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Electron heating and the Electrical Asymmetry Effect in capacitively coupled RF discharges

JULIAN SCHULZE, Ruhr-University Bochum

For applications of capacitive radio frequency discharges, the control of particle distribution functions at the substrate surface is essential. Their spatio-temporal shape is the result of complex heating mechanisms of the respective species. Enhanced process control, therefore, requires a detailed understanding of the heating dynamics. There are two known modes of discharge operation: α- and γ-mode. In α-mode, most ionization is caused by electron beams generated by the expanding sheaths and field reversals during sheath collapse, while in γ-mode secondary electrons dominate the ionisation. In strongly electronegative discharges, a third heating mode is observed. Due to the low electron density in the discharge center the bulk conductivity is reduced and a high electric field is generated to drive the RF current through the discharge center. In this field, electrons are accelerated and cause significant ionisation in the bulk. This bulk heating mode is observed experimentally and by PIC simulations in CF_4 discharges. The electron dynamics and mode transitions as a function of driving voltage and pressure are discussed. Based on a detailed understanding of the heating dynamics, the concept of separate control of the ion mean energy and flux in classical dual-frequency discharges is demonstrated to fail under process relevant conditions. To overcome these limitations of process control, the Electrical Asymmetry Effect (EAE) is proposed in discharges driven at multiple consecutive harmonics with adjustable phase shifts between the driving frequencies. Its concept and a recipe to optimize the driving voltage waveform are introduced. The functionality of the EAE in different gases and first applications to large area solar cell manufacturing are discussed. Finally, limitations caused by the bulk heating in strongly electronegative discharges are outlined.