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Electron-temperature control for plasmas passing through a negatively biased grid

Kohgi Kato, Satoru Iizuka, and Noriyoshi Sato
Department of Electronic Engineering, Tohoku University, Aoba-Ku, Sendai 980, Japan

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Electron-temperature control is performed on plasmas passing through a coarse mesh grid from a discharge region. By increasing a negative potential applied to the grid, the electron temperature is continuously decreased in a very wide range covering almost two orders of magnitude down to the value nearly equal to the background gas temperature in case of direct current argon or helium gas discharge. The temperature decrease is accompanied by an increase in the electron density. This method of electron-temperature control can also be applied to plasmas produced by radio-frequency and electron cyclotron resonance discharges.

In weakly ionized discharge plasmas, it is quite difficult to control electron temperature over a wide range. With an increase in the discharge power, the plasma density increases, but there occurs no practical change of the electron temperature. If a special method cannot be contrived for the electron-temperature control, it is almost impossible to measure dependencies of particle elementary processes and plasma collective phenomena on the electron temperature in such weakly ionized plasmas, although they are often very sensitive to the electron temperature. In reactive plasmas widely used for material processings, there should be strong effects of the electron temperature on products obtained from such processings. The electron-temperature control is essential to find out the best conditions in the next-stage fabrications of devices for ultra-large-scale integration (ULSI) and other material processings. Thus it is now of crucial importance to establish a simple method of electron-temperature control covering a wide range for weakly ionized plasmas.

There have been several experiments on electron-temperature control for weakly ionized plasmas. In the experiment of Alexeff and Jones,[1] the electron temperature was decreased by replacing high-energy electrons with cold electrons emitted thermionically from an auxiliary hot electrode. On the other hand, Mackenzie *et al.*[2] raised the electron temperature from 0.5 to 4.0 eV by applying a positive potential to an auxiliary cold electrode consisting of fine tungsten mesh, which was considered to absorb low-energy electrons. The method employed by Hershkowitz *et al.*[3] is mechanical. A grounded plate was moved in the region of surface multipole magnetic field. The electron temperature was observed to change by a percentage up to 30%, depending on the plate position which determines the plasma surface geometry. Sato *et al.*[4] also employed a mechanical method using pins installed in a large hollow cathode. The pin position was changed in the hollow cathode under a weak axial magnetic field. The electron temperature was found to decrease by an order of magnitude with an increase in the pin length. Here, we report a new simple method of the electron-temperature control for weakly ionized plasmas. The electron temperature is controlled by almost two orders of magnitude from a few eV to 0.035 eV in a plasma passing through a coarse grid biased negatively. Some preliminary results have already been reported in Ref. 5.

The experimental setup, which is shown in the Fig. 1, is situated in a stainless-steel vacuum vessel 26 cm in diameter and 220 cm long. The stainless-steel cylinder of the setup, 7 cm in diameter and 12 cm long, has an open end covered by a coarse mesh grid which is stretched across a circular, 4.2-cm-diam aluminum frame. The other end is closed. The grid separates the experimental region into regions I and II. Six different mesh sizes are employed in the measurements. For mesh sizes of 6.8, 5.1, 3.4, and 1.7 mm, the grids are made of 4.2-mm-diam stainless-steel wires. The grids with mesh sizes of 0.51 and 0.25 mm are made of 0.05-mm-diam stainless-steel and 0.02-mm-diam tungsten wires, respectively. An argon or helium plasma is generated by electron emission from three tungsten filaments biased negatively with respect to the cylinder (anode) in region I, which is electrically grounded together with the vacuum chamber. The grid is biased negatively at the potential V_G (<plasma potential in region I). The plasma parameters are measured by small movable Langmuir probes of 0.13 mm in diameter and 2 mm long. The electron densities, electron temperatures, and space potentials in regions I and II are distinguished by adding subscripts I and II to n_e, T_e, and V_s, respectively.

The plasma produced in region I passes through the grid into region II. Unless $V_G > V_{sI}$, the plasma parameters are almost independent of V_G in region I. In region II, however, they are very sensitive to V_G. In Fig. 2, dependencies of

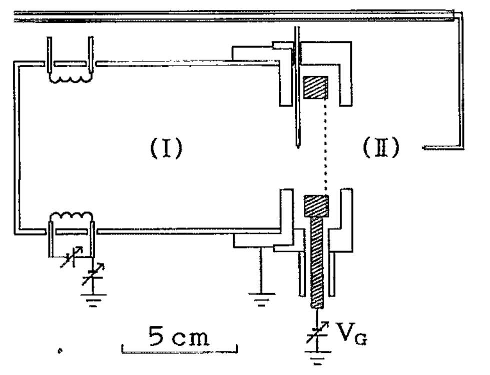

FIG. 1. Schematic of setup used for control of electron temperature.

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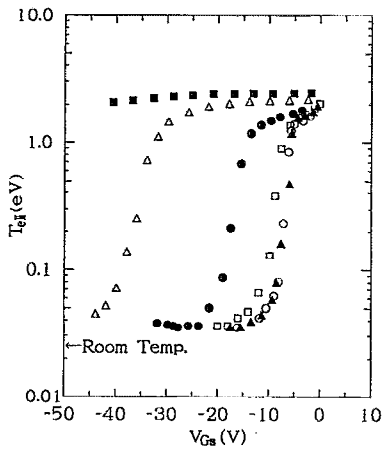

FIG. 2. Electron temperature T_e vs potential difference V_{Gs} between grid potential V_G and space potential V_{sI} at $z=7.0$ cm in region II for various grids with mesh sizes of 6.8 (■), 5.1 (△), 3.4 (●), 1.7 (□), 0.51 (▲), and 0.25 (○) mm. Argon gas pressure is 0.4 Pa.

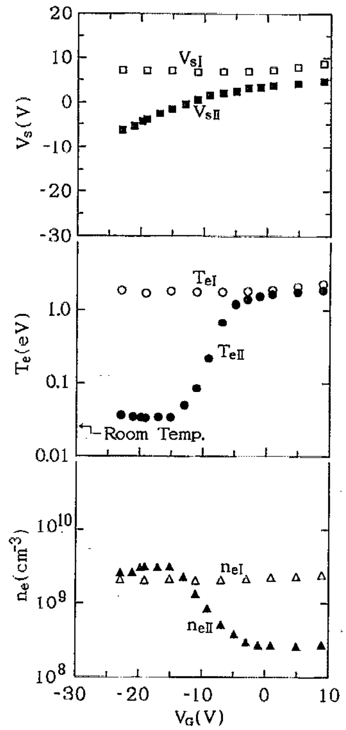

FIG. 3. Electron densities n_e, temperatures T_e, and space potentials V_s vs grid potential V_G at $z=1.0$ cm in region I and $z=7.0$ cm in region II. Grid mesh size is 3.4 mm. Argon gas pressure is 0.4 Pa.

the electron temperatures T_{eII} in region II on potential difference $V_{Gs}(=V_G-V_{sI})$ are presented for the six different grids mentioned above. Here, the argon pressure is 0.4 Pa and the Langmuir probe is located at $z=7.0$ cm from the grid position. It is found that the grid with a mesh size of 6.8 mm is too coarse for T_{eII} to depend strongly on V_{Gs}. For other mesh sizes, however, there appears a drastic decrease in T_{eII} with a decrease in V_{Gs}. The results are almost the same for mesh sizes of 0.51 and 0.25 mm. The lowest electron temperatures, 0.035 eV, are almost the same for mesh sizes of 3.4, 1.7, 0.51, and 0.25 mm. This value is smaller by almost two orders of magnitude than $T_{eII}(\simeq T_{eI})$ for $V_G \simeq V_{sI}$ and is supposed to be almost equal to the neutral gas temperature. Figure 3 shows typical plots of the electron densities, electron temperatures, and space potentials measured also at argon pressure 0.4 Pa at $z=-1.0$ cm in region I and at $z=7.0$ cm in region II as a function of the grid potential V_G. The grid mesh size is 3.4 mm. For $V_G \lesssim V_{sI}$, $n_{eI} \simeq 2.5\times10^9$ cm^{-3}, $T_{eI} \simeq 2.0$ eV, and $V_{sI} \simeq 7.0$ V are almost independent of V_G in region I. In region II, however, they depend on V_G. V_{sII} decreases gradually as V_G is decreased. With a decrease in V_G from -5 to -15 V, there appears a clear drop of T_{eII} from 1.3 to 0.035 eV, which is accompanied by an increase in n_{eII} from 2.5×10^8 cm^{-3} to 2.8×10^9 cm^{-3}. For $V_G<-15$ V, T_{eII} and n_{eII} are almost constant. It should be remarked that $T_{eII} \simeq 0.035$ eV with n_{eII} is higher than n_{eI} in this range of V_G.

In order to clarify the cooling mechanism of electrons in region II, we present an axial variation of Langmuir probe traces in Fig. 4. The probe is axially moved from the grid position in region II. It can be found that there are only high-energy electrons near the grid. At $z=0.2$ cm, their density is 1.2×10^8 cm^{-3}, which is about 5% of n_{eI}. These high-energy electrons corresponds to the high-energy tail electrons in region I, which can pass through the retarding potential difference provided by the grid biased negatively. With an increase in z, however, the high-energy electrons are found to decrease gradually, being accompanied by an increase in the low-energy electron density. At $z=2$ cm, there are no appreciable high-energy electrons and we obtain $n_{eII} \simeq 5.4\times10^9$ cm^{-3} and $T_{eII} \simeq 0.035$ eV. For $z>2.0$ cm, there are no remarkable changes of V_{sII}, n_{eII}, and T_{eII}, although V_{sII} and n_{eII} decrease gradually as z increases.

The density of the electrons passed through the retarding potential difference provided by the grid is theoretically estimated to be much smaller than n_{eII} observed in region II. In order to understand the density increase observed in region II, we have to take account of ionization due to these electrons. The electrons produced there are free from maintenance of the discharge which is sustained in region I. Thus they need not be accelerated, providing the low electron temperature in region II. In general, the plasma density is deter-

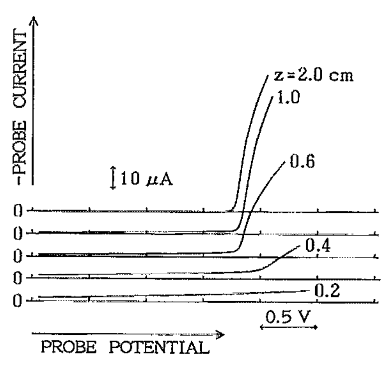

FIG. 4. Langmuir probe traces at different positions z in region II. Grid mesh size is 3.4 mm. Grid potential $V_G=-30$ V. Argon gas pressure is 0.8 Pa.

mined by a balance between plasma production and diffusion loss in such a low-density plasma as in our experiment. Since the diffusion coefficient decreases with electron temperature, the density increase is enhanced by the decrease in T_{eII} in region II. Being concerned with the ionization in region II, the cumulative ionization due to collisions between electrons and metastable atoms might not be neglected. The phenomena observed become drastic as V_G is decreased. This decrease in V_G reduces the flux and energy of the electrons supplied from region I. Even if the electron energy would decrease down to a value not sufficient for direct ionization of argon atoms, it could still be high enough for the cumulative ionization. In order to confirm this assumption, the same measurements have been made on a plasma produced by helium gas discharge. The direct ionization potential for helium atoms, 24.6 eV, is much higher than that for argon atoms, 15.8 eV. On the other hand, the cumulative ionization potentials are almost the same, i.e., 4.1 and 4.7 eV for metastable argon and helium atoms, respectively. Besides, the metastable helium atoms have a very long lifetime ($\gtrsim 6\times10^5$ s) compared with that of the metastable argon atoms ($\gtrsim 1.3$ s). It has been found in the measurements that a helium plasma with low electron temperature is produced in region II as in case of the argon discharge in spite of the higher direct ionization potential of the helium atoms. It is reasonable to consider that this is due to the long lifetime of the metastable helium atoms in addition to almost the same cumulative ionization potentials of the argon and helium metastable atoms.

We have also applied our method of electron-temperature control to large-diameter plasmas produced by magnetron-typed radio-frequency (rf) discharges and electron cyclotron resonance (ECR) discharges, which are uniform within a few percents of plasma density in diameter up to 20–40 cm. The grid with mesh size of 3.9 mm has been employed in the measurements. In the region separated by the grid from the discharge region, the electron temperature decreases down to the value $\lesssim 0.1$ eV with an increase in the negative potential applied to the grid.

In conclusion, we have established a new method of electron-temperature control for weakly ionized plasmas. The electron temperature is controlled in the region separated by the grid from the discharge region. By increasing a negative potential applied to the grid, the electron temperature is decreased by almost two orders of magnitude down to the value of 0.035 eV, which is supposed to be almost equal to the neutral gas temperature.

This decrease in the electron temperature is accompanied by an increase in the plasma density. We cannot neglect the cumulative ionization due to collisions between electrons and metastable atoms in a region separated from the discharge region. Our method would be useful for investigations on dependencies of particle elementary processes and plasma collective phenomena on electron temperature in weakly ionized plasmas. It could also be applied to processing plasmas to find out the best conditions in the material processings.

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