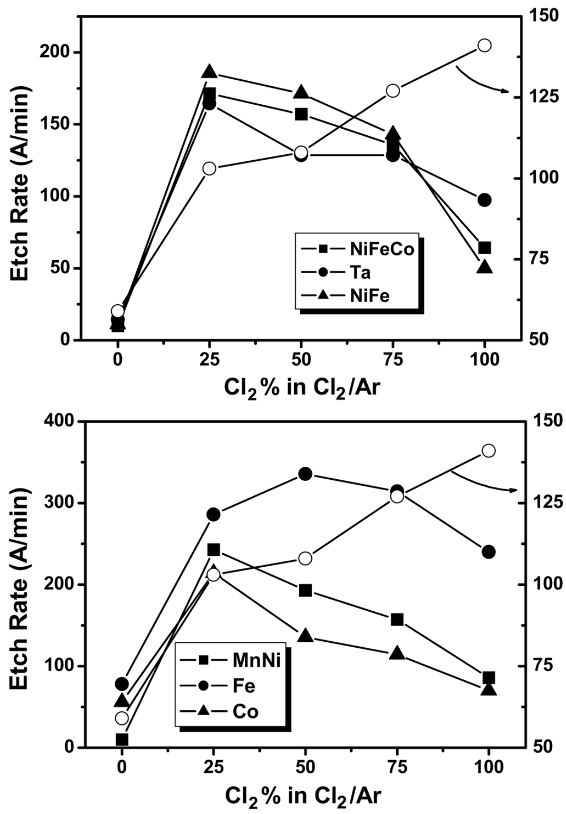


Fig. 2. Effect of Cl_2 concentration on etch rate and dc bias voltage at 700 W ICP, 150 W rf, and 5 mTorr.

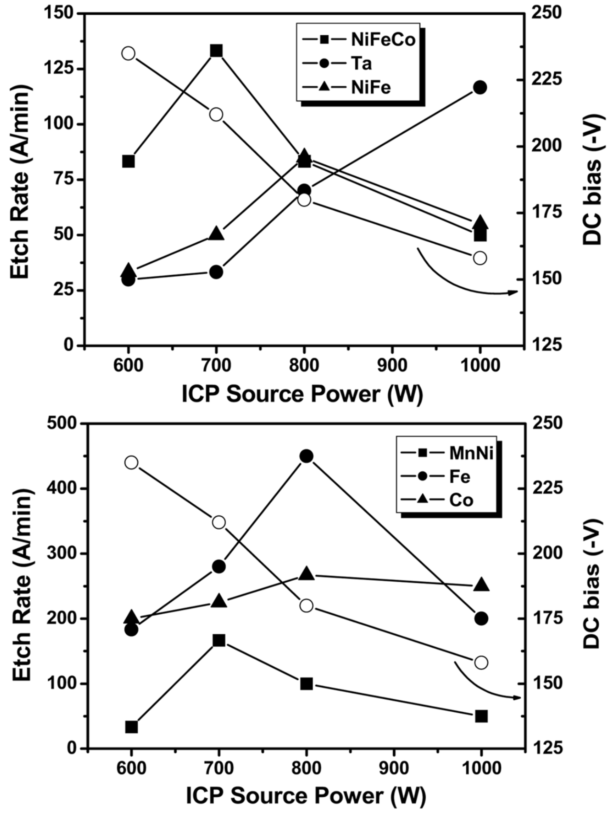


Fig. 3. Effect of ICP source power on etch rate and dc bias voltage at 150 W rf, 5 mTorr, and 50% Cl_2.

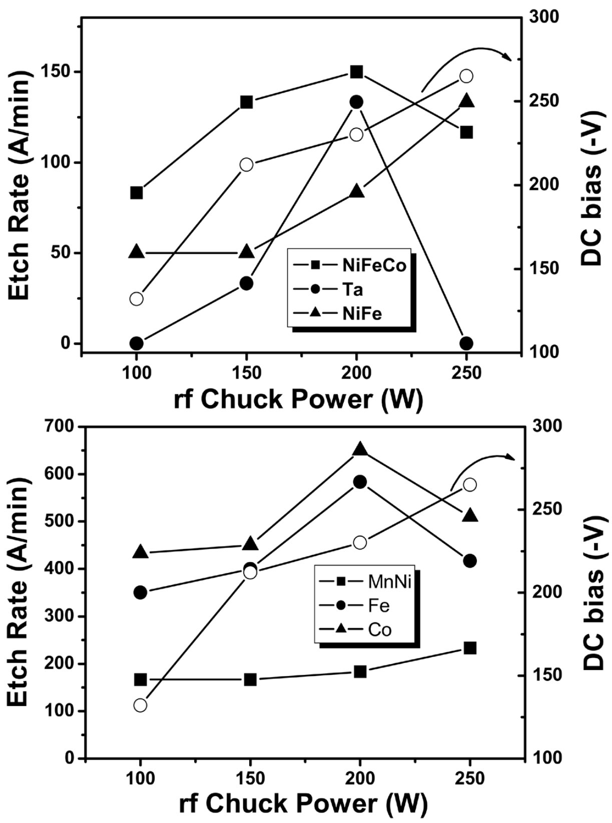


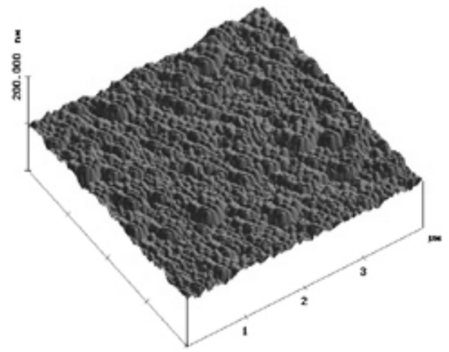
Fig. 4. Effect of rf chuck power on etch rate and dc bias voltage at 700 W ICP, 5 mTorr, and 50% Cl_2.

of magnetic thin films and dc bias. During these experiments the plasma conditions were kept constant at 700 W ICP source power, 150 W rf chuck power and 50% Cl_2 concentration (10 sccm Cl_2/10 sccm Ar). The dc bias voltage increased with the operating pressure. The magnetic films except Co showed a similar trend: a decrease in etch rate with the operating pressure. This might be due to several factors, including a lower ion flux to the substrate surface, a poorer coupling of power to plasma, and a higher number of adsorbed neutrals blocking the surface from ion bombardment. However, it is worthwhile to note that the etch behavior of the magnetic films is quite dependent on material, indicating that a further study on the etch mechanism of individual materials is required.

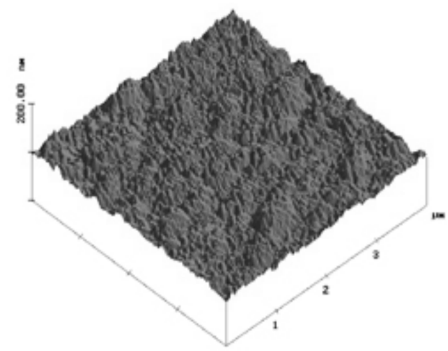
The effect of Cl_2 concentration on the etch rate and dc bias was examined at constant ICP source power (700 W), rf chuck power (150 W), and operating pressure (5 mTorr) and the results are shown in Fig. 2. All the magnetic materials except Fe went through a maximum etch rate at 25% Cl_2, which is a behavior observed frequently for the materials producing relatively low-volatility etch products. The contribution of the physical sputtering by pure Ar discharges was minimal, resulting in the slowest etch rate (<80 Å/min). However, as the Cl_2 concentration increased, the etch rate increased rapidly, indicating a dominant chemical component in the etch mechanism. A substantial decrease in the etch rate beyond a particular concentration (for example, >25%) is attributed to an increase in the formation of the chloride etch products and less formation of ions. The dc bias voltage increased with increasing the Cl_2 concentration. This is probably due to the additional collisional energy losses present with increasing the concentration, which in turn results in less production of incident ions with the Cl_2 percentage and thus the slowest etch rates at 100% Cl_2 [Im et al., 2001].

The etch rates of the magnetic thin films were a strong function of ICP source power with Cl_2/Ar discharges. As shown in Fig. 3, the etch rate of most of the magnetic thin films went through a maximum value at 700 or 800 W, but that of Ta increased with the ICP source power. In general, a greater ion flux is obtained at a higher ICP source power. The increase in the etch rate with the ICP source power is thus attributed to an ion-enhanced chemical etch mechanism. However, when the ions are generated enough at a certain high power, they sputter adsorbed reactive species out of the surface prior to etch reaction [Hahn et al., 1999; Park et al., 2002]. Hence, the decrease in the etch rate at a higher source power may be explained by this sputter desorption of the species adsorbed on the surface.

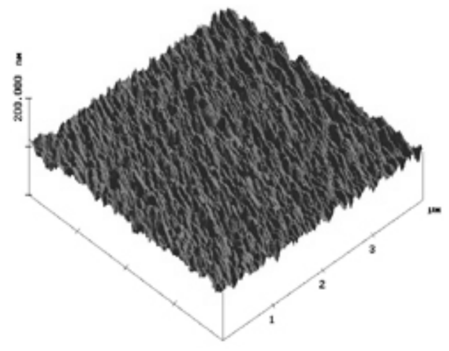
The effect of the rf chuck power on the etch rates and the dc bias is shown in Fig. 4. The etch rates increased up to 200 W and decreased beyond 200 W. The etch rates are quite dependent of the magnetic materials: NiFeCo, Ta, Co, and Fe showed maxima at 200 W, but NiFe and MnNi showed an increase in the etch rate with the chuck power. The surface morphology of the etched magnetic thin films was also examined by using AFM. Fig. 5 shows the effect of the rf chuck power on the surface morphology of the NiFeCo etched at 750 W ICP, 10 mTorr, and 50% Cl_2. The surface roughness was relatively independent of the rf chuck power up to 200 W. However, etching at higher rf chuck powers (>250 W) showed a rougher surface due to increased ion-bombarding energy. Other magnetic films showed similar trends to the NiFeCo film.



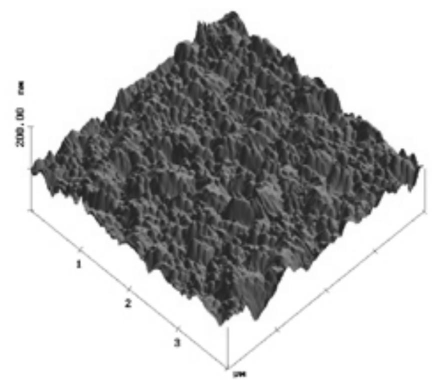
(a) Control sample (RMS = 4.207nm)



(b) 100 W (RMS = 6.470nm)



(c) 200W (RMS = 6.350nm)



(d) 250W (RMS = 9.281nm)

Fig. 5. AFM images of etched NiFeCo as a function of rf chuck power at 750 W ICP, 10 mTorr, and 50% Cl_2.

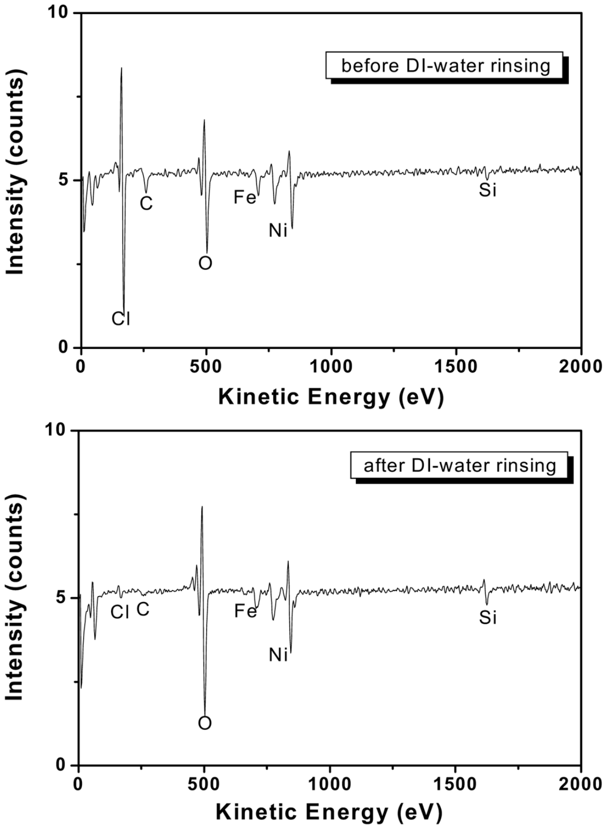
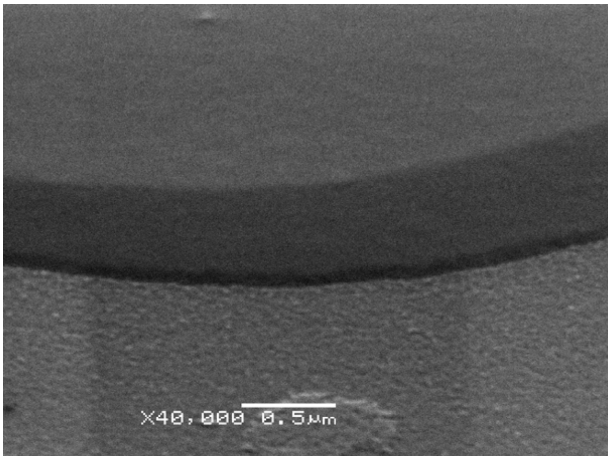
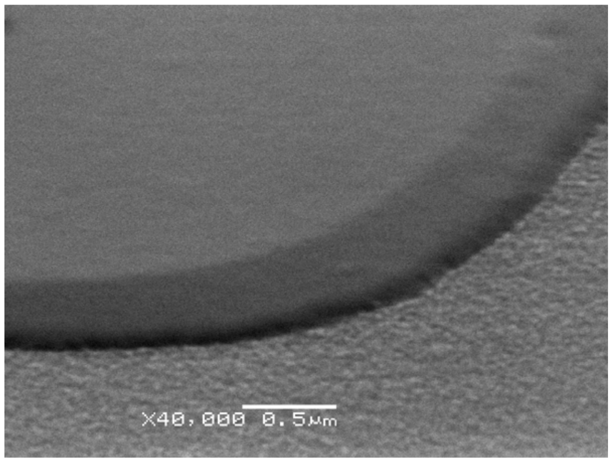


Fig. 6. AES surface scans of etched NiFe before (top) and after (bottom) post-etch treatment of water rinsing (Samples were etched at 750 W ICP, 150 W rf, 10 mTorr, and 50% Cl_2).

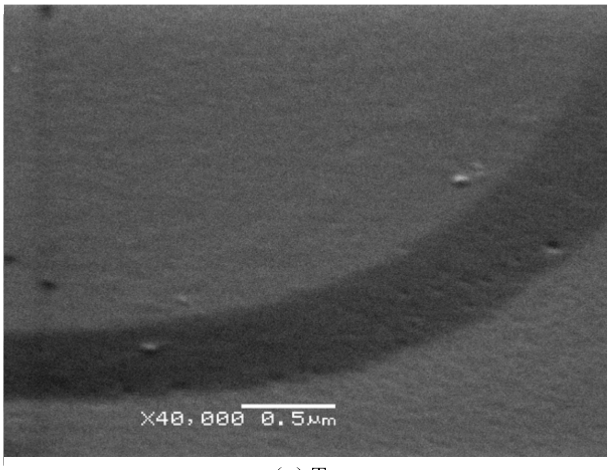
As the etching of the magnetic films with Cl_2/Ar produces a corrosion problem on the features, a post-etch treatment was carried out to counteract this problem. The samples were simply rinsed with de-ionized water for 5 min after etching. Fig. 6 shows the AES surface scans of the etched NiFe before and after cleaning of chlorine residues with the water, respectively. A significant amount of residual chlorine remained after the etching (top), but with the post-etch cleaning technique the chlorine is at detection limit (bottom), indicating that water rinsing is an effective method to remove the chlorine residues. Fig. 7 shows SEM micrographs of the etch profiles of NiFe, NiFeCo, and Ta etched at 700 W ICP, 150 W rf, 5 mtorr, and 50% Cl_2. All the samples showed quite smooth surface: NiFe showed a vertical profile, but NiFeCo and Ta presented sloped profiles.



(a) NiFe



(b) NiFeCo



(c) Ta

Fig. 7. SEM micrographs of NiFe, NiFeCo, and Ta etched at 700 W ICP, 150 W rf, 5 mTorr, and 50 % Cl_2.

SUMMARY AND CONCLUSIONS

NiFe, NiFeCo, Ta, Fe, Co, and MnNi were etched in the inductively coupled Cl_2/Ar plasmas. The magnetic films except Co showed a similar trend of a decrease in the etch rate with the operating pressure. All the magnetic materials went through a maximum etch rate at 25% Cl_2. A substantial decrease in the etch rate beyond a particular concentration is attributed to an increase in the formation of chloride etch products and less formation of the ions. The effects of the ICP source power and the rf chuck power on the etch rate and surface roughness were quite dependent on the materials. An ion-enhanced chemical etch is a dominant mechanism for the magnetic films. The surface roughness of the etched samples were relatively constant of the rf chuck power up to 200 W, but a higher chuck power produced a rougher surface. Post-etch cleaning of the magnetic films in de-ionized water reduced the chlorine residues substantially.

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