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Study of Bipolar Pulsed Plasma Dynamics for Surface Processing Applications

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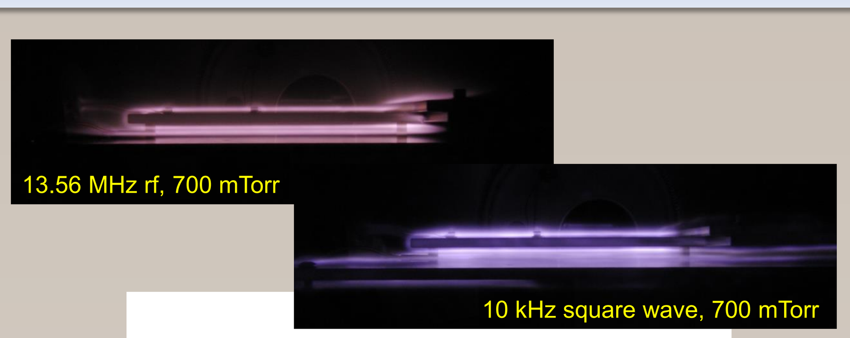
1. Background

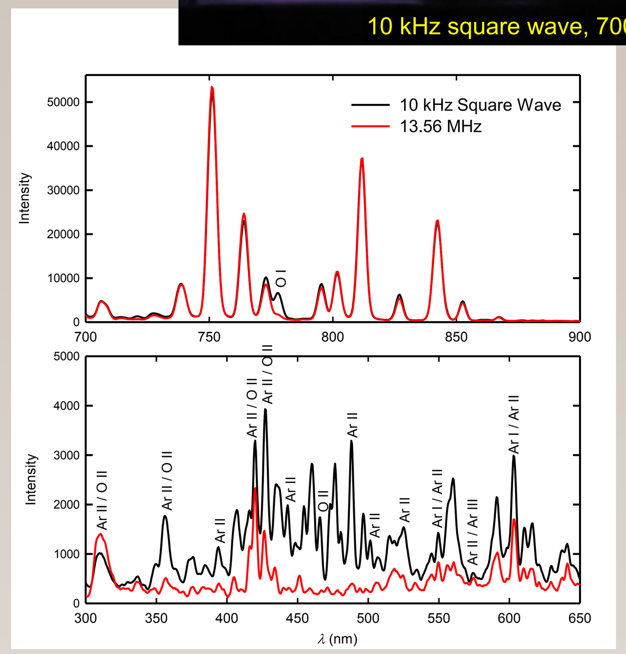
- Plasma techniques are ubiquitous in many surface processing applications, e.g. material etching, surface cleaning, film deposition.
- Both rf and pulsed dc plasmas are commonly employed.
  - Particularly, rf capacitively-coupled plasma for plasma etching and cleaning.
  - Pulsed-dc plasma for depositing thin films.
- Pulsed plasma is of particular interest:
  - Enhancement of ion energy through an intense peak voltage.
  - Eliminate target poisoning using an asymmetric bipolar pulse by preferential sputtering.
  - Control of electron energy distributions and plasma properties uniformity for microelectronic fabrication via pulse frequency and duty cycle.
  - Flexibility in controlling critical plasma parameters, e.g. ion/radical densities and fluxes, ion energies, electron temperature.
- Previously demonstrated the ability to manipulate the plasma parameters (density, E/N) of a small-scaled pulsed plasma.
- Scaled up to larger system of interest to plasma processing community.
  - Comparison between rf and pulsed plasmas revealed interesting differences that could benefit certain applications.
- Objective is to probe the dynamics of a pulsed plasma to better understand its mechanism.

2. Observation with Large-Surface Plasma

Optical Emission Spectroscopy

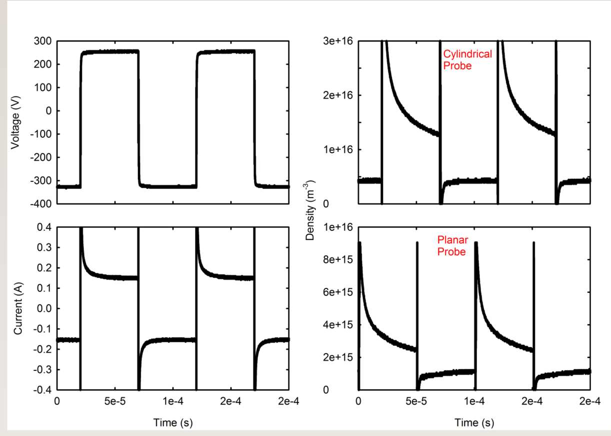
- Asymmetric parallel-plate assembly in a 700-liter cylindrical vacuum chamber.
- OES signals analyzed for plasmas generated by 10 kHz bipolar square wave vs. 13.56 MHz rf using 80/20% Ar/O_2.
- Plasma generated by square wave at similar powers looks visibly "bluer".
  - Confirmed by OES signals showing stronger lines in 'blue' region. Most of the peaks identified as ion lines.
  - Bluer lines → higher-energy transitions → higher electron energy → higher ionization?
  - Higher ion density/flux to electrode surface?





Langmuir Probe

- Cylindrical probe inserted ~mid-height in AK gap.
- Planar probes affixed to grounded plate.
- Probes biased at -45 V to collect ion saturation current.
- Ion density estimate: 10^{15}-10^{16} m^{-3}.
  - Correlates well with simulation.
- Comparison with dc discharges suggests field reversal plays a major role.
  - What happens at field reversal?
  - How does it impact ionization? OES signals suggest increased ionization for square waves.



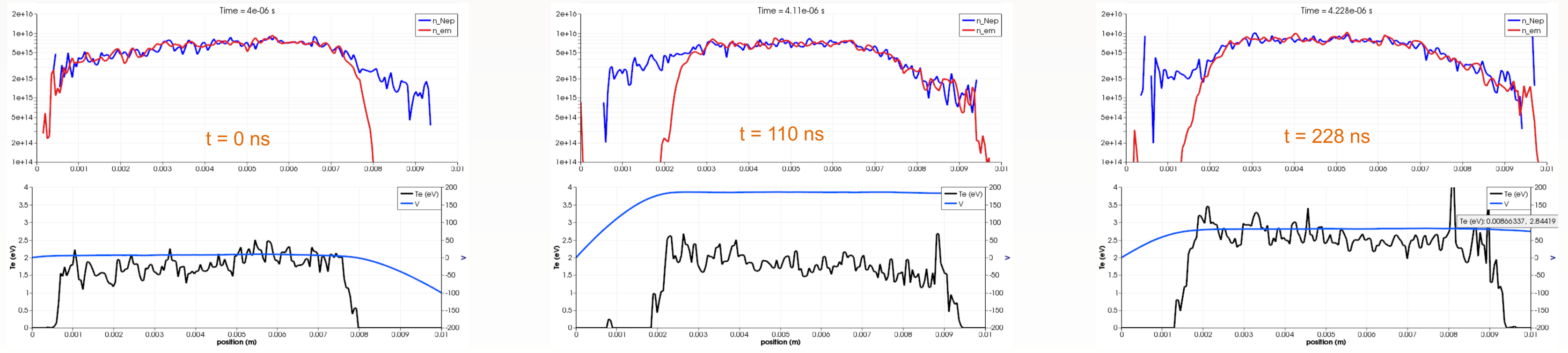
3. Modeling and Simulation

- Scoping study to address questions raised by experimental observations.
  - PIC for coupled particle-field plasma simulation.
  - DSMC for particle kinetics/chemistry.
- Modeling expedients taken:
  - gas was neon (existing set of neon chemistry; vetted cross section).
  - 1D3V: 1-cm domain.
  - 500 kHz (reduced computational time) – quasi-steady state in <1 μs.
- Polarity switch in low-frequency square wave causes much more abrupt potential variation than sinusoidals to support interesting transport phenomena; ions will not see electric field at high frequency.

Polarity Reversal

- Electron pulsing: generation of a "wave" of higher temperature electrons leading to more ionization.
- "Sheath capture" of low energy ions: a higher density bolus of ions that are accelerated to the wall when the polarity switches.
- Plasma state at beginning of polarity switch.
  - Deep vs. shallow (at 110 ns vs. 0 ns) sheath structure at left boundary.
  - A population of ions "captured" and will be accelerated into the wall.
  - Increased electron temperature at 228 ns.

Time relative to 100-ns polarity switch

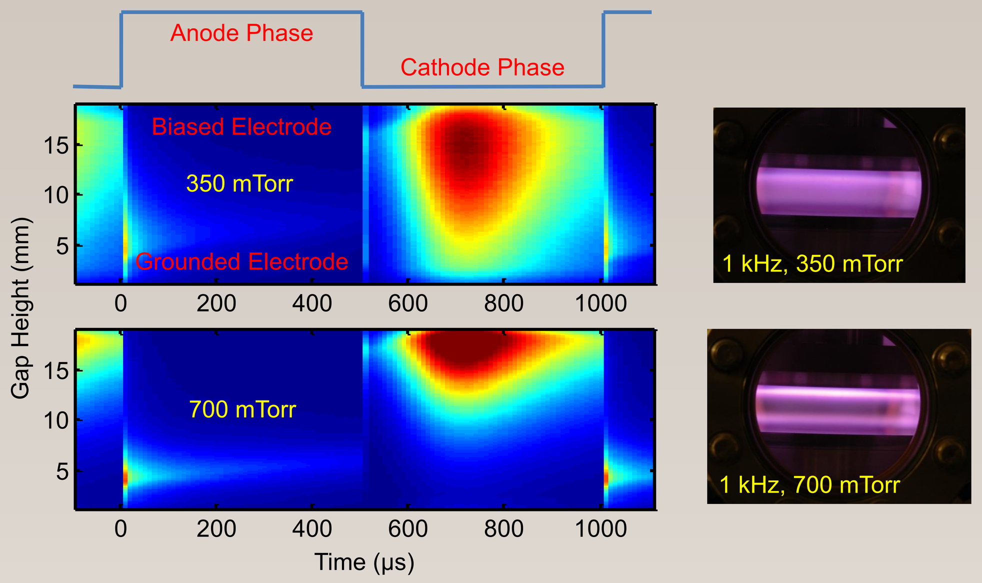


4a. Dynamics of Square-Wave Plasma

- Experimental observation in the large system and simulation suggested interesting plasma dynamics during pulses and especially during polarity switch.
- Brief investigation in the large system revealed pressure dependence of the dynamics.
- Set up an asymmetric parallel-plate test bed to investigate argon dynamics with optical diagnostics.

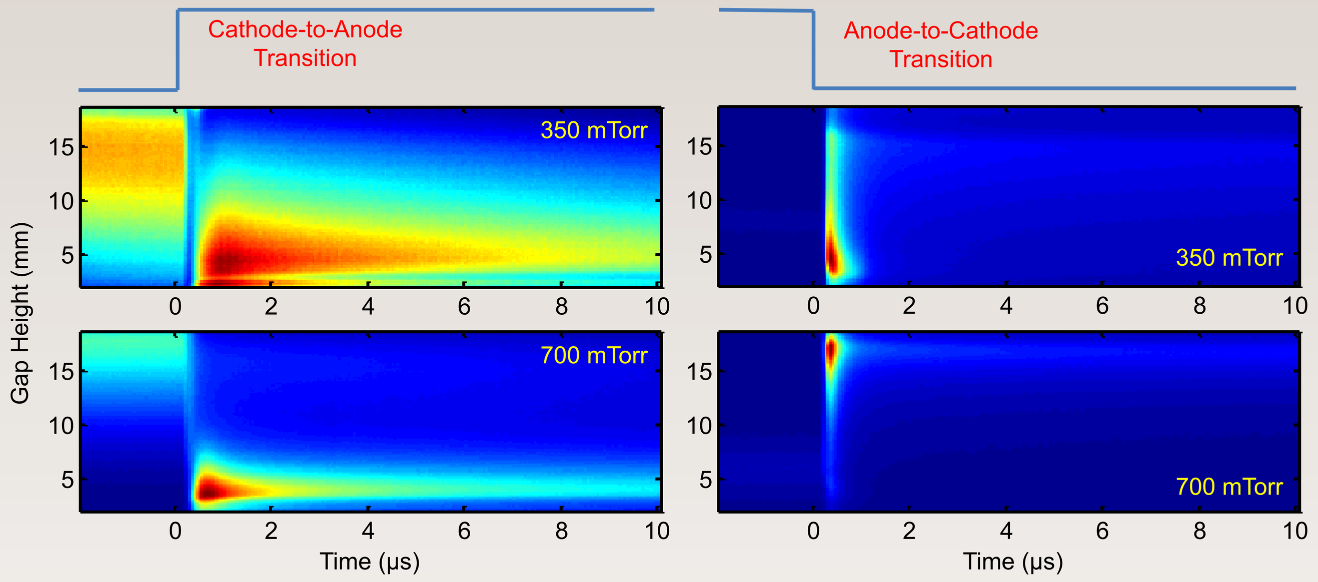
4b. Plasma Induced Emission

- ICCD camera to capture plasma formation during pulses.
- Streak-like images revealed pressure-dependent dynamics.
  - Collisionality dependence?
- PIE showed that "active" plasma occurs largely during the cathode phase.
  - Localized vs. diffused at high vs. low pressures.
- During the anode phase, plasma persists for short duration.
  - More energetic at higher pressure.



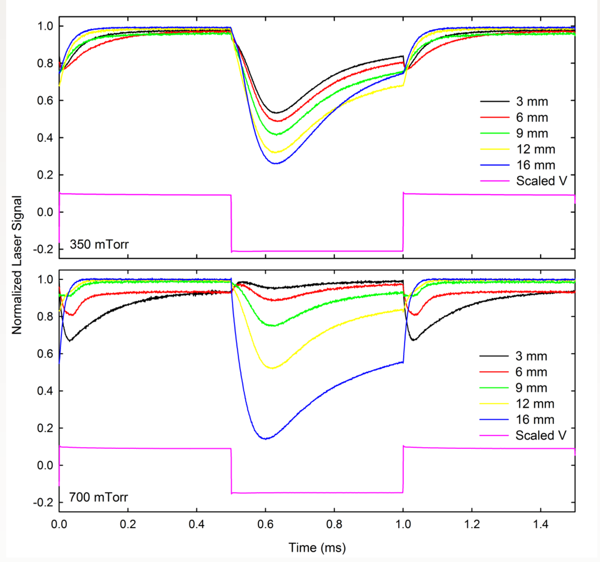
Polarity Reversal

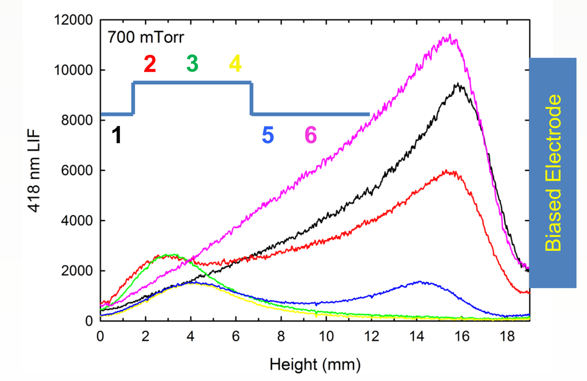
- PIE revealed fine structure near polarity switch.
- Transition occurs rapidly, ~hundreds of ns to μs time scale.
- During cathode-to-anode transition, plasma rapidly transitions from biased to grounded electrode to establish anode-phase plasma.
- During anode-to-cathode transition, a transient plasma forms as polarity switches before the main cathode-phase plasma forms.



4c. Evolution of Argon Metastable

- Probe plasma excitation state and track dynamics by measuring Ar $1s_5$ metastable concentration.
  - Diode laser absorption: probe 811.5-nm Ar $1s_5 \rightarrow 2p_9$ transition.
  - Planar LIF: excite Ar from $1s_5$ to $3p_2$ state, monitor 418.2-nm $3p_2 \rightarrow 1s_3$ transition.
- Laser absorption (top figure) shows evolution of Ar metastable during pulse as function of height in electrode gap.
  - Strong pressure dependence in the dynamics.
  - Cathode-to-anode transition displays drastically different dynamics at the two pressures.
  - Electrode area ratio scaling study might prove beneficial – at lower pressure, plasma is more diffused, more of the chamber wall acts as "grounded" electrode. How does this affect dynamics?
- LIF measures Ar metastable at discrete time-points of square wave pulse.
  - Transition of main plasma region from biased to grounded electrode as pulse moves from cathode to anode phase.
  - Drastically reduced metastable concentration at the end of anode phase, consistent with PIE observation.
  - Onset of metastable generation in anode-to-cathode transition.





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