Abstract—Complex spatio-temporal electron heating dynamics are observed in kinetic simulations of geometrically symmetric low-pressure capacitive argon plasmas driven by multiple consecutive harmonics of 13.56 MHz. These dynamics are caused by an electrically induced asymmetry that leads to the self-excitation of plasma series resonance oscillations of the current. Such oscillations cause a nonsinusoidal movement of the boundary sheath edges and multiple phases of fast sheath expansions. These expansion phases lead to the generation of negative space charges that propagate into the bulk, where they affect the heating rate significantly and relax quickly.

Index Terms—Plasma sheaths, plasma simulation, plasma sources, plasmas.

Low-pressure capacitive radio frequency (RF) plasmas are frequently used for etching and sputtering of dielectric substrates. In order to optimize these applications, customized ion flux energy distributions are required. A novel concept to realize such distributions is voltage waveform tailoring [1]: N consecutive harmonics of a fundamental frequency, f, with adjustable harmonics amplitudes, $\phi_k$, and phases, $\theta_k$, are applied to one electrode, whereas the other is grounded, i.e., the driving voltage waveform is

$$\phi(t) = \sum_{k=1}^{N} \phi_k \cos(2\pi ft + \theta_k) \quad \text{with} \quad \phi_{\text{tot}} = \sum_{k=1}^{N} \phi_k. \quad (1)$$

Here, we investigate the spatio-temporal electron heating dynamics in a geometrically symmetric argon plasma by 1d3v particle in cell/Monte Carlo collisions (PIC/MCC) simulations. One of two plane parallel electrodes is driven by $N = 4$ consecutive harmonics of $f = 13.56$ MHz according to equation (1). All phase shifts are set to $0^\circ$ and $\phi_{\text{tot}} = 800$ V. The harmonics amplitudes are $\phi_1 = 320$ V, $\phi_2 = 240$ V, $\phi_3 = 160$ V, and $\phi_4 = 80$ V according to a criterion defined in [2].

In conclusion, we observe complex electron heating mechanisms in multi-frequency geometrically symmetric capacitive discharges operated at low pressures. The complexity of
Fig. 1. Spatio-temporal distribution of the electron heating rate in a geometrically symmetric capacitive RF discharge operated in argon and driven by four consecutive harmonics of 13.56 MHz obtained from PIC/MCC simulations (3 Pa, $\theta_{e0} = 800$ V, 3 cm electrode gap, $\gamma = 0.2$). Dashed white rectangle: phase of initial sheath expansion at the powered electrode, where the most complex features are observed. This region is shown again in Fig. 2. The color scale is saturated to make weaker features inside the bulk visible.

Fig. 2. Zoomed-in-view of Fig. 1 during the time of the initial sheath expansion at the powered electrode (dashed rectangle in Fig. 1).

Fig. 3. Spatiotemporal plot of the net density, $n_i - n_e$, during the time of the initial sheath expansion at the powered electrode.

the underlying mechanisms has not been revealed by prior analytical or fluid-dynamic models of electron heating and is clearly not fully understood. A more detailed investigation of these mechanisms is required. Phase resolved emission spectroscopy might be used to study the electron heating dynamics experimentally.

REFERENCES


