A Novel Sputter System with Dynamically Controlled Plasma

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Abstract - A new type of plasma system based on the Magnetic Neutral Loop Discharge (NLD) concept has been developed for sputter application. This system is characterized by plasma production around the magnetic null field on the target surface, where an RF electric field is applied. From the experimental results and numerical analysis of electron behavior in this system, we found that electrons around the magnetic null region on the target surface moved in meandering orbits like in the original NLD concept. Varying the magnetic flux density of magnets and their arrangement can control effective electron heating around the null region.

Keywords : magnetic null field, electron heating, neutral loop discharge, sputtering

1. Introduction

Presently, magnetron sputtering is a well-established technology, successfully used in a wide range of applications, many of which have been scaled up for industrial use. However, the target utilization of magnetrons currently produced is low of about 20-30 %. It can be increased up to 50-60 % in the case when the magnetron has an optimized magnetic field. Since the magnetron discharge forms a closed loop, there is always a certain part of the target inside the closed loop where no target sputtering occurs. In principle, there are two ways how to achieve full erosion of the target: To design a magnetron with full erosion target, i.e., a target without a center, which is not sputtered and to control the sputtering region dynamically on the target surface during discharge using an appropriate magnetic method. The first method resulted in the realization of magnetrons, for example, interpolate target magnetron, toroidal plasma type magnetron and rectangular magnetron, but some of these methods are somewhat complicated structurally⁽¹⁾. The second method, if it can be realized, will be very convenient and effective for full target erosion, however, there has been no report on this. This study addresses the latter method.

In recent years, a neutral loop discharge (NLD) plasma⁽²⁾⁻⁽⁵⁾ is a new plasma source utilizing the magnetic null discharge, where electrons move in a non-linear manner around the null region with effective electron heating at pressures of less than 1 mTorr and yet achieving high plasma density. It is also that kind of technology where the null region can easily be controlled by varying currents in the coils. By this processing over large surfaces areas with high uniformity can be realized and thus is attracting a lot of attention. In etching applications adequate work has been done making the NLD technology industrially viable with good results⁽⁴⁾⁽⁵⁾. We have been conducting process application in the NLD technology. In addition, we seek to suggest a capacitive-coupled NLD plasma

without the use of an antenna in order to realize to sputtering applications⁽⁹⁾. With the dynamic controllability of the NLD technology made applicable to sputter processes there is the possibility of overcoming the erosion problem as well as achieving low pressure and high efficiency in operation. In this research we present the design and construct of the new type null plasma sputtering system. We also seek to quantify through simulation and experiments, to clarify the plasma formation and structure. For the evaluation of the sputter efficiency, thin-film growth experiments have been conducted.

2. Experimental Arrangement and Methods

Figure 1 shows the arrangement of the equipment. The chamber was of stainless steel having an inner diameter of 308 mm. The target was of doughnut shape having a width of 70 mm with the anode on the inner and outer sides of the target.

Eight pairs of permanent magnet (neodymium, size: 10×20×5

Fig. 1. Schematic arrangement of the experimental apparatus

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mm) were arranged on the outer and inner peripherals of the target inside the anode. The target holder was made from the stainless steel, and the width of the disk was 74.8 mm including the width of the target. Cooling water was circulated through the target holder to prevent overheating. The inner diameter of the cylinder that housed the permanent magnet was 40 mm and its outer diameter was 220 mm, both cylinders being electrically grounded. The gap between the electrodes was set to less than the Paschen minimum (2 mm) for the pressure (0.1-10 Pa order) to prevent unnecessary discharge. For the generation of the plasma, permanent magnets are arranged symmetrically as shown in Fig. 1. With the same magnetic field strength, four adjacent groups of magnets are arranged as shown in the figure. The magnetic null region is formed as a point at the center of the plane, containing the magnets, and spatially a line in the z- direction perpendicular to the target. When high frequency electric field is applied to the null region via the target by a 13.56 MHz RF generator, the structure and direction of the electric and magnetic fields are similar to those produced in the inductively coupled NLD plasma. Thus electrons move in a similar manner (meandering motion) in the electric and magnetic fields as in the inductive type. By this kind of motion, effective electron heating⁽²⁾ and high electron densities are expected. Furthermore, the inner and outer peripherals of the cathode are designed to have 18mm high walls. This consideration was given so that electron flowing along magnetic filed lines from the null region towards the anode will be reflected back due to the walls. Thus the electron lifetime will be extended in the null region and electron heating will be enhanced. The position of the null region in any adjacent 2 pairs of magnet can be achieved by varying the magnetic field strength and position. If the erosion region of the target is concentrated around the null, it will be possible to control it by varying the magnet strength and position. The widths of the magnetic null areas with flux density (on the magnet surface) 60, 120, and 300 mT were 20 mm, 10 mm and 4 mm respectively. The magnetic field distribution was determined by calculation and measurement with a gauss meter.

In order to measure the 2 dimensional distributions of the electron density and electron temperature of the area over the doughnut target, the measuring probe and its supporting flange were both designed to allow 2 stage rotation. The 2-stage rotational probe consists of the double probe itself, inner flange and outer flange. By the simultaneous rotation of the probe and the inner flange, the measurement points over the target can be easily chosen. Measurements were performed in a 0~90° sector that included 2 null regions and the parameters of measurements were the electron temperature and electron density distributions. Expressing the null regions in co-ordinate form (r, θ), they become (54.3 mm, 22.5°) and (54.3 mm, 67.5°). The measured data was acquired with the probe tips set at 20 mm from the target surface and in intervals of 5°. The double probe technique (which minimizes errors from magnetic field) was used tungsten tips of diameter 0.5 mm and length 5 mm. In the probe experiments a stainless steel target (comparatively of low sputter rate) was used. However, for the sputter experiments, Cu target were used.

3. Numerical and Experimental Results

Figure 2 show the magnetic field configuration on the target surface and the results of magnetic field distributions when the location of the number magnet was rotated from 0° to 45° by

rotating the outer magnets. The magnetic field components H_r and H_θ can be written as

$$H_r = \frac{m}{2\pi \mu_0 r^3} \cos \theta \dots\dots\dots (1)$$

and

$$H_\theta = \frac{m}{4\pi \mu_0 r^3} \sin \theta \dots\dots\dots (2)$$

Where m [Wb·m] is magnetic moment of magnet, and μ_0 is the permeability of free space. With the magnetic field calculations around the magnets, which are arranged on the outer area of the target, 120 mT was assumed to be the flux density at 10mm from the center of the magnet.

As shown in Fig. 2, with a rotation angle of 45°, the initial magnetic null was rotated 22.5°, with its new coordinates at (54.3 mm, 45°) -there was no significant change in radius in method of

Fig. 2. Variation of magnetic null-field distribution for rotation of outer magnets

rotation.

Fig. 3(a)~(c) show the examples of the electron trajectory in the x-y and r-z planes where the radius, $r=(x^2+y^2)^{1/2}$ and temporal variation of electron kinetic energy. The movement of the electrons was calculated based on the following equation.

$$m \frac{dv}{dt} = -e(E + v \times B) \quad (3)$$

Fig. 3. Calculation examples of the electron trajectory and electron kinetic energy

The Eq.(3) governs the motion of an electron in an electromagnetic field. E is the electric field [V/m], B is the magnetic field [T], and e is the elementary electron charge. The calculations of magnetic field B were made based on the magnetic moment with the radial component of the field H_r and the corresponding angle component H_θ in Eqs.(1) and (2) respectively. We assumed that the electric field E decays exponentially with distance z from the target surface to the substrate as following equation;

$$E(z,t) = E_0 e^{-|z|/\delta} \cos(\omega t + \phi) \quad (4)$$

where E_0 was the electric field strength at target surface ($=5 \times 10^3$ V/m) and the decay length δ was 10 mm. The frequency was 13.56 MHz, corresponding to angular frequency ω and the phase ϕ was simply fixed to zero. In this calculation of electron behavior, using the Runge-Kutta method, Eq.(3) was employed to directly trace the trajectory of electrons. The initial point of the electrons were set at the null region, and was 10mm away from the target surface ($z=10$ mm). The initial energy of electrons was set to be 0.01 eV for all conditions. Also, collisions were not considered because the mean free path between an electron and neutral particle for 1.8 mTorr is about 180 mm. We assumed that when the electrons approached the cathode walls, the electric field at the walls repelled the electron. It was also assumed that when the electrons traversed a distance of 100 mm in the z direction (i.e. over the substrate), they had been emitted from the target and the calculation was terminated. As shown in Fig. 3, the electron exhibits a complex meandering motion around the null region, and moved with a spiral motion along magnetic field lines all the way to the substrate and wall of the chamber. When it traveled to the high magnetic field region beyond null region, it was reflected by the mirror effect. The electron chiefly gains and loses energy around null region, whereas there was no clear change of electron energy in the other region.

Figures 4(a)~(c) show the ion current density, electron density and electron temperature over the target surface, respectively. Experimental conditions are as follows: gas pressure=1.8 mTorr, RF power=350 W and magnetic strength (at the magnet surface)=120 mT. The width of the region with 1mT and below under the mentioned conditions was 10 mm. The probe tips were set at $z=20$ mm (i.e. 20 mm from the target surface) and made to go through the null region at $r=55$ mm while rotating from 0° to 90° in intervals of 5° as mentioned above. The ion current density, electron density and electron temperature were measured at interval of radial 11.6 mm. As shown in Fig. 4(a), the peaks of the ion current density profile were 0.6 mA/cm^2 and 0.57 mA/cm^2 at two null regions respectively. For electron density of Fig.4(b), they were $8.35 \times 10^{17} \text{ m}^{-3}$ and $8.2 \times 10^{17} \text{ m}^{-3}$ respectively at the same points of measurement. In the profiles, the peak values are about 1.55 and 1.3 times the minimum values for the ion current density and electron density respectively. On the other hand, it is seen from Fig. 4(c) that the minimum of the electron temperature occurs around the null field regions with value 6.2 eV and 6.6 eV.

The result cannot be explained with the previous experimental report⁽³⁾. This can be understood at two points of view, and the detail discussion is described in Sec.4.

Figure 5 shows the thickness profile of a copper (Cu) film deposited by the null plasma sputter system. The Si samples of $1.5 \times 1.5 \text{ cm}^2$ size, which were located in A-A' line in Fig. 3(a) were 100 mm away from the target surface, and the deposition time was 45 minutes. The film thickness evaluated by a SEM

Fig. 4. Measured Ion current density, electron density and electron temperature

observation represents the average value for about 5 samples obtained from the same deposition condition. When the substrate distance z was 100 mm, the maximum thickness with value about $1.55 \mu\text{m}$ was obtained at the position of 0° , 45° and 90° between the null region. The minimum of the thickness profile at the null position of 22.5° and 67.5° were about $1.4 \mu\text{m}$. The uniformity of film thickness was $\pm 5.1\%$. Also, the average deposition rate was

Fig. 5. SEM photograph of Cu thin film

about 32 nm/min . This wave-like thickness profile on the substrate implies, as explained with the Knudsen's cosine law, that the erosion area in the target surface during the deposition is non-uniform, which is closely related to the spatial distribution of the bombarding ions on the target surface as shown in Fig. 4(a). On the other hand, the thickness uniformity was remarkably improved with the substrate rotation, and the best thickness uniformity was $\pm 0.26\%$ within a 20 cm diameter. We thus believe that the thickness uniformity is well enhanced with the dynamical plasma control although further detail work is necessary to establish this. Also, an erosion pattern of the target surface was examined. The eight erosion regions over the target surface could be confirmed. This indicates that the sputtering occurs intensely around null region on the target surface and this eroded area can be actively controlled with the angular rotation of magnetic null field, which can be seen in Fig. 2.

4. Discussion

First, we discuss the calculated results shown in Fig. 2. Until now, the magnetic field configuration used in the previously mentioned inductive type NLD was of closed loop type, thus it was dealt with approximately by simple numerical expression, such as slab model⁽²⁾. Also, the extent of calculation was almost confined to around the null region, which was symmetrical model centering on the null point. However, this condition leads the electron repeatedly accelerates and decelerates with the meandering motion along infinite neutral line, and is not connected with actual experimental situations. 2D and 3D models in consideration of more practical factors showed that the electron meandering motion is limited spatiotemporally⁽⁶⁾⁽⁷⁾. As shown in Fig. 2, the magnetic field configuration of our device is unclosed, asymmetric and multi-type structure. It is therefore expected that the effect on the electron behavior compared with the slab model will be somewhat different. However, the dominant features of electron behavior from our numerical and experimental results show that the same type of electron heating could be expected to occur in this new system. The detailed is described below in discussion of Figs. 3 and 4. Furthermore, the result of Fig. 2 implies that the location of null region on the surface of target can be varied with rotating the outer magnets. If magnets of different flux densities are used, varying the radial position of the null region is possible. If electron heating in the null region in this new device can be confirmed, then it is possible to dynamically control the plasma on the target surface.

It can be seen from Fig. 3 that the actual asymmetric magnetic and electric field configuration affect electron behavior.

Depending on the z axial region (distance from the target surface) under consideration, some different electron motion can be seen. In the 0–20 mm region, electron gains energy from the electric field by the meandering motion around the null region, and this is the same as the results from the above-mentioned calculation models⁽²⁾⁽⁶⁾⁽⁷⁾. In the 20–60 mm region, electron still exhibits the characteristic meandering motion around null region with a larger spiral radius caused by decrease of the magnetic and electric field strength. Beyond about 60 mm, electron flows along weak magnetic field line all the way upstream without clear acceleration, and this is because that the electric field strength is too weak to accelerate electron although this area corresponds to the null region in a wide meaning. It can be seen from the above-calculation result that the spatial extent of the electric field is the most dominant factor in deciding the electron heating region of the system. In the calculation, it is assumed that the RF electric field E decreases exponentially with distance z from the target surface with a decay length of 10 mm. These results therefore indicate that this capacitive type magnetic null field configuration is useful for the electron heating, and effective plasma production can be also expected in the new system.

From the results shown in Fig. 4, where the ion current density and electron density have peaks around the null area, it is thus understood that the plasma production occurs effectively in the magnetic null region. This agrees with the theory of plasma production reported by Yoshida and Uchida⁽²⁾. However, it is seen from Fig. 4(c) that the measured value of the electron temperature is low in the null area. This experimental result is not in agreement with the results already obtained in the inductively coupled NLD experiments⁽³⁾⁽⁷⁾. We believe that this should be considered from the point of view of the plasma production conditions based on capacitive coupled plasma concept rather than by only electron heating, and describe at two points of view as follows. First, a distinct feature of this capacitive type plasma for existing NLD plasma is that the plasma generation region is near to the cathode target. Thus, the measured profile of electron temperature is greatly influenced by the behavior of the secondary electrons emitted from the target surface. This presents a striking contrast to inductive type NLD in which it is not necessary to consider the existence of a high-energy component⁽³⁾. In case of capacitive type plasma, the secondary electrons with high energy ($>>100$ eV) emitted from the whole cathode surface during the discharge process are accelerated across the high field cathode sheath. The emitted secondary electrons around null region are almost accelerated toward the substrate. On the other hand, for case of secondary electrons at the high magnetic field area, their path is modified by the $E \times B$ Lotrentz force. One component of their motion is a helical path for the magnetic field lines. The electrons traveling along these helical lines are eventually returned the target where the magnetic field lines intersect the surface and the repulsive electric field encountered repeatedly. Therefore, it can be understood that the measured electron temperature distribution of Fig. 4(c) is a reflection of the trapping effect of these high-energy secondary electrons by the magnetic fields near the target, and thus is chiefly dependent on the calculated null field configuration of Fig. 2(0°). Second, the disagreement of the experimental condition between our Fig. 4(c) and the above-mentioned previous report should be considered quantitatively based on evaluation index for the plasma formation conditions, such as the normalized electric field F . Here, F is defined as⁽⁸⁾,

$$F = \frac{E_0}{L \omega B_0} \dots\dots\dots (5)$$

where E_0 is the RF electric field intensity, L is the width of the magnetic null areas, ω is the angular RF frequency and B_0 is the magnetic field strength, which satisfies electron cyclotron resonance (ECR) condition. The conditions for the plasma production under various conditions of the electric field, frequency and the magnetic field strength can be normalized using the value of F . The value of F for previous experimental report⁽³⁾ is around 1 (≤ 1), while that of our experiment is very high (at least >3) when E_0 and L at the measurement position assumed to be 675 V/m and 10 mm, respectively, from the calculation condition of Fig. 3. In fact, a characteristics of inductive type NLD for $F > 3$ was not clarified because the production of the plasma satisfying that condition was experimentally difficult. Besides, it was well known that the measured profiles under $F \leq 0.2$ are similar to those of ICP, and peak profile does not exit by the previous report⁽⁸⁾. This case of $F \leq 0.2$ corresponds to the practical conditions of NLD plasma for etching process where E_0 and L are about 200 V/m and 30–50 mm respectively⁽⁴⁾⁽⁵⁾. Therefore, it seems to be unsuitable that all experimental results obtained from NLD condition under $F \leq 1$ are expected to reappear in this capacitive type system for $F > 3$. However, in spite of the above-described distinctions from the plasma generation conditions, our experimental results that the electron density and ion current density possessing peaks at the null region indicate that the electron heating around null region is also essential for plasma production in this capacitive type system.

5. Summary and Conclusion

In this work, a new NLD plasma production technology for sputter application has been proposed. The electron behavior was investigated on experiment and simulation platforms. The results were in agreement with the existing inductively coupled type NLD. On the calculation platform, the electron motion around capacitive type magnetic null region exhibited the characteristic meandering motion. The same type of electron heating can be expected to occur in this new type plasma. From the experimental results that the electron density and ion current density possessing peaks at the null region, it was ascertained that the electron heating around null region is also essential for plasma production in this capacitive type null field configuration. Also, two distinctive factors, such as secondary electrons trapping and normalized electric field (F) were found to explain the measured profile of the electron temperature. From the thin film experiments, it could be found that the thickness uniformity was well enhanced with the substrate rotation and dynamical plasma control although further detail work is necessary to establish this. Furthermore, it is expected that the dynamic control of plasma over the target surface will be realized, because rotating and arranging the outer permanent magnets can actively control the position and area of magnetic null field region. With plasma application, the enhancement of target erosion and its uniformity are possible.

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