Frequency coupling in dual frequency capacitively coupled radio-frequency plasmas

T. Gans, a) J. Schulze, D. O’Connell, and U. Czarnetzki
Institute for Plasma and Atomic Physics, CPST, Ruhr-University Bochum, 44780 Bochum, Germany
R. Faulkner, A. R. Ellingboe, and M. M. Turner
National Centre for Plasma Science and Technology, Dublin City University, Dublin 9, Ireland

(Received 26 July 2006; accepted 27 November 2006; published online 29 December 2006)

An industrial, confined, dual frequency, capacitively coupled, radio-frequency plasma etch reactor (Exelan®, Lam Research) has been modified for spatially resolved optical measurements. Space and phase resolved optical emission spectroscopy yields insight into the dynamics of the discharge. A strong coupling of the two frequencies is observed in the emission profiles. Consequently, the ionization dynamics, probed through excitation, is determined by both frequencies. The control of plasma density by the high frequency is, therefore, also influenced by the low frequency. Hence, separate control of plasma density and ion energy is rather complex. © 2006 American Institute of Physics. [DOI: 10.1063/1.2425044]

Surface modifications using nonequilibrium low temperature plasmas are used in numerous technological applications. These surface processes are governed by the synergy of impacting ions and reactive particles approaching the surface. The plasma chemistry, and thus concentrations of reactive particles, is predominantly driven by energetic electrons. The electron dynamics is, therefore, of crucial significance in processing plasmas, governing dissociation, excitation, and ionization processes.

Capacitively coupled plasmas (CCPs) operated simultaneously with two radio frequencies (rf) are used to achieve separate control of plasma density and ion impact energy onto the substrate.1–9 The plasma density is expected to be controlled by the higher frequency, while the ion energy is mainly determined by the lower frequency. This functional separation has been observed in an asymmetric CCP with two frequencies applied to different electrodes.3 The electron dynamics in a sheath governed by both frequencies simultaneously is significantly more complex and not yet fully understood.1,8,9 There is, in particular, a considerable lack of experimental investigations.10

Phase resolved optical emission spectroscopy (PROES) yields direct insight into electron dynamics and power coupling mechanisms.11–14 In this letter, PROES, with temporal resolution within the low-frequency rf cycle, is applied to investigate a modified industrial dual frequency CCP (2f-CCP) etch reactor (Exelan®, Lam Research).

A modified industrial 2f-CCP etch reactor (Exelan®, Lam Research) has been investigated (Fig. 1). The gap between the two, plane, parallel plate, electrodes is 13 mm and the radius is 110 mm. The bottom electrode is powered with both frequencies (2 and 27.12 MHz) simultaneously and the top electrode is grounded. A showerhead design of the top electrode is used for gas supply. Measurements were taken with a silicon wafer clamped to the bottom electrode and cooled with He gas flow. Two quartz rings surrounding the electrode gap produce a pressure gradient between the discharge volume (wafer area) and the pump region. The electrical isolation provided by the dielectric rings in combination with the reduced pressure in the pump region, prevents plasma breakdown in the outer region, resulting in a symmetric discharge in the wafer area.

The commercial reactor was modified allowing access for optical diagnostics. The viewport was expanded and a small section of the confinement rings has been replaced by an optical quality quartz block providing optical access across the entire discharge gap. The plasma emission is imaged onto the entrance slit of a 2 m spectrometer (PGS 2, 1302 grooves/mm).

The detector used is an intensified charge coupled device (ICCD) camera (PicoStar, LaVision) allowing very high repetition rates. These high repetition rates allow the collection of photons originating from a particular rf phase, in every low-frequency rf cycle, with one-dimensional spatial resolution along the discharge axis. Each measurement is the temporal integration of numerous rf cycles. The camera is triggered and synchronized with the low-frequency signal (Fig. 2).

Figure 3 shows the time and space resolved optical emission from a dual frequency discharge operated at $P_{27}$=800 W and $P_2$=200 W. The emission recorded is from the He $^3$S state at $\lambda=706.5$ nm ($\tau=36.1$ ns) in a He–O₂ discharge [1500 SCCM (SCCM denotes cubic centimeter per minute at STP) He, 1000 SCCM O₂ at 490 mTorr]. The entire low-frequency cycle is scanned with a resolution of 36.88 ns, averaging over the dynamics within the high-frequency cycle. In Fig. 3 the abscissa shows the phase of the 2 MHz cycle, whereas the ordinate corresponds to the distance between bottom ($y=0$) and top ($y=1$) electrodes.

The emission and corresponding excitation exhibit a pronounced dynamics within the low-frequency cycle. The confined discharge is symmetric with similar excitation mechanisms occurring in front of both electrodes. Two double peak structures can be easily identified: two peaks (indicated as 2 and 27) at the bottom electrode at different phases in the rf cycle and two peaks (indicated as 27’ and 2’) close to the top electrode at the same phases. The two peaks at each electrode are separated by half a low frequency cycle. Separate

a)Present address: Centre for Plasma Physics, Queen’s University Belfast, Belfast BT7 1NN, Northern Ireland, United Kingdom; electronic mail: timo.gans@web.de

0003-6951/2006/89(26)/261502/3/$23.00 89, 261502-1 © 2006 American Institute of Physics
power variations of both frequency components show a “diagonal correlation” of the peaks. With increasing 27 MHz power the peaks indicated as 27 and 27' increase in relation to the other two peaks, and for increasing 2 MHz power the peaks indicated as 2 and 2' increase correspondingly. These dependences illustrate that the excitation mechanisms in front of both electrodes are of the same nature and hence 180° out of phase.

The pronounced maxima around the sheath edge are typical for CCPs in α mode, where energetic electrons are created in the rapidly moving sheath and penetrate into the plasma bulk. An interesting feature becomes obvious when comparing the dynamics of the dual frequency discharge to the dynamics in single frequency operation with 2 MHz only. Figure 4 shows the temporal modulation of the emission, spatially integrated and normalized to the phase averaged emission, for single and dual frequency operations. The emission maxima, of dual and single frequency operation, are clearly separated by distinct phase shifts of about 45°.

The two maxima in single frequency operation are caused by two processes: energetic electrons, created in the rapidly moving sheath during the sheath expansion phase, and secondary electrons, produced when ion bombardment of the electrode is highest. Excitation during the sheath expansion occurs typically about 45° after the sheath collapse and maximum ion bombardment can be expected, due to ion inertia, about 45° after maximum sheath potential.

Consequently, the dynamics in the dual frequency discharge, including the observed frequency coupling, with diagonal correlation under power variations, and the phase shift in comparison to single frequency operation, can be understood in the following picture.

The rapid oscillations of the sheath edge, determined by the high-frequency component, drive the energy gain of electrons. The velocity of these oscillations depends on the spatial movement of the sheath edge and, therefore, on the local ion density. The spatial structure of the sheath is predominantly governed by the large low-frequency voltage. Thus, the position of the sheath edge oscillation is strongly determined by the low frequency. Ion flux conservation in the sheath results in a decrease of ion density towards the electrode. Depending on the phase of the low-frequency voltage, and the corresponding ion density in the vicinity of the sheath edge, the same high-frequency voltage change results in different spatial movements of the sheath edge. The lower the ion density, the larger the spatial movement, resulting in higher sheath velocities and, hence, increased energy gain for electrons.

This explains the strong coupling of both frequencies. Maximum energy gain for electrons can be expected around
the minimum voltage of the low-frequency component, when the sheath edge is close to the electrode, corresponding to low ion densities and extremely fast instantaneous sheath-edge velocities. Thus, the peaks $2$ and $2'$, corresponding to minimum low-frequency sheath voltages, are strongly dependent on the 2 MHz power, which governs the spatial structure of the sheath. Excitation through energetic electrons, created during these phases, decreases with penetration through the plasma bulk. Additional energy gain and increased excitation can be observed close to the opposite electrode at maximum sheath extension (peaks $27'$ and $27$). This energy gain, through high-frequency oscillations, is less dependent on the 2 MHz power since the spatial structure of the sheath is not as relevant.

The authors thank Paul Swift for his help with the experimental system. Support from Lam Research Inc., Enterprise Ireland ATRP/01/403, SFI, the EU (FP5), and the DFG (SFB 591 and GRK 1051) is greatly acknowledged.