Modeling of the Electron Motion in a Capacitively Coupled Magnetic Null Plasma

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***Abstract*—A new type of plasma system based on the neutral loop discharge (NLD) concept is being developed for research aimed at sputtering application. This system is characterized by plasma production around the multinull magnetic field on the target surface, where a capacitive RF electric field is applied. From the results of the electron motion modeling 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. Initial modeling results on electron behavior and a photograph of plasma emission taken from the new NLD system are presented.**

***Index Terms*—Capacitively coupled plasma, electron meandering motion, magnetic null-field, neutral loop discharge plasma, sputtering.**

IN THIN-FILM processing for integrated circuit fabrications and various coating applications, glow-discharge plasmas are widely used. In order to meet the requirements for finer products that are becoming more and more stringent, plasmas with controlled electron density and temperature, and with uniform profiles over large wafer sizes have been required. A neutral loop discharge (NLD) plasma was proposed as a new plasma source that would allow very uniform processing over a large area [1]. This NLD plasma system uses a magnetic neutral loop (NL) generated from three electromagnetic coils arranged outside a chamber, and an RF electric field applied in the direction perpendicular to the magnetic field using a loop antenna placed inside the chamber. Controlling the position and diameter of the neutral loop provides a very easy means of varying the position and diameter of the plasma. Since the principle of the NLD concept was proposed for plasma processing applications in 1994 [1], there have been many theoretical and experimental researches on it. The theoretical basis of plasma production for the NLD concept was firmly established by studying electron behavior around the NL based on the slab model of magnetic field configuration [2]. This study showed that electrons had a meandering motion around the NL and acquired high kinetic energies from the applied RF field at the region between the NL and the electron cyclotron resonance (ECR), the length of which is designated by L. We have made investigations about the electron behavior both theoretically and experimentally. Regarding the experiments, we used laser Thomson scattering to measure T_e and n_e profiles and also laser-induced fluorescence (LIF) to measure distributions of excited atoms [3]. The measured profiles of T_e and excited atoms had a peak on the NL while the n_e profile had a peak at a region inward from the location of the NL [3]. In our numerical studies, analyses of the electron behavior were carried out using a model that included the effects of a two-dimensional electromagnetic field with a spatial decay of an RF electric field, and the limitation of the spatial extent of electron motion. These factors were found to explain the existence of the optimum condition for the formation of NLD plasmas [4].

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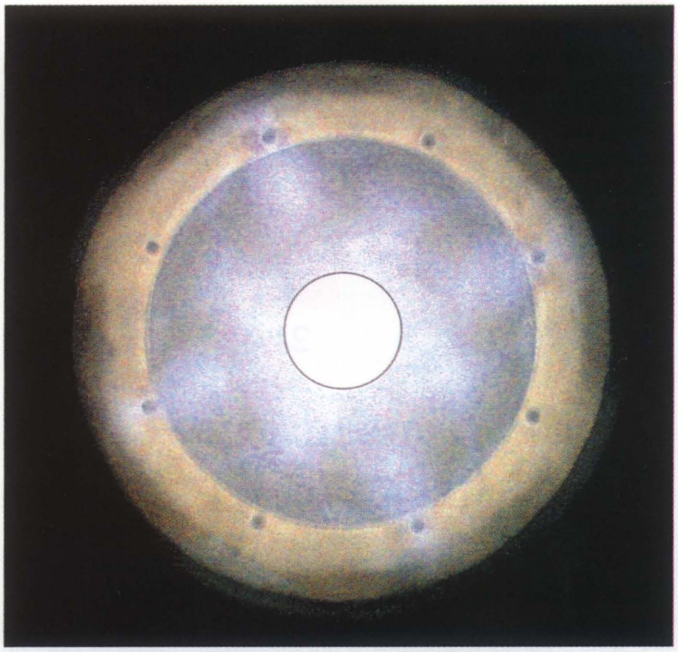

Fig. 1. Photograph of NLD plasma showing eight strong emission regions.

For an application to a sputter deposition using the NLD concept, we propose a new capacitive-type NLD plasma system. The device consists of three plate coaxial electrodes and 8 pairs of permanent magnets arranged circularly. A middle ring plate is the stainless-steel target electrode, to which an RF electric field is applied relative to the grounded cylindrical rings outside of it. The array of magnets forms eight magnetic null regions perpendicular to the target surface.

Fig. 1 shows a photograph of a plasma emission. Applying 300 W of RF power to the stainless-steel target produced the plasma in Ar at a pressure of 0.9 mtorr. Eight regions of strong emission are visible, which coincide with the null regions.

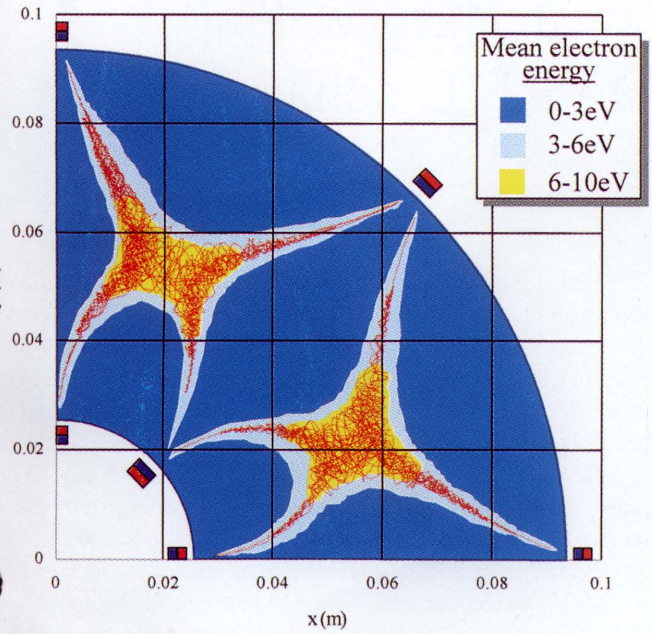

Fig. 2. Simulated electron orbit and electron energy in the two null regions within a 90° sector.

Fig. 2 shows an example of the calculated electron orbits (around the null region) and the mean electron energy distribution of 10^4 particles on the target surface with respect to the initial position. The six rectangles indicate magnets. For this arrangement and by using magnets of 3 kG, the calculated null points are located on the 0.06 m radius at angles of 22.5° and 67.5°, with additional symmetric positions in the other 270° sector. The initial velocity of electrons was set at $v_x = v_y = v_z = 1 \times 10^5$ m/s. The calculation time was up to about 50 RF periods. The electric field was assumed to be 500 V/m and uniform over the target surface. Each particle, however had different direction of motion and position and obeyed the equation, $\mathrm{m}d\boldsymbol{v}/dt = -e(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B})$. Electron heated with the characteristic meandering motion around the null region [2] and moved with a spiral motion along the magnetic field lines; when it traveled to a distance far from the NL, it was reflected at high field points by the mirror effect [4]. Detailed analyses of the electron behavior in the three-dimensional configuration suggested that similar electron heating is expected in this new capacitively coupled NLD plasma system.

From the initial probe experiments, the maximum values measured for T_e existed around the null regions, also similar to the original NLD plasma [5]. In addition, the spatial control of these peaks over the target surface is possible with the adjustment of the field strength and arrangement of magnets. In sputtering applications, high erosion uniformity of target surface can be achieved by controlling these peaks or rotating the target. Detailed experiments and modeling are in progress.

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References

[1] T. Uchida, "Application of radio-frequency discharge plasma produced in closed magnetic neutral line for plasma processing," *Jpn. J. Appl. Phys.*, vol. 33, no. 1A, pp. L43–L44, 1994.

[2] Z. Yoshida *et al.*, "Plasma production using energetic meandering electrons," *Jpn. J. Appl. Phys.*, vol. 34, pp. 4213–4216, 1995.

[3] T. Sakoda *et al.*, "Studies of a magnetic neutral loop discharge based on laser diagnostics of electron behavior and atomic processes," *Jpn. J. Appl. Phys.*, vol. 36, pp. 6981–6985, 1997.

[4] Y. M. Sung *et al.*, "Studies on the optimum condition for the formation of a neutral loop discharge plasma," *J. Vac. Sci. Technol. A*, vol. 18, no. 5, pp. 2149–2152, 2000.

[5] Y. Okraku-Yirenkyi *et al.*, "Experimental and numerical analyses of electron temperature and density distributions in a magnetic neutral loop discharge plasma.," *J. Vac. Sci. Technol. A*, vol. 19, no. 5, pp. 2590–2595, 2001.