Effect of Electron Heating Mode on Charge-Up Damage in Dual-Frequency Capacitive Discharges

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***Abstract*—In dual-frequency capacitive discharges, the effect of electron heating mode on charge-up damage is investigated through a 3-D charge-up simulator coupled with a 1-D particle-in-cell Monte Carlo collision simulation. The local charge-up damage on the trench decreases as the electron heating mode is changed from collisionless to collisional heating.**

***Index Terms*—Plasma control, plasma heating, plasma properties.**

CAPACITIVELY coupled RF discharges have been used for selective anisotropic etching process in the semiconductor industry. However, the motion difference between anisotropic ions and isotropic electrons causes the electron shading effect which generates a high charge-up potential in the case of high aspect ratio. This charging effect results in many plasma-process-induced damage problems, such as bowing, trenching, and notching [1].

The shape of electron energy probability function (EEPF) in the bulk region is determined by the dominant mode (collisionless or collisional) of electron heating [2], [3]. This shape affects the sheath potential drop, which is a crucial parameter in determining the kinetics of ions and electrons arriving at the electrode [3]. The effects of electron heating mode on charge-up damage in microscopic feature have been investigated in this paper.

In this paper, 1-D particle-in-cell Monte Carlo collision (PIC-MCC) simulations have been performed for capacitively coupled argon discharges [4]. The gap width, area of electrode, and operating gas pressure are taken to be 4.5 cm, 314 cm^2, and 10 mtorr, respectively. Two RF current sources with frequencies of 27 and 2 MHz are applied to the powered electrode. The ratio of the high-frequency (27 MHz) current density (J_h) to the low-frequency (2 MHz) current density (J_l) is varied from three to nine while the sum of the two current densities is fixed at 0.8 $\mathrm{mA} \cdot \mathrm{cm}^{-2}$. The effective frequencies [2] are 5.45, 6.77, and 11.86 MHz for the current density ratios of 3, 4, and 9, respectively. Self-consistently calculated energy and angle distribution functions of particles from 1-D PIC-MCC simulation are used as input parameters of a 3-D charge-up simulator [5]. The schematic of charge-up simulation consisting of SiO_2 layer with an aspect ratio of three is shown in [5, Fig. 2].

Fig. 1(a) shows the EEPFs in the bulk region and spatial profiles of the dissipated RF power density for each species (electron and ion) for different ratios of current density. As the effective frequency increases, the EEPF evolves from a bi-Maxwellian to a Maxwellian-like distribution function, and the effective electron temperature increases from 1.79 to 4.56 eV. This result indicates that the electron heating mode changes from collisionless to collisional heating. In other words, the power dissipation for electron heating in the bulk region increases, and the power dissipation for ion acceleration in the sheaths decreases. Because the ratio of electron-dissipated power to ion-dissipated power increased, the sheath potential decreases, and the average energy of ions arriving at the electrode decreases.

Fig. 1(b)–(d) shows the charge-up potential profile on the $x-y$ cross section at position $z = 0.1$ μm. As the effective frequency increases, the positive potential at the bottom of the trench decreases from 120 to 55 V, and the negative potential on the top surface of the trench decreases from -10.3 to -7.6 V. The electron charging on the top of the surface, which affects the flux of electrons at the bottom of trench, is affected by the average energy of electrons on the electrode. It means that the number of electrons arriving at the trench bottom increases by decreasing the average electron energy on the electrode. On the other hand, a decrease in ion average energy on the electrode results in a decrease in positive potential at the trench bottom, owing to a decrease in ion flux.

In conclusion, the charge-up potential has decreased as the electron heating mode changes from collisionless to collisional heating mode. Because the trajectory of incident ions with energy lower than the charge-up potential is changed significantly, the uniformity of potential profile in the trench is improved at lower charge-up potential. This charge-up potential and its uniformity play important roles in making etching profiles. So, the local charge-up damage is decreased at collisional electron heating mode.

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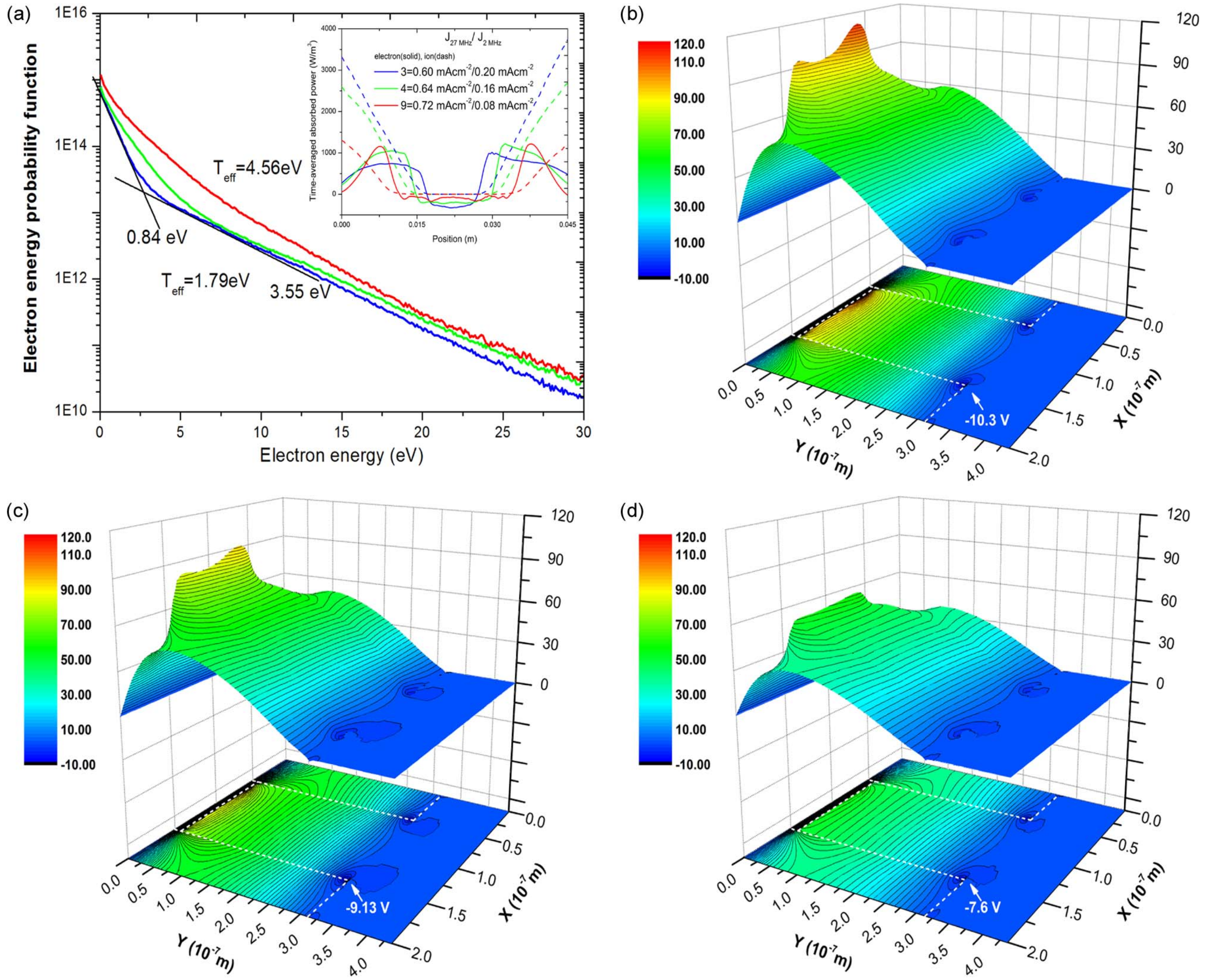

Fig. 1. (a) EEPFs in the bulk region and absorbed power density for each species: (Solid line) Electron and (dashed line) ion. (b)–(d) Charge-up potential profile on the $x-y$ cross section (the white dashed line indicates the wall of the trench) at $z = 0.1\ \mu$m with the various current ratios of the dual-frequency (2 and 27 MHz) sources: (b) 3 ($J_h = 0.6$ mA $\cdot$ cm^{-2}/$J_l = 0.2$ mA $\cdot$ cm^{-2}), (c) 4 ($J_h = 0.64$ mA $\cdot$ cm^{-2}/$J_l = 0.16$ mA $\cdot$ cm^{-2}), and (d) 9 ($J_h = 0.72$ mA $\cdot$ cm^{-2}/$J_l = 0.08$ mA $\cdot$ cm^{-2}). The software OriginPro 8 (OriginLab Corporation, USA) was used to produce the image.

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