A Novel and Simple Method for Independent Control of Ion Energy and Flux

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One of the major demands in plasma processing has always been the independent control of ion energy and ion flux. Dual-frequency discharges with one low frequency in the MHz range and a second high frequency of typically several 10 MHz partially fulfill this requirement. However, recent investigations have shown that electron heating is dependent on both frequencies and a fully independent control is usually not achieved. Here we propose an alternative concept based on a simple, but previously overlooked asymmetry effect that should allow fulfilling the above demand in an almost ideal way [1, 2].

The idea is that when a temporally symmetric, multi-frequency voltage wave form containing one or more even harmonics is applied to a discharge, even a geometrically symmetric one, the two sheaths are necessarily asymmetric and a DC self bias develops. Optimally this is achieved with a dual frequency discharge that uses the phase locked fundamental frequency and its second harmonic, e.g. 13.56 MHz and 27 MHz, with both voltages having the same amplitudes. The resulting DC self bias and hence the ion energy is a nearly linear function of the phase angle between the two applied RF voltages (Fig. 1). This works especially well in geometrically symmetric discharges, and the roles of the two electrodes can be reversed using the phase. Therefore, the ion energy can be precisely controlled over a wide dynamic range of typically a factor three to four between the minimum and maximum energy (Fig. 2). While the energy at one electrode is increasing it is decreasing accordingly at the other electrode. The effect is self-amplifying since the different sheath voltages resulting from the temporal asymmetry lead to different sheath densities and thereby increase the asymmetry effect. While the ion energy changes with phase, the total power put into the discharge, the plasma density, and the ion flux to the substrate and electrode remain constant within a few percent.

The concept is developed and analyzed in three ways: An analytical proof and model, a hybrid hydrodynamic and Monte-Carlo kinetic model [1], and a self consistent particle-in-cell simulation (PIC) [2]. All three models yield identical results with the PIC simulation revealing further insight into kinetic details. The presentation will explain the theoretical basis of the novel concept and will present results from the model and simulations on the voltage waveform, the ion energy and flux, the electron heating and energy distribution function, the bias control, and parameter dependences.

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[1] Brian G. Heil, Uwe Czarnetzki, Ralf Peter Brinkmann, Thomas Mussenbrock, accepted for publication JPhysD: Appl. Phys. (2008)

[2] Zoltan Donkó, Julian Schulze, Brian G. Heil, Uwe Czarnetzki, in preparation for JPhysD: Appl. Phys. (2008)

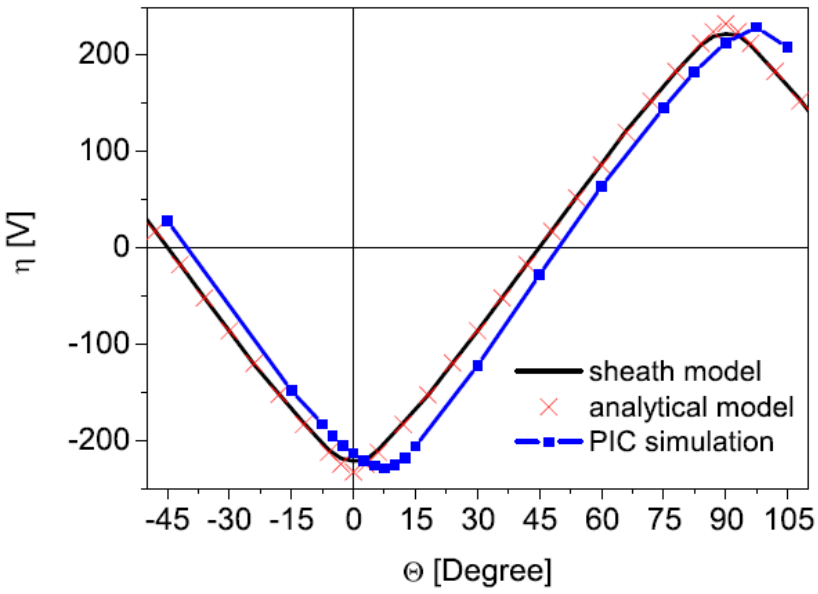

Fig. 1: Self-bias voltage η versus phase angle θ for a symmetric CCP discharge with the following discharge conditions: p = 2.7 Pa (Ar), electrode gap = 6.7 cm. The applied RF voltage is composed of a fundamental component at f = 13.56 MHz and its second harmonic with equal voltage amplitudes V_0 = 315 V: $V_{AC}(t)=V_0\left(\cos(2\pi f t+\theta)+\cos(4\pi f t)\right)$

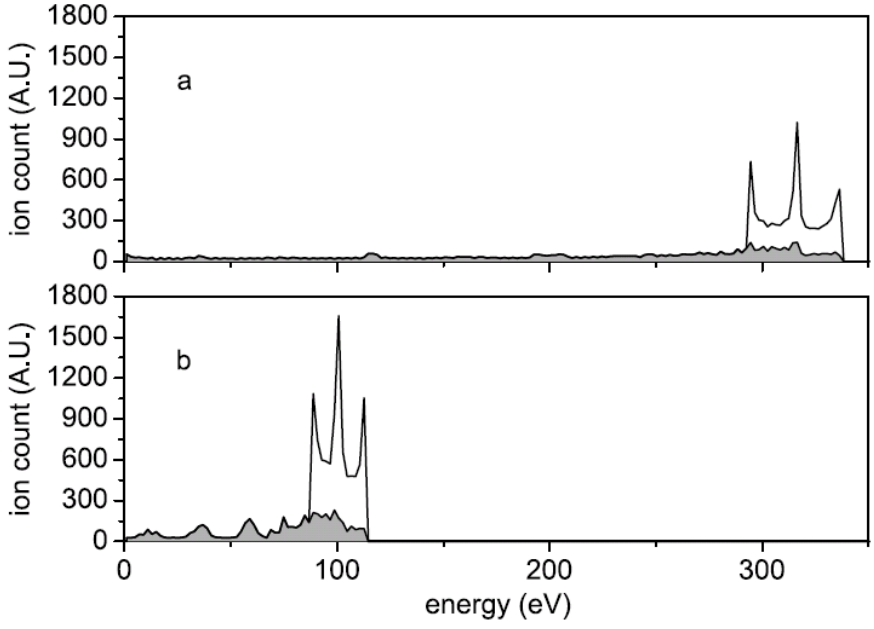

Fig. 2: Ar-ion energy distribution functions (IEDs) shown for phase-angles θ = 0 and θ = π/2. When θ = 0, (a) is the IED for the powered electrode and (b) is the IED for the grounded electrode. When θ = π/2, (b) is the IED for the powered electrode and (a) is the IED for the grounded electrode. The IED for all ions reaching the electrode is plotted. The shaded region only marks the fraction of the IED that is due to ions that underwent an ion exchange collision before reaching the electrode.