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The Electrical Asymmetry Effect in Capacitive RF Discharges

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Technical plasmas are often generated by radio-frequency (RF) fields in the MHz regime. In particular capacitively coupled RF plasmas have found wide industrial application ranging from semiconductor etching to thin film deposition as e.g. in large area production of solar-cells. In all cases the processes on the substrate surface are critically dependent on the energy and flux of the impinging ions. Therefore, independent control of these parameters is the major aim of various alternative concepts developed in the past. However, in practice this is realized even in the best case only to some rough approximation.

The recently invented electrical asymmetry effect provides a novel solution by adjusting as a control parameter the relative phase between two harmonic RF frequencies [1]. This meets not only the above requirements in an almost ideal way but allows in addition for the first time breaking the symmetry in geometrically symmetric discharges (Fig. 1). There the phase can be set so that the ion energy is increased on one electrode and reduced on the other or vice versa. This has not only a number of technical advantages but leads also to a highly interesting dynamics of the electrons and ions in the plasma. The physics of the resulting non-linear system can be reduced to a few basic principles that allow an analytic treatment. The results of the analytical model are compared with particle-in-cell (PIC) / Monte Carlo (MC) simulations and experiments [1-5]. Although the system is characterized by a high degree of complexity all three approaches show remarkable agreements. Ultimately this leads to a detailed understanding not only of the dynamics of the electrical asymmetry effect but also of the physics of capacitively coupled plasmas in general.

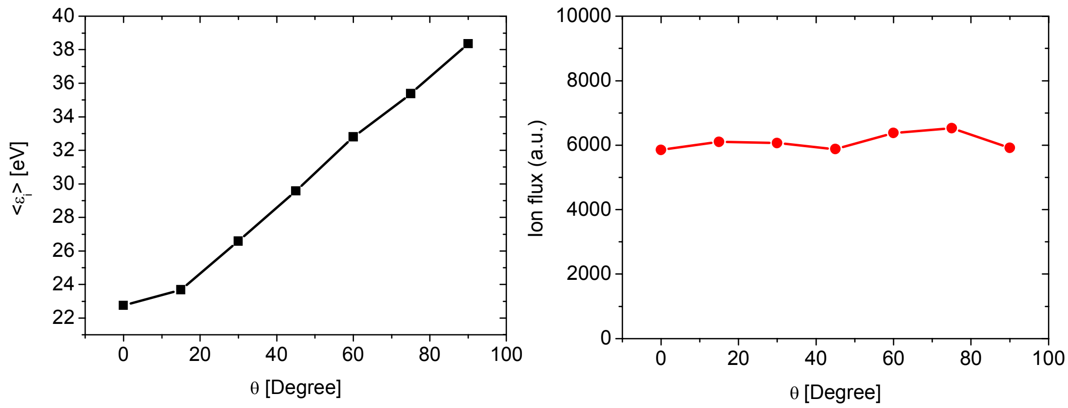

Fig. 1: Measured ion energy and ion flux as a function of the phase angle between the applied RF voltages at 13.56 MHz and 27.18 MHz in an argon discharge at p = 4 Pa [4].

The effect can be understood by the concept of an approximately temporally constant space charge Q in the discharge. This space charge is distributed almost entirely in the sheath regions. At the extremes of the applied RF voltage, the sheath voltages collapse and the corresponding space charge is approximately zero at one sheath while it is maximum at the other. Since the total space charge has to be conserved and the sheath voltages are related to the space charge by Poisson's equation this leads ultimately to a relation between the self-bias and the extremes of the applied RF voltage waveform $\left(\tilde{\phi}_{m1} > 0 > \tilde{\phi}_{m2}\right)$:

$$\eta = -\frac{\tilde{\phi}_{m1} + \varepsilon\,\tilde{\phi}_{m2}}{1+\varepsilon}. \tag{1}$$

The key parameter in this relation is the symmetry parameter ε:

$$\varepsilon = \left(\frac{A_p}{A_g}\right)^2 \frac{\bar{n}_{sp}}{\bar{n}_{sg}}. \tag{2}$$

The symmetry parameter depends on the sheath area ratio (powered electrode and ground) and the corresponding mean ion densities in the sheaths. In a totally symmetric discharge ε = 1. For a single applied frequency the two voltage extremes cancel and no bias exists. However, if the voltage amplitudes differ in their absolute values a finite bias results. Such a difference can be realized by adding an even harmonic to a fundamental frequency. The effect is strongest for the combination ω plus 2ω. By normalizing the RF voltage to the voltage amplitudes of the individual frequencies and choosing equal amplitudes for both frequencies the applied RF waveform is:

$$\tilde{\phi}(t) = \frac{1}{2}\left(\cos(\omega t + \theta) + \cos(2\omega t)\right). \tag{3}$$

The amplitude and sign of the bias is then a pure function of the relative phase of the two frequencies. On the other hand, combinations of the fundamental frequency with an odd harmonic can never generate any bias.

Once a bias is established a difference in the mean sheath voltages and consequently also in mean ion densities results. According to equation (2) this causes the symmetry parameter to deviate from unity and by equation (1) the bias is further enhanced. This behaviour is called the self-amplification of the electrical asymmetry effect (Fig. 2). It is strongest at low pressures since in the collisionless case the mean ion density is more sensitive to the sheath voltage than in the highly collisional case at high pressures.

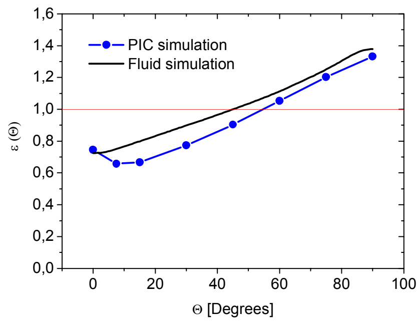

Fig. 2: Variation of the symmetry parameter in a geometrical symmetric discharge in argon at 2.7 Pa and U = 315 V with an electrode separation of d = 6.7 cm [2]. The small difference between the pure fluid dynamical simulation using the Brinkmann sheath model and the PIC-MC simulation is due to the finite variation of the total space charge by about 10 %. This variation is neglected in the pure fluid dynamical simulation.

Control of the bias results in a similar control of the ion energy since the ions can respond only to the temporal average of the sheath voltage due to their high inertia (Fig. 3).

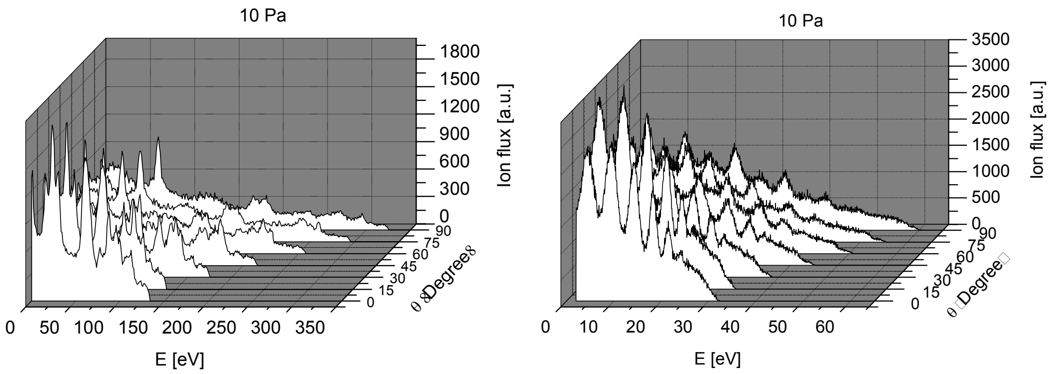

Fig. 3: Control of the ion energy by the phase angle in an argon discharge at 13.56 MHz and 27.12 MHz. On the left the result of a PIC-MC simulation is shown (electrode spacing d = 2 cm, U = 300 V) [2], on the right experimental data obtained by a Balzer Plasma Process Monitor (PPM422) are presented (d = 2.5 cm, U = 65 V) [4].

The flux to the electrodes is approximately independent of the phase angle since the power input into the electrons does not vary. Although the temporal distribution of the power input is a strong function of the phase angle, the integral over the total RF period is in good approximation a constant. Using the quadratic charge-voltage relation for the RF sheath [6] and ignoring the bulk contribution to the total voltage an analytical expression for the charge in the sheath can be derived [1]. This yields by differentiation the current density and finally the power coupled to the electrons:

$$P_e(t) \propto j^2 \propto \frac{1+\varepsilon}{4} \frac{\dot{\tilde{\phi}}(t)^2}{\tilde{\phi}_{m1} - \varepsilon^2 \tilde{\phi}_{m2} - (1-\varepsilon)\tilde{\phi}(t)}. \tag{4}$$

The denominator is only weakly dependent on the time varying RF voltage and consequently the value of the period averaging integral is dominated by the nominator. However, the value of the integral over the nominator is independent of the phase. A minor phase dependence is introduced by the symmetry parameter and the voltage extremes which also vary with the phase θ as shown above. The actual variation of ε(θ) can not be calculated by the analytical model but using values from the PIC simulation it can be shown that this has only a small effect and the power coupled to the electrons is approximately independent of the phase angle. Since the plasma density and the Bohm flux into the sheath are determined mainly by the power coupled to the electrons also the ion flux stays constant.

The opportunity to control the symmetry of the discharge allows also for the first time the generation of non-linear self-excited series resonance (PSR) oscillations of the current in geometrically symmetric discharges. This effect has been shown recently to play an eminent role in the power deposition in low pressure strongly asymmetric discharges [6-8]. There, the non-linearity of the sheath at the powered electrode together with the bulk forms a non-linear oscillator that is excited by the collapse of the sheath and then oscillates at frequencies typically an order of magnitude higher than the applied RF frequency. However, this non-linearity vanishes for two symmetric sheaths as is the case in geometrically symmetric discharges. By the electrical asymmetry effect this symmetry can be broken and consequently PSR oscillations can be switched on and off by adjusting the phase.

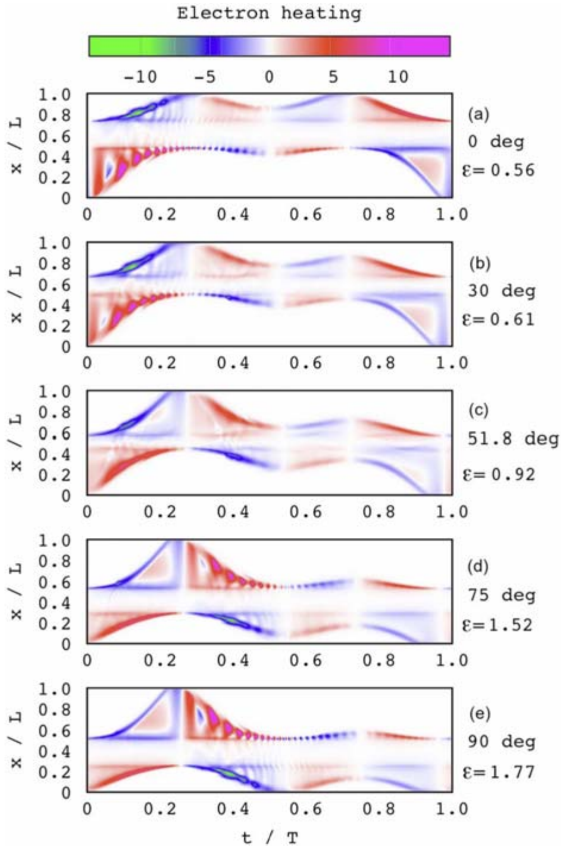

Fig. 4: Electron heating rate at various phase angles calculated by a PIC-MC simulation in argon at a pressure of p = 3 Pa. High frequency oscillations are clearly visible for values of the symmetry parameter deviating from unity [3].

The presentation will show further results on the excitation and charge dynamics and the optimization of the amplitude ratio. Finally, first applications in industry on thin-film solar-cell production are shown. They demonstrate superior performance by immediately more than doubling the deposition rate of silicon without loss in quantum efficiency.

Acknowledgement

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