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Suppression of Super High-Energy Species by VHF-DC Superimposed Magnetron Sputter Plasma

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Magnetron discharge is maintained with very low target DC voltages (100~200 V) by applying 40 MHz VHF power to the target, without decreasing sputter deposition rate. From measurement of Ar^+ energy distribution function (EDF) and simulation of Ar^+ and Ar EDFs, it is confirmed that the VHF-DC magnetron discharge suppresses the maximum kinetic energy of backscattered Ar atom. This magnetron sputter source is applied to the deposition of magnetic multilayer film for perpendicular magnetic recording. From measurements of atomic force microprobe, the VHF-DC magnetron sputtering shows drastically-improved film flatness, compared with conventional DC magnetron sputtering.

Keywords: backscattering, magnetron sputtering, multilayer film

1. INTRODUCTION

Sputter film deposition by magnetron plasma is widely used in various industrial areas such as surface coating engineering, semiconductor devices, magnetic recording films, superconducting devices and so on. However, recent applications of the magnetron plasma to nanotechnologies such as nano-scale controlled magnetic multilayer films require not only precise control of film thickness of each layer but also atomic-scale flat interfaces with no mixing of atoms at the interface. It is well known that surface qualities of sputtered films are influenced by incidence of particles having kinetic energies much higher than bond energies of film materials [1-3]. In our previous work, we have clarified that the energy distribution function (EDF) of energetic Ar ions or atoms critically depends on the DC voltage applied to the sputter target, and have pointed out that energetic Ar ions and atoms can be suppressed by decreasing the target DC voltage [4,5]. In this paper, we demonstrate control of energetic Ar ions and atoms using a VHF-DC superimposed magnetron discharge, where 40 MHz VHF voltage and DC voltage are simultaneously applied to the magnetron target. Application of the VHF power realizes the plasma production at very low DC target voltage (~100 V), which results in reduction of the kinetic energy of backscattered energetic rare gas atoms. The Ar^+ EDF is monitored by a mass spectrometer with an energy filter and the result is compared with that of conventional DC magnetron sputter plasma. Furthermore, the VHF-DC magnetron sputter source is applied to the deposition of magnetic multilayer films, and film characteristics such as surface flatness or magnetic properties are compared with those of films deposited by conventional DC magnetron sputter source.

2. EXPERIMENTAL

In this study, a stainless steel vacuum vessel was equipped with a magnetron sputter source and was evacuated by a turbomolecular pump at a base pressure of $\sim 10^{-7}$ Torr. Ar gas was introduced in the vessel at a pressure of 0.67 Pa. Both 40MHz VHF and DC powers were applied to sputter targets (5 cm in diameter) of permalloy (Ni 80%, Fe 20%) or tungsten, as shown in Fig. 1. The periphery of the sputter target (cathode) is surrounded by a grounded anode with a clearance of 2 mm. VHF power (P_{VHF}) was less than 100 W. Target DC voltage (V_{DC}: <600 V) was controlled by the DC power supply, whereas target DC current (I_{DC}: <0.8 A) was controlled by the VHF power (P_{VHF}). V_{DC} is negative with respect to the ground potential and was described as absolute value unless otherwise denoted. For the comparison, conventional DC magnetron discharge was also investigated using the same magnetron sputter source, by applying only the DC power to the target.

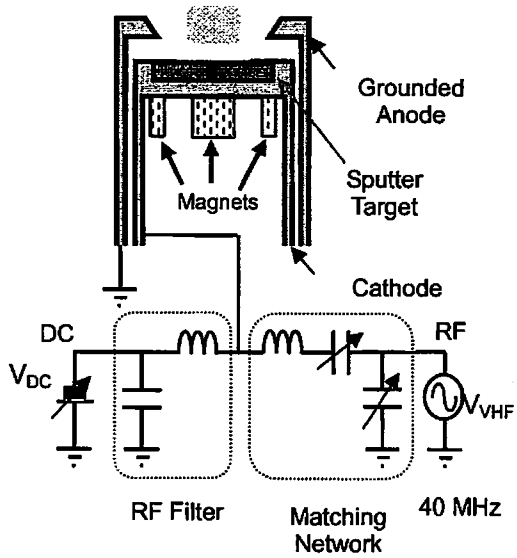

Fig. 1 Schematic of VHF-DC magnetron source.

To monitor energetic Ar ions, a differentially pumped quadrupole mass analyzer (QMA) with an energy filter (energy resolution: ~0.5 eV) was installed. Distance between an orifice of the QMA and the target was 11 cm. Deposition rate was monitored by a quartz crystal microbalance.

3. EXPERIMENTAL RESULT

3.1 Sputtering rate of VHF-DC magnetron plasma

Figure 2(a) shows the VHF power dependence of the target DC current at a target DC voltage of 200 V. Target is permalloy and Ar pressure is 0.67 Pa. Target DC current monotonically increases with the VHF power, and reaches ~0.6 A at P_{VHF}=70 W. Figure 2(b) shows the sputter deposition rate of permalloy as a function of the V_{DC} in the cases of VHF-DC and conventional DC magnetron plasmas. In the case of conventional DC magnetron plasma, the minimum V_{DC} of ~330 V is required to sustain the discharge. Above the minimum V_{DC}, the sputter deposition rate monotonically increases with increasing the V_{DC}. In contrast to the conventional DC discharge, the V_{DC} of VHF-DC discharge can be controlled independently from the power. The sputter deposition of permalloy is observed even at V_{DC}~100 V, and the deposition rate monotonically increases with the V_{DC}. Sputter deposition rate of 0.16 nm/s is obtained at V_{DC}=260 V. It is notable that the VHF-DC magnetron discharge can attain similar sputter deposition rates to those of the DC magnetron discharge at V_{DC}=100~250 V, which is 200~300 V lower than that of the DC magnetron discharge. This result implies that the VHF-DC discharge has an advantage of low target DC voltage over DC magnetron discharges, without decreasing the sputter deposition rate. Such high sputter deposition rate of the VHF-DC magnetron discharge presumably originates from the enhanced target DC current due to the VHF power application.

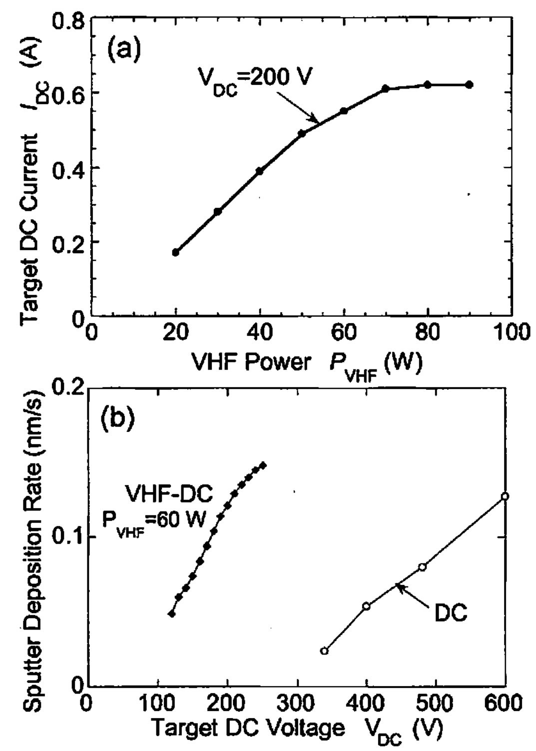

Fig. 2 (a) Target DC current as a function of the VHF power. (b) Sputter deposition rate as a function of the target DC voltage.

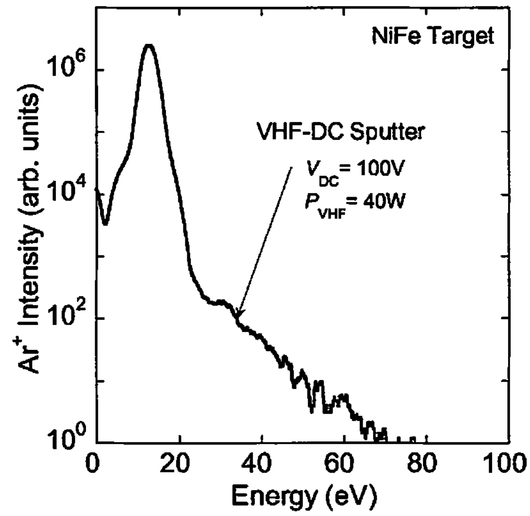

Fig. 3 Ar^+ EDFs of VHF-DC discharge with permalloy target.

3.2 Ar^+ energy distribution of VHF-DC magnetron plasma

In our previous paper, we have demonstrated that energetic Ar atoms are produced through backscattering of target-impinging Ar^+ ions, and also that some of energetic backscattered Ar atoms are converted into energetic Ar^+ ions through collisions in the gas phase [5]. This implies that there is a strong correlation between EDFs of Ar ions and Ar atoms. To give insight into the energetic particles (Ar ion and Ar atom) in the VHF-DC magnetron plasma, Ar^+ ion EDFs in VHF-DC and DC magnetron plasmas are measured by the energy-resolved QMA. Figure 3 shows Ar^+ EDFs of VHF-DC discharge with the permalloy target. Target voltage of the VHF-DC is 100 V. The most intense Ar^+ signal which originates from the bulk plasma ion is observed at Ar^+ kinetic energy of ~15 eV. Besides the intense Ar^+ signal at low energies, energetic Ar^+ ions up to ~80 eV is observed although their intensity is about 4~6 orders of magnitude lower than that of the bulk plasma ion signal. Such Ar^+ EDF with high energy tail suggests the existence of energetic Ar atoms in the DC magnetron discharge. In our previous measurement, energetic Ar^+ ions as high as ~120 eV has been observed for the Ar^+ EDF of conventional DC sputtering at the same deposition rate. The maximum energy for the DC sputtering is ~50 eV higher than that of the present VHF-DC magnetron discharge. Considering that energetic Ar ions originate from energetic Ar atoms, this result suggests that the VHF-DC magnetron discharge suppresses not only energetic Ar^+ but also energetic Ar atoms.

Figure 4 shows Ar^+ EDFs of tungsten targets at target DC voltages of 100 V and 300 V. Ar pressure and VHF power are 0.67 Pa and 40 W, respectively. At higher V_{DC} (300 V), the maximum energy of Ar^+ becomes ~200 eV. The maximum Ar^+ energy at V_{DC}=100 V, which is ~30 eV higher compared with the case of the permalloy target (fig.

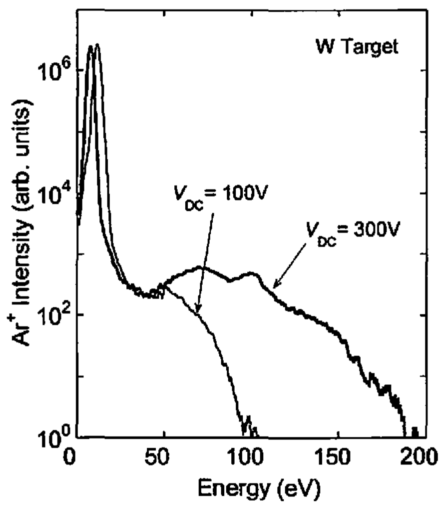

Fig. 4 Ar^+ EDFs at V_{DC}=100 V and 300 V in the cases of tungsten target.

3). This is roughly explained by the mass dependence of the backscattering energy E_B supposing the two body collision process;

$$E_B = [(\mu-1)/(\mu+1)]^2 E_I \quad (2)$$

Here, μ is mass ratio of bombarding ion (M_1) and target atom (M_2), i.e., $\mu = M_2/M_1$. This means that a combination of light impinging ion and heavy target atom increases the kinetic energy of surface-neutralized and backscattered atom.

4. SIMULATION OF ENERGETIC Ar ATOMS AND IONS

To confirm that the VHF-DC magnetron discharge suppresses the energetic Ar ions and Ar atoms, a Monte Carlo simulation code is developed and the simulated result is compared with the experimentally obtained Ar^+ EDF. This code is basically similar to the previously reported one

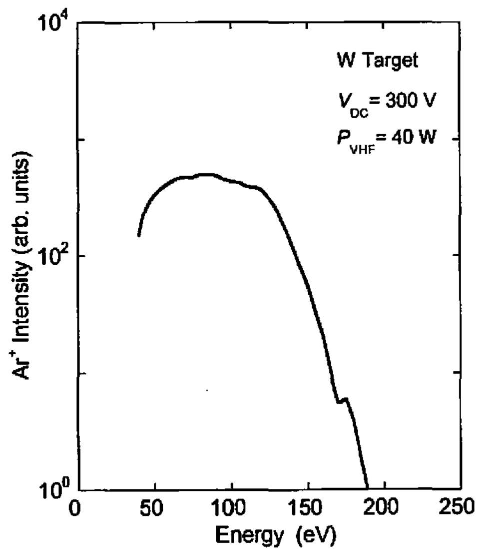

Fig. 5 Simulated Ar^+ EDFs with tungsten target.

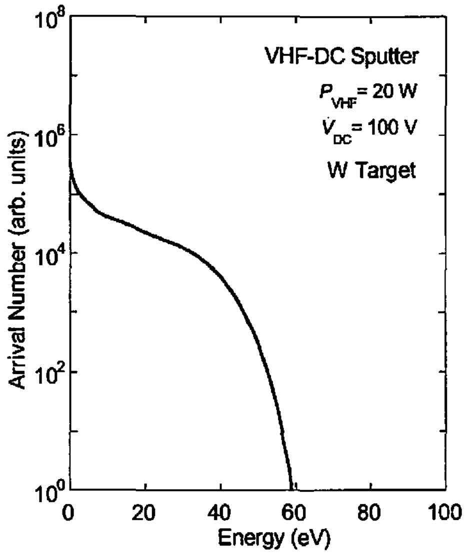

Fig. 6 Simulated energy distributions of Ar atom arriving at the QMA in the cases of VHF-DC magnetron discharges.

[5] and is briefly explained including modified points for the simulation of the VHF-DC discharge. The simulation is composed of two parts, i.e., the first part to simulate backscattering process on the sputter target surface, and the second part to simulate collision processes (elastic collision and ionization) in the gas phase. In the simulation of the Ar backscattering on the target, Ar ions are perpendicularly injected to the target and energy and angular distributions of backscattered Ar atoms are obtained using TRIM code [7]. In the present simulation, energy distribution of the surface-injected Ar^+ ion is taken into account because the target voltage varies at a frequency of 40 MHz. Next, backscattered Ar atoms are then injected from the target surface into the gas phase with a set of initial kinetic energy and direction of backscattered atoms in the table obtained by the TRIM code. Collision processes and trajectories of backscattered Ar atoms are simulated by the Monte Carlo method, including energetic Ar^+ ions those are produced through gas phase collisions of backscattered Ar atoms. To include the influence of the plasma potential on the Ar^+ ion EDF, spatial profile of the plasma potential is measured by the Langmuir probe, and is included in the simulation.

Figure 5 indicates simulated Ar^+ ion EDF in the case of the tungsten target. The conditions are the same as the result of fig. 4 at V_{DC}=300 V. A good agreement between the simulation and the experiment (fig. 4) is obtained for the maximum energy of Ar^+ EDF. Figure 6 shows simulated EDF of Ar atom in the case of VHF-DC discharge. Target material is tungsten and Ar pressure is 0.67 Pa. The simulated result indicates that the maximum energy of energetic Ar atom is ~60 eV. This value is much smaller than that of DC magnetron discharge [5], which indicates that the VHF-DC sputter deposition suppresses the impingement of energetic Ar atom to the film-depositing surface.

5. MAGNETIC MULTILAYER DEPOSITION BY VHF-DC MAGNETRON PLASMA

One of the important advantages of VHF-DC sputtering is the suppression of atom mixing at the multilayer interface. For example, perpendicular magnetic recording film requires flat and distinct interface with no atom-mixing layer. However, when the layer thickness becomes thinner, atom-mixing layer at the interface becomes enhanced and degradation of magnetic property occurs. To elucidate superiority of the VHF-DC discharge, magnetic multilayer for the perpendicular magnetic recording film is deposited by the DC and the VHF-DC discharge using the same magnetron target. The magnetic multilayer films are deposited as follows. First, 20 nm-thick platinum layer is deposited on a SiO_2 substrate. Then a set of 0.2 nm-thick cobalt layer and 0.4 nm-thick platinum layer is repeatedly deposited for twenty times. Finally, 5 nm-thick platinum layer is deposited on the top surface. Target voltages for platinum and cobalt layer depositions are indicated in the figure. In the case of the VHF-DC magnetron sputtering, VHF power is controlled to obtain the same deposition rate as that of the DC sputter deposition. After the film deposition, surface roughness of film is measured by the AFM. Figure 7 (a) and (b) shows the AFM results for DC and VHF-DC sputter deposited films, respectively. The AFM result shows that the RMS surface roughness of the VHF-DC is 0.14 nm which is almost 2/3 of the DC sputtered film. Such difference in surface flatness between the DC and VHF-DC deposited films is presumably due to the suppression of energetic Ar atom flux to the film depositing surface.

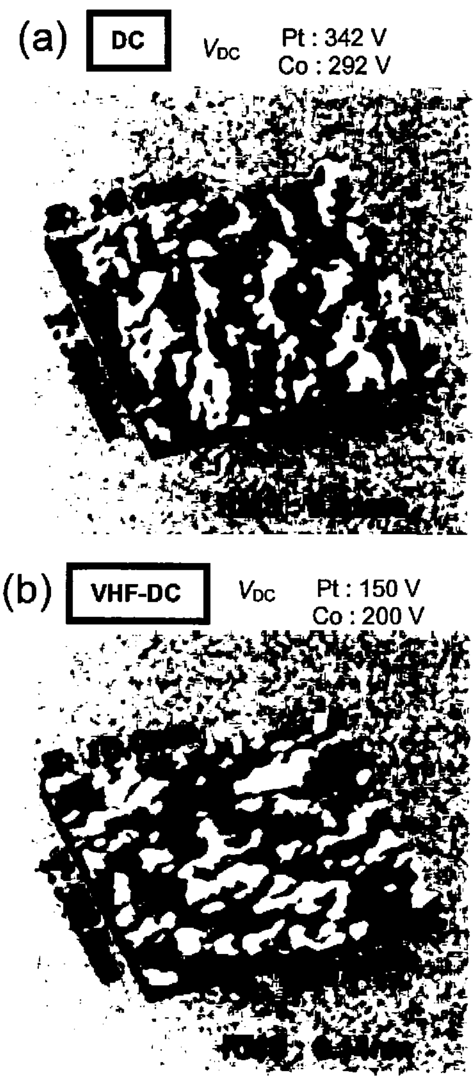

Fig. 7 AFM images of mutilayer magnetic films deposited by (a) DC magnetron sputtering and (b) VHF-DC magnetron sputtering.

6. CONCLUSIONS

We demonstrated the VHF-DC magnetron plasma source as a method of reducing energetic Ar atoms from the sputter target surface to the deposition surface. Energetic Ar species were suppressed by decreasing the target DC voltage, which was strongly related to the energetic Ar atom backscattered form the target. Application of the VHF power to the target realized the suppression of the target DC voltage without decreasing the sputter deposition rate. Ar^+ EDF was measured by a energy-resolved mass analyzer. It was shown that the maximum energy of Ar^+ was decreased by the VHF-DC discharge. A simulation code to elucidate EDFs of Ar atom and Ar ion in VHF-DC discharge was developed. The simulated Ar^+ EDF showed a good agreement with the experimental result. Finally, the VHF-DC magnetron discharge was applied to the deposition of the magnetic multilayer film. The film deposited by the VHF-DC and the conventional DC sputtering were compared, and the film deposited by the VHF-DC magnetron sputtering showed much better surface flatness than the DC sputtered film.

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