Property of plasma by radio frequency discharge with the use of multi hollow cathodes

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Abstract. A denser plasma with a lower electron temperature is produced by radio frequency discharge with the use of multi hollow-cathode (HC). The effect of HC discharge and the diffusion of the plasma between HC and anode are depended on the gas pressure. A highly uniform plasma generated on the anode is modified by changing the effective width of grooves on the HC. The correction of the electron density distribution with the effect of HC discharge is important compared with that of the electron temperature distribution.

1. Introduction
Various types of electric discharges are used for the plasma processing [1]. Electron density is required to be higher than $10^{17}$ m$^{-3}$ for high-speed processing [1]. Moreover, the lower electron temperature is known to result in the lower damage to the substrate than the case of the higher one. Also, uniform plasmas are need for efficient processing. The necessary uniformities are $\pm 2 \sim 3$ % for a semiconductor chip and $\pm 4 \sim 5$ % for a liquid crystal display.

One of the various promising discharges is a compound radio frequency (RF) discharge with the hollow-cathode (HC) discharges, which produces the denser plasma resulting in the lower electron temperature. Both the RF and the HC discharges are well known for yielding high electron density plasmas [1, 2]. In the RF discharge, the electron density increases proportionally to the input RF power [3]. The spatial diffusion of the plasma produced by the HC discharge [4] induces better effects, such as the higher electron density, the lower electron temperature, maintenance voltage sag, and so on. The effect of HC discharge brings about the plasma generation of high dense and low temperature [3]. The HC discharge is known to depend on the value of product $pD$, which $p$ is the working gas pressure and $D$ is the width of grooves separation on the plane HC. Although the value of the operating gas pressure has to be fixed, the effective range of $D$ can be extended by the use of a tapered shape HC, which has different cathode separations at the upper and the lower ends of the HC [5]. The tapered shape HC enables us to realize the plasma processing such as the etching (low $p$, $< 10$ Pa) and the deposition high $p$, $> 50$ Pa) in the wider range of the operating $p$ with the use of one electrode. The RF discharge with the use of the tapered shape HC has been studied in our laboratory, and the realization of uniform plasma has been experimentally demonstrated [3, 5-7]. Also, we successfully produced dense plasma ($10^{17}$ m$^{-3}$) and low temperature (1.7 eV) by RF (13.56 MHz) discharge with the used of multi HCs [3]. And we successfully produced a highly uniform plasma on the surface of flat electrode (anode) by using the modified multi HCs (MHC), in which each width of the grooves on the HC is changed with inserting electrode sticks in each groove [8]. This method causes the slightly decrease of the effect of HC discharge. Especially, the density of the plasma at the center of MHC is by half less than that of...
HC in the present configuration at the same level of input power. However, the important properties of HC discharge, that is the high electron density and the low electron temperature, are essentially inherited by MHC discharge [8]. The effect of HC discharge and the diffusion of plasma between cathode and anode depend on the gas pressure [3]. Also, the distribution in the perpendicular direction to the grooves on the multi HC's depend on the gas pressure. Therefore, the generation of the uniform plasma is needed to consider the balance between the production rate and the diffusion of plasma in each gas pressure.

In this paper, we present detailed measurements of phenomena occurring in the compound RF discharge plasma with the use of the HC and the MHC. The dependences of the ion saturation current $I_{\text{sat}}$, the electron density $n_e$, and the electron temperature $T_e$ on the gas pressure $p$ and supplied RF power $P_{RF}$ are shown by probe measurements. It is necessary for me to consider the diffusion of plasma on each gas pressure in both the $x$- and $z$-directions to generate the uniform plasma.

2. Experimental setup

2.1 Experimental apparatus and measurements

Experiments were carried out in a plasma chemical vapor deposition device (PDE-301, Anelva) [3]. The cylindrical chamber is constructed of the type 304 stainless-steel with the inner diameter of 296 mm and the height of 200 mm. The vacuum pump system consists of a rotary pump and a diffusion pump to exhaust the chamber to less than $10^{-5}$ Pa. The powered electrode (cathode) is capacitively coupled to the RF power supply (PRF-53B, Anelva) through a matching unit. The $P_{RF}$ with a frequency of 13.56 MHz is varied up to 300 W. The operating Ar gas pressure $p$ is fixed in the range from 2 to 100 Pa with the use of a mass-flow controller.

The values of $n_e$ and $T_e$ are measured and evaluated by using the double-probe method. The double-probe consists of two cylindrical probes of 0.3 mm in diameter and 1.0 mm long, which are made of tungsten. The distance between the tips of the probe is 1.0 mm. The rest of each probe electrode inside the discharge region is covered by an alumina tube with the length of 120 mm, for electrical insulation. The inner and outer diameters of the alumina tube are 0.4 and 1.0 mm, respectively. The two probes are installed in a stainless-steel tube with outer diameter 15 mm and length 500 mm and mounted on the probe driving system. Probe signals are taken through a BNC coaxial connection with small flange (ICF 034) and connected to the double probe circuit (bias voltages $V_{\text{bias}} = \pm 20$ V) through a low-frequency pass filter. The probe current and voltage in the double probe circuit are recorded by an X-Y recorder. In this system, the nearly ideal symmetrical characteristics of the double probe are always obtained, without the influence of the high power (5 ~ 300 W) RF electric fields [8].

2.2 Electrodes

The structure of a square hollow-cathode with a tapered shape (HC) with the side length of 144 mm is made of stainless-steel [3]. The HC has thirteen grooves. Cross-section of each groove is a tapered shape in the direction of depth (24 mm). The widths of the upper and the lower ends of the groove are 10 and 4 mm, respectively. The average width $D_{av}$ of the groove, corresponding to the cathode separation $D$ of the HC, is 7 mm. The modified hollow-cathode (MHC) equips the electrode sticks, which are inserted in the grooves, for changing the width of grooves on the HC [8]. The depth of grooves also changes largely with the electrode stick. The grounded electrode operates as an anode. The distance between the anode and the cathode is 30 mm. The surfaces of the anode and the cathode are defined as $x = 0$ and $\pm 72$ mm, respectively. The center and edge of the cathode in the perpendicular direction to the grooves are defined as $x = 0$ and $\pm 72$ mm, respectively.

3. Experimental results and discussion

3.1 Diffusion on gas pressure

In this system, the substrate for the plasma processing is usually placed on the anode [3]. I seemed from this experimental result that the effect of HC discharge becomes maximum at around $p = 8.35$ Pa
for the present electrode with $D_{av} = 7$ mm [3]. The effect of HC discharge and the diffusion of plasma between cathode and anode depend on the gas pressure [3]. Also, the distribution in the perpendicular direction to the grooves on the multi HCs depend on the gas pressure. Therefore, the generation of the uniform plasma is needed to consider the balance between the production rate and the diffusion of plasma in each gas pressure.

The distributions of ion saturation current in the HC, $I_{is}^{HC}$, in the $x$-direction at $p = 8.35$ Pa and $P_{RF} = 100$ W are shown in Fig. 1. The $I_{is}^{HC}$ distributions of all $z$ positions decrease in the edge region of $x$-direction. The $I_{is}^{HC}$ distribution becomes maximum at $z = 15$ mm. The $I_{is}^{HC}$ distribution at $z = 25$ mm is influenced by the groove shape. The average value of $I_{is}^{HC}$ distribution at $z = 25$ mm is almost equal to that at $z = 5$ mm. The value of $I_{is}^{HC}$ distribution at $z = 5$ mm is about 0.6 times as that at $z = 15$ mm. On the other hand, the distributions of $I_{is}^{HC}$ in the $x$-direction at $p = 33.4$ Pa and $P_{RF} = 100$ W are shown in Fig. 2. In this case of high $p$, the effect of HC discharge is weak compared with the case of $p = 8.35$ Pa. The $I_{is}^{HC}$ distributions of all $z$ positions increase in the edge region of $x$-direction. The values of $I_{is}^{HC}$ distribution at $z = 15, 20,$ and $25$ mm are almost equal, but that at $z = 25$ mm is also influenced by the groove shape. The $I_{is}^{HC}$ distribution at $z = 5$ mm is peaked at the edge, however, those at $z = 10 \sim 25$ mm are peaked around $x = 50 \sim 65$ mm. The values of $I_{is}^{HC}$ distribution decrease between $z = 5$ and $10$ mm. Therefore, the diffusion of plasma from cathode to anode is suppressed in the case of high $p$.

In order to investigate the diffusion rate on the gas pressure in the $x$-direction, the ratios of $I_{is}^{HC}$ at $z = 5$ mm over $I_{is}^{HC}$ at $z = 10$ or $15$ mm, $I_{is}^{HC}(5) / I_{is}^{HC}(z)$, at $p = 8.35$ and $33.4$ Pa are shown in Fig. 3.

![Figure 1](image1.png)  
**Figure 1.** Ion saturation current distributions for the HC in the $x$-direction at $p = 8.35$ Pa and $P_{RF} = 100$ W.

![Figure 2](image2.png)  
**Figure 2.** Ion saturation current distributions for the HC in the $x$-direction at $p = 33.4$ Pa and $P_{RF} = 100$ W.

![Figure 3](image3.png)  
**Figure 3.** Distributions of ratio of ion saturation current for the HC in the $x$-direction at $p = 8.35$ and $33.4$ Pa.
The values of $I_n^{HC}(5) / I_n^{HC}(z)$ at $p = 8.35$ Pa are larger than those at $p = 33.4$ Pa without the edge region. It is seen that the distributions of $I_n^{HC}(5) / I_n^{HC}(z)$ at $p = 8.35$ Pa decrease in the edge region of $x > 40$ mm. On the other hand, the distributions of $I_n^{HC}(5) / I_n^{HC}(z)$ at $p = 33.4$ Pa increase in the edge region. It is considered that the diffusion of plasma at $p = 8.35$ Pa overflows and that at $p = 33.4$ Pa is weak, because the plasma particle flows only outward at the edge. Additionally, the production of plasma by the effect of HC discharge is small at $p = 33.4$ Pa. Consequently, the diffusion of plasma in the $x$-direction is not enough in the case of high $p$. It is necessary for me to consider the diffusion of plasma on each gas pressure in both the $x$- and $z$-directions to generate the uniform plasma.

3.2 Generation of uniform plasma

The uniform plasma on the anode surface is generated by changing the effect of HC discharge. The approach is based on modifying the $I_n$ distribution over the anode surface in order to compensate for the non-uniform part of $I_n$ distribution [8]. Figure 4 shows the $I_n$ distributions for the HC, $I_n^{HC}$, and the MHC, $I_n^{MH}$ in the $x$-direction at $P_{RF} = 100$ W, $p = 8.35$ Pa, and $z = 5$ mm. Also, the distribution of $I_n^{HC}$ at $p = 33.4$ Pa is shown in the figure. The difference of $I_n^{HC}$ at $p = 8.35$ Pa at the edge to that at the center is about ±29%, while, that at $p = 33.4$ Pa is about ±21%. In the MHC discharge, the uniformity of $I_n^{MH}$ distribution attains ±1.7%. In order to flatten the $x$-direction distribution at $p = 8.35$ Pa, the high current around the center should be suppressed or the lower current at the edge should be enhanced. If the groove width adjusts for high $p$ case ($p > 8.35$ Pa) to obtain the effect of HC discharge, it is possible to manage the uniform plasma in the same way. The effect of HC discharge will be suppressed in the region of edge, because the diffusion of plasma in the $x$-direction is suppressed in the case of high $p$.

The electron density distributions for the HC, $n_e^{HC}$, and the MHC, $n_e^{MH}$, in the $x$-direction at $P_{RF} = 100$ W, $p = 8.35$ Pa, and $z = 5$ mm are shown in Fig. 5. Also, the distribution of $n_e^{HC}$ at $p = 33.4$ Pa is shown in the figure. The value of $n_e^{HC}$ at $p = 8.35$ Pa decreases in the edge region of $x$-direction, while, that at $p = 33.4$ Pa increases. The difference of $n_e^{HC}$ at $p = 8.35$ Pa at the edge to that at the center is about ±39%, while, that at $p = 33.4$ Pa is about ±28%. The difference of $n_e^{MH}$ is about ±2.8% and $n_e^{MH}$ is about 0.55 times as $n_e^{HC}$ at $x = 0$ mm and $p = 8.35$ Pa.

The electron temperature distributions for the HC, $T_e^{HC}$, and the MHC, $T_e^{MH}$, in the $x$-direction at $P_{RF} = 100$ W, $p = 8.35$ Pa, and $z = 5$ mm are shown in Fig. 6. Also, the distribution of $T_e^{HC}$ at $p = 33.4$ Pa is shown in the figure. The value of $T_e^{HC}$ at $p = 8.35$ Pa is about 2.00 eV at $x = 0$ mm and increases from 2.05 eV to 2.38 eV in the edge region of $x > 40$ mm and the difference of $T_e^{HC}$ is about ±16%. On the other hand, the value of $T_e^{HC}$ at $p = 33.4$ Pa keeps about 2.3 eV and the difference of $T_e^{HC}$ is ±2.6%. And the $T_e^{MH}$ at the center is 2.17 eV and the uniformity is ±2.7%. Thus, the case of high $p$ is...
good uniformity without modification. In the case of $p = 33.4$ Pa, the difference of $T_{e}^{\text{HC}}$ is found to be less than that of $n_{e}^{\text{HC}}$. Consequently, the correction of the $n_{e}^{\text{HC}}$ distribution is important compared with that of the $T_{e}^{\text{HC}}$ distribution.

4. Conclusions

I have examined the property of plasma by the RF discharge with the use of multi HCs. It is necessary for me to consider the diffusion of plasma on each gas pressure in both the $x$- and $z$-directions to generate the uniform plasma. In order to flatten the $x$-direction distribution of $I_{as}$, the high current around the center or the edge should be suppressed or the lower current should be enhanced. If the groove width adjusts for high $p$ case to obtain the effect of HC discharge, it is possible to manage the uniform plasma in the same way. The difference of $T_{e}^{\text{HC}}$ is found to be less than that of $n_{e}^{\text{HC}}$. Thus, the correction of the $n_{e}^{\text{HC}}$ distribution is important compared with that of the $T_{e}^{\text{HC}}$ distribution.

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