Electron-Temperature Control by Movable Pins Installed in a Hollow Cathode for Discharge Plasmas

著者	飯塚　哲
journal or publication title	Applied Physics Letters
volume	62
number	6
page range	567-569
year	1993
URL	http://hdl.handle.net/10097/35448

doi: 10.1063/1.108913

Electron-temperature control by movable pins installed in a hollow cathode for discharge plasmas

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(Received 12 June 1992; accepted for publication 7 December 1992)

In order to control electron energy distributions in discharge plasmas, we have developed a new hollow cathode with pins inside. With an increase in the pin length, the electron temperature is observed to decrease continuously by an order of magnitude, being accompanied by a change of local plasma structure, in weakly magnetized low-pressure Ar dc discharge plasmas.

Electron energy distributions are of crucial importance for various kinds of elementary processes and collective phenomena in plasmas. In weakly ionized reactive plasmas widely used for material processings, reactive processes occurred are sensitive to the electron energy. Thus, there should be strong effects of the electron temperature on results in the material processings. It is, however, almost impossible to change the electron temperature in weakly ionized discharge plasmas if the geometry and gas (including its pressure) used are fixed.[1] When the power for discharges is increased, the plasma density increases, but the electron temperature remains almost constant. Under the circumstances, it is difficult to know dependencies of the material processings on the electron temperature.

In the work of Alexeff and Jones,[2] an electron emitting electrode was immersed in hot cathode discharge plasmas in order to control the electron temperature. This electrode absorbs energetic electrons from the plasmas and replaces them with relatively cold electrons emitted thermionically, yielding a decrease in the electron temperature. They succeeded in decreasing the electron temperature by an order of magnitude by changing the electron emission from the electrode, but, it might come into question to apply this method to processing plasmas because the emitter material should evaporate, increasing impurities in the material processings. Recently, Hershkowitz *et al.*[3] employed a mechanical method for control of the electron temperature in rf discharge plasmas. A grounded metal plate was moved in the region of surface multipole magnetic field. The plate position determines the plasma surface geometry which has an influence on the plasma loss to the wall. According to their measurements, the electron temperature changes by a percentage up to some 30%, depending on the plate position.

In this letter, we report a new method to control the electron energy distribution. In our experiment, we use large hollow cathodes with pins inside (pin-hollow cathodes) for low pressure dc discharge plasmas under a weak axial magnetic field. The pin length is varied in the hollow cathode, resulting in a drastic change of the electron temperature, which is accompanied by a change of local plasma structure. For Ar discharges in the gas pressure range 5×10^{-4}–1×10^{-2} Torr the electron temperature is observed to decrease by an order of magnitude with an increase in the pin length. Some preliminary results of our work have been reported at the symposiums and the conference.[4]

A typical example of the pin-hollow cathodes proposed here is schematically shown in upper figures in Fig. 1. The cathode is much larger than the usual hollow cathode.[5] It consists of 100-mm-diam stainless steel cylinder with 70-mm-diam hole at the front edge and 2-mm-diam pointed stainless steel pins (needles) installed inside. The eighteen pins, which are electrically connected with the cylinder, are set axisymmetrically with a separation of about 10 mm on a circle of 60 mm in diameter. They are inserted from the back endplate into the cylinder. By moving the pin tips from the back to front edge of the cathode, the pin length δ is varied from 0 to 50 mm.

In low-pressure dc discharges, electrons are accelerated by a large potential gradient in the cathode fall formed in front of the cathodes. These primary electrons are responsible for maintaining the discharge. Equipotential lines in the cathode fall region inside the pin-hollow cathode are schematically described in lower figures in Fig. 1. It is important to know potential profiles in the pin-hollow cathode in order to understand a role of the pins. Even in the absence of the pins, the potential is axially hill shaped in the radially outer region terminated by the front and back edges, providing a hollow-cathode effect due to axial reflection of the primary electrons. Since a weak magnetic field (strong enough for electrons) is applied in the axial direction, the electrons accelerated radially inward drift azimuthally, staying longer time in the cathode fall region, just as in case of the PIG discharge.[6] Thus, the discharges can be maintained at quite low gas pressures. When the pins are inserted, the potential decreases at the pin positions, forming a periodic structure in the azimuthal direction. If the pin tips approach the front edge of the cathode, a radial potential profile becomes also hill shaped in the region between the cylinder and the circle connecting the pins. The primary electrons are well trapped in this potential hill in the axial and radial directions, being accompanied by azimuthal drifts under the axial magnetic field. The electrons stay much longer time than in the absence of the pins. Thus, the pins enhance the hollow-cathode effect, resulting in a further increase of discharge efficiency.

In our experiment, an Ar plasma is produced by low-pressure dc discharge with the pin-hollow cathode described above. The experimental setup is schematically shown in Fig. 2, where the axial magnetic field is 100–150

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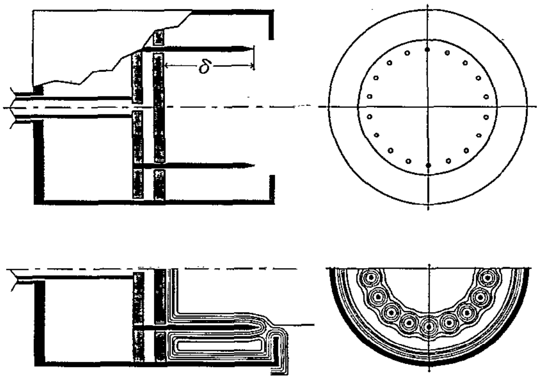

FIG. 1. Hollow cathode with pins inside (pin-hollow cathode): structure (upper figures) and equipotential lines in the cathode fall region (lower figures). The equipotential lines are schematically described by assuming the Child–Langmuir law for the potential variation in the cathode fall region.

G. The Ar gas is fed directly into the cathode. A 150-mm-diam anode with a hole of 30 mm in diameter is placed at an axial distance of 200 mm from the cathode front. We also have an axially movable 100-mm-diam target behind the anode with a separation of 100–500 mm. The anode is always grounded electrically, together with the vacuum chamber of 350 mm in diameter and of 1500 mm in length. The target is grounded or floated. The discharge is triggered by applying a negative potential (300–400 V) to the cathode with respect to the anode. Under our situation, the discharge is maintained even at a low gas pressure of 5×10^{-4} Torr. Movable Langmuir probes are used in the measurements of plasma density and electron temperature. Electron energy distributions are obtained from the derivatives of the probe characteristics because electrons are strongly magnetized.

When there is no pin inside the cathode ($\delta=0$), there appears a glowing plasma column in the axial direction, the diameter of which is approximately equal to the hole diameter of the cathode front in the region up to the anode. The plasma passes through the anode hole and is terminated by the target. The anode hole is small enough to cut the outer part of the plasma between the cathode and the anode. As δ is increased, the radial glow structure is observed to change. Between the cathode and the anode, with an increase in δ, the glow becomes weak gradually in the radially inner part of the plasma. For $\delta=50$ mm, the inner core part is completely dark and the glow is observed to be limited only in the radial region outside the circle on which the pins are located, as shown in Fig. 2. Between the anode and the target, we have this core part of the plasma, which passes through the anode hole. The outer glowing part is terminated by the anode.

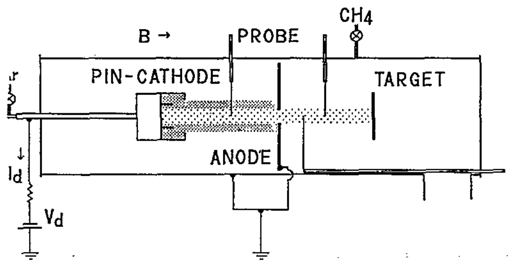

FIG. 2. Experimental setup using pin-hollow cathode.

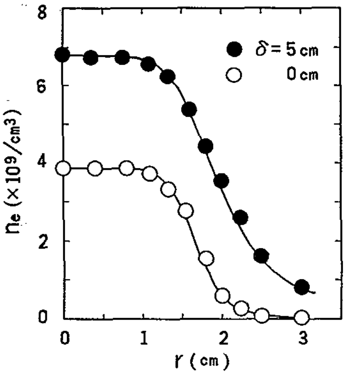

FIG. 3. Profiles of electron density n_e in the radial direction r for $\delta=0$ and 50 mm at a distance of 100 mm from the anode toward the target. Discharge current is 100 mA and gas pressure is 8×10^{-3} Torr.

According to the probe measurements, the plasma density increases in the core region even when the glow becomes weak with an increase in δ. The radial density profiles for $\delta=0$ and 50 mm in the region between the anode and the target are presented in Fig. 3, where the discharge current is 100 mA and the gas pressure is 8×10^{-3} Torr. It can be found that the density is higher for $\delta=50$ mm than for $\delta=0$ mm although there is no glow at all for $\delta=50$ mm. The profiles are fairly flat except the radial edge region. The electron energy distributions measured are demonstrated with δ as a parameter in Fig. 4. As δ is increased, the energy spread is found to decrease gradually. For $\delta=0$ mm, the electron temperature T_e is 4.0 eV.

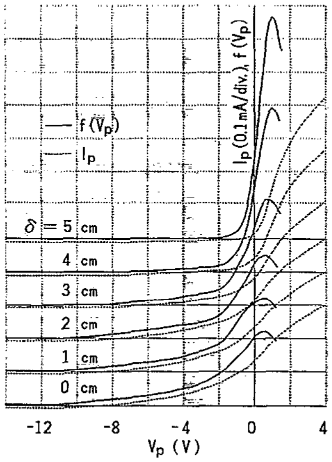

FIG. 4. Electron energy distribution $f(V_p)$ and probe current I_p of the core plasma as a function of probe voltage V_p with pin length δ as a parameter at discharge current of 100 mA and gas pressure of 8×10^{-3} Torr. $f(V_p)$ is proportional to a derivative of I_p with respect to V_p because electrons are strongly magnetized. By assuming the Maxwellian energy distribution, T_e is obtained from the relation $f(V_p)=n_e(m_e/2\pi T_e)^{1/2}\exp(eV_p/T_e)$ where m_e is the electron mass.

For $\delta = 50$ mm, however, T_e is found to be 0.3 eV, smaller by an order of magnitude than T_e for $\delta = 0$ mm. As mentioned before, by increasing the pin length, the primary electrons are well trapped in the region between the inner cathode side wall and the circle connecting the pins. This is the reason why the glow is gradually limited in the radially outer region with an increase in δ. Low energy electrons produced there occupy the inner region of the plasma between the cathode and the anode and the all plasma region between the anode and the target.

In order to produce a larger plasma, a pin-hollow cathode of 200 mm in diameter has also been used. In this case, the hole diameter of the cathode front is 170 mm. The pin number is 48 and $\delta = 0$–70 mm. They are located on a circle of 160 mm in diameter. The differences among the diameters of this circle, the cathode front hole, and the cathode cylinder and also the pin separation ($\simeq$ 10 mm) are kept to be the same as in case of the previous cathode in order to provide the same potential configuration around the pins. These distances are determined by taking account of the measured width ($\simeq$5–10 mm) of our cathode fall across the magnetic field. A 300-mm-diam anode with hole diameter of 100 mm is situated with a separation of 200 mm from the cathode front. The anode-target separation is 100–500 mm. The results obtained are almost the same as in the previous case. The plasma diameter is now about 100 mm between the anode and the target, suggesting a possibility for production of much larger plasmas. Under our conditions, the results have been confirmed to be almost independent of the pin number if the pin separation is less than ~20 mm.

Preliminary measurements have also been performed on an influence of the electron temperature on reactive plasmas by introducing a small amount of CH_4 gas into the Ar plasma. A drastic change on ion species, including a production of a lot of negative hydrogen ions, is recognized when the electron temperature is decreased by increasing δ. Thus, there is a remarkable effect of the electron temperature on the reactive processes in the plasma. Details of the result will be published elsewhere.

In conclusion, the pin-hollow cathodes are quite useful for a continuous control of electron temperature in low-pressure discharge plasmas. Our experimental arrangement, one of examples using the pin-hollow cathodes, would be appropriate for basic plasma experiments and for some kinds of material processings.

Finally, we are grateful to Professor R. Itatani for his continuous encouragements. We also thank H. Ishida for his technical assistance. This work is supported by Grant-in-Aid for Scientific Research from the Ministry of Education, Science, and Culture of Japan.

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