Reactive Ion Etching Characteristics of Permalloy Thin Films

*Dept. of Metallurgical Engineering, Seoul National University, 151-742, Seoul, Korea
Thin Film Technology Research Center, Korea Institute of Science and Technology, 136-791, Seoul, Korea

(Received; May 6, 1998 Accepted; August 26, 1998)

Permalloy thin films were reactive ion etched using CO and NH₃ gases. The dependence of etching rate on various etching conditions (e.g. gas flow rate, gas pressure, CO/NH₃ ratio, etc.) was investigated. Changes in magnetic properties with etching were also investigated. Etching rate remains nearly constant at about 100 Å/min regardless of gas flow rate when only NH₃ gas is used. In the case of CO and a mixture of CO/NH₃, etching rate depends on etching condition and the fraction of gas mixture. As the thickness of permalloy thin films decreases by etching, coercivity increases. The coercivity increase is larger for NH₃ than for CO or CO/NH₃. Change in the magnetic properties is mainly due to surface roughness and etching related damages.

Key words: reactive ion etching, permalloy thin films, etching rate, etching damage, coercivity

1. Introduction

Dry etching, such as IBE (ion beam etching), RIBE (reactive ion beam etching) and RIE (reactive ion etching), is a key technology in the fabrication of micro-size devices. Due to its selectivity and anisotropy, RIE is more popular than other processes. However, RIE has seldom been applied for the etching of magnetic materials. The main reason is that reactive gases containing chlorine or fluorine do not form volatile reaction products with Fe, Co and Ni that are main constituents of magnetic materials.

Permalloy (Ni₈₀Fe₂₀), which has good soft magnetic properties, is widely used in a variety of magnetic devices, e.g. thin-film head, MRAM, micro-inductor, etc. and has been fabricated by IBE due to the reason described above. IBE, however, has some undesirable consequences in pattern delineation and many efforts have been made in etching permalloy thin films by RIE. In recent years, Khamsephour et al. and Nakatani reported their success in etching permalloy thin films by RIE. In recent years, Khamsephour et al. and 350 Å/min by Nakatani, respectively. The rather high value reported by Nakatani using a CO/NH₃ mixture may indicate that RIE can be a suitable tool for the micro-fabrication of magnetic materials. In this paper, we also used CO and NH₃ gases and investigated the dependence of etching rate on the etching conditions as well as effects of RIE on the magnetic properties of permalloy thin films.

2. Experimental

Permalloy thin films were deposited on (100) Si substrates by RF magnetron sputtering. The dimension of the samples was 10 mm × 10 mm × 7000 Å. The schematic diagram of the apparatus used in this work is shown in Fig. 1. A high plasma density, which permits a high etching rate, was obtained by attaching magnets to outer grounded shield as shown in Fig. 1. After evacuation down to 1.0 × 10⁻⁶ Torr, reactive gases were introduced to the chamber through a shower-type inlet. These gases were designed to flow downward and be pumped out by turbomolecular pump. When a mixture of CO/NH₃ were used, the gases were pre-mixed in the mixing block. Gas flow rate was varied from 1 to 20 sccm in case of pure gas, and when the mixed gas was used, total flow rate was kept at 10 sccm and only the mixing ratio was changed. To see the pressure dependence of the etching rate, the pressure was changed widely from 1.5 to 20 mTorr by adjusting pumping speed. The pressure was maintained at 5 mTorr to investigate the effect of flow rate. RF input power was fixed at 300 W all the time.

To examine the effects of RIE on the magnetic properties of permalloy thin films, the films were exposed to RIE environments for a fixed time followed by a M-H loops measurement. This procedure was repeated until the film thickness was reduced to 1000 Å. Etching rate was measured by surface profiler. Magnetic properties were measured by VSM (vibrating sample magnetometer). Surface roughness was observed by AFM (atomic force microscopy).

[Fig. 1 Schematic diagram of RIE system.]
3. Results and discussion

Etching rate as a function of flow rate is shown in Fig. 2. In the case of CO gas, etching rate increases with flow rate, showing a maximum value of 80 A/min at 10 sccm, after which it decreases slightly. A similar behavior was previously observed in the etching of SiO$_2$ by CF$_3$[5]. The flow rate dependence on etching rate can be understood by the mechanism in Ref. 5, that is, the linear increase of etching rate is caused by the increase of reactants at low flow rate where a high utilizing factor$^9$ is expected and reaction products are dominant in gas phase. However, on the contrary to our expectation, the utilizing factor of this system is calculated to be very low and this is attributed to a small size of our samples. Since experiments on flow rate effect are conducted under a constant pressure of 5 mTorr, the increase of flow rate will decrease the residence time of the reactant gas in the chamber. Therefore, the possibility that the reactants are pumped away before they can react with the sample increases and this results in the decrease of etching rate at a high flow rate. In case of NH$_3$ gas, etching rate of 100 A/min is obtained even at a low flow rate of 1 sccm and is independent on the flow rate. Inferring from this independency and the redeposition of etched permalloy on the chamber wall, permalloy thin films are not reactive-etched but are sputter-etched by NH$_3$ gas. This is indirectly confirmed by the effects of RIE on the magnetic properties as will be described later. The etching rates of 80 and 100 A/min obtained here by using the pure gases are about 2-3 times higher than those reported by Nakatani$^9$.

In RIE using CO/NH$_3$, the reaction products are believed to be the metal carboxylic Ni(CO)$_n$ and Fe(CO)$_m$[5], and NH$_3$ plays a role of suppressing the decomposition of CO molecules in the CO/CO$_2$ equilibrium, resulting in the increase of etching rate. As shown in Fig. 3, etching rate increases with NH$_3$/CO ratio reaching a maximum at 80% mole fraction of NH$_3$. Our result is to be compared with the results of Nakatani who showed a maximum value at 48%. This discrepancy seems to originate from the difference in the system configuration and is confirmed by the fact that a maximum occurs at 50% even in our system in the absence of the magnets. In Fig. 4, the dependence of etching rate on the pressure is shown. Here, the mole fraction of NH$_3$ is kept at 80% and total flow rate is 10 sccm. As shown in Fig. 4, etching rate strongly depends on the pressure and reaches a maximum value at 5 mTorr. Although the etching rate using the pure gases is higher than that reported in the literature, no significant increase of etching rate is observed within the use of CO/NH$_3$ mixture.

It is practically important to know the variation of magnetic properties due to RIE. The variation of coercivity of permalloy thin films with the film thickness, i.e. etching time, is shown in Fig. 5. In the case of CO, coercivity increases gradually until the thickness of 2000 Å, which coercivity increases rather steeply reaching 5 Oe at 1000 Å. This increase in the low thickness region is mainly due to the increase of surface roughness. AFM measurement reveals that average roughness ($r_{rms}$) increases from 10 to 30 ~ 40 Å by RIE. Since surface roughness is known to affect domain wall...
motion and becomes important especially at smaller thicknesses, this increase of surface roughness by RIE is mainly responsible for the increase of coercivity. When NH₃ gas is used as reactive gas, coercivity increases considerably even at the early stage of RIE, eventually reaching up to 28 Oe at 800 Å. This remarkable increase of coercivity is comparable to that of IBE. This is in good accord with the inference made previously that permalloy is sputter etched by NH₃ gas. In this case, besides surface roughness, etching related damages seem to be responsible for this remarkable increase of coercivity. When a CO/NH₃ mixture is used, the behavior of coercivity is similar to that observed for pure CO gas. This can be understood by the role of NH₃ in the reactive etching of permalloy by CO. If NH₃ does not take part in the etching reaction of CO with permalloy but acts as an independent etchant, the degree of coercivity increase is supposed to be in the intermediate state between pure NH₃ and CO because of the sputter-etch nature of NH₃ gas. The results for the CO/NH₃ mixture, however, are closer to those for CO pure gas, meaning that NH₃ introduced is consumed in the suppression of CO decomposition, not in sputter-etching.

4. Conclusions

Permalloy (Ni₈₀Fe₂₀) thin films deposited by RF magnetron sputtering are reactive ion etched by pure CO or NH₃ gas, or a mixture of CO/NH₃. When pure CO gas is used, etching rate shows a maximum value of 80 Å/min at 10 sccm, while in the case of pure NH₃ gas, etching rate remains nearly constant at 100 Å/min regardless of flow rate. The addition of NH₃ to CO increases etching rate and at mole fraction of 80%, a maximum etching rate is achieved. Etching rate also strongly depends on the pressure in the case of the gas mixture and a maximum etching rate is observed at 5 mTorr. Magnetic properties are not strongly affected by RIE in case of both pure CO gas and CO/NH₃ mixture, although, in the low thickness region, coercivity increases up to 5 Oe. This increase is mainly attributed to the surface roughness increase by RIE. When NH₃ gas is used alone, permalloy thin films do not be reactive-etched but sputter-etched by NH₃ and resulting in a considerable increase of coercivity comparable to IBE results. In this case, etching related damage is responsible for the increase of coercivity as well as surface roughness increase.

References