AIP Applied Physics Letters

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Citation: Appl. Phys. Lett. **85**, 4872 (2004); doi: 10.1063/1.1805704
View online: http://dx.doi.org/10.1063/1.1805704
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v85/i21
Published by the American Institute of Physics.

APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 21 22 NOVEMBER 2004

Low energy electron cooling induced by a magnetic field in high pressure capacitive radio frequency discharges

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(Received 14 June 2004; accepted 18 August 2004)

A study is conducted on a magnetic field effect on electron heating in capacitive rf discharges under a collisional regime, where the electron mean collision frequency is much higher than the rf frequency. The evolution of an electron energy distribution function (EEDF) over a magnetic field range of 0–30 G in 300 mTorr Ar discharges is measured and calculated for the investigation. A significant change in the low-energy range of the EEDF is found during the evolution. The observed result reveals the application of the magnetic field to the high-pressure capacitive plasma gives rise to a cooling effect on the low-energy electrons. This is in contrast to the low-pressure case where the magnetic field enhances the low-energy electron heating. The calculated result of the EEDF is in good agreement with the experiment. © *2004 American Institute of Physics*.
[DOI: 10.1063/1.1805704]

Capacitive rf discharge is the most simple and commonly used plasma source in semiconductor processing. It is a promising source especially for dielectric etching, owing to better uniformity and selectivity and higher energy ions compared to other rf discharge sources. Its advantages for semiconductor processing have attracted many researchers, and numerous studies have been conducted to understand the physics involved.[1,2] In particular, the electron heating has been of major concern and actively under investigation.[3–6]

Research on electron heating in capacitive rf discharges has mainly focused on low pressure discharges including both unmagnetized and magnetized cases. When an external magnetic field is absent, the low pressure capacitive discharges are known to be maintained by collisionless electron heating occurring in the sheath region through stochastic electron–sheath interactions and the compression and rarefaction of electrons. In this case, the electron energy distribution function (EEDF) exhibits a bi-Maxwellian form with two distinct low and high energy groups: a low-temperature low energy group and a high-temperature high energy group.[4] A simple interpretation of this grouping is possible. The high energy electrons, which are able to overcome the dc ambipolar potential barrier, can penetrate into the sheath region where the collisionless electron heating takes place strongly and thereby be effectively heated. On the contrary, the low energy electrons remaining in the bulk gain energy just through collisional heating process that is usually weak because of a low collision frequency at low pressure and a small electric field in the bulk. This low temperature characteristic in the low-energy range is intensified in the Ramsauer gas discharges such as Ar discharges.[4] When a magnetic field is applied transverse to the electric field, the nonlocal electron motions causing the grouping in the EEDF are suppressed and collisional bulk heating becomes dominant. It has been reported that a small magnetic field of 10 G can change the EEDF shape from the bi-Maxwellian to Maxwellian[5] and induce a heating mode transition from collisionless to collisional heating dominated state.[6]

In a high-pressure regime where collisional heating is dominant, the electron heating characteristics are quite different from those of low-pressure cases previously described. For an unmagnetized case, the electron sees the electric fields as dc fields rather than oscillating fields during its free flight without collision if the collision time is much shorter than the rf period. In this condition, electron energy gain from the field is proportional to the electron mean free path ($\Delta\epsilon = eE\lambda_{en}$). The mean free path of low energy electrons is longer than that of high energy electrons because of the Ramsauer minimum of collision cross section near 0.2 eV in the Ar discharge. Therefore, compared with the high energy electrons, the low energy electrons are effectively heated. As a result, the EEDF exhibits Druyvesteyn-type form.[4] For a magnetized case, there has not been any study on the electron heating in the high-pressure discharges as opposed to the low pressure case in spite of the long history and wide applications of the capacitive plasma.

In this letter, we investigate the magnetic field effect on the electron heating in high-pressure capacitive rf discharges. We will show both experimentally and theoretically that the EEDF in 300 mTorr Ar discharges evolve from Druyvesteyn-type to Maxwellian-type distribution as the magnetic field increases from 0 to 30 G. It reflects the low-energy electrons are effectively cooled down by the magnetic field. This result is opposite to the low pressure case where the magnetic field enhances the collisional bulk electron heating and thus the low-energy electron heating.[5,6] The experiment was performed in a transversely magnetized capacitive discharge as shown in Fig. 1. The reactor is similar to that in Ref. 16 except for gap length 25 mm. The experiments were performed at 300 mTorr where the mean value of the electron–neutral collision frequency $\overline{\nu}_{en}$ is much higher than the rf angular frequency $\omega(\overline{\nu}_{en} \approx 17\omega)$, and so collisional heating is dominant.

To acquire the EEDFs, the ac signal superposition method was used.[7] The probe sweep is done at 2 Hz and the superposed signal frequency is 40 kHz with amplitude less than 0.3 V. Measurement data were averaged in a digital oscilloscope and transferred to a PC through a general purpose interface bus (GPIB) interface. The measured I_e'' is pro-

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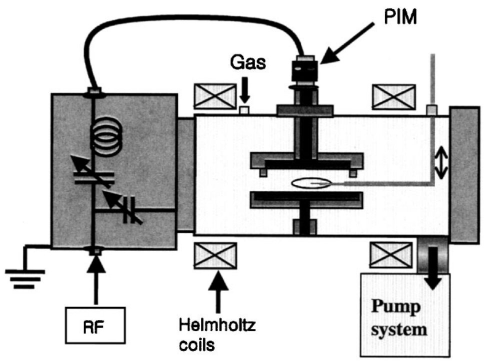

FIG. 1. Schematic diagram of a transversely magnetized capacitively coupled plasma (CCP).

portional to the electron energy probability function (EEPF) $f_e(\epsilon)$ and related to the EEDF $g_e(\epsilon)=\epsilon^{1/2}f_e(\epsilon)$ as follows:[8]

$$g_e(\epsilon)=\frac{2m}{e^2A}\left(\frac{2\epsilon}{m}\right)^{1/2}I_e''(\epsilon),\quad \epsilon=-eV_b, \tag{1}$$

where e, m, A, I_e, and V_b are electron charge, electron mass, probe area, electron current, and probe voltage referenced to the plasma potential. Electron density n_e and effective electron temperature T_{eff} can be calculated from the EEPF $f_e(\epsilon)$.[8]

The EEDF measurements were performed using the rf compensated Langmuir probe.[7] A Langmuir Probe made of tungsten wire 4 mm long and 0.15 mm in diameter was placed at the center of the two discharge electrodes. Figure 2 shows a homemade rf compensated Langmuir probe system. The probe system is composed of a small probe tip and a floating-loop reference probe with choke coils that reduces rf distortion of the probe characteristics. The influence of the weak magnetic fields on the Langmuir probe is negligible because the probe radius is much smaller than the electron gyro radius.[9] Since there are many high-order harmonics in asymmetrically driven capacitive discharge,[10] the rf compensations for high order harmonics are essential for proper measurements of EEDF.[11] In this experiment, we used series-connected choke coils near the probe tip to reduce the higher harmonic distortions (first, second, and third) as shown in Fig. 2.

Increasing the transverse magnetic field, we measured the EEPFs under a discharge condition of 0.3 A rf current and presented the results in Fig. 3. The EEPF at $B=0$ G shows a Druyvesteyn-type distribution with $\partial f_e/\partial\epsilon\to 0$ as $\epsilon\to 0$. As we mentioned before, these are typical for a high pressure capacitive discharge or a dc Ar discharge.[4,12,13] The

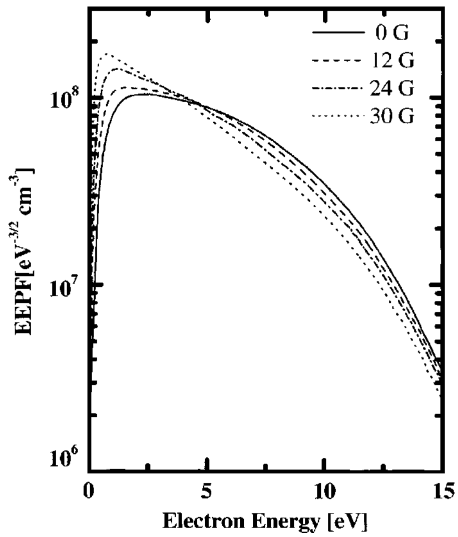

FIG. 3. Measured EEPFs for various magnetic fields at 300 mTorr, 0.3 A.

distribution is characterized by the high-temperature low-energy electron group and the low-temperature high-energy electron group. In this case, the electron energy gain from the rf field is proportional to the electron mean free path and thus inversely proportional to the electron–neutral collision frequency υ_{en} as a dc plasma, i.e., $\Delta\epsilon\propto\lambda_{\mathrm{en}}\propto 1/\upsilon_{\mathrm{en}}$.[4] Therefore, we can deduce $\Delta\epsilon^l>\Delta\epsilon^h$ since $\upsilon_{\mathrm{en}}^l<\upsilon_{\mathrm{en}}^h$, where the superscripts l and h represent low and high energy group, respectively. As the magnetic field increases, the high-temperature low-energy electron group disappears. It reflects that the magnetic field effectively cools down the low-energy electrons by preventing electron heating from the rf field.

The cooling of the low-energy electrons induced by the magnetic field can be understood as follows. While increasing the magnetic field, υ_{en}^l can become lower than the electron cyclotron frequency ω_{ce}, while υ_{en}^h is still higher than ω_{ce}. If this condition is satisfied, the low-energy electrons complete more than at least one gyro-motion before the collision and cannot see the electric field as a dc field anymore. Then, their energy gain from the electric field can be significantly diminished by gyro-period averaging. The energy gain for magnetized plasma can be expressed as $\Delta\epsilon\propto\upsilon_{\mathrm{en}}/[(\omega\pm\omega_{\mathrm{ce}})^2+\upsilon_{\mathrm{en}}^2]$, where the signs "+" and "−" in the denominator correspond to the left-handed and right-handed components of electric fields, respectively.[14] This relation can be approximated as $\Delta\epsilon^l\propto\upsilon_{\mathrm{en}}^l/(\omega\pm\omega_{\mathrm{ce}})^2\ll 1/\upsilon_{\mathrm{en}}^l$ and $\Delta\epsilon^h\propto 1/\upsilon_{\mathrm{en}}^h$ in the two limiting cases, $\upsilon_{\mathrm{en}}^l\ll\omega_{\mathrm{ce}}$ and υ_{en}^h

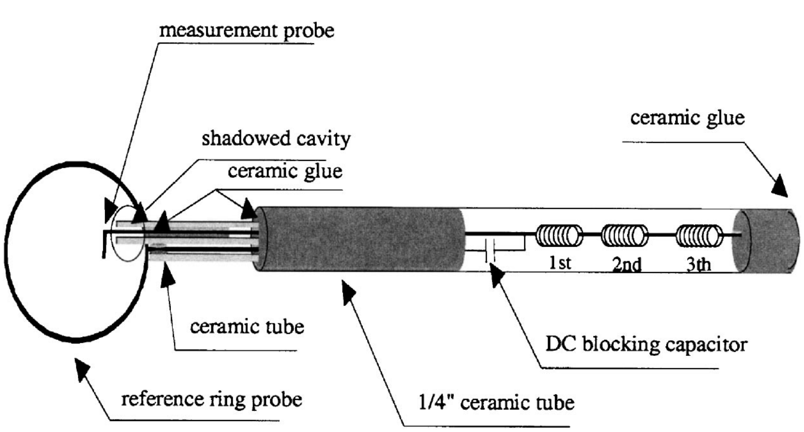

FIG. 2. rf-compensated Langmuir probe with series-connected choke coils.

$\gg \omega_{ce}$, respectively. Therefore, the energy gain can be very small compared to the unmagnetized case as the electron energy goes to 0.2 eV where the Ramsauer minimum appears. It is expected that the cooling effect is prominent in the energy range where the collision frequency is comparable to or less than the cyclotron frequency. In our experimental conditions, the energies where $\upsilon_{en}=\omega_{ce}$ is satisfied are given by 1.7, 2.5, and 2.9 eV for 12, 24, and 30 G, respectively. Below these energies, the population of electrons increases drastically as shown in Fig. 3.

In order to confirm these arguments on the experiments, we theoretically investigated the EEPF evolution using a Fokker–Planck code.[15] We obtained the EEPF by solving the following Fokker–Planck equations:

$$\frac{1}{\upsilon}\frac{d}{d\epsilon}\upsilon\left[(D_\epsilon + D_{ee} + D_{en})\frac{df_e}{d\epsilon} + (V_{ee} + V_{en})f_e\right] = I, \qquad (2)$$

where D_ϵ is the energy diffusion coefficient describing the electron heating by the electric field, $D_{ee(n)}$ and $V_{ee(n)}$ are the coefficients of diffusion and dynamical friction caused by electron–electron (neutral) collisions, and I represents inelastic collisions including ionization and excitation. The energy diffusion coefficient can be calculated from the quasilinear term in the Boltzmann equation using a similar approach as in Ref. 15. The result is given as

$$D_e = \tfrac{1}{2}(D_e^+ + D_e^-)$$

with

$$D_e^\pm = \frac{e^2\upsilon^2\upsilon_{en}|E^\pm|^2}{3[(\omega \pm \omega_{ce})^2 + \upsilon_{en}^2]}, \qquad (3)$$

where $|E^\pm|$ are the magnitude of the left-handed (+) and right-handed (−) components of electric fields, respectively. The diffusion coefficient in Eq. (3) becomes identical with that in the unmagnetized case as the magnetic field goes to zero.[3] Under the assumption of $E \approx E\hat{x}$, the electric field can be estimated using

$$J = -\frac{ie^2E}{3m_e}\int\left(\frac{1}{\omega + \omega_{ce} + i\upsilon_{en}} + \frac{1}{\omega - \omega_{ce} + i\upsilon_{en}}\right)\epsilon^{3/2}\frac{\partial f_e}{\partial \epsilon}d\epsilon, \qquad (4)$$

where J is the current density and $\hat{x}$ is the unit vector in axial direction. In our experiments, the magnitude of J is fixed as $|J|=2.76$ mA/cm^2. The estimated electric fields from Eq. (4) using the measured f_e and $|J|$ are $|E|=23.5$, 23.2, 20.9, and 21.2 V/cm at $B=0$, 12, 24, and 30 G, respectively. The calculated EEPFs using these values of the electric field under the same condition as the experiment are presented in Fig. 4 They are qualitatively well consistent with the experimental results in Fig. 3. As the magnetic field increases, the EEDF changes Druyvesteyn-type to a Maxwellian-type one and the low-energy electron temperature strongly decreases. Coincidentally with the experiments, the cooling effect occurs effectively in the energy where $\upsilon_{en} \lesssim \omega_{ce}$ is fulfilled.

In conclusion, through the EEDF measurement of a magnetized high-pressure capacitive Ar discharge, we observed the efficient cooling for low-energy electrons induced by a magnetic field. Unlike the previously reported results for low-pressure discharge[5,6] where the magnetic field enhances the low-energy electron heating, the magnetic field reduces the heating for the low-energy electrons at high pressure. This is because the low-energy electrons with low collision frequencies of $\upsilon_{en} \lesssim \omega_{ce}$ see oscillating fields instead of dc-like fields during their gyro-excursions in the magnetic field. So, in the low-energy range, the heating characteristic becomes analogous to that of high-frequency discharges where the heating efficiency is proportional to the collision frequency. The calculated result based on the kinetic theory is in good agreement with the experiment.

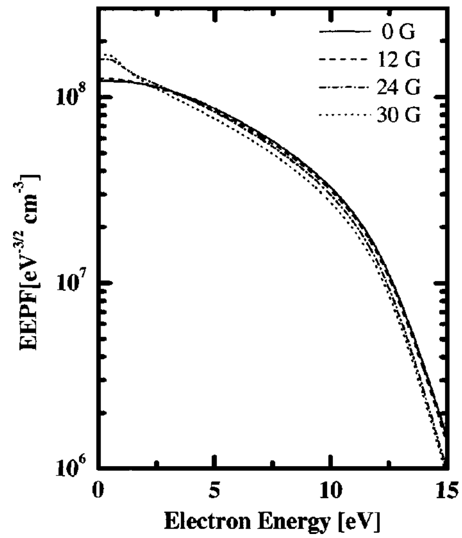

FIG. 4. Calculated EEPFs for various magnetic field at 300 mTorr, 0.3 A.

The authors are grateful to Dr. I. G. Kaganovich for his helpful comments on this work. This work was sponsored in part by the SYSTEM I.C. 2010 of the Ministry of Science and Technology (MOST) and the Ministry of Commerce, Industry and Energy (MOCIE) and by a grant from the Interdisciplinary Research Program of KOSEF. This work was also supported in part by the National Research Laboratory Project of Korea (M1-0104-00-0071). One of the authors would like to thank PLASMART. Inc for its technical and financial support for this work. The work of S.S.K. was supported by the Korea Ministry of Science and Technology under the HANBIT project contract.

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