Experimental study of a high-VHF multi-electrode capacitively coupled plasma for thin layer surface processing

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Abstract

Excitation of radio-frequency capacitively coupled plasma (CCPs) at very-high-frequency (VHF), 30-300MHz, have many advantages over conventional 13.56MHz CCPs for industrial processes. VHF facilitates lower ion energy bombardment, higher electron density and high energy reactions particularly ionisation and dissociation, while the average electron velocity remains low. Despite the numerous advantages over conventional 13.56MHz CCP, including application to PECVD of nc-Si [1] and SiN [2], there is still a lack of experimental data to fully explain and demonstrate the power coupling and plasma chemistry associated with VHF discharges. In this paper, we present an experimental study of a multi-tile electrode CCP operating at 162MHz, that eliminates electromagnetic standing wave and edge effects inherent to VHF. Electrode current and voltage is monitored and spatial electron density is investigated with a resonance hairpin probe. Energy resolved quadrupole mass spectrometry is utilized for ion energy distribution functions at both electrode centre and edge. Electropositive (Ar) and electronegative (O_2) discharges are investigated for several operating conditions and for different power coupling mechanisms.

Experimental Apparatus and Diagnostics

The plasma reactor used in this experiment is presented in Figure 1.

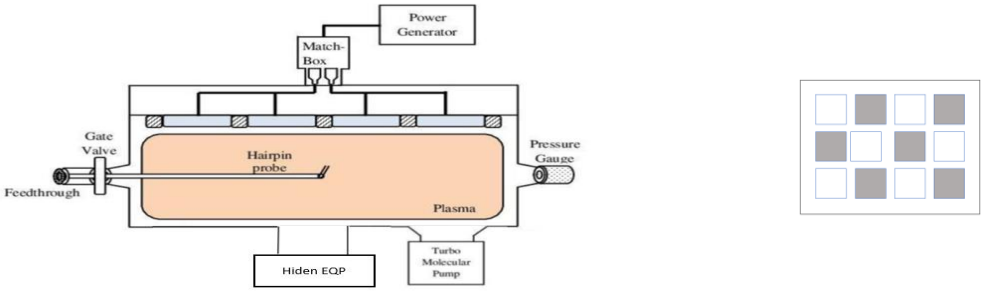

Figure 1. Side view of the apparatus (left) and multi-tile electrode checkerboard configuration (right)

The upper, powered, multi-tile electrode consists of a 3x4 array of 10x10 cm square aluminium tiles separated by 1cm wide alumina (resulting electrode size is 45x34 cm). The plasma discharge gap is 5.5 cm. 162MHz radio-frequency power is supplied via a matching unit and a Power Splitting Transmission Line Device (PSTLD). The PSTLD distributes the RF power equally among the 12 tiles in the 3x4 array. For this experiment, tiles are powered in checkerboard (push-pull) configuration, which means that each tile is 180^0 out of phase from its neighbouring tiles, shown in Figure 1 with white and grey coloured tiles representing 0 and 180^0 respectively. Current and voltage measurements are recorded simultaneously at each of 4 tiles in middle row of the reactor using Bergoz CT-E1.0-S probes and in-house made capacitive-voltage divider probes. Ion energy distributions (IEDs) and mass spectra are obtained with a Hiden Analytical electrostatic quadrupole plasma (EQP) system at the grounded electrode. A rotatable off-centre flange was designed and added to the end of the EQP system so that the orifice sampling position could be rotated from tile centre to tile edge.

Plasma density is measured by using a floating resonance hairpin probe. The probe, inserted by the side wall of the reactor, is positioned ~3cm from the multi-tile electrode, and the plane of the hairpin is perpendicular to the axis of both the probe and the multi-tile array for best plasma density resolution between tile centre and tile edge.

Results and Discussion

A. Powered Electrode Current and Voltage

Current I, voltage V, and phase shift between them φ, are measured at each of the 4 tiles in the middle row of the reactor. Power is calculated from $P = \frac{1}{2} IVcos\varphi$. Figure 1 shows calculated power values at each of the tiles as function of total input power. Power is split equally to all 12 tiles via the PSTLD and twisted pair system [1].

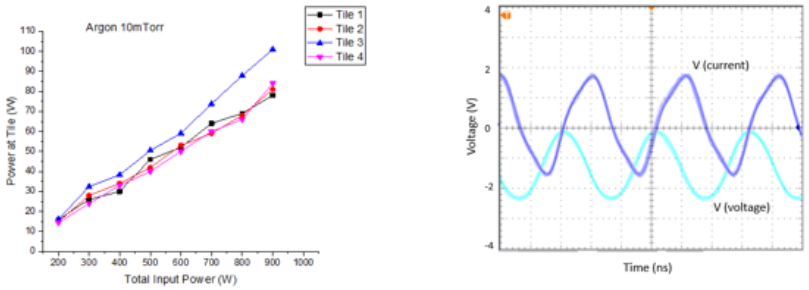

Figure 1. Power at tile electrode as function of total input power for Argon 10mTorr (left) and unprocessed current and voltage probe outputs (right)

B. Electron Density

Electron density is measured via a resonance hairpin probe across the 4 tiles in the middle row of the reactor. Figure 2 shows the uniform plasma density profile, i.e. full radial profile, measured for both Ar (left) and O_2 (right).

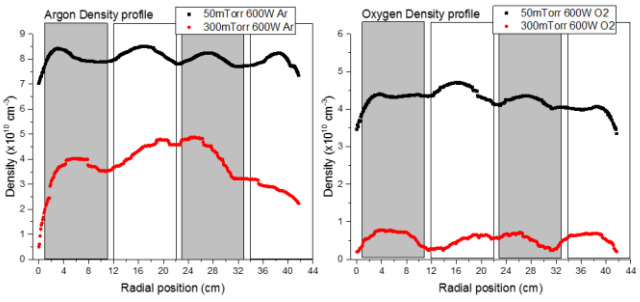

Figure 2. Spatial electron density profile for Ar (left) and O_2 (right) across 4 tiles. Coloured boxes present tile dimension and alternating phase.

The density profile shows good uniformity from tile centre to tile edge, i.e. variation in electron density is within 10%. Figure 2 shows two different operating pressures, 50 and 300mTorr, at fixed power level of 600W. At a fixed VHF power level, the decrease in density with increase in pressure is mainly due to increase in the collision energy lost per electron-ion pair production. This is evident in both cases. In case of O_2, as a molecular gas, such losses are higher due to excitation of rotationally, vibrationally or electronically excited states ion electron collisions with neutral gas molecules [2]. Thus, the high energy electrons are effectively involved in producing rotationally/vibrationally excited states and less energy is available for ionisation processes and therefore the plasma density decreases more profoundly with increase in operating gas pressure as compared with atomic Ar. Despite the uniformity,

however, there are subtle spatial structures imposed on the profile attributed to different power coupling mechanisms. For both Ar and O_2, at lower pressure of 50mTorr, electron density is higher at tile centre, whereas at higher pressure of 300mTorr, electron density is higher at tile edge. This change at higher pressure is due to the electrostatic field at the tile edge boundary. Power into these electrostatic fields scales with the sheath volume, tile-voltage and are dependent on the ratio of ν_{ei}/ω_{rf}, where ν_{ei} is the electron ion collision frequency. For a constant plasma excitation frequency, the ratio ν_{ei}/ω_{rf} increases with increasing pressure and therefore causes enhanced ionisation at the tile edge. This in turn causes higher plasma density at tile edge for higher pressure. Figure 3 shows plasma density variation at tile centre and tile edge for both gases as function of power. Power dissipated into the plasma increases with increasing power, and thus increases plasma density.

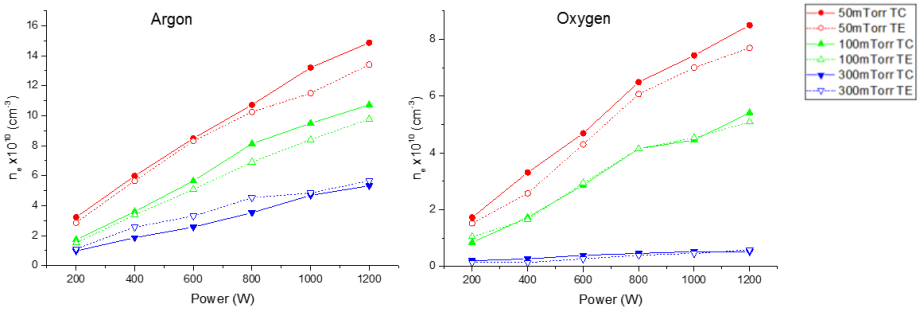

Figure 3. Electron density measured at tile centre (TC) and tile edge (TE) as function of power.

C. Grounded Electrode IEDs

The ion energy distribution functions measured by the EQP locates at tile centre and tile edge are shown in Figure 4 for Ar^+ at 300W and 50mTorr pressure. The IED shape is dominated by the ratio of the ion transit time, τ_{ion}, to the RF period, τ_{rf}. In the high frequency regime, which is the case for 162MHz, the ions no longer respond to the oscillating RF sheath, so the phase in which the ions enter the sheath is no longer relevant. Consequently, all the measured IEDs exhibit a single peak structure that is centred around the time-averaged sheath potential, $\overline{V_p}$. The ion energy is uniform from tile centre to tile edge with an average variation of $\approx$ 1eV when increasing power. The relative ion flux, however, determined from the area integral of the IED, increases at tile edge, as shown in Figure 4, for both Argon and Oxygen. This trend is also observed in measurements of positive ion flux using a planar electrostatic probe (not presented in this paper).

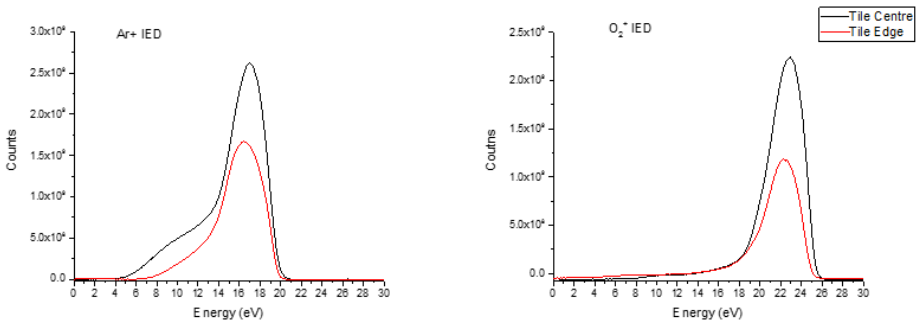

Figure 4. Ar^+ IED at 300W 50mTorr at tile centre and tile edge

Ar^+ ion energies do not increase more than 2eV with increasing power from 200W to 1000W for all pressures of 10, 50, and 100mTorr. This behaviour is also observed for Oxygen ions, O_2^+ and O^+, at pressures of 50 and 100mTorr. However, at 10mTorr in Oxygen, the ion energies initially increase, but then decrease after 600W, as shown in Figure 5 (left). This suggests a possible change in the sheath voltage resulting from volume produced negative ions in the bulk. As shown in Figure 3, electron density increases almost linearly with power, so to balance the suggested increase in negative ion production, we would expect to see a rise in relative flux of positive O^+ ions after 600W, we which do. This behaviour is evident at both tile centre and tile edge, and is shown in Figure 5.

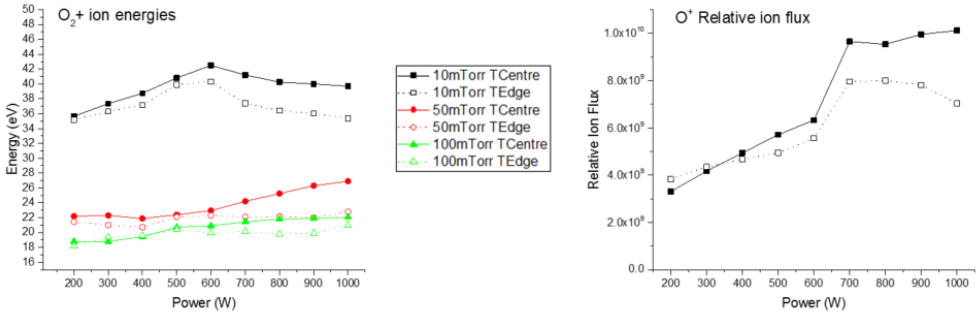

Figure 5. O_2^+ ion energies (left) and O^+ relative ion flux as function of power

Conclusions

An experimental study of a multi-tile electrode CCP operating at 162MHz has been presented. The power splitting device and twisted pair transmission lines distributes power equally to all 12 tiles shown from current and voltage measurements at each tile in 1 row. Uniform plasma density profile is presented (<10% variation from tile edge to tile centre). Changes in the subtle imposed spatial structures are attributed to different power coupling mechanisms. Ion energy distributions are obtained at both tile centre and tile edge. Uniform ion energy (within ≈ 1eV) is presented, but higher ion flux is observed at tile centre. The experimental results show that favourable uniform plasma can be maintained over a large area, and such, highly non-equilibrium conditions at VHF excitation can produce unique gas phase plasma chemistry to drive favourable surface reactions for material processing

References

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