Laser Thomson Scattering Measurements and Modelling on the Electron Behavior in a Magnetic Neutral Loop Discharge Plasma

Youl-Moon Sung, Hee-Je Kim and Chung-Hoo Park

Abstract - Laser Thomson scattering measurements of electron temperature and density in a neutral loop discharge (NLD) plasma were performed in order to reveal the electron behavior around the neutral loop (NL). The experimental results were examined by using a simulation model that included effects of a three dimensional electromagnetic field with spatial decay of the RF electric field, and the limitation of the spatial extent of the electron motion and collision effect. From the experiments and modeling of the electron behavior, it was found that NLD plasma possesses the electron temperature T_e and density ne peaks around the NL because that the electron heating and ionization around NL is essential for the formation of plasma. Also, the optimum condition of plasma production could be simply estimated by the calculation of U_{av} and F_0.
Keywords - Laser Thomson scattering, Neutral loop discharge (NLD) plasma, Electron behavior, Electron temperature, Electron density

1. Introduction

For plasma sources to be used in the plasma processing for the fabrication of the semiconductor devices, uniformity over the large area and controllability to obtain desirable plasma parameters are required. A magnetic neutral loop discharge (NLD) plasma has been proposed as a new plasma source which satisfies these requirements[1]. The position and the diameter of the plasma can be easily changed by controlling the position and the diameter of a neutral loop (NL)[2]. It has been theoretically shown that the motion of an electron becomes nonlinear in the spatially varying magnetic field around the NL, in which the radio frequency (RF) electric field was applied along the produced NL perpendicular to the magnetic field lines[3,4]. The electron makes meandering motions and acquires kinetic energy of several tens of electron-volts from the RF field where the meandering range contains the region between NL and the electron cyclotron resonance (ECR), the length of which is designated by L. Through such a process, the electrons are heated efficiently without collision. The electron behavior at and near the NL determines the uniqueness of this plasma production technique and therefore the details at its operating conditions are needed.

An experimental and numerical analyses of electron behavior are needed in order to accurately understand the characteristics of NLD plasma. For this purpose, we performed laser Thomson scattering measurements of T_e and n_e and then examined the experimental results by using computer simulations based on a simple model in which three dimensional effects were taken into account. Until now, measurements of electron temperature T_e and density n_e profiles around the NL have been performed experimentally[5,6], but no numerical analyses of these experimental results have been reported. Laser Thomson scattering is a long established technique for measuring electron temperature T_e and density n_e in high density discharge such as fusion plasmas. Recently, it has also been used to measure electron properties in some types of low temperature glow discharges[7,8]. As a diagnostic method, Thomson scattering has the followings adventages ; firstly it is non-disturbing and secondly, the detected signal can be interpreted relatively simply in order to obtain electron properties. Consequently, Thomson scattering is considered to be the most reliable method for mesuring electron properties.

In this work, we experimentally studied T_e and n_e distributions around the NL and the plasma production rate by measuring the ion flux density. The experimental results were then examined by using computer simulations based on a simple model in which the 3-dimensional effects were taken into account. For obtaining the optimum conditions for plasma generation, the relationship between the normalized electric field F_0 and the average electron energy U_{av} was also investigated.

2. Electron Motion Around the NL

An electron motion around the NL has been theo-

The authors wish to thank Prof. K. Muraoka of kyushu University for their valuable contribution.

Manuscript received: June 20, 2001 accepted: Oct. 4, 2001.

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retically analyzed[3,4]. Here, we only explain the outline of that analysis, which covers the following discussion of experimental results. Assume an inhomogeneous magnetic field as shown in Fig. 1, where the magnetic field **B** is directed in the y direction and the strength is varyings in the x direction. The magnetic field strength B is zero at x = 0. The RF electric field **E** (angular frequency ω) is directed in the z direction. B becomes B_0 (= $m_e \omega/e$; m_e: electron mass) at $x=\pm L$, which satisfies electron cyclotron resonance (ECR) condition. The normalized RF electric field F, which the RF electric field is normalized by the magnetic field, is defined as where E_0 is the real

$$F=F0\sin\omega t, \quad F_0=\frac{E_0}{L\omega B_0} \tag{1}$$

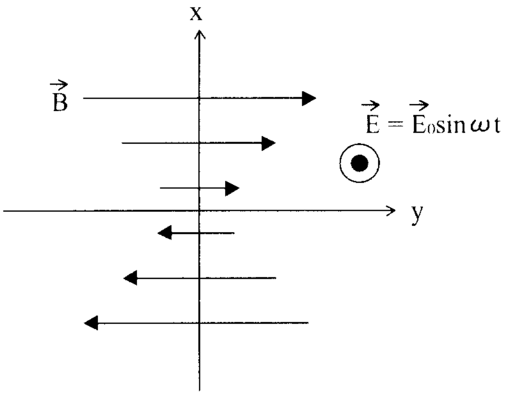

Fig. 1 Arrangement of electric and magnetic field around NL (slab model)

amplitude of the RF electric field. The electron orbit around the NL were calculated by solving the electron kinetic equation; it undergoes a chaotic meandering motion in the region of $-2L<x<2L$ as shown in Fig. 2 only when F_0 has about the value of 1. As the meandering range contains the ECR point, the electron absorbs the energy from the RF electric field.

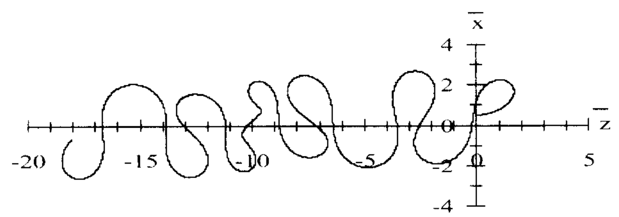

Fig. 2 electron orbit arounf NL

3. Experiment and Methods

Fig. 3 shows a schematic diagram of the NLD plasma device and the Thomson scattering system. Three coils, shown as coils 1, 2 and 3 in Fig. 3, were placed coaxially surrounding the stainless steel chamber.

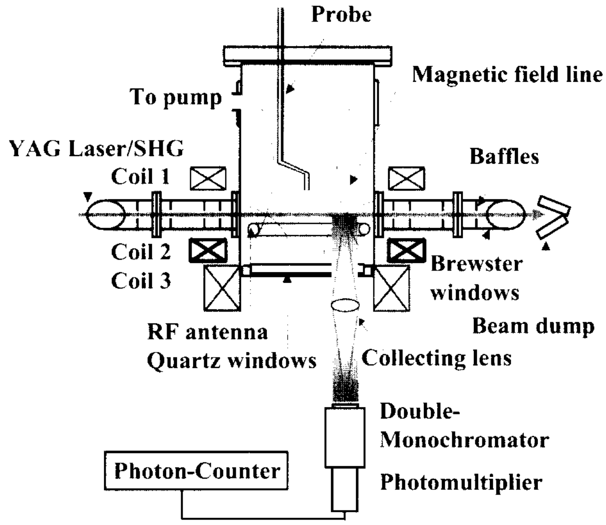

Fig. 3 Experimental arrangement.

The inner diameter of the chamber was 308mm. The currents in coils 1 and 3 (I_1 and I_3, respectively) flowed in the same direction while that in the coil 2 (I_2) in the opposite direction. An NL was formed in the plane of coil 2 as depicted in the figure, and had a radius of R_{NL}=100mm when the current of the three coils were adjusted to I_1=66.8A, I_2=193A and I_3=115A. The magnetic field strength corresponding to the ECR condition at the RF frequency of 13.56MHz is B= 0.48mT. The magnetic field strength was measured using a Gaussmeter having a Hall element. The Gaussmeter had an uncertainty of ± 0.03 mT in its indicated values, which meant that the setting position of the NL had an uncertainty of ± 2 mm in both the radial and axial directions. A one-turn RF antenna with 130mm in radius was placed inside the chamber, 10mm from the NL in the axial direction. It was insulated from the plasma by a quartz glass tube with a cross-sectional diameter of 10mm. The laser beam for Thomson scattering measurements passed through the NL in the radial direction. The discharge gas was argon of 3mTorr. The gas pressure was measured using an ionization gauge which was calibrated in the range of 1-20mTorr using a diaphragm gauge (Baratron 390; its full scale was 10Torr and its nominal precision was 0.08% of the readout value). The linearity of the diaphragm gauge itself was checked using Rayleigh scattering of laser light in the pressure range of 1mTorr - 10Torr. We estimated the error of the pressure to be about ±10 %[5]. The light source of the Thomson scattering apparatus was the second harmonic of a Nd: YAG laser which had an energy of 0.5 J, a duration of 10 ns and a repetition rate of 10 Hz. The detection solid angle was 3×10^{-2} sr. Radial measurements of electron density and temperature were performed along the laser beam path from the center to a radius r = 120 mm. The laser beam was focused by a lens having a focal length of 1000 mm into the plasma.

The focused beam inside the chamber had a radius of approximately 1 mm. A photon counting technique was used for signal detection and the detection limit of electron density was extended down to 5×10^{16} m^{-3}. The peak value of the RF electric field strength on the NL was about 204V/m when the input RF power was 400W. The measurements of the RF electric field strength were performed using a magnetic probe.

4. Experimental Results and Discussion

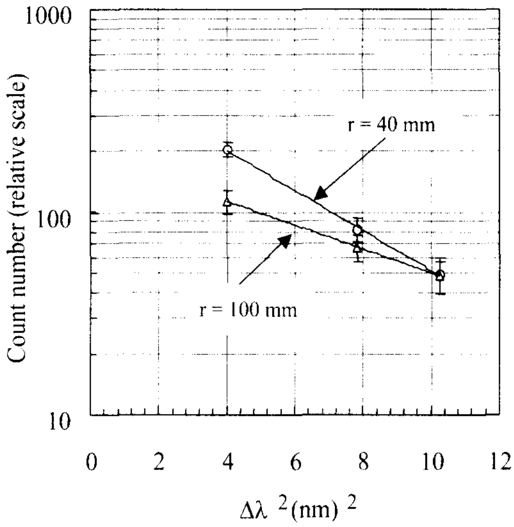

Fig. 4 Examples of Thomson scattering spectra measured at radial positions of r = 40 and 100 mm

Fig. 4 shows examples of spectra which were measured at radial positions of r = 40 mm and 100 mm for the case when the NL radius was set at RNL= 100 mm. The ordinate is the detected photon number in a logarithmic scale, where the photon counting at each measuring point was performed for up to 2000 laser shots so that the detected photon number was more than 100. Possible errors of data points were estimated from photon-statistics and are shown by the error bars in Fig. 4. In this plot, a straight line indicates a Gaussian spectrum, and therefore, indicates a Maxwellian electron energy distribution function. T_e and n_e were obtained from the gradient and square of this plot line[4]. For the determination of n_e, scattered signal intensities were calibrated at each measuring radius using Rayleigh scattering signals from argon gas. Values of T_e and n_e thus obtained typically had errors of ±15%.

Fig. 5(a) shows the measured results of radial profiles of T_e and n_e for the case when the NL radius, R_{NL}=100mm and Fig. 5(b) for the case, R_{NL}=120mm. n_e profiles have peaks at radii inward of the NL. These radii are at r=65mm for R_{NL}=100mm and r=85mm for R_{NL}=120mm, respectively. The T_e profiles for Figs. 5(a) and 5(b) had peaks on the NL. It is understood that the T_e peak coincides with the position of the NL for both cases R_{NL}=100mm and R_{NL}=120mm. The existence of T_e peak on the NL indicates that the plasma source region is the NL. We note that the T_e values are high at positions for which the magnetic field strength is in the range of B=0-0.5mT. This fact is consistent with the prediction of theoretical analysis of NLD plasmas[3,4]. The mean free path of electrons with respect to collisions with neutral argon atoms at 3 mTorr is about 100 mm, which is much longer than the spatial extent of the region of B = 0-0.5 mT (16 mm). Therefore, the requirement, outlined in Ref. 3 and 4, that the electrons should have a meandering motion in this extent is satisfied. However, the shift of n_e peak inward of the NL is a phenomenon that has not been explained and must be further studied.

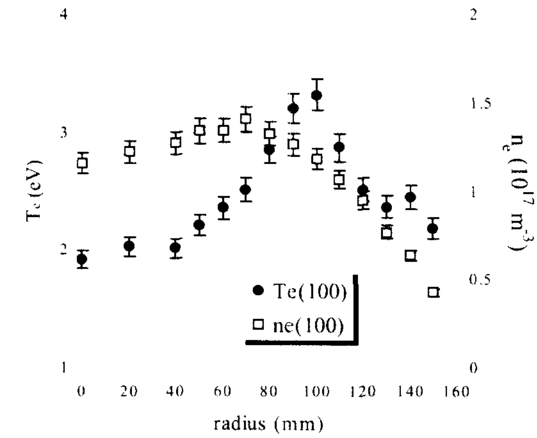

Fig. 5a Radial profiles of T_e and n_e for the case when the NL radius, RNL=100[mm]

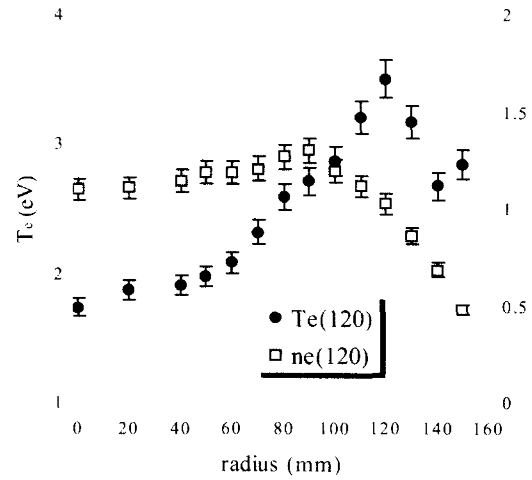

Fig. 5b Measured results of radial profiles of Te and ne for the case when the NL radius, RNL=120[mm].

5. Simulation and Discussion

The motion of a single electron under the influence of an electric field E and a magnetic field B can be expressed by the following equation:

$$me\ dv/dt = -e(E + vB) \qquad (2)$$

Here, E[V/m] is the electric field, B[T] the magnetic field, e[C] the elementary electron charge and m[kg] the mass of an electron. Until now, the electron behavior around the NL has been analyzed by solving Eq. (2) in a magnetic field expressed by the slab model[3,4]. In this model, the magnetic field is directed in the y-direction in the x-y plane. The field intensity B is proportional to x and the sign of B reverses across the x-axis. The NL forms a plane with an infinite extent. In place of the above-described model, we propose a new one, which has the capability of tracing three dimensionally, the behavior of electrons around the NL. The configuration of this model is given in Ref. 9. The magnetic field is expressed as $B=B_0$ (y/L, x/L, 0). In this expression, B_0 is the magnetic field strength corresponding to the magnetic field strength of the ECR, and 0.48mT when the RF frequency is 13.56MHz, as stated previously. The NL is a line with an infinite length and is formed on the z-axis. The ECR points form a cylindrical surface having a radius of L. The induced RF electric field is directed in the z-direction. The finite extent of the RF electric field and the existence of the chamber wall were also considered. We assumed that the RF electric field decayed exponentially as a function of the distance from the NL, with a decay length δ. δ was 30mm and determined from the measurement of the RF magnetic field in the NL plane of Fig. 3. The measurements were performed using a magnetic probe, which was scanned in the radial direction from the center to the NL. We assumed that electrons were lost by recombination on reaching the walls. Elastic collisions of electrons with neutral particles were also taken into account. When electrons traversed the length of the mean free path λ, the direction of the electron motion was assumed to be randomized.

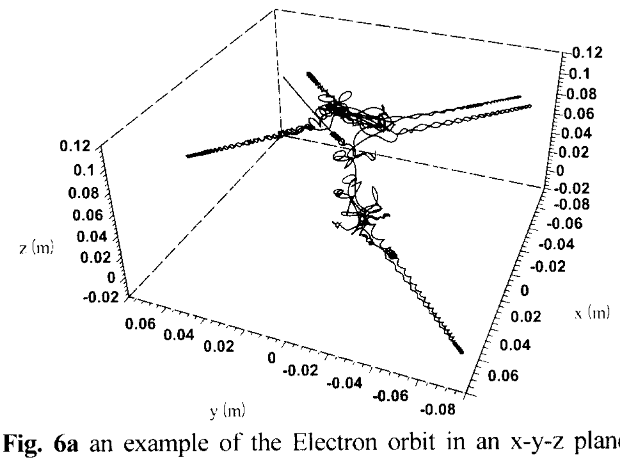

Fig. 6a an example of the Electron orbit in an x-y-z plane.

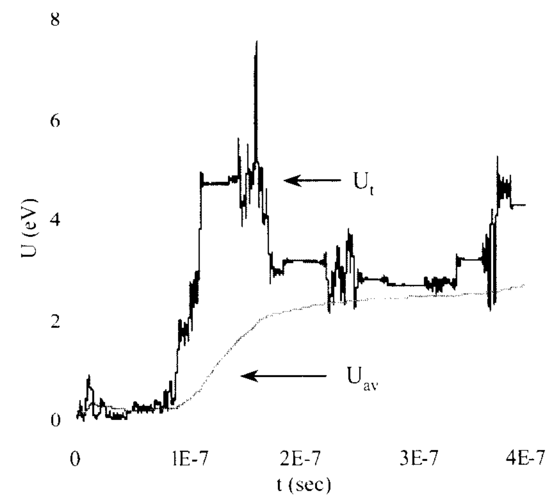

Fig. 6b Time variation of the electron kinetic energy.

Fig. 6a shows the examples of the electron trajectory calculated for the case without walls, and Fig. 6b shows the time variation of the electron kinetic energy under the same condition. The electron motion is a spiral along magnetic field lines in the planes of y = x and y = -x and advanced in the z or z directions. When it traversed a distance beyond 2L, it was reflected at high field points by the mirror effect. The electron characteristics were also investigated outside the region of 2L. When the electron was placed beyond the radius of 2L, there was no significant change in the electron energy. The fact that electrons gain energy from the electric field inside the range of the radius of 2L is the same as the results from the slab model[3].

Fig. 7 shows the calculated average electron energy U_{av} distribution of 10^4 particles along the x-axis without chambers walls. The calculations were done under common conditions: RF electric field on the NL, E_0=204V/m, δ=30mm, mean free path, λ=0.1m, initial energy, U_0= 0.1eV and L=6mm. Each particle however had different direction of motion and initial position and obeyed the equation of motion in Eq. (2). The calculations show that the average electron energy U_{av} distribution is concentrated within 5L of the NL, which is equivalent to about 30mm. The region outside this interval showed that the energy of the electron is negligible about 0.2eV. This implies that the electrons absorbed high energy within 2L of the NL, and these energetic electrons are distributed within 5L. Also, It was shown that the electron heating around the NL is essential for the formation of NLD plasma.

Electron trajectories were traced by using the proposed model for various conditions and the dependence on the value L, of U_{av} of electrons was examined. The F_0 profile in that case was also calculated. The results are shown in Fig. 8. We calculated U_{av} during the tracing of the electron motion since U_{av} is related to electron temperature as with the previous calculation[9], which is in

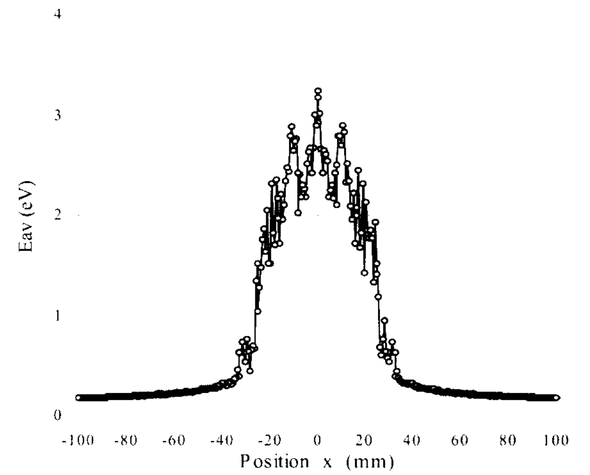

Fig. 7 Average electron energy U_{av} along the x-axis

turn closely related with the plasma production rate. The initial energy of electron was set to be 0.1eV for all conditions. Calculations were performed for many different directions of initial velocity and positions, which were set in the radial range of 0-5L. The time duration of the calculation was up to about 50 RF periods, and the calculation was terminated when the electron reached the walls.

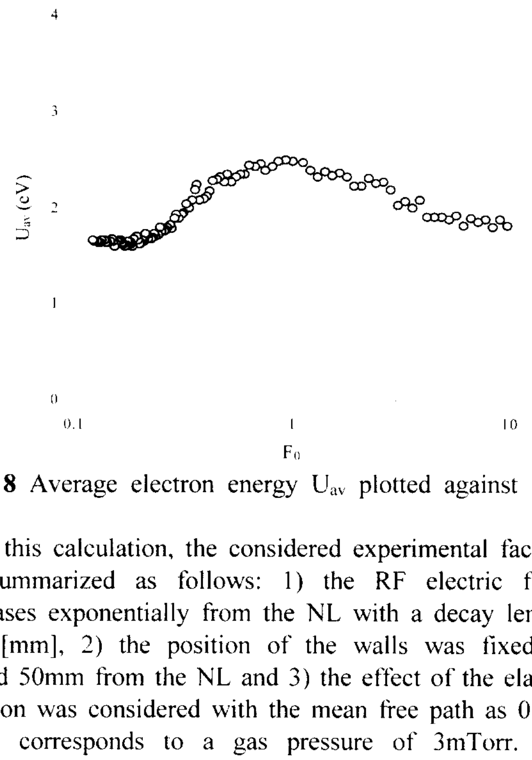

Fig. 8 Average electron energy U_{av} plotted against F_0.

In this calculation, the considered experimental factors are summarized as follows: 1) the RF electric field decreases exponentially from the NL with a decay length of 30[mm], 2) the position of the walls was fixed at around 50mm from the NL and 3) the effect of the elastic collision was considered with the mean free path as 0.1m which corresponds to a gas pressure of 3mTorr. An electron, which has energy of around 2.5eV, collides with neutrals once within an interval of one or two RF periods. It has been shown that electron motion governed by Eq. (2) becomes nonlinear when the normalized electric field F_0 is of the order of 1 and thus the electron are heated efficiently without collisions[3]. U_{av} was maximum when F_0 was about 1 as seen in Fig. 8. The fundarmental calculations conditions were the same as Fig. 7. The abscissas are the values of experimental conditions such as the electric field, the magnetic field and the frequency, respectively. The circles in these figures are refer to the averaged values obtained by 400 calculations for various direction of electron motion, in which initial positions of electrons were set around NL. The value of F_0 reflect the electron heating around the NL[9]. Therefore, This figure implies that both F_0 and U_{av} could be simply estimated the efficiency of the plasma production because the electron heating and ionization on/around the NL is essential for the formation of the NLD plasma.

Although the model described above is useful for the discussion of the most dominant feature of the electron behavior, it is not sufficient to obtain quantitative guidelines for the design and the operation of the NLD device. Further research in 3D modeling in this direction is in progress. Furthermore, work for etching applications using NLD plasma and that for a new NLD sputter system is on going.

6. Summary and Conclusions

In order to ascertain the plasma production and construction of a new plasma source, a magnetic neutral loop discharge (NLD), electron behavior was studied experimentally and numerically. The results are summarized as follows:

1. In the Thomson scattering measurements, the results showed that the electron temperature T_e had a peak on the NL and, in contrast, the electron density n_e had a peak at a position radially inward from the NL.
2. The electrons absorbed high energy within $\pm 2L$ around the NL, and these energetic electrons are distributed within $\pm 5L$, which is equivalent to about 30mm. Also, It was shown that the electron heating around the NL is essential for the formation of the NLD plasma.
3. The optimum condition of plasma production could be simply estimated by the calculation of U_{av} and F_0 because these values reflect the electron heating around the NL.

Acknowledgements

The authors wish to thank Prof. K. Muraoka of kyushu University for their valuable contribution.

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