On the similarity and scaling laws of low-temperature plasmas

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Similarity and scaling laws are essential for correlating discharge plasmas of different dimension scales, particularly useful for the plasma devices for which experimental studies are not feasible. [1-3] In this report, the history of the similarity laws (SL) is revisited, and recent studies of the similarities of low-temperature plasma discharges, including scaling laws for the gas breakdown and steady-state discharges are summarized. [4-6] Similar discharge phenomena in local and nonlocal kinetic regimes are demonstrated by experiments and numerical simulations, e.g., particle-in-cell (PIC) simulations [7,8].

Figure 1 demonstrates the PIC simulation results on the similarity and scaling laws for capacitive radio frequency (rf) discharges. The discharge models are shown in Fig. 1(a), in which the rf plasmas are geometrically symmetric between two parallel-plate electrodes. Under the similar discharge conditions, the gas pressure p, gap distance d, and driving frequency f are simultaneously tuned by the scaling factor, i.e., $k = p_k/p_1 = d_1/d_k = f_k/f_1$. Under the f-scaling conditions only the driving frequency is changed by $k = f_k/f_1$, keep the gas pressure and gap dimension unchanged. Figure 2(b) shows the time-averaged electron density at the center of the gap in rf discharges at steady state and the scaling factor k is from 1 to 10. The electron densities from PIC simulations with and without SEE both agree well with the theoretical SL prediction, showing a straight line with a slop of two in the log-log plot, which exactly confirms the theoretical electron density scaling in similar discharges.[8] Interestingly, although the gas pressure and the gap distance are not tuned as the SL scaling does, the f-scaling holds the same scaling for electron density, expect for [p_{10}, d_{10}] at lower frequencies, as shown in Fig. 2(b). Furthermore, the effects of the nonlinear collision processes, such as stepwise ionizations, on the validity of the similarity laws are characterized for low-pressure capacitive radiofrequency plasmas. The application potentials of the similarity and scaling laws in the field of low-temperature plasmas are also discussed.

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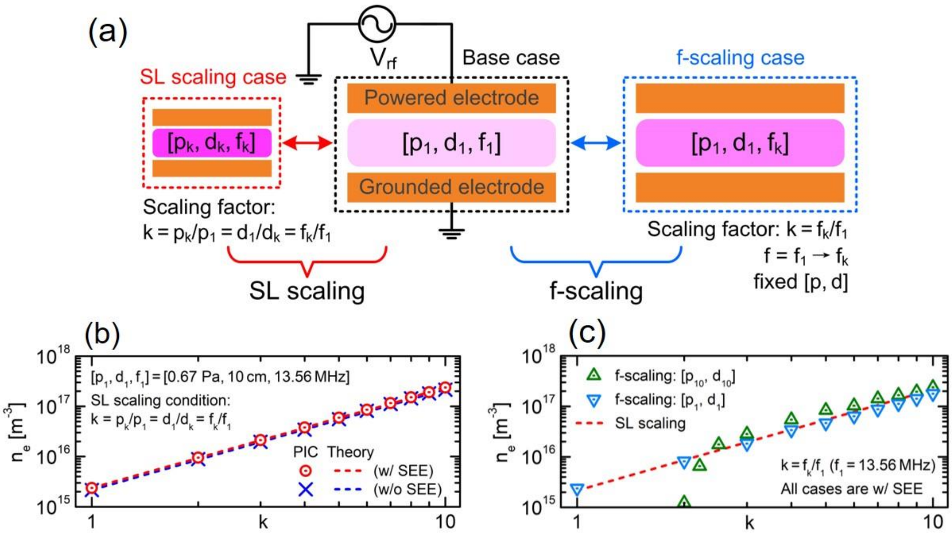

Figure 1. (a) Illustration of the rf discharge models. Under the SL conditions, the gas pressure, gap distance, and driving frequency are simultaneously changed by the scaling factor $k = p_k/p_1 = d_1/d_k = f_k/f_1$ while under the f-scaling conditions only the driving frequency is changed by $k = f_k/f_1$, keep the gas pressure and gap dimension unchanged. (b) Demonstration of the SL scaling for the time-averaged electron density at the gap center with and without SEE; [p_1, d_1, f_1] = [0.67 Pa, 10 cm, 13.56 MHz] is the base case with $k = 1$. (c) Verification of the f-scaling for electron density with [p_1, d_1] = [0.67 Pa, 10 cm], which holds approximately the same dependence on the driving frequency as the SL scaling (dashed line) whereas violations of the f-scaling are observed for [p_{10}, d_{10}] = [6.7 Pa, 1 cm] at lower frequencies.