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High-density radio-frequency magnetized plasma sputtering source with rotational square-shaped arrangement of rod magnets for uniform target utilization

Md. Amzad Hossain [a], T. Ide [b], K. Ikari [b], Y. Ohtsu [a, b, *]

[a] Department of Science and Advanced Technology, Graduate School of Science and Engineering, Saga University, 1 Honjo-machi, Saga, 840-8502, Japan
[b] Department of Electrical and Electronic Engineering, Graduate School of Science and Engineering, Saga University, 1 Honjo-machi, Saga, 840-8502, Japan

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ABSTRACT

We have developed a high-density radio frequency (RF) magnetized sputtering plasma source with a rotational square-shaped magnet arrangement for uniform target utilization. Eight neodymium rod magnets of 30 × 5 × 3 mm, where the connection between N-pole and S-pole magnets is one side of the square, are mounted on a circular iron yoke disc and an iron cover of 5 × 3 × 1 mm is also used for magnetic shielding of otiose magnetic fields from the permanent magnets. The magnetic field simulation, the measurement of the target erosion and the time-averaged ion flux to the target have been investigated (a) without iron cover and no air gap between N-pole and S-pole magnets, (b) with iron cover and no air gap, and (c) with iron cover and 5 mm air gap, respectively. It is found that the iron covers suppress the horizontal magnetic flux density and the copper target utilization percentage increases from 74.15% to 87.49%. Moreover, by decreasing the air gap between the shielded magnets, the copper target utilization percentage rises from 83.85% to 87.49%. The target utilization as well as the time-averaged ion flux to the target is optimum for case (b).

1. Introduction

Plasmas and their particles play an important role for nanotechnology and semiconductor manufacturing [1,2]. Various kinds of plasma sources have been developed for plasma processing. In particular, capacitively coupled plasmas (CCP) driven by radio frequency (RF) power supplies (13.56 MHz) are widely used for plasma processing, because their setup and maintenance are simple [3,4]. However, CCP sources suffer from the fact that (1) productivity and deposition rates are low due to the low plasma density of less than 10^9 cm^{-3} (depends on discharge conditions) and (2) the plasma density and the energy of ions at the electrodes cannot be controlled separately in single frequency CCPs [5]. On the other hand, it is well known that high-density plasmas can be produced by hollow cathode discharges [6–18], because electrons are effectively confined in the hollow trench.

The RF magnetized sputtering plasma source is widely utilized in the microelectronic industry for functional thin film deposition [19–25] and to produce magnetic films [26,27], because the setup is simple and their thin films are not conductive. Its application extends to surface treatment and cleaning [13,14], flat panel display fabrication; transparent conductive oxides film preparation [19,20] for solar cells and mobile phones and many other rapidly growing areas [2].

In particular, the RF magnetron sputtering process has become popular for the deposition of a variety of industrial surface coatings. This is because, at a RF input power of more than 1000 W, the magnetron discharge plasma attains a high-density of charged particles of $10^{10} - 10^{11}$ cm^{-3} at low gas pressures around 1 Pa due to plasma confinement by the $\boldsymbol{E} \times \boldsymbol{B}$ drift motion [2], where $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric field perpendicular to the target and the magnetic flux density parallel to the target, respectively.

The target surface is continuously eroded during the magnetron operation, but the target material is not used effectively due to the non-uniformity of the plasma density. Thus, the sputtering occurs highly localized in the region of the electron confinement. This leads to the formation of a narrow and deep erosion groove and a low target material utilization [2]. In conventional magnetron sputtering sources, the target utilization is approximately 20–30%

* Corresponding author. Department of Electrical and Electronic Engineering, Graduate School of Science and Engineering, Saga University, 1 Honjo-machi, Saga, 840-8502, Japan.
E-mail address: ohtsuy@cc.saga-u.ac.jp (Y. Ohtsu).

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due to the narrow and deep groove erosion of the target [28]. It was reported that the target erosion influences the ion distribution function in the near-cathode region as well as the deposition rate to the substrate [29].

The estimated utilization of the target is increased to approximately 60–70% for planar magnetron sputtering using a rotating tilted unbalanced and asymmetrical yoke magnet [30], whereas RF magnetron plasmas based on stationary monopole arrangements attain a target utilization of up to 59% for a magnet spacing of 10 mm [31]. Rotating the permanent magnet in a circular cathode is a common technique for expanding the eroded area and increasing the target utilization. However, at the center and outside the target, some non-eroded areas remain. From the view-point of the practical operation of resources, improvement of the target material utilization, uniform target erosion and high density plasmas as well as the prediction of functional thin film deposition rates is required.

This paper discusses a method to increase the target utilization and deposition rate for uniform erosion over the entire area of the target. It is based on the rotation of a neodymium permanent rod magnet of square-shaped arrangement with respect to the circular target. In section 2, the experimental setup for the proposed RF magnetized plasma sputtering system is explained in detail. In section 3, the magnetic field profiles obtained based on the squared-shaped magnets are described. In section 4, the plasma emission and discharge characteristics are discussed. In section 5, the copper target erosion profile and ion saturation current are investigated explicitly. In section 6, the results obtained in this paper are summarized.

2. Experimental setup

The experiments are performed in a stainless-steel cylindrical vacuum chamber with an outer diameter of 235 mm, inner diameter of 160 mm and a height of 195 mm such as shown in Fig. 1. In this experiment, a Cartesian coordinate system is used, because the magnetic fields produced from eight permanent rod magnets are not axisymmetric. In this set-up, before starting the experiment, an initial vacuum pressure in the chamber of 2.8×10^{-4} Pa is realized based on a turbo molecular and an oil rotary pumps. Argon (Ar) gas at 1.03 Pa is used by regulating a flow meter. A RF power of 50 W at 13.56 MHz was applied to target via an impedance matching network including a blocking capacitor. The electrode (target) dimensions are $160 \times 160 \times 3$ mm. A copper plate with 3 mm thickness was used as the target to measure the sputtering characteristics based on rotational square-shaped magnet schemes in the proposed high density RF magnetized plasma sputtering source. An aluminum disc was only used to measure plasma parameters in order to avoid thin film deposition on the Langmuir probe. The discharge voltage between the RF powered electrode and the grounded vacuum wall was measured by a high-voltage probe. The typical discharge voltage changed from 800 to 600 Vpp (peak-to-peak value) with increasing gas pressure from 1 Pa to 5 Pa at a RF input power of 50 W. The sputtering time period was 4 h to measure the erosion depth of the target and to perform a calculation to obtain the target utilization percentage. The origins of axial z and radial r positions are defined at the surface and at the center of the RF powered target, respectively. Experimental conditions are shown in Table 1.

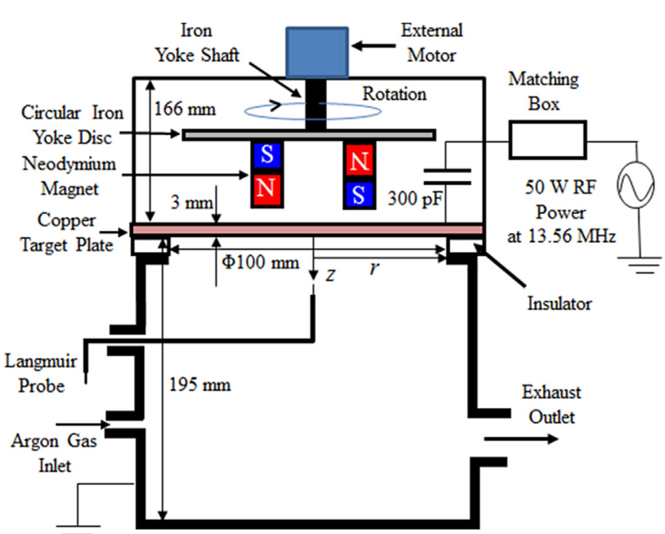

Fig. 1. Experimental setup for the proposed high density RF magnetized plasma sputtering source.

Eight Neodymium rectangular rod magnets of 30 mm length, 5 mm width, and 3 mm height, where the connection between N-pole and S-pole magnets is one side of the square, are mounted on a circular iron yoke disk. The iron yoke is set up with a gap of 1 mm from the copper target plate. An iron (Fe) cover of $5 \times 3 \times 1$ mm is used for magnetic shielding of otiose magnetic fields from the permanent magnets. The three magnet arrangements including magnetic shielding material and the iron cover of 1 mm thickness are shown in Fig. 2 for the proposed high density RF plasma sputtering system. Details of the three magnet arrangements will be explained later. The circular iron yoke disk with the magnet arrangement was rotated by an iron yoke shaft at a speed 40 rpm by an external motor. A precision surface tool was used to measure the erosion depth of the copper target as a basis to calculate the target utilization percentage.

The plasma parameters such as the time-averaged ion saturation current is measured to obtain the ion flux to the target by a tiny tungsten wire probe of 1.0 mm in diameter and 10 mm in length. The time-averaged ion saturation currents were measured by moving the L-shaped needle probe in axial z and radial r directions as shown in Fig. 1. In order to avoid the influence of the RF potential oscillations on the probe current voltage characteristics, the probe wire was connected to an LC filter circuit [1–5]. The ion flux to the target is calculated from the ion saturation current by negatively biasing the probe including a resistance of 100 Ω positioned at $z = 10$ mm.

3. Magnetic field profile analysis of square-shaped schemes

In order to investigate the effect of the magnetic field pattern induced by the square-shaped permanent rod magnet schemes on the plasma production, three arrangements of magnets are used: (a) without iron (Fe) cover and no air gap between the N-pole and the S-pole magnets, (b) with iron (Fe) cover and no air gap and (c) with iron (Fe) cover and 5 mm air gap [see Fig. 2(a)–(c)]. Eight

Table 1
Experimental conditions.

Item	Specification
Initial vacuum base pressure (Pa)	3.2×10^{-4}
Argon gas introduce pressure (Pa)	1.03
Sputtering time (hours)	4
RF input power (W)	50
RF discharge voltage (Vpp)	796
Self-biased DC voltage (V)	−389
Rotational speed for iron yoke (rpm)	40
Neodymium magnet size (mm)	$30 \times 5 \times 3$
Copper target size (mm)	$160 \times 160 \times 3$