Electron heating mode transition observed in a very high frequency capacitive discharge

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The effect of excitation frequency in the 13.56–60 MHz range on the electron energy distribution function (EDF) of capacitively coupled plasma is investigated. Under a fixed rf voltage (50–130 V peak-to-peak) and argon pressure (100 mTorr), a remarkable change in the EDF is observed: a Druyvesteyn type at low frequencies (≃13.56 MHz) evolves into a bi-Maxwellian type in a very high frequency (VHF) above 30 MHz. The transition frequency decreases with increasing the rf voltage. The observed frequency effect on the EDF is tentatively explained in terms of the transition of electron heating mode from the *collisional ohmic heating* at low frequencies into the *plasma surface heating* in the VHF range.
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A recent trend toward large-area low-damage plasma processing has pushed improvement of capacitively coupled plasmas by raising the excitation frequency from 13.56 MHz to a range of very high frequency (VHF) from 30 to 60 MHz. Various benefits of VHF capacitive plasmas in materials processing have been reported: for example, the higher growth rate and better uniformity of *a*-Si:H film deposition[1] and a high etch rate and less microloading effect.[2] Furthermore, the measurement of optical emission from the VHF plasma[2] suggested a change of *electron energy distribution function* (EDF) such as suppression of high-energy tail electrons, along with a decrease in the electron temperature. The effect of excitation frequency on capacitive discharges has been investigated in a particle in cell (PIC) Monte Carlo simulation model[3] and in a fluid model.[4] Both models predicted the plasma density scaled as frequency squared at a fixed rf voltage. In contrast to the experimental results, the electron temperature was almost independent of frequency in the 10–100 MHz range.[3,4] On the other hand, the 13.56 MHz argon discharge shows an abrupt decrease of the effective electron temperature at a critical pressure when lowering the pressure.[5] This has been interpreted as the transition of electron heating mode from collisional ohmic heating characterized by Druyvesteyn EDF, to collisionless sheath heating characterized by bi-Maxwellian EDF.[5] However, the bi-Maxwellian EDF is alternatively explained in the nonlocal electron kinetics,[6] where plasma surface heating[7,8] plays an essential role.

This letter reports the observation of electron heating mode transition caused by a change of the excitation frequency of a VHF capacitive plasma at a fixed rf voltage and argon pressure.

The capacitive discharge was driven between two parallel electrodes of 15 cm in diameter with the gap distance $L=6.6$ cm. The lower electrode was connected to a power supply (13.56–60 MHz, 100 W) through a matching box, while the upper electrode and the chamber walls were grounded. The voltage wave form at the powered electrode was monitored using a calibrated high voltage probe while the net dissipated power P_{in} was estimated using a subtractive method.[9] Typical discharge conditions are the argon pressure ≃100 mTorr and the rf voltage $V_{RF}=50$–130 V peak-to-peak (V_{pp}). The excitation frequency used throughout this work were 13.56, 27, 37, 44, 50, and 57 MHz. For plasma diagnostics, Langmuir probes including a second reference probe and resonant filters for the first and second harmonic were used.[10] As is well known, the second derivative of the probe $I-V$ characteristic gives the *electron energy probablity function* (EEPF) $f_p(\epsilon)$, which is expressed as $f_p(\epsilon)=\epsilon^{-1/2}F(\epsilon)$ where $F(\epsilon)$ is the EDF. EEPF data acquision was made by calculating the second derivative at discrete energy increment $\Delta\epsilon=0.02$ eV.[11] The effective electron temperature $T_{eff}=(2/3\,n_e)\int_0^\infty \epsilon F(\epsilon)d\epsilon$, the electron density n_e, and the electron-neutral momentum transfer collision frequency ν_m were found by integrating the measured EEPF, while the plasma potential V_p is found from the zero crossing voltage of the second derivative $I''(V)=0$ or from the $I(V)$ characteristic, using the intersecting slopes technique.

Figure 1 shows the dissipated power and the plasma potential against the excitation frequency at a fixed voltage

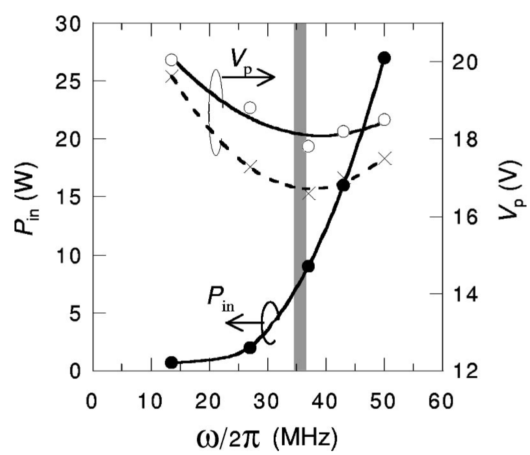

FIG. 1. Dissipated power P_{in} and plasma potential V_p as a function of excitation frequency $\omega/2\pi$ at $V_{RF}=80\ V_{pp}$ and argon pressure 100 mTorr. Cross and open circle denote the plasma potential determined from zero crossing of $I''(V)$ and from intersecting slopes of $I(V)$, respectively.

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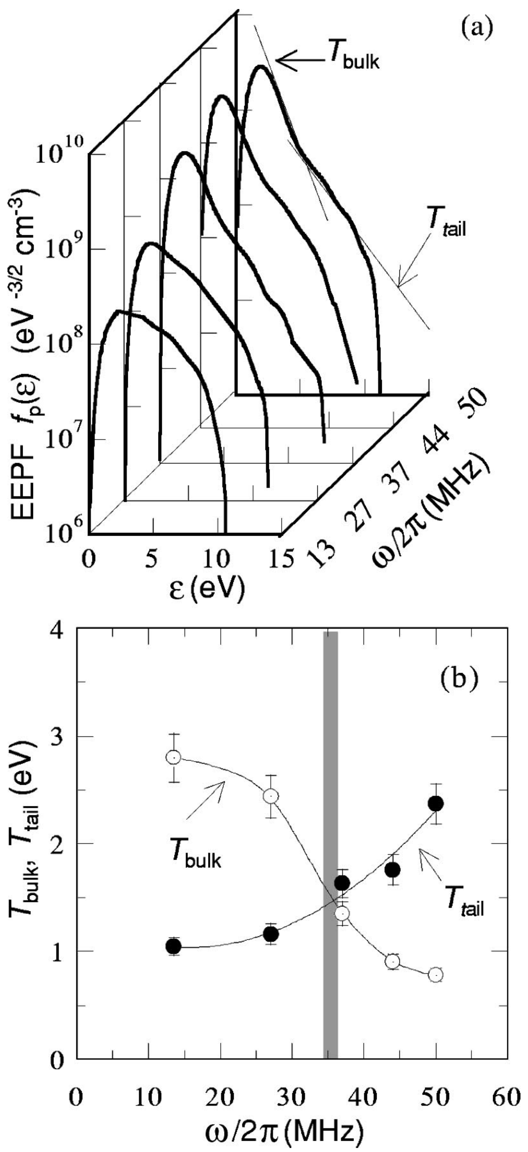

FIG. 2. (a) EEPF for different excitation frequencies at $V_{RF}=80\ V_{pp}$ and argon pressure 100 mTorr, and (b) bulk temperature T_{bulk} and tail temperature T_{tail} as a function of excitation frequency $\omega/2\pi$. The shaded strip indicates to the transition frequency band around 35 MHz.

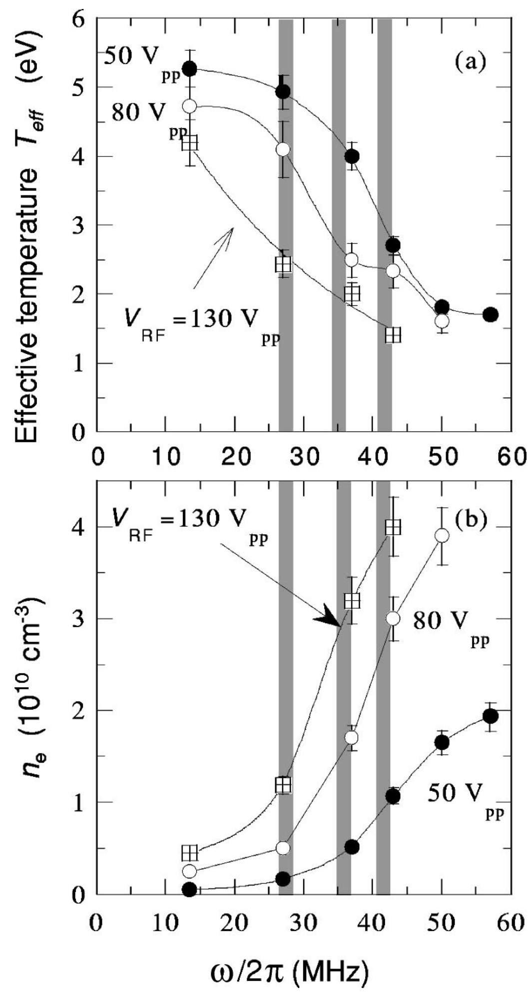

FIG. 3. (a) Effective electron temperature T_{eff} and (b) electron density n_e as a function of excitation frequency $\omega/2\pi$ for different values of V_{RF}. The shaded strips indicate to the transition frequency band.

$V_{RF}\simeq 80\ V_{pp}$. A remarkable increase in the dissipated power together with the plasma potential drop is observed at the frequencies higher than $\simeq$35 MHz as indicated by the shaded strip in Fig. 1. This reveals significant change in the power coupling mechanism.

Typical examples of EEPFs measured at argon 100 mTorr and $V_{RF}\simeq 80\ V_{pp}$ for different frequencies are shown in Fig. 2(a). At any frequencies, strong depletion is observed in the energy range $\epsilon \geqslant 12$ eV since high energy electrons passing through the ambipolar potential well are lost to the wall. As the excitation frequency increases, one can observe the transition in a shape of the EEPF from a Druyvesteyn type with a convex curvature, toward a bi-Maxwellian type with a concave curvature. This suggests the transition of main electron heating mode from the ohmic heating at lower frequencies to the plasma surface heating which gives bi-Maxwellian EDF as observed also in microwave discharges.[7,8] In Fig. 2(a), we define the bulk (T_{bulk}) and the tail (T_{tail}) temperatures using the slopes of EEPF at $\epsilon \sim 3$ and $\sim$8 eV, respectively. It is clearly shown in Fig. 2(b) that the two temperatures have an opposite trend against the excitation frequency. The shaded strip in Fig. 2(b) indicates the transition frequency band around 35 MHz. The transition frequency was observed to depend on the rf voltage. For $V_{RF}\cong 130\ V_{pp}$, the heating mode transition takes place around 27 MHz while it appears at about 41 MHz for $V_{RF} \cong 50\ V_{pp}$. This tendency can be seen in the excitation frequency dependences of n_e and T_{eff} shown in Fig. 3, where the transition frequency positions are indicated by shaded strips. As inferred in Fig. 2(a), the present data may miss a part of the EEPF at very low energies ($0<\epsilon<2$ eV).[12] The low energy depletion of the EEPF can be compensated by extrapolating the measured distribution function to zero energy before integration. However, the results obtained in this way showed almost the same frequency dependence of n_e and T_{eff} as in Fig. 3.

It is known in 13.56 MHz argon discharges that the location of electron heating is an important factor determining the EDF shape. Namely, the plasma bulk heating at high pressure gives the Druyvesteyn type EDF while the plasma surface heating leads to bi-Maxwellian type EDF in the nonlocal regime.[6] The nonlocal electron kinetics stands for the electron energy relaxation length λ_ϵ much greater than the plasma half length $L/2$; $\lambda_\epsilon/(L/2)=10$–50 in the present experiment. Under the nonlocal condition, a great majority of low-energy electrons are trapped in a dc ambipolar potential well of energy ϵ_{amb}. A minority group of high energy electrons ($\epsilon \geqslant \epsilon_{amb}$) is accessible to the plasma-sheath boundary where the oscillating sheath induces the plasma surface heating of these electrons. Namely, the surface heating power is primarily deposited to a high-energy tail of EDF, thus forming the bi-Maxwellian type distribution. To the contrary, the ohmic power is mostly deposited to a low energy part ($\epsilon \leqslant T_{eff}$) of EDF, inducing the Druyvesteyn type distribution. This is because the ohmic power ΔP_{ohm} deposited to electrons of the number $\Delta n(\epsilon)$ at the energy ϵ is scaled as $\Delta P_{ohm} \propto \epsilon^{-1/2} \sigma(\epsilon)^{-1} E_{RF}^2 \Delta n(\epsilon)$ for the collision cross section $\sigma(\epsilon)$ and the rf electric field E_{RF}. As the excitation frequency increases, the surface heating creates more high-energy electrons, which produce cold electrons by ionization in the plasma bulk. Thus, a balance between production and loss of electrons leads to lower value of the effective temperature T_{eff} in the VHF range.

A mechanism of the collisionless surface heating due to the oscillating sheath has been understood as *stochastic heating*[13] (a type of Fermi acceleration) in a so-called "hard wall" model. Furthermore, the alternate interpretation based on nonstochastic *pressure heating*[14,15] has been proposed, where a transit time heating of electron passing through the sheath plays an essential role in terms of single particle trajectories. First of all, we compare our observations with the stochastic heating model. According to Ref. 13, the ratio of stochastic heating power P_{stoc} to the ohmic heating power P_{ohm} per unit area for the rf sheath voltage $\tilde{V}$ is given as

$$P_{stoc}/P_{ohm} = 0.52(e/m)^{1/2}(hd\nu_m)^{-1}\tilde{V}^{1/2} \quad (1)$$

where d is the sheath thickness and h is the ratio of electron density at the sheath edge to the bulk electron density ($h \simeq 0.1$ in the present conditions). Apparently, the ratio is independent of ω, however, T_{eff} (i.e. $F(\epsilon)$) changes with the frequency so that ν_m in Eq. (1) varies with ω. For comparison with the experimental results, we put $\tilde{V} = V_{RF}/4$ and the value of $\nu_m = (N_g/n_e)\int_0^\infty \sigma(\epsilon)\nu(\epsilon)F(\epsilon)d\epsilon$ is computed for the argon gas density N_g, taking account of strong Ramsauer effect on $\sigma(\epsilon)$.[16] Thus, Fig. 4 represents the ratio of P_{stoc}/P_{ohm} as a function of the excitation frequency for different discharge voltages.

As one can see in Fig. 4, the stochastic heating prevails over the ohmic heating as the frequency increases for the fixed rf voltage. The transition frequency is identified to be at $P_{stoc}/P_{ohm} = 1$, decreasing from 37 MHz at $V_{RF} = 50\ V_{pp}$ to about 15 MHz at $V_{RF} = 130\ V_{pp}$. These transition frequencies appear to roughly agree with those determined from the measured EEPF in Fig. 3. Strictly speaking, however, a factor of 2 should be multiplied to P_{stoc} with the two sheaths taken into account.

On the other hand, a PIC Monte Carlo simulation of the pressure heating[14] clearly shows a bi-Maxwellian type EDF in 13.56 MHz argon discharge at 10 mTorr. A fluid theory of the pressure effects[14] predicts the ratio of the pressure heating power P_{pres} to the ohmic power P_{ohm} at low pressure as

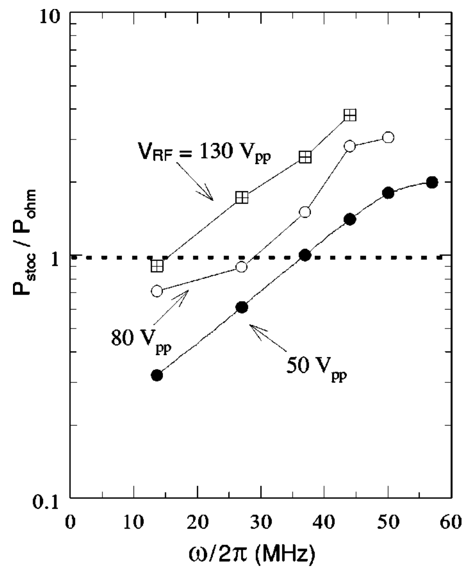

FIG. 4. Stochastic to ohmic heating power ratio P_{stoc}/P_{ohm} as a function of excitation frequency $\omega/2\pi$ for different values of V_{RF} at argon 100 mTorr.

$$P_{pres}/P_{ohm} \simeq (5/16)(L/2x_0) \quad (3)$$

for the electron density profile in a form of sech (x/x_0). Accordingly, the power ratio depends on neither the excitation frequency nor the pressure, and it is on the order of 1 as $L/2x_0 \sim 3$. However, this ratio is sensitive to the density profile characterized by x_0 which usually varies with the pressure and the excitation frequency. In the VHF range, the electron density becomes considerably high, which squeezes the rf field out of the plasma bulk, thus enhancing the plasma surface heating through the pressure heating rather than the stochastic heating. Such strongly localized surface heating will necessitate a self-consistent kinetics theory to find the EDF of a VHF capacitive discharge.

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