Initial Measurements and Modeling of a Novel Reactor to Control Plasma Electron and Ion Distribution Functions

Vincent M. Donnelly and Demetre J. Economou

Department of Chemical and Biomolecular Engineering

University of Houston
Houston, TX 77204

Student: Wieye Zhu
Postdocs: Hyungjoo Shin, Paola Diomede

Funding: Department of Energy, NSF

Plasma Science Center
Predictive Control of Plasma Kinetics
Part 1: Experimental Studies

Motivations

• Control electron and ion energy and angular distributions through manipulation of plasma power modulation, boundary electrode voltages and charged particle and/or metastable injection.

• Further develop and validate the trace rare gases optical emission spectroscopy (TRG-OES) method for measurements of EEDFs (especially at high energies) and then make the method available to the center.
Plasma Reactor for Advanced Control of IEDFs and EEDFs

Features

• Pulsed rf power at 13.56 MHz delivered to lower plasma source.

• Faraday shield to eliminate rf plasma potential.

• Bias on boundary electrode controls the plasma potential.

• Ion energy controlled by either boundary electrode or substrate bias, or both.

• Top plasma source ignites and/or injects ions, electrons, radicals, metastables, etc into the lower plasma.
Plasma Reactor for Advanced Control of IEDFs and EEDFs

Biased or grounded stage (or movable Langmuir probe)

Faraday shield

Main ICP

Auxiliary ICP (not yet operational)

Biasable Boundary electrode

Faraday shield

Biased or grounded stage (or movable Langmuir probe)

To Optical Emission Spectrometer

Periscope
Langmuir probe measurements of positive ion densities in a 10 mTorr, 40 sccm Ar plasma.
• rf plasma potential measured on the “reference electrode” of the Langmuir probe.
• Faraday shield virtually eliminated the rf plasma potential – hence sharper IEDF
• Faraday shield also reduced the DC floating potential.
Effect of Faraday Shield on Plasma Density

300W 10mTorr

- without FS $n_i$
- with FS $n_i$
$T_e$ comparison with and without Faraday Shield

10 mTorr Ar

$T_e$ (eV) vs. $z$ (mm)

- Black line: without Faraday Shield
- Red line: with Faraday Shield
$n_e$ and $n_i$ as a Function of Power

10mTorr Ar
$n_e$ and $n_i$ as a Function of Pressure

300W, Ar

Langmuir probe-induced plasma charging
V_p (and hence mean ion energy) control by biasing the boundary electrode

![Diagram showing the relationship between V_p and z (mm) for different bias voltages.](image)

![Diagram showing the relationship between n_e (cm^-3) and z (mm) for different bias voltages.](image)
Pulsed plasma system

• 13.56 MHz power, 10kHz modulation frequency

• Vary duty cycle
• Measure $T_e$, $n_e$, $n_i^+$, etc.
• Motivation: Reduce IEDF, IADF
$T_e$ & $V_p$
$n_i \& n_e$

Graph showing the variation of $n_i$ and $n_e$ with time (us). The graph displays two separate plots for $n_i$ and $n_e$, with ON and OFF periods highlighted.
Unusual I-V Characteristics in the initial stages of the ON period under some conditions
EEPFs @10us into ON cycle as a function of duty cycle

- Cause of this unusual behavior still under investigation

*Different duty cycle results in different avg. power into plasma.

*The peak was observed except for CW.

period = 100 µs
location = 180 mm
Trace Rare Gases Optical Emission Spectroscopy (TRG-OES)

• Add non-perturbing traces (1% each) of Xe, Kr, Ar, and Ne to the process gas.

• $T_e$ and even EEDFs derived from optical emission from the Paschen 2p levels.

• $T_e$ is determined from a comparison of measured intensities with relative intensities computed from a model, with $T_e$ or the EEDF as an adjustable parameter.

Comparison of EEDFs in Cl₂ Plasma Measured with a Langmuir Probe and Derived from TRG-OES

- Current method: select lines that probe different e-energies and obtain “Tₑ”. Piece together EEDF from different Tₑs.
- Further development: 1) use function instead of Maxwellian EEDF, 2) use matrix method.

Rare gas e-impact cross sections

Electron Kinetic Energy (eV) vs. EEPF (eV⁻³/₂ cm⁻³) for different pressures (2 mTorr, 10 mTorr, 20 mTorr).

Cross Section (cm⁻²) vs. Energy (eV) for Ne, Ar, Kr, Xe.
Summary

• Novel reactor partially completed and successfully tested.
• Behavior as expected except for unusual oscillation in I-V characteristic during initial portion of ON cycle of pulsed ICP.

Future Work

• Investigate other rare gases, molecular gases
• Invoke full capabilities of the reactor (vary boundary voltage, pulsing of both ICPs, etc) and measure IEDFs.
• Explore injection of upper plasma into lower plasma for influencing EEDF.
• Begin TRG-OES validation and collaborations with center members
Part 2: Modeling and Simulations

Goals and Approach

• **General Goal**: Develop methodologies to achieve “tailored” plasma electron and ion energy distribution functions (EEDFs and IEDFs).

• Focus of this presentation is IEDFs.
  – **Conventional problem**: Given the plasma operating parameters, predict or measure the resulting IEDF.
  – **Inverse problem**: Given a desired IEDF, predict or establish the plasma operating parameters that will yield that IEDF.

• Ultimate goal is solution of the inverse problem.
• Use combination of experiments and modeling/simulation.
• Modeling is semi-analytic.
• Simulation is PIC using in-house codes (Nam, Economou and Donnelly, PSST, 16, 90 (2007)) or PDP1 (Verboncoeur, Alves, Vahedi, Birdsall, J. Comp. Phys., 104, 321 (1993)).
“Tailored” Ion Energy Distributions

Pulsed plasma with synchronous application of a boundary voltage, allow the generation of a nearly monoenergetic IEDF with controlled energy.


Pulsed Plasma can also Improve Ion Directionality

\[ \theta_{IAD} \sim \arctan \left( \frac{kT_{i,sh}}{eV_{sh}} \right)^{1/2} \]

Assumes collisionless sheath

- \( \theta_{IAD} \) : Ion angular distribution at substrate
- \( T_{i,sh} \) : Ion temperature in the plasma sheath edge
- \( V_{sh} \) : Sheath potential

\( T_{i}^{sh} \) scales with \( T_e \)

Lower \( T_e \) can improve the directionality of ions
Electrode Immersed in Semi-infinite CW Plasma

Plasma density and electron temperature are not affected by electrode potential

Bulk Plasma ($n_0, T_e$)

Sheath

Electrode (Target)

Blocking capacitor, $C_b$

Applied rf, $V_{rf}$
Semi-analytic Model (cont.)

Schematic of the sheath region

1. Electrode immersed in semi-infinite plasma of given electron (ion) density and electron temperature.
2. Electron, ion and displacement currents flow through the sheath.
3. Non-linear sheath capacitance $C_s$ is calculated from the electric field at the electrode, $E$.

$$C_s = -\varepsilon_0 A \frac{\partial E}{\partial V_s}$$

$$E = -\sqrt{2n_e kT_e \varepsilon_0 \left[ \exp \left( \frac{e(V_s - V_1)}{kT_e} \right) + \frac{V_s}{V_1} - 2 \right]^{1/2}}$$

Semi-analytic Model (cont.)


Desired voltage $V_{rf}$ is applied through blocking capacitor, $C_b$.

Given $n_0$, $T_e$, $V_{rf}$ and $C_b$, calculate $V_d$, $V_T$ and $V_p$.

Subscripts T and G refer to “target” and “ground” electrodes, respectively.

\[
C_b \frac{d}{dt}(V_{rf} - V_T) + C_T \frac{d}{dt}(V_P - V_T) + I_T = 0
\]

\[
C_T \frac{d}{dt}(V_P - V_T) + C_G \frac{d}{dt}V_P + I_T + I_G = 0
\]

\[
\frac{dV_d}{dt} = - \frac{V_d - V_T}{\tau_i}
\]

Ions respond to a “damped” potential $V_d$. 
Semi-analytic Model

- Having determined $V_d$, find ion energy distribution $P(E)$.

\[
P(E) = \frac{1}{2\pi} \left| \frac{dV_d}{d(\omega t)} \right|_{E=eV_d}^{-1}
\]

Tailored Voltage Waveforms

Apply a “tailored” voltage waveform (non-sinusoidal) on a target electrode so that the desired IEDF is obtained.

Tailored voltage waveforms: Spikes

Target voltage and Ar+ IEDF

PIC simulation:
\[ n_e = 4 \times 10^{16} \text{ m}^{-3}, \ T_e = 2 \text{eV} \]
Tailored voltage waveforms: Spikes

Semi-analytical model:

\[ n_e = 4 \times 10^{16} \text{ m}^{-3}, \quad T_e = 2 \text{ eV}, \quad C_B = 5 \text{ \mu F} \]
Tailored voltage waveforms: Staircase

Target voltage and Ar$^+$ IEDF
F. L. Buzzi et al. PSST, 18 (2009) 025009

PIC simulation:
$n_e = 4 \times 10^{16} \text{ m}^{-3}$, $T_e = 2 \text{eV}$
Tailored voltage waveforms: Staircase

Semi-analytical model:
\[ n_e = 4 \times 10^{16} \text{ m}^{-3}, \quad T_e = 2 \text{ eV}, \quad C_B = 5 \mu\text{F} \]
Tailored voltage waveforms: Square Wave (1)

Experiments (dashed line): H$_3^+$ ions
P.Kudlacek et al. JAP 106 (2009) 073303

PIC simulation:
$n_e = 2 \times 10^{16} \text{ m}^{-3}, T_e = 0.15 \text{ eV}$
Tailored voltage waveforms: Square Wave (1)

Semi-analytical model:
\[ n_e = 2 \times 10^{16} \text{ m}^{-3}, \quad T_e = 0.15 \text{ eV}, \quad C_B = 5 \mu\text{F} \]
Tailored voltage waveforms: Square Wave (2)

**PIC simulation:**

\[ n_e = 2 \times 10^{16} \text{ m}^{-3}, \ T_e = 0.15 \text{ eV}, \ f = 13.56 \text{ MHz} \]

![Voltage waveform](image1)

![Ion flux vs. ion energy](image2)
Tailored voltage waveforms: Square Wave (2)

Semi-analytical model:
\( n_e = 2 \times 10^{16} \text{ m}^{-3}, \quad T_e = 0.15 \text{ eV}, \quad C_B = 5 \ \mu\text{F} \)
Summary & Future Work

- The energy distribution of ions bombarding the substrate can be tailored by applying voltage waveforms with special shapes (e.g., spikes, staircase, square wave).
- Semi-analytic model can rapidly identify voltage waveforms that can result in tailored IEDFs.
- PIC simulation is useful for verifying and fine tuning such waveforms, and for studying the effect of collisions.

Future Work: Apply modeling/simulation to UH experiments, study effect of collisions, attack inverse problem.