Potential of High-density Convergent Plasma Sputtering Device for Magnetic Film Deposition

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Received: 15 February, 2019; Accepted: 7 March, 2019; Published: 23 March, 2019

A high-density convergent plasma sputtering device has been developed for magnetic film deposition. The external convergent magnetic field is produced by a solenoid coil and a permanent magnet positioned behind the ferromagnetic metal target. The ion density and the ion accelerating voltage are individually controlled since the ion production and sputtering areas are separated like an ion beam sputtering device. Iron (Fe) thin films are deposited on an unheated substrate using argon plasmas under the target to substrate distance of 54 mm. The films consist of the α-Fe phase with a body-centered cubic crystal structure. The deposition rate was about 25 nm min⁻¹ at a sputtering gas pressure of 0.2 Pa.

Keywords Plasma sputtering; Physical vapor deposition; High density plasma; Ferromagnetic metal target

I. INTRODUCTION

In the field of plasma sputtering, magnetron sputtering is utilized for thin film formations at a higher deposition rate in comparison with other sputtering techniques such as a parallel flat plate type sputtering [1, 2]. In the magnetron sputtering, \( E_x \times B_x \) drift contributes to a plasma confinement on the sputtering target. Here, \( E_x \) is the electric field vertical to the target surface, and \( B_x \) is the magnetic field horizontal to the target surface. The \( E_x \times B_x \) drift motions generally arise from negatively biased voltages of sputtering cathode and permanent magnets placed behind the target. The \( E_x \times B_x \) drift motions hardly occur on the target when a ferromagnetic metal target is used, because the target works as a magnetic yoke. Therefore, a thin target and a strong magnet are generally employed to increase leakage magnetic fluxes over the target surface. However, the leaking area is extremely narrow even in these cases. The racetrack-erosion profile in narrower area results in a low target utilization efficiency in comparison with non-ferromagnetic metal targets. The decreased target utilization efficiencies require frequent target replacements, so that operation efficiency also decreases and maintenance cost increases. Window et al. proposed magnetron sputtering sources for a ferromagnetic material [3]. Furthermore, the sputtering from two facing targets was proposed for the magnetic film deposition as an alternative method of magnetron sputtering [4].

The ion beam sputtering is the most potential technique for physical vapor depositions using a ferromagnetic target [5–7]. The ion density and the ion accelerating voltage are individually controlled, because the ion production and sputtering areas are separated in the device. However, a lower deposition rate is a pragmatic problem because of the difficulty in obtaining ion-current of a few tens of milliamperes compared with general plasma sputtering. Hoshi et al. reported that the deposition rate was 3 nm min⁻¹ when they deposited iron-cobalt alloy thin films using an ion beam sputtering device [5]. Therefore, we focus attention on the use of a high density helicon plasma generation source; that is, the ion source of the ion beam generation source is replaced with a helicon plasma generation source. To further increase the ion density near the sputtering target, the convergent magnetic fields are formed by an external solenoid coil and a permanent magnet placed behind the target [8].
This plasma sputtering device can be used irrespective of the state of the target material such as magnetic or liquid states [9]. In this study, the discharge characteristics of Ar plasmas are shown. Then, a magnetic film deposition using a Fe target is conducted to verify the potential of the proposed device.

II. EXPERIMENTAL

Figure 1 shows the schematic drawing of experimental setup. The magnetic field strength in Tesla is shown in the background of Figure 1 (colored contour map) when the solenoid coil current, \( I_c \), is 70 A. The magnetic vector potential is also shown by gray lines. A disk-shaped neodymium permanent magnet (25 mm in diameter and 9 mm in thickness) was embedded behind the target. The vacuum chamber was evacuated, using a turbo-molecular and rotary pump system, to a base pressure of lower than \( 5 \times 10^{-4} \) Pa. The Ar gas was introduced from the top of the glass tube, and controlled at 10.0 sccm and then a gas pressure was approxi-
mate 0.2 Pa. A Fe sputtering target (27 mm in diameter and 5 mm in thickness) was connected to a DC power supply applying a bias voltage of \(-450\) V. A glass plate (Corning Eagle XG, 10 mm \( \times \) 10 mm \( \times \) 1.1 mm) was positioned at \( z = 172 \) mm (target to substrate distance of \( \sim 54 \) mm) and held on the inner surface of top vacuum flange. The antenna and the external magnetic fields are designed to excite a right-handed circular polarized wave along the magnetic field lines (i.e., a helicon wave) [10–13]. The input RF power for plasma production was pulsed with a duration time of 200 ms and pulse interval of 1000 ms (duty ratio of 20%). Thus, the net sputtering process time was 60 min when the device operation time was 300 min. A directional coupler, inserted between the RF power supply and the matching box, was used to measure the forward and reflect-
ed RF powers, \( P_f \) and \( P_r \), respectively. The ratio of reflected RF power to forward RF power, \( P_r/P_f \), was typically 0.05. The typical antenna resistance, \( R_{ant} \), and the power transfer efficiency, \( \eta_p \), were 0.25 \( \Omega \) and 0.6–0.8, respectively, throughout the experiments [14]. The electron density, \( n_e \), was estimated from an ion saturation current obtained by a Langmuir probe, and the measured typical electron temperature was 4.5 eV [15]. The Langmuir probe was located at \( x = 0 \) mm and \( z = 172 \) mm (not shown in Figure 1). The platinum probe tip was 2 mm in length and 0.2 mm in diameter. The length direction of the probe is perpendicular to the magnetic field lines. We consider that the probe measurements for ion saturation current were hardly affected by the magnetic field strength of \( \sim 0.05 \) T; because the ion Larmor radius was 8.7 mm when the ion temperature of 0.45 eV was assumed. Crystallographic characterization was executed using an X-ray diffractometer (XRD: RINT 2110V, Rigaku). A scanning electron microscope (SEM: S-4300, Hitachi) equipped with an energy dispersive X-ray spectrometer (EDS: EX-420, Horiba) was used to evaluate the chemical compositions of films. The thickness of the film was measured by an atomic force microscope (AFM: VN-8010, Keyence). The deposition rate was determined by dividing the film thickness by the net process time of sputtering. The surface image and the arithmetic average roughness, \( S_a \), of deposited films were measured by a laser microscope (VK-X1000/1100, Keyence). The \( S_a \) value was calculated at five visual fields on the deposited film surface.

![Figure 1: Experimental setup and magnetic field configuration.](image-url)
III. RESULTS AND DISCUSSION

Figure 2 shows the electron density, $n_e$, depending on the net power transported to the plasma, $P_{\text{net}}$, and the solenoid coil current, $I_c$. The $P_{\text{net}}$ dependence at a constant $I_c$ value of 70 A is shown in Figure 2(a). The $I_c$ dependence at a constant $P_{\text{net}}$ value of 500 W is shown in Figure 2(b). The time average values and these standard deviations are shown in symbols and bars, respectively, because the measured ion saturation current includes the RF fluctuations.

The $n_e$ value was approximate $10^{17}$ m$^{-3}$ at both $P_{\text{net}} < 50$ W in Figure 2(a) and $I_c < 10$ A in Figure 2(b). In these cases, a capacitively coupled plasma (CCP) discharge occurs between the double loop antenna and the punching plate (see Figure 1). In the $P_{\text{net}}$ range from 50 W to 300 W in Figure 2(a), the $n_e$ value increases and plasma discharge mode changes from a CCP to an inductively coupled plasma (ICP). Thereafter, the $n_e$ value is saturated at 300 W and higher. In Figure 2(b), $n_e$ increases with increasing $I_c$ excluding less than 10 A. The ICPs are transported along the convergent magnetic field lines, and they reach to the measurement point at $z = 172$ mm when $I_c$ is 10 A and higher. We think that the gradual increase in $n_e$ in the range $I_c \geq 20$ A is due to the convergence of magnetic field lines. The inflow ion current to the target is obtained when plasmas reach the target surface. These conditions are $I_c \geq 10$ A and $P_{\text{net}} > 300$ W because magnetized ICPs induce an effective plasma transportation. Helicon plasmas could be produced at $I_c$ over 40 A, and the region up to 70 A, exhibiting relatively high RF fluctuations, represents the discharge mode transition from ICPs to helicon plasmas. These $n_e$ variations shown in Figure 2 are consistent with those in our previous studies on a small etching device [15]. The experimental conditions with $I_c = 70$ A and $P_{\text{net}} = 500$ W were adopted to obtain a high $n_e$ value higher than $5 \times 10^{18}$ m$^{-3}$.

The convergent plasma sputtering using a Fe target was conducted at the experimental conditions of $I_c = 70$ A and $P_{\text{net}} = 500$ W. The deposition rate was $\sim 25$ nm min$^{-1}$. Figure 3 shows a typical surface image of deposited thin film, which is taken by a laser microscope. The $S_a$ value was 2.6 nm. Figure 4 shows an EDS pattern from the specimen. It is found that the film mainly consists of iron, because silicon and oxygen peaks are originated from the glass substrate.

Figure 5 shows XRD patterns from a glass substrate and from specimens sputtered for 0.5 h and 1 h, though sharp peaks at 26.7° and 45.2° in $2\theta$ are originated by a carbon compound to fix samples. The broad peaks at 44.6° are due to a-Fe (110) referred by the XRD database JADE4.0 (Materials data, Inc.), and their intensity increases with increas-
ing deposition time. On the other hand, the intensity of the broad peaks at around 24.0°, which is originated from the glass plate, decreases with increasing deposition time, i.e., due to thickening the films. The crystal structure of α-Fe is stable at 911°C and lower temperatures [16, 17], and (110) is the closed-pack face of the body centered cubic crystal structure. Kim et al. showed that the XRD patterns having Fe (110) peak were obtained at temperatures lower than 400°C and at sputtering gas pressure ranging from 4 mTorr to 40 mTorr [18]. Therefore, it is reasonable that α-Fet(110) preferentially grows on an unheated glass substrate in this study.

Finally, we discuss future works of the proposed sputtering device. A sputtering system having multiple targets is needed to obtain multilayered magnetic film deposition [19]. In order to build sputtering system having multiple targets, it is important to maintain the individual controllability of the ion density and the ion accelerating voltage, and this will be challenges for the future. When the bias voltage is ~450 V, the input power to the target is only 20 W and the inflow ion-current to the target is ~50 mA. The power density to the target is approximate 3.5 W cm−2 because the target diameter is 2.7 cm. This power density is lower than conventional magnetron sputtering devices. Even when a low input power 20 W was applied to the target, the Fe deposition rate was 25 nm min-1. We estimate that a high density plasma in a low sputtering gas pressure becomes advantages for the high Fe deposition rate whose value is about ten times higher than that using an ion beam sputtering [5]. High density plasmas produce a large quantity of sputtered atom. A low pressure sputtering leads to not only a collisionless deposition process for sputtered atoms but also a surface migration of energetic adatoms on the substrate [20]. These physical behaviors of high density and low gas pressure sputtering plasma will be studied as an important issue for future works.

IV. CONCLUSIONS

A high density convergent plasma sputtering device for magnetic film deposition was addressed in this paper. The convergent magnetic field, which is produced by an external solenoid coil and a permanent magnet positioned behind the target, is utilized to increase the ion density near the target. This device has an advantage of being able to maintain the structural feature of ion beam sputtering system because the ion production and acceleration areas are separated. The Fe films are deposited on an unheated glass plate in the experimental conditions of an Ar gas pressure of 0.2 Pa and a target-substrate distance of ~54 nm. The EDS and XRD analyses show that the deposited film has an oriented α-Fe film phase, which is stable at 911°C and lower temperatures.

Acknowledgments

This study was partially supported by a JSPS KAKENHI Grant No. JP16745058 [Grant-in-Aid for Scientific Research (C)]. The author wishes to acknowledge the assistance provided by Mr. Satoru Fukamachi, Mr. Osamu Matsuda, Dr. Masato Uehara and Dr. Morito Akiyama of AIST.

Note

This paper was presented at Annual Meeting of the Japan Society of Vacuum and Surface Science 2018 (JVSS 2018), Kobe International Conference Center, Kobe, Japan, 19–21 November, 2018.

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