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Electron temperature control by varying size of slits made in a grid

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Electron temperature is controlled by varying the length of slits made in a grid immersed in a weakly ionized discharge plasma. The grid, which is kept at floating potential, has six slits in this experiment. With a decrease in the slit length from 6 to 0 cm, the electron temperature decreases from 2.1 to 0.09 eV, being accompanied by an electron-density increase from 0.32×10^9 to $1.53\times10^9\ \mathrm{cm}^{-3}$ at argon gas pressure of 1.5 mTorr. This method of electron–temperature control is applicable to reactive plasmas in which grids are often covered by insulators. © *2000 American Institute of Physics.* [S0003-6951(00)04205-4]

In reactive plasmas widely used for material processing, there would be big effects of electron temperature (strictly speaking, electron energy distribution) on products obtained. Therefore, a control of the electron temperature is of crucial importance for finding the best conditions of chemical reactions necessary for the material processing. In general, however, it is difficult to control electron temperature in weakly ionized discharge plasmas, although several methods for electron–temperature control have been reported.[1–5]

In our method using a mesh grid,[5] the electron temperature is decreased by almost 2 orders of magnitude by varying a negative dc potential applied to the grid. This temperature decrease is accompanied by an increase in the electron density. In this grid-bias method, a plasma is produced in a region surrounded by a chamber wall and the grid. High energy electrons in the plasma can pass through the grid into the other region surrounded by the chamber wall and the grid. Ionization occurs due to the electrons in this region, resulting in production of cold electrons which are not responsible for maintaining the discharge in the region of plasma production.[6,7] The low electron temperature observed was also found to be responsible for the result of low ion temperature.[8] The grid-bias method applied to rf plasmas including silane and hydrogen was found to yield a good reproducible fabrication of hydrogenated amorphous silicon (*a*-Si:H) film with high drift mobility.[9] We also applied this method to negative-ion production in rf hydrogen plasmas, which was enhanced by the electron–temperature decrease.[10]

The grid-bias method, however, is not applicable to reactive plasmas in which grids are often covered by thin films of insulators. Here, we report a method also using a grid for the electron temperature control. In this method, slits are made in the grid. By varying the slit length mechanically, the electron temperature is observed to be controlled by more than 1 order of magnitude even if there is no external potential applied to the grid. This method can be applied to reactive plasmas where the grids are covered by such insulators as hydrogenated amorphous and diamond-like carbon films because it is not necessary to apply an external potential to the grid.

A typical apparatus used in our experiment is shown in Fig. 1. The experiment is carried out in low-pressure discharge plasmas produced by a plane slotted antenna with permanent magnets for electron cyclotron resonance (ECR), which is situated in a vacuum chamber of 35 cm in diameter and 160 cm long.[11] The magnets used have a maximum magnetic field of about 3 kG at the surface center. The ECR condition ($\simeq$875 G) is met in a limited region within 6 mm from the antenna surface. A 27-cm-diam grid with mesh size of 1.59 mm(16 lines/in.) is made of 0.3-mm-diam stainless steel wires. The grid has six slits in this experiment. The experimental device is divided by the grid into two regions. A plasma is generated by the ECR discharge in region I. A flux of high energy electrons passing through the grid into region II is controlled by varying the length of the slits in the grid. The electron temperature, electron density, and space potential are measured by a small movable Langmuir probe made of a clean tantalum wire of 0.3 mm in diameter and 2 mm long.

A front view of the grid structure for varying the slit length is shown in Fig. 2. The six slits with radial width W_s and azimuthal length L_s along the circumference of 12 cm in radius are made in the grid which is electrically isolated from the vacuum chamber. These slits can be covered by six shutters made of small metal plates, which are mechanically rotated in the azimuthal direction. The slit length decreases when shutters rotate clockwise. L_s is varied externally in the range of 0–6 cm at $W_s=0.6$ and 1.2 cm.

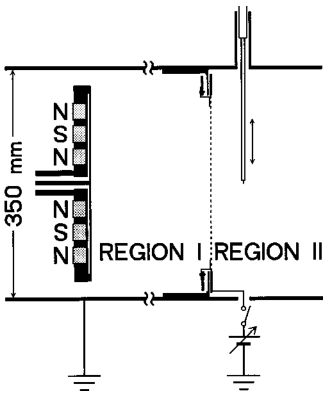

FIG. 1. Schematic of experimental apparatus.

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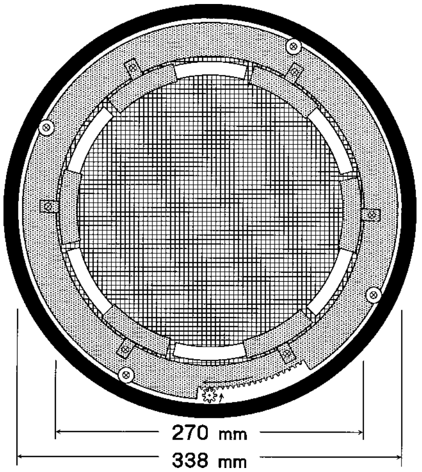

FIG. 2. Front view of grid with variable slit.

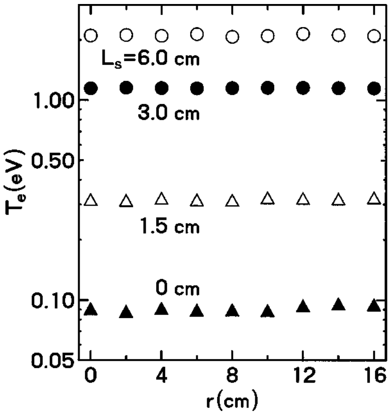

FIG. 4. Radial profiles of T_e at $z=5$ cm for $L_s=0$ (▲), 1.5 (△), 3.0 (●), and 6.0 (○) cm in region II. The experimental conditions are the same as in Fig. 3.

At first, we have measured dependencies of the electron temperature T_e on the grid potential V_G at $L_s=0$ cm to confirm the grid-bias method. The results show that $T_e=0.09$ eV at $V_G=-3.2$ V (floating potential) and $T_e=0.054$ eV at $V_G=-5.1$ V in region II. As reported in Ref. 5, the electron temperature in region II increases with an increase in the mesh size even when the mesh grid with no slit is kept at floating potential, where the grid floating potential is estimated to $V_G-V_{sI}\simeq-10$ V from $T_{eI}\simeq2$ eV and plasma space potential $V_{sI}\simeq7$ V in region I. Here, it is noted that the most important difference between the experiments in Ref. 5 and in the present paper is the way to use the grid. In Ref. 5 the mesh size is varied over the whole grid area, where the change of T_e is observed to saturate over the mesh size of 6.8 mm. However, in the present experiment, only a small part of the grid of 16 lines/in. is opened by the six slits, which are located locally around the outer circumference. In our letter, as shown in Fig. 2, the total area of the six slits is much smaller than the whole area of the grid with a diameter of 27 cm. Therefore, electron temperature in region II does not saturate and still increases even when the slit area is greater than 6.8×6.8 mm^2. The increase in the slit length is equivalent to the increase in the mesh size in the sense that the hot bulk electrons are supplied from region I and heat the electrons in region II. The hot bulk electrons penetrating through the space of the slit distribute almost homogeneously in region II in spite of the fact that the slits are located on outer radial locations. Therefore, even when the grid is kept at floating potential, the electron temperature depends on the slit length. In Fig. 3, the electron temperature T_e and density n_e measured at 5 cm away from the grid on the axis of the device in region II are plotted as a function of L_s, where argon gas pressure $=1.5$ mTorr and microwave power $=200$ W. W_s is 1.2 cm in (a) and 0.6 cm in (b), respectively. In Fig. 3(a), there appears a clear drop of T_e from 2.1 to 0.09 eV with a decrease in L_s from 6 to 0 cm. This temperature decrease is accompanied by an increase in n_e from 0.32×10^9 to 1.53×10^9 cm^{-3}. When the grid is removed, T_e and n_e at the same probe position are measured to be 2.3 eV and 0.53×10^9 cm^{-3}, respectively, which are, roughly speaking, almost equal to the values obtained at $L_s\simeq5-6$ cm in the presence of the grid with variable slit. Therefore, we can control the electron temperature from T_e corresponding to that in the production region I down to 0.09 eV, i.e., by more than 1 order of magnitude, by varying L_s from 6 to 0 cm. On the other hand, it is found in Fig. 3(b) that with a decrease in L_s from 6 to 0 cm, T_e decreases from 0.56 to 0.09 eV and n_e increases from 0.87×10^9 to 1.53×10^9 cm^{-3}. The results in (a) and (b) imply that variation rates of T_e and n_e against L_s can be adjusted by varying W_s. When W_s is large, T_e and n_e are very sensitive to the change of L_s. Only a small change of L_s makes a big variation of T_e and n_e. Therefore, a fine control is required for the change of L_s. On the contrary, when W_s is small, the above requirement is more reduced, because T_e and n_e are less sensitive to the change of L_s.

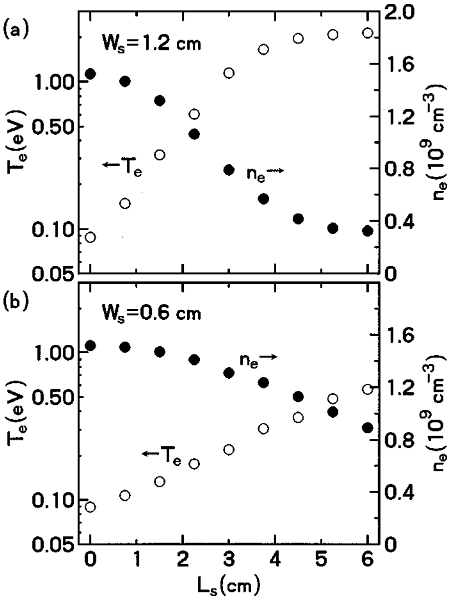

FIG. 3. Dependencies of electron temperature T_e and electron density n_e on slit length L_s in cases of the slit width $W_s=1.2$ cm in (a) and 0.6 cm in (b) at $r=0$ cm and $z=5$ cm away from the grid in region II. Argon gas pressure $=1.5$ mTorr and microwave power $=200$ W.

Figure 4 shows radial profiles of T_e measured at $z=5$ cm for cases of $L_s=0$, 1.5, 3.0, and 6.0 cm in region II, where the grid with $W_s=1.2$ cm is used under the same experimental conditions as in Fig. 3. Radially uniform T_e profiles are found in all the cases. The results of this uniformity are attributed to the six slits made in the radially outer edge region of the grid. We must be careful of the slit num-

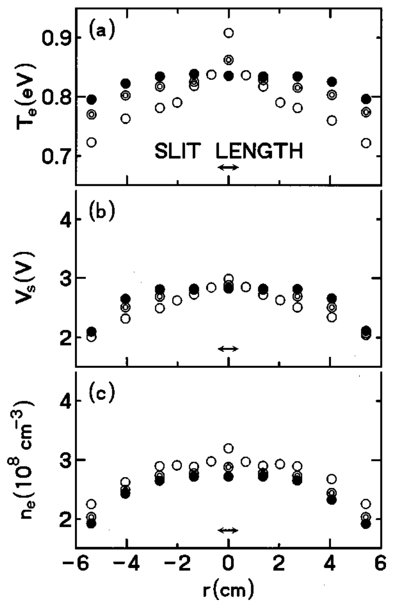

FIG. 5. Radial profiles of plasma parameters (a) T_e, (b) V_s, and (c) n_e in region II at $z=0.3$ (○), 1.0 (◎), and 2.0 (●) cm from the grid with a square of slit (0.78×0.78 cm^2) opened around the center. The experimental conditions are the same as in Fig. 3.

ber and position in order to have such a uniform profile of T_e as in Fig. 4.

To clarify a local structure of the plasma near each slit, we have used another grid with a square (0.78×0.78cm^2) slit opened around the center. Radial variations of T_e, n_e, and V_s in front of the slit are measured by an axially movable Langmuir probe. Figure 5 shows the results at $z=0.3$, 1.0, and 2.0 cm in region II, respectively. The experimental conditions are the same as in Fig. 3. At $z=0.3$ cm, T_e, V_s, and n_e are found to have a peak at the position corresponding to the slit center. But, they become gradually uniform with an increase in z. T_e and V_s are almost uniform in $|r|\lesssim4$ cm at $z=2.0$ cm, while n_e is uniform in $|r|\lesssim3$ cm. From these results, although the electron temperature is not uniform just in front of the slit, it becomes quite uniform in the range $z\geqslant2$ cm. The slit size and position in Fig. 2 have been determined by taking these results into account.

Finally, we remark that this method of electron temperature control has been confirmed to be also applicable to plasmas produced by radio frequency (rf) and direct current (dc) discharges with various gases of H_2, CF_4, and CH_4 in the pressure range 0.5–50 mTorr.

In conclusion, we have demonstrated a method using a mesh grid with variable slit for electron–temperature control. This method works even when the grid is covered by insulators such as hydrogenated amorphous film, diamond-like carbon film, and so on. By varying the length of slits arranged on the circumference of the mesh grid at floating potential, the electron temperature is controlled by more than 1 order of magnitude. The radial profile of the electron temperature is quite uniform in spite of the local arrangement of the slits in the grid.

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