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Electron Temperature Control by Applying DC Voltage to a Mesh Grid Blanketed with Thin Films in Reactive Plasmas

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Electron temperature is controlled by varying a dc voltage applied to a mesh grid blanketed with a thin film made of a diamond-like carbon known as an insulating material, deposited on CH_4/H_2 plasma. With a decrease of the grid potential from 40 to -10 V, the electron temperature decreases from 1.0 to 0.045 eV at argon gas pressure of 20 mTorr in a cold-cathode discharge plasma, accompanied by an electron density increase. We also proved theoretical discussions to clarify how the resistance of the film deposited on the metal grid affects the efficiency of the control of the electron temperature in the case of the grid-bias method. This technique of electron-temperature control is applicable to reactive plasmas in which grids are often deposited by thin films made of hydrogenated amorphous substance, diamond-like carbon and so forth.

Keywords: electron-temperature control, grid-bias method, thin insulating film, CH_4/H_2 plasma

1. Introduction

During the last 20 years, control of electron temperatures in reactive plasmas has attracted strong interest, growing rapidly year by year, because many species of radicals and the structure of the ion sheath formed between plasma and substrate are often very sensitive to the electron temperature, so that we must select desirable radical species and ion energy by controlling the electron temperature. In general, however, it is difficult to control electron temperature over a wide range in weakly ionized discharge plasmas, although several methods for electron temperature control have been reported[$1-3$].

We have reported a grid-bias method for electron temperature control in weakly ionized plasmas. The electron temperature is controlled over almost two orders of magnitude from 2.2 eV to 0.035 eV by applying negative dc bias to the grid accompanied by an increase in electron density[2]. Up to now, several important studies on the application of electron temperature control using a grid-bias method have been performed[$4-7$]. We have achieved remarkable results by applying a grid-bias method for control of electron temperature to the effective generation of negative hydrogen ions (H^-)[4], high quality diamonds[6] and so forth.

It is generally believed that the grid-bias method is not applicable to reactive plasmas, in which grids are often covered with thin insulating films. In this paper, however, we present that this method can be still applied to electron temperature control even if the conductivity of the grid is diminished by the deposition of a dielectric substance such as diamond-like carbon film. Even in this case, by varying the dc voltage of the grid from 40 to -20 V, the electron temperature is controlled by more than one order of magnitude.

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2. Experimental Methods

The experimental setup is shown in Fig. 1. A mesh grid with wire spacing of 1.59 mm(16 lines/in) consists of 0.3-mm-diameters stainless steal wires. The 4.2-cm diameter grid separates the experimental region into two regions I and II. Two types of grids are used. One is covered with a diamond-like carbon thin film in order to determine whether control of electron temperature T_e by the grid-bias method is possible. The other is a bare metal grid which is connected in series with a resistor in order to clarify the effect of electrical resistance R of the grid on T_e control. This resistor is also connected to the dc power supply. Five different resistances are employed in the experiment.

An argon plasma is generated by applying dc voltage to a cylindrical electrode (cold cathode) biased at $V_D = -600$ V with respect to the grounded cylinder (anode) in region I. T_e is controlled by applying the dc voltage V_G to the mesh grid at a pressure of 20 mTorr in region II. A Langmuir probe for measuring T_e is fixed at the position in region II. Before each $I-V$ trace the probe tip is cleaned by applying a negative voltage -100 V for about 10 seconds, the result of ion bombarding.

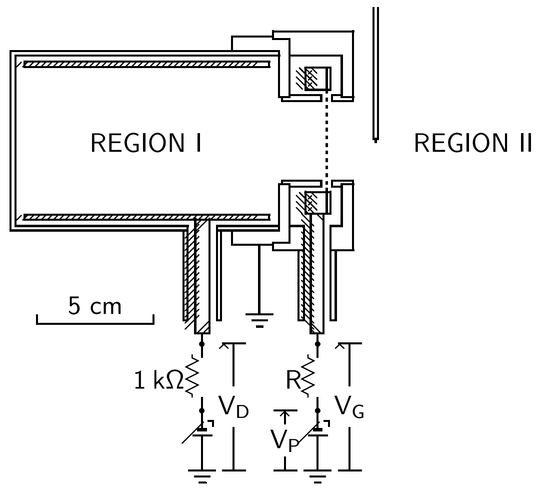

Fig 1. Schematic illustration of cold cathode discharge device for electron temperature control.

3. Experimental Results

Figure 2 shows typical plots of plasma parameters (T_e, n_e, and V_s) measured as a function of V_G which is the potential of the bare mesh grid. Here,

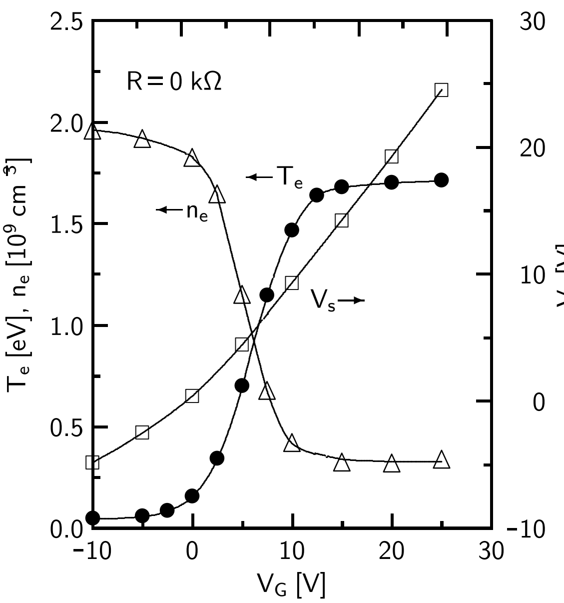

Fig. 2. Plasma parameters T_e, n_e, and V_s vs grid potential V_G at $z = 2.5$ cm from the bare mesh grid in region II.

the resistance R is kept at 0, so that the grid voltage V_G is equal to the voltage of the power supply V_P. T_e decreases suddenly from 1.7 to 0.05 eV with a decrease in V_G from 15 to -5 V. This temperature drop involves a sharp increase in n_e from 0.33×10^9 to 1.9×10^9 cm^{-3} and a decrease in V_s from 14 V to -2.4 V. The properties of the plasma parameter variation observed are also consistent with those described in refs. 2 and 3.

Figure 3 shows the dependence of T_e on the voltage of power supply V_P for the case of $R = 0$, 1 kΩ, 10 kΩ, 0.1 MΩ, and 1 MΩ in region II. The grid is used under the same experimental conditions as those in Fig. 2, except that the resistor is connected in series between the grid and the power supply. We regard this resistance as that of the thin film deposited on the grid, although the resistor is not directly in contact with the plasma sheath.

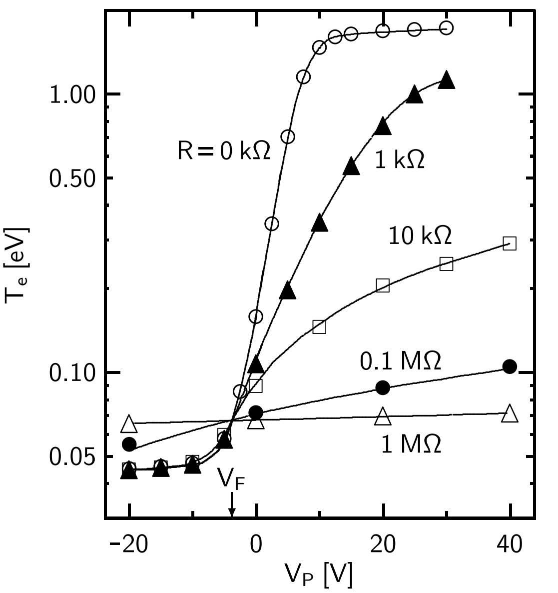

Fig. 3. Dependences of T_e on the voltage of the dc power supply V_P with R as a parameter in region II.

In the case of $R = 0$, V_P is equal to V_G, so that the dependence of T_e on V_P corresponds to the result shown in Fig. 2. The rates of variation in T_e become small as R increases. This result is attributed to the fact that for the same V_P, the potential difference $V_{GP}(= V_G - V_P)$ increases with increasing R. Although in the case of $R = 10$ kΩ the range of T_e variation diminishes to a narrow range of 0.045 to 0.29 eV, we expect that, by expanding the range of voltage of the dc power supply V_P application, T_e can be controlled over a wide range as shown in the case of $R = 0$ kΩ. We also note that, in all cases of R, T_e has a constant value of 0.068 eV at $V_P = -3.8$ V (floating potential).

After removing the grid and resistor we place another bare grid covered with the film of diamond-like carbon for more than 10 hours by using the grid-bias method in RF CH_4/H_2 plasma[8]. Before this grid was installed in the device shown in Fig. 1, by using a multimeter we had confirmed that the resistance between the grid surface and the surface of the film deposited on the grid was more than 40 MΩ. Then, T_e is measured after the carbon film is sputtered by argon ions at $V_G = -100$ V. Bombarding times T_b are 0, 20, and 40 minutes, respectively. The dependence of T_e is shown in Fig. 4 as a function of $V_G(= V_P)$ with T_b as a parameter. The experimental conditions are the same as in Fig. 2, except that the grid is coated with diamond-like carbon film.

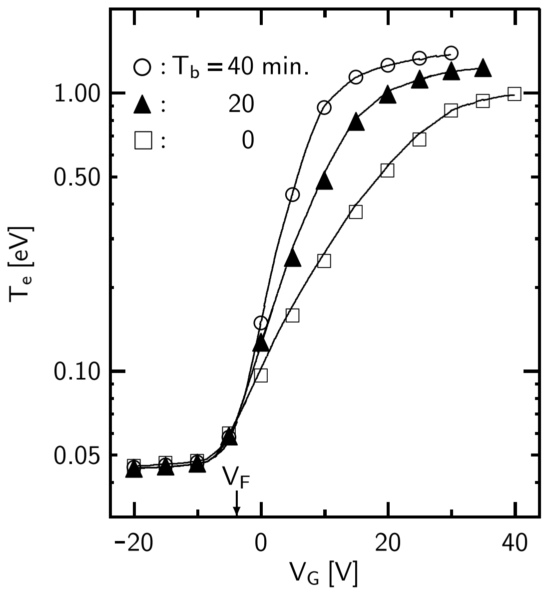

Fig. 4. Variation of T_e as a function of V_G with ion bombarding times T_b as a parameter.

In all cases sharp drops in T_e appear as V_G decreases. The rate of variation of T_e vs V_G becomes large as T_b is lengthened from 0 to 40 min. This result implies that the resistance of the carbon film on the grid decreases with bombarding time T_b, because the carbon film is thinned by the sputtering of bombarding argon ions. Therefore, the variation of T_e as a function of V_G becomes sharp due to the increase in T_e. We note here that the film thicknesses are 30 and 3 μm for the cases of $T_b = 0$ and 40 min, respectively. Comparing the results in Figs. 3 and 4 we note that the resistances of carbon films deposited on the grid for $T_b = 0$, 20, and 40 minutes correspond roughly to 2, 0.5, and 0.1 kΩ, respectively. During the thin film deposition in the CH_4/H_2 plasma, the film grows irregularly due to the effect of ion bombardment, which forms a very large number of micro channels in the film through which electrons and ions pass from the film surface to the grid.

4. Discussion

The current density i in the sheath near the grid is expressed approximately as

$$i = en_i u_s - en_e \nu_{T_{e\mathrm{I}}} \exp\left\{-\frac{e(V_{s\mathrm{I}} - V_{GS})}{\kappa T_{e\mathrm{I}}}\right\}, \quad (1)$$

where $T_{e\mathrm{I}}$ and $V_{s\mathrm{I}}$ are the electron temperature and the space potential, and $\nu_{T_{e\mathrm{I}}}$ and u_s are the electron thermal velocity and the sound velocity in region I, respectively. The surface potential V_{GS} of the film is given by

$$V_{GS} = V_G + IR, \quad (2)$$

where $I = iS$ is the net current flowing from region I to the grid through the sheath and the film. S and R are the surface area and the resistance of the film, respectively. By setting $n_i = n_e = n_p$, we obtain a relation among the potentials

$$V_{GS} = V_G + \alpha|V_F| \times \left[1 - \sqrt{\frac{m_i}{m_e}} \exp\left\{-\frac{e(V_{s\mathrm{I}} - V_{GS})}{\kappa T_{e\mathrm{I}}}\right\}\right], \quad (3)$$

where $\alpha = en_p u_s SR/|V_F|$ is a parameter of film resistance, $|V_F|$ is the absolute value of the floating potential V_F that can be obtained from $i = 0$ in Eq. (1). By setting $i = 0$ and $V_{GS} = V_F$ in Eq. (1) we have

$$\exp\left\{-\frac{e(V_{s\mathrm{I}} - V_F)}{\kappa T_{e\mathrm{I}}}\right\} = \frac{u_s}{\nu_{T_{e\mathrm{I}}}} = \sqrt{\frac{m_e}{m_i}}. \quad (4)$$

Eq. (4) is reduced to

$$V_F = V_{s\mathrm{I}} - \frac{\kappa T_{e\mathrm{I}}}{2e} \ln \frac{m_i}{m_e}. \quad (5)$$

Using $m_e = 9.1 \times 10^{-31}$ kg for the electron and $m_i = 6.68 \times 10^{-26}$ kg for the argon ion we have

$$V_F = V_{s\mathrm{I}} \left(1 - 5.60 \frac{\kappa T_{e\mathrm{I}}}{eV_{s\mathrm{I}}}\right). \quad (6)$$

Figure 5 shows the relation between V_{GS} and V_G calculated from Eqs. (3) and (6), i.e., $V_{GS} = f(V_G)$, with α as a parameter in the case of $eV_{s\mathrm{I}}/\kappa T_{e\mathrm{I}} = 3.6$ and $V_F = -3.8$ V for argon ion. In the case of $\alpha = 0$, we obtain $V_{GS} = V_G$. On the other hand, at the limit of $\alpha \to \infty$, we obtain $V_{GS} = V_F = -3.8$ V, because it is independent of the grid potential V_G. In the case of the intermediate value of α, the surface potential V_{GS} of the film can be varied with the grid potential V_G. This means that the electron temperature can be varied with the grid potential due to the change in the surface potential of the film V_{GS}, although the rate of variation of T_e with V_G is small compared with that in the case of $\alpha = 0$.

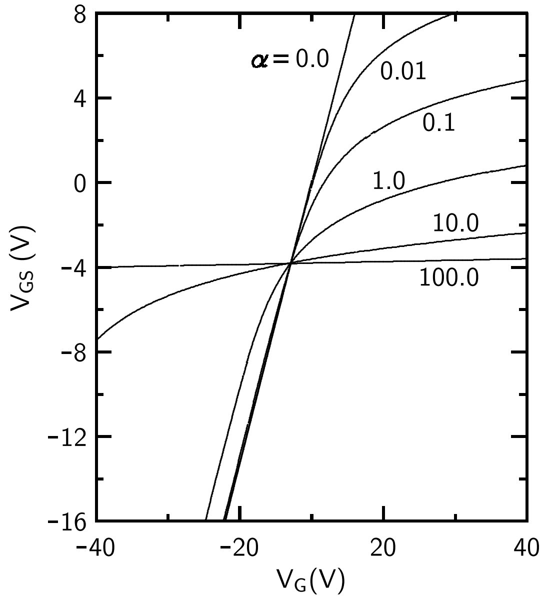

Fig. 5. Relation between V_G and V_{GS} calculated from Eqs. (3) and (6) with α as a parameter in the case of $eV_{s\mathrm{I}}/\kappa T_{e\mathrm{I}} = 3.6$ and $V_F = -3.8$ V for argon plasma.

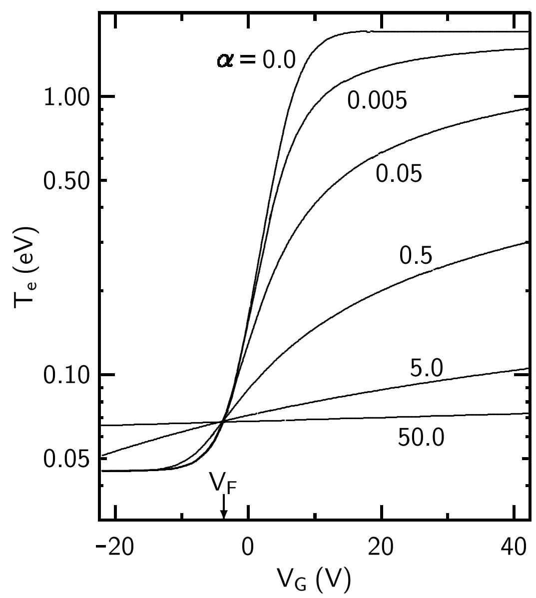

Fig. 6. Relation between T_e and V_G obtained from Eqs. (3), (6), and (7) with α as a parameter in the case of $eV_{s\mathrm{I}}/\kappa T_{e\mathrm{I}} = 3.6$ and $V_F = -3.8$ V for argon plasma.

In order to evaluate the effect of α on variations in T_e, we derive a function $T_e(V_G)$, which expresses the dependence of T_e on the grid potential V_G at $\alpha = 0$. From the experimental data using the bare metal grid shown in Fig. 2, we obtain

$$T_e(V_G) = \frac{1}{2}(T_{e,M} - T_{e,m}) \tanh\left(\frac{V_G - V_0}{\Delta}\right) + \frac{1}{2}(T_{e,M} + T_{e,m}) \quad (7)$$

where $T_{e,M} = 1.705$ eV and $T_{e,m} = 0.045$ eV are the maximum and minimum electron temperature, respectively. $V_0 = 6.0$ V is the grid potential at $T_e = (T_{e,M} + T_{e,m})/2 = 0.875$ eV. $\Delta = 4.560$ V is obtained by substituting $T_e = 0.068$ eV and $V_G = V_F = -3.8$ V, which are obtained from Fig. 3, into Eq. (7). By substituting the relation $V_{GS} = f(V_G)$ obtained from Eqs. (3) and (6) into V_G in Eq. (7), the electron temperature variation $T_e(V_G)$ for the grid covered with thin film with finite resistance is expressed as shown in Fig. 6. We note that by comparing Fig. 6 with Fig. 3, $\alpha = 0.5$ corresponds to $R = 10.0$ kΩ in this experiment. Since α is proportional to R, α =50, 5.0, 0.05, and 0.005 correspond to R =1.0 MΩ, 0.1 MΩ, 1.0 kΩ, and 0.1 kΩ, respectively. The experimental results of the dependence of T_e on the grid potential V_G with R as a parameter shown in Fig. 3 agree well with the theoretical evaluations shown in Fig. 6.

5. Conclusions

We have demonstrated the method for T_e control by varying the dc voltage applied to the mesh grid coated in a thin insulating film. With a decrease of V_G, T_e of argon dc discharge plasma is controlled over more than one order of magnitude at 20 mTorr. The resistance of the film obtained after more than 10 h of diamond deposition in CH_4/H_2 plasma is about 2 kΩ in our experiment. We have also confirmed that the experimental data obtained by changing the dc voltage to a mesh grid covered with a thin film agree with theoretical estimations using a simple model for variations of T_e. This technique of T_e control is available to reactive plasmas in which grids are often deposited by thin films made of diamond-like carbon and other materials.

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