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High density plasma reactive ion etching of CoFeB magnetic thin films using a CH_4/Ar plasma

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ABSTRACT

In this study, high density plasma reactive ion etching of CoFeB magnetic thin films was investigated using CH_4/Ar and CH_4/O_2/Ar gas mixes. The etch rate, etch selectivity and etch profile of CoFeB thin films were obtained as a function of gas concentration and etch parameters. The etch rate of CoFeB thin films and Ti hard mask gradually decreased with increasing CH_4 or O_2 concentrations. As the CH_4 gas was added to Ar gas, the etch profile of the CoFeB thin films improved. The addition of O_2 gas into the CH_4/Ar gas mix also led to anisotropic etching of the CoFeB thin films. With an increase in the dc-bias voltage supplied to the substrate and a decrease in gas pressure, the etch rates increased and the etch profile became vertical without any redepositions or etch residues. Based on the etch characteristics and surface analysis of the etched films by X-ray photoelectron spectroscopy, it can be concluded that the etch mechanism of CoFeB thin films in CH_4/Ar and CH_4/O_2/Ar plasmas does not follow the reactive ion etch mechanism but rather a chemically assisted physical sputtering mechanism.

1. Introduction

The continued growth in the information technology industry has demanded the development of nonvolatile semiconductor memories for next generation computing. Magnetic random-access memory (MRAM), which is one of the next-generation memory devices, is composed of magnetic-tunnel-junction (MTJ) stack and complementary metal oxide semiconductor. The MRAM device may be used as an effective replacement for static random-access memory devices, dynamic random-access memory devices, flash memory devices, and their combinations because it can provide high-speed operation, low operating voltage, and nonvolatile storage [1–5].

For the realization of high-density MRAM devices, efficient methods to pattern and etch MTJ stacks must be developed. The MTJ stack is composed of various magnetic materials, metals, and a tunneling barrier layer. It is well known that dry etching of magnetic materials is hard to achieve because the magnetic materials rarely react with the chemically reactive species in the plasma. Since ion milling also has limitations such as sidewall redeposition and etching damage, the chemically assisted ion etching and reactive ion etching have been employed. However, this approach still produces a slow etch rate and slanted etch profile without great improvement. In order to overcome these problems, dry etching using a high density plasma has been applied [4,6,7]. Among magnetic materials, the CoFeB films have been used as a key layer of the MTJ stack due to their excellent magnetic properties. Previous studies on the etching of CoFe, CoFeB and CoFeSiB thin films were carried out using various gases containing Cl_2, ICl, IBr and CO/NH_3 [8-13]. Recently, high density plasma etchings of CoFe and CoFeB thin films using CH_4/Ar and CH_3OH gases, respectively were reported [14].

In this study, the etch characteristics of CoFeB thin films were investigated in CH_4/Ar and CH_4/O_2/Ar plasmas using an inductively coupled plasma reactive ion etcher (ICPRIE). Ti thin films were employed as a hard mask to increase the etch selectivity. The gas concentrations in the CH_4/Ar and CH_4/O_2/Ar gases and other etch parameters including dc-bias voltage to substrate and gas pressure were varied to explore the etch characteristics and to elucidate the etch mechanism of CoFeB thin films. The surface chemistry of the CoFeB films etched under different gas concentrations was examined by X-ray photoelectron spectroscopy (XPS).

2. Experimental details

Dry etching of CoFeB thin films patterned with a Ti hard mask was performed to investigate the etch characteristics such as etch rate, etch selectivity and etch profile as a function of the gas concentration. CoFeB and Ti thin films were prepared on Si wafers using direct-current magnetron sputtering and were then patterned by photolithography using the 1.2 μm-thick conventional photoresist. To study the etch profile, Ti thin films were deposited on CoFeB thin films, followed by photolithography for patterning. Subsequently, the Ti hard

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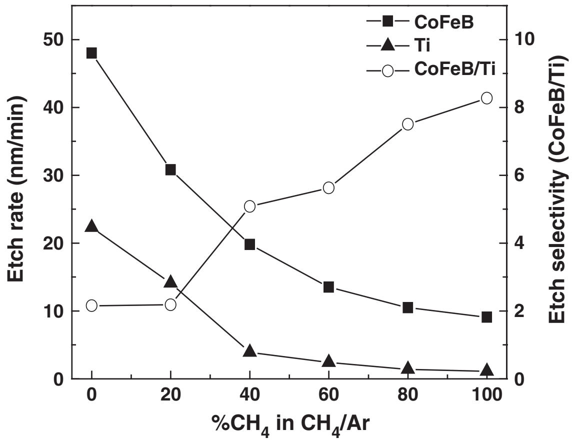

Fig. 1. Etch rate of CoFeB films and Ti hard mask, and etch selectivity of CoFeB to Ti films at different CH_4 concentrations in the CH_4/Ar gas; etch condition: ICP rf power of 800 W, dc-bias voltage of 300 V, and gas pressure of 0.67 Pa.

mask patterned with a photoresist was etched by reactive ion etching in a Cl_2/C_2F_6/Ar gas. The photoresist mask was removed using a stripping solution and O_2 plasma ashing after the Ti hard mask was etched, leaving the patterned Ti hard mask on the CoFeB thin films.

The etching processes were carried out using an ICPRIE system (A-Tech System, Korea) equipped with a loadlock chamber. The substrate was cooled by He gas, which was filled between substrate and susceptor. The susceptor was chilled through cold fluid in a circulator that was maintained at 15 °C. The main coil, which was connected to a 13.56 MHz rf power supply, was located in the lid on a process chamber and used to generate high density plasma. A dc-bias voltage induced by rf power at 13.56 MHz was capacitively coupled to the substrate susceptor to control the ion's energy in the plasma. The schematic of the etching equipment is shown in elsewhere [15].

CH_4/Ar and CH_4/O_2/Ar gases were employed as the etch gas. The etch rates, etch selectivity and etch profiles of the CoFeB thin films were examined at different gas concentrations. In addition, the effects of etch parameters on the etch rate and etch profile were investigated. The main etch parameters used in this study were dc-bias voltage to substrate and gas pressure. A surface profilometer (Tencor P-1) was used to measure the etch rates. The etch profiles of the films were observed by field emission scanning electron microscopy (FESEM: Hitachi S-4300) at an operating voltage of 20 kV. In addition, XPS (Thermo Scientific K-Alpha) with X-ray source of Alα and X-ray beam energy of 12 kV was utilized to examine the existence of possible etch products, and to understand the etch mechanism of the CoFeB thin film in CH_4/Ar and CH_4/O_2/Ar plasmas.

3. Results and discussion

The etching of CoFeB thin films patterned with a Ti hard mask was examined at different CH_4 gas concentrations in CH_4/Ar gas at ICP rf power of 800 W, dc-bias voltage to substrate of 300 V, and gas pressure of 0.67 Pa. Fig. 1 shows the changes in the etch rates of CoFeB and Ti films and the etch selectivity of the CoFeB films to Ti hard masks. As the CH_4 concentration increased, the etch rates of CoFeB and Ti films gradually decreased while the etch selectivities increased from 2 in pure Ar to 8 in 100% CH_4 gas, which indicates that the etch rate was not enhanced at higher CH_4 concentrations. The decrease in the etch rates was attributed to the reduction of the ion bombardment onto the specimen due to the decrease of energetic Ar ions and/or the hindrance of instantaneously formed layer containing hydrogen in a CH_4 plasma. These results suggest that the etching of

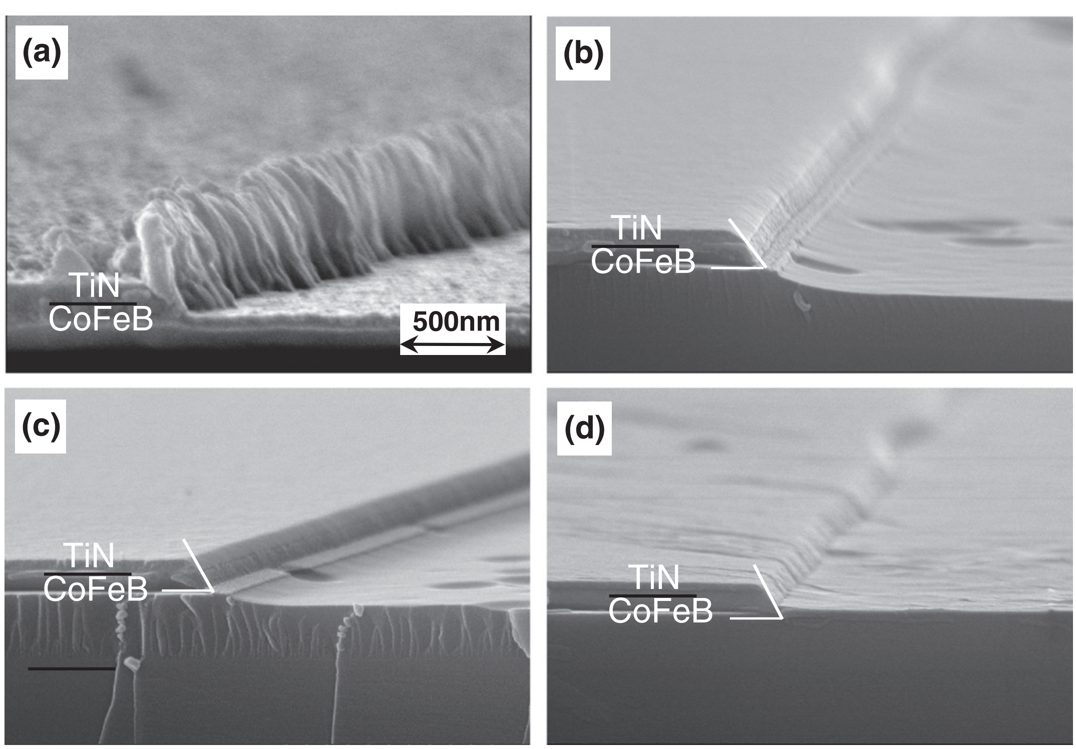

Fig. 2. FESEM micrographs of CoFeB films etched using (a) pure Ar, (b) 40% CH_4/Ar, (c) 60% CH_4/Ar, and (d) 80% CH_4/Ar; etch condition: ICP rf power of 800 W, dc-bias voltage of 300 V, and gas pressure of 0.67 Pa.