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The bounce resonance heating of low-energy electrons in capacitively coupled discharges

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Abstract
Low-energy electrons are confined in the bulk plasma by the ambipolar potential and are typically heated inefficiently due to their low collisionality and the weak rf electric field present in the bulk when their mean-free path is much larger than the system length in capacitively coupled discharges. It is shown in this study, however, that electrons in the bulk that bounce inside the electrostatic potential well with a frequency equal to the rf excitation frequency are efficiently heated by coherent interaction with the rf field. This resonant heating manifests itself as a plateau in the electron energy probability function and is observed in a wide range of pressures from 25 mTorr to 1 Torr while decreasing the gap distance. The weak transverse magnetic field significantly influences the bounce frequency of the low-energy electrons. As a result, the electrons not in the resonant condition in the absence of a magnetic field can be led to satisfy the resonant condition, becoming effectively heated in the presence of a weak transverse magnetic field.

1. Introduction

Capacitively coupled discharges have been extensively used over the past few decades as a key source in semiconductor manufacturing. They have attracted much attention in an effort to understand their interesting physics in wide operation regimes ranging from milliTorrs to the atmospheric pressure range [1, 2]. Numerous studies to investigate their electron heating mechanism and the related kinetics have been actively investigated. Collisional (Ohmic) heating caused by the collisions of electrons with atoms or molecules in a neutral background is the dominant mechanism to sustain the discharges. In a regime in which the electron mean-free path is comparable to the system length, however, capacitively coupled discharges are maintained by collisionless heating [3, 4]. High-energy electrons capable of interacting with high electric fields in the sheaths gain energy collisionlessly while low-energy electrons are confined in the bulk plasma by the electrostatic potential. These low-energy electrons are weakly heated because the rf electric fields in the bulk and the electron collision frequency are low. As a result, strong non-Maxwellian electron energy probability functions (EEPFs) in low-pressure argon discharges have been examined [3].

An interesting effect that can lead to enhanced heating for bounded low-pressure discharges is the bounce resonance when the bounce frequency Ω_b of electrons in the electrostatic potential well is equal to the frequency ω of the driving rf field [5–12]. Aliev *et al* [5] calculated the electron energy diffusion coefficient in bounded low-pressure capacitively coupled discharges while accounting for the interaction between the electron bouncing motion and the oscillating sheath. The electron energy distribution with a plateau in the low-energy electron range, indicating strong electron heating in the energy range due to the bounce resonance, was measured experimentally in capacitively coupled discharges under a pressure that decreased to 10 mTorr [9]. Park *et al* [12]

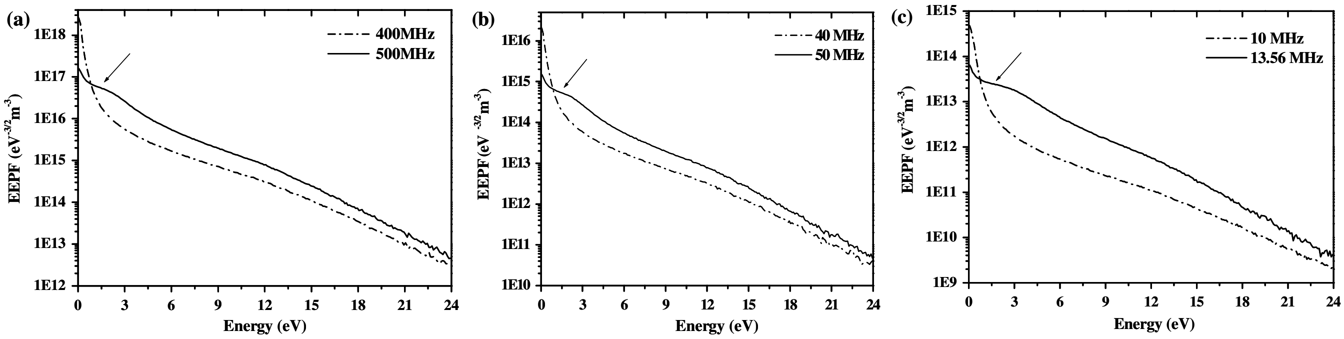

Figure 1. EEPFs at the centre of the discharge for capacitively coupled discharges driven by a 40 V voltage source in three regimes: (*a*) 1 mm (1 Torr), (*b*) 1 cm (100 mTorr) and (*c*) 4 cm (25 mTorr).

showed that as a result of non-linear interaction between the electron motion and the weak rf field present in the bulk, low-energy electrons can be heated efficiently even if they do not interact with the large electric field in the sheath regions when they satisfy the bounce resonance condition ($2\pi\Omega_b \approx \omega$). However, most of the bounce resonance phenomena were observed at a low pressure ($\leqslant$25 mTorr) in the non-magnetized discharges.

In this paper, the heating mechanism of low-energy electrons in capacitively coupled discharges for a wide range of regimes (25 mTorr, 100 mTorr and 1 Torr) is reported. It is shown that low-energy electrons satisfying a bounce resonance condition can be effectively heated collisionlessly in cases with and without a weak transverse magnetic field.

2. Particle-in-cell/Monte Carlo collision simulations

For this study, an electrostatic particle-in-cell (PIC) simulation method coupled with a Monte Carlo collision (MCC) model validated for wide plasma applications was utilized [12–15]. The simulations are one-dimensional in space and three-dimensional in velocity. Argon discharges were sustained between two parallel-plate electrodes separated by a gap distance of d. The discharges were driven by an rf voltage source applied to an electrode positioned at $x = 0$ while the electrode at $x = d$ was grounded. In the first experiment, the amplitude of the voltage source was fixed at 40 V while the pressures for three gap distances (1 mm, 1 cm and 4 cm) were varied maintaining the same value of pd, where p is the pressure in Torr. In this experiment, the value of pd was 0.1 cmTorr to ensure that the mean-free path of low-energy electrons ($\varepsilon < 2$ eV) was much larger than the system length d. In the second experiment, the frequency, pressure and amplitude of the voltage source were fixed at 13.56 MHz, 25 mTorr, and 40 V, respectively, and the gap distance was varied from 3.5 to 5.5 cm. In the third experiment, discharges driven by a frequency of 35 MHz with the amplitude of the voltage source set to 40 V were sustained between electrodes with a gap distance of 2 cm at a pressure of 50 mTorr while varying the transverse magnetic field from 0 to 10 G. In order to obtain meaningful results in the steady state, several thousand rf cycles were simulated for each run. For simplicity, secondary electron emissions were not included in the simulation, and coulomb collisions were neglected: for the discharge conditions reported in this paper, the electron–electron collision frequency for low-energy electrons is much lower than the electron–neutral collision frequency.

3. Results and discussion

The EEPFs measured at the discharge centre for two frequencies are compared for each regime in figure 1. For three gap distances (1 mm, 1 cm and 4 cm), the pressure for each distance is determined by maintaining a constant value of $pd = 0.1$ cmTorr in these cases (1 Torr for 1 mm, 100 mTorr for 1 cm and 25 mTorr for 4 cm). At these regimes, the mean-free path of low-energy electrons ($\varepsilon < 2$ eV) is much larger than the system length d. At 1 mm (1 Torr), the EEPFs at 400 and 500 MHz were compared. The driving frequencies for other regimes were scaled down with the same ratio to increase the gap distance (40 and 50 MHz for 1 cm and 10 and 13.56 MHz for 4 cm). The EEPFs at lower frequencies (400, 40 and 10 MHz) for three regimes are bi-Maxwellian with the large low-energy electron population caused by nonlocal electron kinetics. According to nonlocal electron kinetics, high-energy electrons can overcome the electrostatic potential well and interact with the oscillating sheaths, enabling these electrons to be strongly heated. On the other hand, low-energy electrons become trapped inside the electrostatic potential well and gain energy mainly through collisional heating. The collisional heating, however, is usually weak due to the low collisionality of low-energy electrons and the weak electric fields present in the bulk. As a result, the electron energy distribution at a low pressure is typically bi-Maxwellian, as shown for the lower frequency cases in figure 1. For the higher frequency cases (500, 50 and 13.56 MHz), however, a plateau in the low-energy region (1–3 eV) of the EEPF can be observed (see figure 1). A similar structure was measured in a capacitively coupled discharge with a gap distance of 35 mm gap when the operating pressure was decreased to 10 mTorr [9].

The formation of a plateau in the EEPF reflects the presence of a strong heating mechanism for electrons in the energy range where the plateau appears. For higher frequency cases, the mechanism causing the plateau in the EEPF is the resonant (collisionless) heating of some low-energy electrons as they bounce in the electrostatic potential field with the same frequency as the excitation rf frequency, i.e. electron bounce resonance [12]. The electron bounce frequencies in

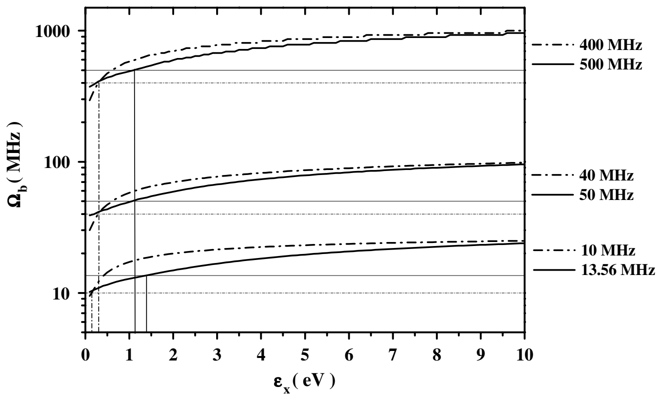

Figure 2. Electron bounce frequency as a function of the x-directional energy for capacitively coupled discharges driven by a 40 V voltage source in three regimes (1 mm, 1 cm and 4 cm). The horizontal straight lines indicate the driving frequencies.

self-consistent time-averaged electrostatic potential wells are shown in figure 2 as a function of the electron energy ε_x. The energy of the electrons for which the bounce frequency is equal to the driving frequency for each regime (500 MHz for 1 mm, 50 MHz for 1 cm and 13.56 MHz for 4 cm) coincides with the energy at which the plateau forms in the EEPF (figure 1). The low-energy electrons are trapped inside the electrostatic potential well and cannot reach the peripheral regions where the rf field is large. Therefore, low-energy electrons can interact only with the small rf electric field that penetrates into the bulk [16] and are typically weakly heated. Low-energy electrons satisfying the bounce resonance condition, however, can be heated effectively by this small rf field [12].

For lower frequency cases, the resonant energy is close to zero and the slope of the bounce frequency with respect to the electron energy near the resonant condition is much steeper compared with the higher frequency cases (figure 2). A large slope implies that resonant electrons are easily driven out of resonance even with small changes in energy. Therefore, it is not possible to have multiple coherent bounces. For this reason, no plateau was observed in the EEPF for the lower frequency cases.

The EEPFs measured at the discharge centre for discharges driven by 13.56 MHz with rf voltage of 40 V at 25 mTorr and gap distances of 3.5, 4 and 5.5 cm are shown in figure 3(*a*). As the gap distance decreases or increases, the plateau shown in the EEPF at 4 cm disappears. The bounce frequency as a function of the electron energy ε_x is shown in figure 3(*b*) for the three discharges (3.5, 4 and 5.5 cm). As expected, the bounce frequency of the electrons increases as the gap distance decreases and decreases as this distance increases. For 3.5 cm, the resonant energy (~0.6 eV) is close to zero and the slope of the bounce frequency with respect to the electron energy near the resonant condition is much steeper than at 4 cm. Moreover, the rf electric field in the bulk plasma is much smaller than at 4 cm, as shown in figure 3(*c*). Therefore, the kinetic energy gained by resonant electrons is relatively small ($\Delta\varepsilon \propto E_o^2$, where E_o is the amplitude of the rf electric field in the bulk). As a result, a plateau was not observed at 3.5 cm (figure 3(*a*)). However, when the driving frequency

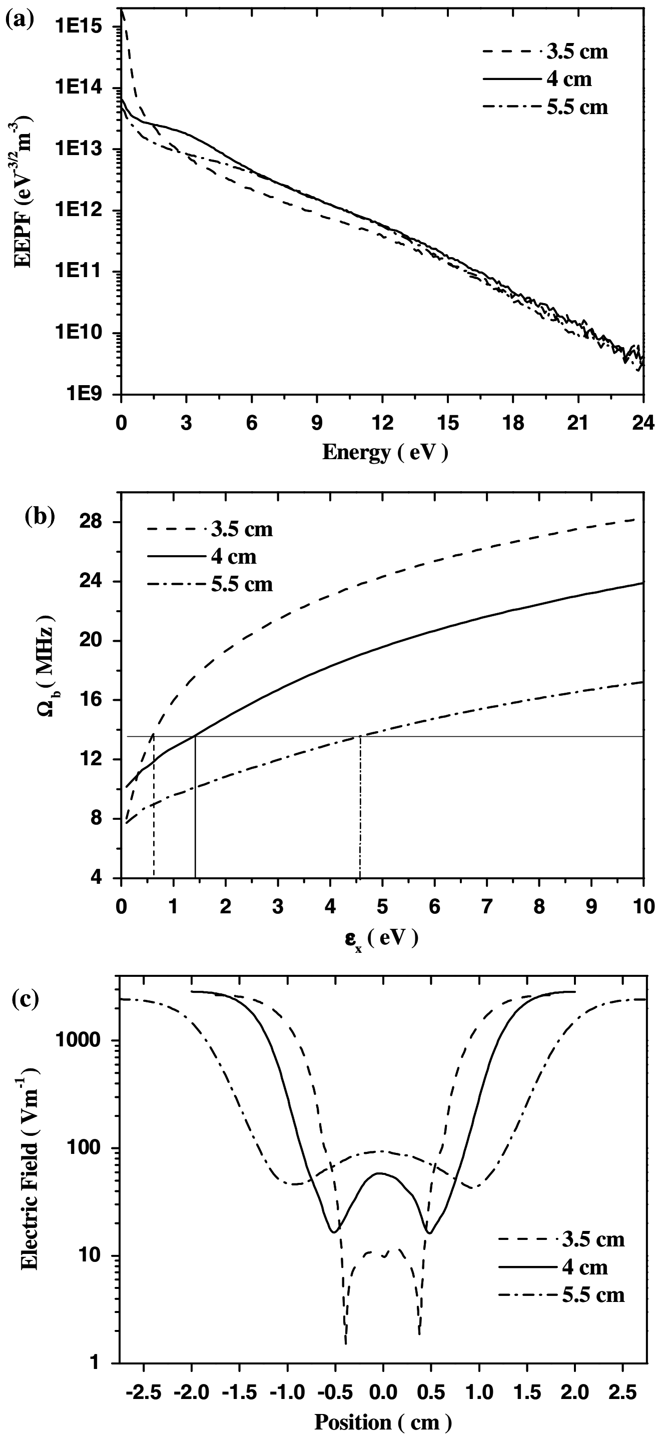

Figure 3. Simulation results for three capacitively coupled discharges driven at 13.56 MHz: (*a*) EEPFs at the centre of the discharge, (*b*) electron bounce frequency as a function of the x-directional energy and (*c*) the spatial profiles of the rf electric field (the centre of the discharge is set to zero for a comparison of the profiles for different gap distances).

increases from 13.56 to 17 MHz at 3.5 cm, a plateau in the low-energy portion of the EEPF appears, as shown in figure 4, as the resonant energy increases to a higher energy and the slope of the bounce frequency becomes moderate at that energy level while the driving frequency increases. At 5.5 cm, the driving frequency equals the bounce frequency for electrons with an

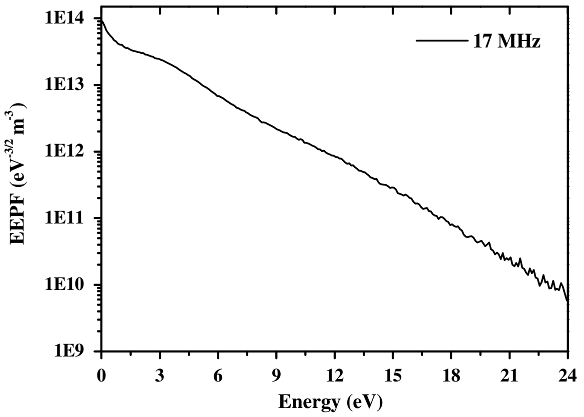

Figure 4. EEPF at the centre of the discharge for a capacitively coupled discharge driven by 17 MHz with a 40 V voltage source at 25 mTorr.

energy ε_x of ∼4.5 eV (figure 3(*b*)). As the collision frequency ν of an electron in that energy range is larger than the driving frequency ($\nu_{4.5\,\mathrm{eV}} \sim 80$ MHz $\gg 20$ MHz), collisions prevent the otherwise resonant electron from experiencing subsequent coherent energy kicks. Therefore, bounce resonance heating has no significant effect on the resulting EEPF at a distance of 5.5 cm, as shown in figure 3(*a*).

The EEPFs measured at the discharge centre for discharges driven by 35 MHz with rf voltages of 40 V at 50 mTorr and a gap distance of 2 cm are shown in figure 5(*a*). For one of two cases, a weak dc magnetic field (10 G) parallel to the electrodes and perpendicular to the electric field was applied. From the previous results (figure 1), the driving frequency at 2 cm leading to the formation of a plateau in the low-energy part of the EEPF due to the emergence of the bounce resonance heating can be estimated. As the driving frequencies that cause the bounce resonance heating at 1 cm and 4 cm are 50 and 13.56 MHz, respectively, for a 2 cm case, the bounce resonance at the discharge driven by approximately 25 MHz may result in a plateau in the low-energy part of the EEPF. When the driving frequency (35 MHz) is higher than expected (∼25 MHz), the resonant energy (∼4.5 eV) becomes excessively high and a plateau is not observed at the low-energy part on the EEPF (see figure 5(*b*)). Therefore, the EEPF for a case in which the magnetic field is absent is bi-Maxwellian with no plateau in the low-energy portion, as shown in figure 5(*a*). The EEPF under a weak transverse magnetic field of 10 G, however, shows a plateau in the low-energy region. Under a weak transverse magnetic field, electrons are affected by the forces resulting not only from the electric field but also from the magnetic field. As the cyclotron frequency under the magnetic field of 10 G is approximately 28 MHz for all electrons, the bounce frequency of electrons whose bounce frequency in the absence of the magnetic field is comparable to or lower than the cyclotron frequency increases when the weak transverse magnetic field is present. As a result, the bounce frequency of electrons less than 2.5 eV for a case under a weak transverse magnetic field is fairly close to the driving frequency of 35 MHz (see figure 5(*b*)). Hence, a plateau appears in the low-energy region of the EEPF due to bounce resonance heating under a weak transverse magnetic

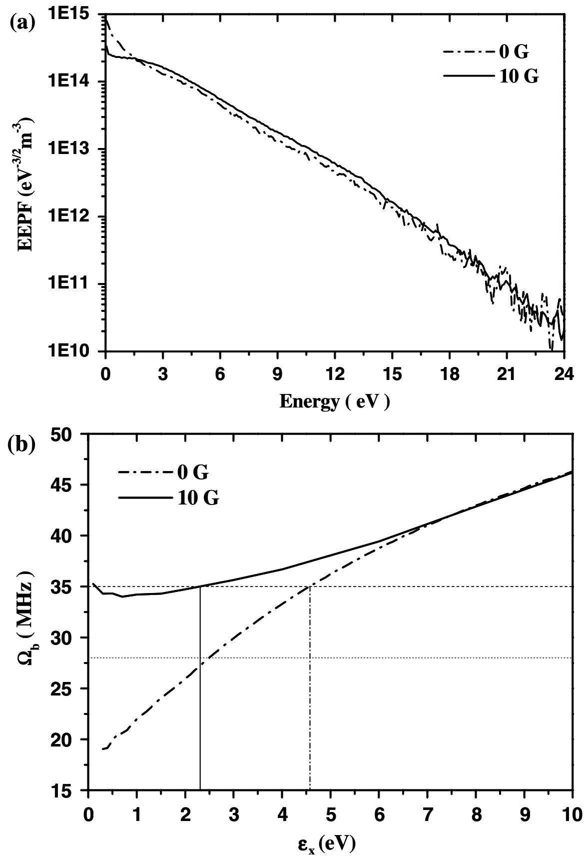

Figure 5. Simulation results for two capacitively coupled discharges driven at 35 MHz: (*a*) EEPFs at the centre of the discharge and (*b*) electron bounce frequency as a function of the x-directional energy (the dashed and the dotted lines indicate the driving frequency (∼35 MHz) and the cyclotron frequency (∼28 MHz), respectively).

field. Although Turner *et al* [17] showed that collisionless heating can be essentially removed by a transverse magnetic field, the collisionless bounce resonance heating is observed in our case to satisfy the bounce resonant condition.

4. Conclusion

A plateau was determined to exist in the low-energy portion of the EEPF of capacitive argon discharges for different regimes of pressures and gap distances. The plateau reflects the efficient electron heating of low-energy electrons which can be explained in terms of the bounce resonant motion of low-energy electrons in the bulk plasma. The weak rf electric field that leaks into the bulk plasma can effectively heat these electrons when the electron bounce frequency resonates with the rf excitation frequency ($2\pi\Omega_b(\varepsilon_x) \approx \omega$). Bounce resonance heating is a feature of capacitively coupled discharges in the regime where the mean-free path of the electrons is comparable to the system length when the resonance condition is satisfied. As the weak transverse magnetic field significantly influences the bounce frequency of the low-energy electrons, the electrons out of the resonant condition in the absence of a magnetic field can be heated effectively when a weak transverse magnetic field is present.

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