Customising ion flux-energy distributions in low-pressure capacitive RF discharges

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Processing applications of plasma sources rely on the interaction of active species (ions and radicals) created in the plasmas with the surfaces that act as electrodes. The actual effect of these species at the surface layers depends on their nature, their flux, as well as their energy [1]. Here, we focus on ionic species and discuss how their flux and energy, or more precisely their flux-energy distribution (Ion Flux-Energy Distribution Function, IFEDF), can be controlled in low-pressure capacitively coupled radio-frequency (RF) discharges. In these plasma sources (space charge) sheaths periodically form and disappear near the electrodes at the pace dictated by the driving frequency, and the remaining space is filled by a quasi-neutral bulk plasma.

The coupling of the external power to the electrons may proceed in different ways. There are three main operation modes of low-pressure capacitive RF discharges: (i) the alpha-mode, where electrons gain energy upon interacting with the rapidly moving edge of the expanding sheaths and induce strong ionization; (ii) the gamma-mode, where a significant flux of electrons is generated at the electrode surfaces under the bombardment of ions (and other species [2]). These electrons are accelerated by the high sheath electric field and multiplied efficiently within the sheath; (iii) the drift-ambipolar mode, typical for electronegative discharges, where the low electron density in the bulk plasma necessiates a high electric field to build up, that in turn, accelerates the electrons to high energies and leads to significant ionization in the bulk and at the collapsing sheath edge. The ions heading towards the electrodes have to traverse the sheaths and their IFEDF is established during this flight.

In the formation of the IFEDF the collisionality of the sheaths and the duration of the transfer of the ions via the sheaths play the commanding roles. At low pressures and narrow sheath widths collisionless transfer prevails, while, in the other extreme case, when the sheaths are much longer than the free path of the ions, low energy ions reach the electrodes under the conditions of highly collisional transport. By changing the pressure and the driving RF voltage amplitude a variety of IFEDFs can be realized. The formation of these is understood by modeling of the ion transport within the sheath [3,4].

Additional control over the IFEDF, and over the separate control of the mean ion energy and the ion flux was first made possible by introducing “dual-frequency (DF) excitation” to drive capacitively coupled plasmas in 1992 [5]. In the case of significantly different driving frequencies, the plasma production and charged particle densities are primarily controlled by the amplitude of the high-frequency voltage, while the transport of the ions across the sheaths is principally defined by the low-frequency voltage amplitude. The properties of plasma sources driven by DF waveforms have thoroughly been studied, e.g. in [6]. It has, however, also been realized that this independent control is limited by "frequency coupling" effects [7], and the secondary electron emission from the electrodes limits the parameter window where nearly independent control of ion properties can be realized [8].

An alternative way to realize the independent control of ion properties was proposed in 2008 [9]. In this scheme, a base radio frequency and its (phase-locked) second harmonic were applied to the discharge. It has been shown that this type of excitation induces a significant DC self-bias and an electrical asymmetry even in the case of geometrically symmetric reactors ("Electrical Asymetry Effect", EAE). This self-bias – that has a direct effect on the energy of the ions at the electrodes – can be controlled by the phase between the harmonics, while the ion flux remains approximately constant. The performance of the EAE in various gases and across pressure regimes has been studied extensively. The possibility of using a higher number of harmonics (leading to "peaks" and "valleys" type waveforms) and the optimization of the harmonic voltage amplitudes have also been explored [10].

As a further step for the optimization of ion properties, and in more general, controlling the charged species dynamics, the use of sawtooth-type waveforms was introduced in 2014 [11]. Recently, excitation by multi-frequency waveforms became known as using "Tailored Voltage Waveforms" (TVWs); for a comprehensive review on this topic see [12]. It is expected that by applying a high number of harmonics and adjusting their amplitudes as well as phases, distinct features in the IFEDF can be realized, as reported in [13].

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