Transition of electron heating mode in a planar microwave discharge at low pressures

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Spatial distributions of electron density n_e, electron temperature T_e, and wave field intensity in a planar microwave discharge at low pressures (10–100 mTorr) are measured with the discharge power as a parameter. Two different modes of electron heating are found: a *bulk heating mode* characterized with high $T_e(\sim 10\,\mathrm{eV})$ in underdense plasma, and a *surface heating mode* with low $T_e(\sim 3\,\mathrm{eV})$ in overdense plasma with a hot layer near the plasma-dielectric boundary. Abrupt transition between the two modes takes place near the cutoff density n_c where the electron plasma frequency coincides with the discharge frequency (2.45 GHz). In the underdense case $(n_e < n_c)$, the microwave penetrates the bulk plasma and heats the majority of electrons confined in the dc ambipolar potential well, leading to high T_e. In the overdense case $(n_e > n_c)$, the evanescent wave (surface wave) near the microwave window strongly heats the electrons in the boundary layer, which are transported to the bulk region and ionize the neutral particles to therein produce relatively cold electrons. © *2000 American Institute of Physics.* [S0003-6951(00)04548-4]

High-power microwave discharges at low pressures (<50 mTorr) can be used to produce high-density ($\sim 10^{12}\,\mathrm{cm}^{-3}$) large-diameter (>40 cm) plasma.[1] This type of high density sources are called *surface wave plasma* (SWP) because the plasma is maintained by surface waves propagating along a plasma-dielectric interface.[2] The SWPs have attracted much attention in a wide area of materials processing owing to their high controllability and feasibility. In addition, recent plasma diagnostics revealed that the electron temperature is lower ($T_e \sim 1.7\,\mathrm{eV}$) in a 2.45 GHz SWP than that ($T_e \sim 2.5\,\mathrm{eV}$) in a 13.56 MHz inductively coupled plasma, for the same electron density ($n_e = 6\times 10^{11}\,\mathrm{cm}^{-3}$), gas species and pressure (20 mTorr).[3] Such a difference in the electron distribution functions (EDFs) dramatically modifies the radical composition in fluorocarbon etching plasma as observed experimentally[4] and demonstrated in a numerical modeling.[5] Thus, EDF measurement and understanding of the electron heating processes are crucial for controlling the plasma chemistry in materials processing.

In this letter, we report the observation of two electron heating modes and the transition between them in planar microwave discharges at low pressures (10–100 mTorr). One is a *bulk heating mode* in underdense plasma, and the other is a *surface heating mode* in overdense plasma. The results reported here are analogous to the previous observation in parallel plate rf discharges[6] at relatively high pressures (0.1–3 Torr). In the rf discharges, the *bulk heating mode* corresponds to the α mode discharge having high electron temperature (~4 eV) and low electron density, while the *surface heating mode* matches the γ mode discharge or the discharge mode driven by the rf oscillating sheath, both having low electron temperature (0.3–1 eV) and high electron density.

The planar surface-wave plasma apparatus[7] in this experiment is shown in Fig. 1. The main part of the plasma chamber has a diameter $2R = 22\,\mathrm{cm}$ and is sealed by a 17 mm thick quartz plate with the specific dielectric constant of $\epsilon_d = 3.7$. A cylindrical coordinate system (r,θ,z) with the z axis along the chamber axis and the origin on the quartz plate surface is introduced. The microwaves at $\omega/2\pi = 2.45\,\mathrm{GHz}$ fed along a rectangular waveguide enter the chamber through a pair of inclined slot antennas. The axial profiles of microwave intensity and plasma parameters are measured using an axially motor-driven probe made of a 0.6-mm-diam tungsten wire inserted into an insulating ceramic and shielding stainless steel tubes (labeled as LP in Fig. 1). The 5 mm long wire tip extending out of those tubes is used as a pickup antenna

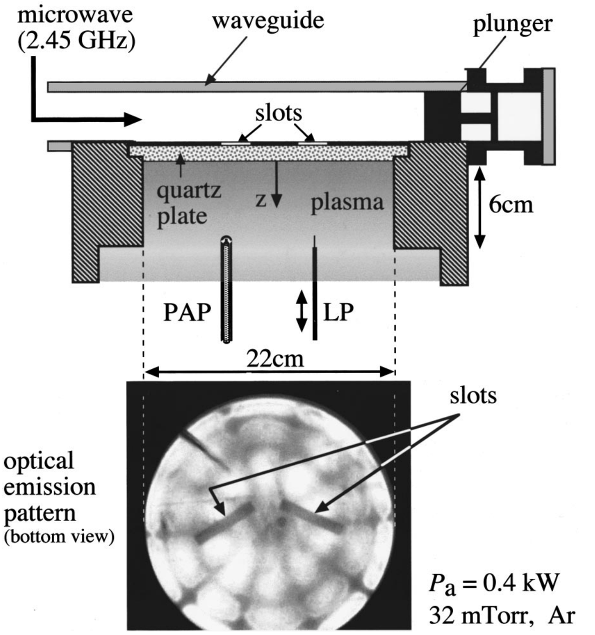

FIG. 1. Sketch of the experimental setup and a photograph of the optical emission from the microwave plasma at absorbed power $P_a = 0.4\,\mathrm{kW}$ in argon at pressure $p = 32\,\mathrm{mTorr}$.

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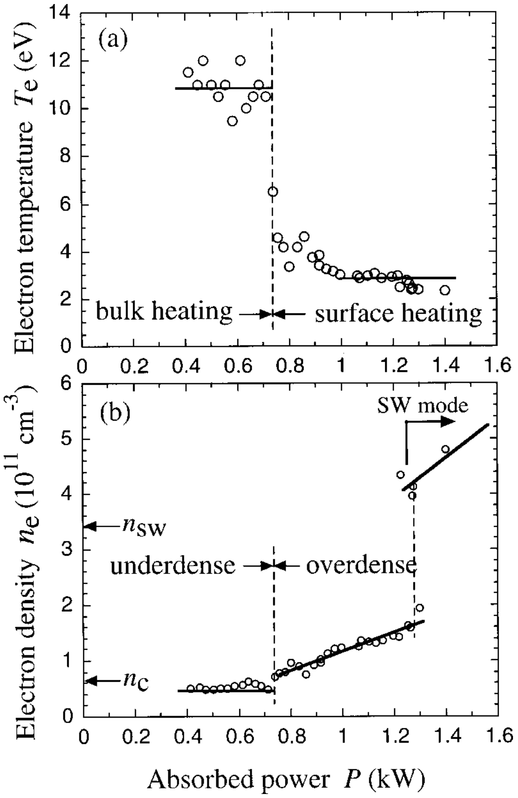

FIG. 2. (a) Electron temperature T_e and (b) electron density n_e measured as a function of absorbed power P_a, using Langmuir probe at $z=r=4$ cm in argon at pressure 12 mTorr; n_c and n_{sw} denote the cutoff density and the surface-wave resonance density, respectively.

to measure the microwave intensity and as a Langmuir probe. It is positioned at $r=4$ cm at an azimuthal angle corresponding to the slot center. Although the antenna tip was directed along z to pickup mainly the z component of electric field, it may also be sensitive to other components, so that we provide the output signal ($|E|^2$) in arbitrary units as a measure of electric field strength ($|E|$). In order to make sure that the Langmuir probe measurement is not critically affected by the microwave field, the absolute electron density was independently measured by a plasma absorption probe (PAP),[8] which is, in principle, free from microwave disturbance. The PAP is located at $r=4$ cm and $z=6$ cm. All measurements were performed in argon.

Changing the absorbed power P_a (incident power minus reflected power) at a constant pressure $p=12$ mTorr, we measured the electron temperature T_e and the electron density n_e by a Langmuir probe at $z=4$ cm, as shown in Fig. 2. Here the value of T_e was derived from the slope in a semilogarithmic plot of the probe $V-I$ characteristics, and hence it simply gives a measure of the mean electron kinetic energy, without arguing the details of electron energy distribution function which will be presented in a forthcoming paper. Figure 2(a) shows the measured T_e versus the discharge power P_a, and one can clearly see a transition at $P_a=0.74$ kW from a high temperature regime ($T_e \sim 10$ eV) to a low temperature regime ($T_e \sim 3$ eV). On the other hand, Fig. 2(b) shows the electron density n_e calibrated by the PAP. Here the cutoff density n_c (the density for which the electron plasma frequency ω_p coincides with the wave frequency ω) is $n_c = 7.4\times10^{10}\,\mathrm{cm}^{-3}$ in the present experiment of $\omega/2\pi = 2.45$ GHz. It is seen in Fig. 2(b) that the abrupt change in the electron temperature takes place around the cutoff density n_c. This explicitly suggests a correlation between wave properties and the electron heating processes. As is well known, plane electromagnetic waves propagate in underdense plasma ($n_e<n_c$) with the wave number k following the dispersion relation, $\omega/k = c(1-\omega_p^2/\omega^2)^{-1/2}$ where c is for the speed of light in vacuum. In overdense conditions ($n_e>n_c$; $\omega_p^2>\omega^2$), however, the externally launched waves cannot penetrate the plasma and are reflected at the plasma boundary.

The electron density n_{SW} giving the surface wave resonance is $n_{\mathrm{SW}}=(1+\epsilon_d)n_c$,[1,2] which is $3.5\times10^{11}\,\mathrm{cm}^{-3}$ in this experiment. When the electron density exceeds n_{SW}, the excitation of discrete eigenmodes of surface waves is predicted, which is often accompanied by density jumps and hysteresis loops.[1,9] In fact, a jump in the electron density is observed at $P_a=1.15$ kW in Fig. 2(b). At higher pressures, one can directly identify the excited wave mode from the optical emission pattern.[7] For example, the photograph at the bottom of Fig. 1 shows the light emission from the plasma at 32 mTorr and 0.4 kW, taken from a bottom view port by a CCD camera. It clearly indicates the pattern of TM_{530} pure surface mode with the azimuthal and radial mode numbers $m=5$ and $n=3$, respectively. The existence of this mode is supported by the measurement of microwave penetration depth along z and the surface mode analysis[2] for the present geometry at the measured n_e.

In order to give an insight into the electron heating processes, we measured the axial profiles of n_e, T_e, and the microwave intensity $|E|^2$ at the same pressure $p=12$ mTorr. Figure 3 shows the data obtained in the three typical cases: (a) underdense plasma at $P_a=0.45$ kW, (b) plasma of cutoff density at $=0.74$ kW, and (c) overdense plasma at $=1.4$ kW. As seen in Fig. 3(a), the microwave penetrates the underdense plasma and forms a standing volume wave with the nodes at $z=0.6$ and 6.5 cm (separation ~half a free-space wavelength). Thus, electrons in the bulk region are collisionally heated by microwaves and confined in the ambipolar dc potential well. This bulk heating mode gives a relatively high temperature ($T_e>10$ eV) in the bulk region.

As the electron density gradually increases with the discharge power, the waves are squeezed out of the bulk region toward the boundary near the quartz plate. When the density slightly exceeds n_c, as in case (b), resonantly enhanced excitation of waves is observed at the resonance layer where the local value of ω_p coinsides with ω, i.e., $n_e(z)=n_c$. Such phenomena have been demonstrated in the previous test wave experiment[10] and numerical analysis.[11] In this case, the wave power is locally deposited to electrons around the resonance layer where the temperature is high with a small density dip. However, the T_e value in the bulk region is lower than in case (a). On the other hand, the data in Figs. 3(a) and 3(b) support the assumption that the T_e measurement by the Langmuir probe is not influenced by the microwave intensity $|E|$. Namely, there is no definite correlation between the measured T_e and the local intensity $|E|$: the T_e value at $z<0.5$ cm in Fig. 3(a) is low in spite of high $|E|$, while the T_e value at $z>3$ cm in Fig. 3(b) is high at $|E|\sim0$.

When the electron density exceeds n_c significantly, as in

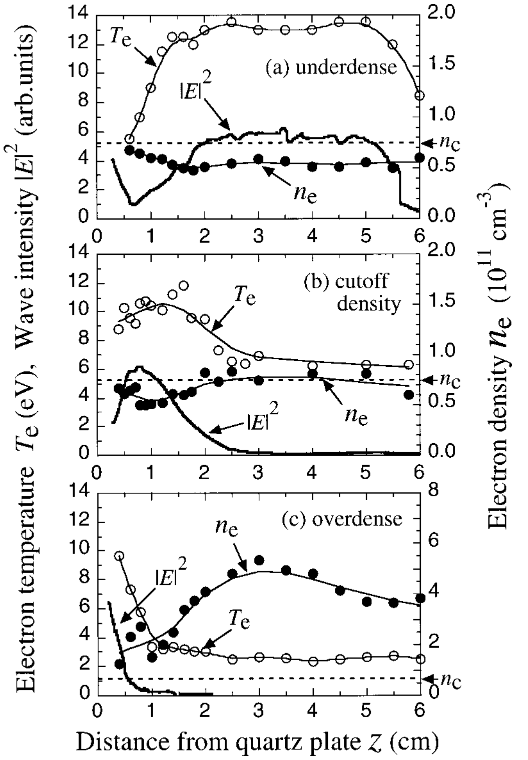

FIG. 3. Axial profiles of electron temperature T_e (open circles), electron density n_e (closed circles), and microwave intensity $|E|^2$ (thick lines) in (a) underdense plasma, (b) plasma of cutoff density, and (c) overdense plasma in argon at pressure $p=12$ mTorr. The dashed lines indicate the level of cutoff electron density n_c; z is the distance between the probe tip and the plasma-dielectric boundary.

case (c), the microwave is reflected at the plasma boundary and decays in a skin depth ($\sim c/\omega_p$), as shown in Fig. 3(c). In such overdense conditions, the electron heating occurs along the plasma boundary and the electron temperature decreases axially from ~10 eV in the hot boundary layer to 2–3 eV in the bulk region. This plasma structure caused by the surface heating can be interpreted qualitatively in terms of nonlocal kinetic theory,[12] as follows. Most of the electrons in the bulk region are confined in the ambipolar dc potential well, and only a small group of high-energy electrons are accessible to the heating zone in the plasma boundary. After being heated there, the hot electrons return to the bulk region, where they produce cold electrons by ionization to compensate the diffusion loss in steady state. The majority of electrons remain relatively cold in the bulk region since no external heating source exists there. Thus, the electron energy distribution in the bulk region can be expressed as a sum of two Maxwellian distributions (a majority group of low-T_e electrons and a minority group of high-T_e electrons), as observed in the preliminary experiment reported in Ref. 3. The high-energy tail electrons are needed to enhance the ionization in the bulk region since the ionization rate by the cold electron group ($T_e \sim 3$ eV) is lower by a factor of $\sim \exp(10\,\mathrm{eV}/3\,\mathrm{eV}) = 28$ in comparison to the bulk heating mode in case (a). A recent report[13] on the presence of high-energy electrons in the surface wave plasma may be related to the above hypothesis. Thus, careful measurements of the EDFs is needed to understand the mechanism of surface heating; possibly collisionless transit-time heating.[14]

When the pressure is decreased from 100 to 10 mTorr with the discharge power $P_a = 0.6$ kW fixed, the Langmuir probe measurement showed an abrupt jump in the electron temperature in the bulk region, at $p \sim 25$ mTorr, from the cold electron mode ($T_e = 2-3$ eV) to the hot electron mode ($T_e \sim 10$ eV). This jump occurs again at $n_e - n_c$, suggesting the transition from the surface heating mode to the bulk heating mode. The detailed measurements of EDFs in the two heating modes and the numerical modeling of the EDFs based on the nonlocal theory are in progress.

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