“Designer” Ion Energy Distributions on Substrates Immersed in a Plasma

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Introduction / Motivation

- Control of the energy of ions bombarding a substrate in contact with plasma is critical for plasma processing.
- The ion energy must be high enough to drive anisotropic etching, but not too high to induce substrate damage and/or loss of selectivity.
- As device dimensions continue to shrink, precise control of the ion energy distribution (IED) becomes increasingly important.
Goal and Approach

**Goal:**
Develop methodologies to achieve “tailored” ion energy distribution functions (IEDFs).

**Approach:**
- Use combination of modeling/simulation and experiments.
- Modeling is semi-analytic.
- Simulation is PIC using XPDP1
  
Electrode Immersed in a Plasma

Plasma density and electron temperature are not affected by the applied potential.

Bulk Plasma \( (n_0, T_e) \)

Sheath

Electrode (Target)

Blocking capacitor, \( C_b \)

Applied rf, \( V_{rf} \)
Semi-analytic Model (1)

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, $E$.

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

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

Semi-analytic Model (2)


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

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

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

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

Ions respond to a “damped” potential \( V_d \).

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 \( V_P \).
Semi-analytic Model (3)

- 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: Spikes (1)

Target voltage and Ar⁺ IEDF, 500 kHz

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

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

PIC simulation:
\[ n_e = 4 \times 10^{16} \text{ m}^{-3}, \quad T_e = 2 \text{ eV}, \quad f = 10 \text{MHz} \]
Semi-analytical model:
\[ n_e = 4 \times 10^{16} \text{ m}^{-3}, \ T_e = 2 \text{ eV}, \ C_B = 5 \ \mu \text{F}, \ A_S/A_T = 1 \]

Tailored voltage waveforms: Spikes (4)
Tailored voltage waveforms: Staircase (1)

Target voltage and Ar⁺ IEDF, 500 kHz

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

Semi-analytical model:
\[ n_e = 4 \times 10^{16} \text{ m}^{-3}, \quad T_e = 2 \text{ eV}, \quad C_B = 5 \mu \text{F}, \quad A_s/A_T = 5 \]

![Graph showing voltage and ion flux vs. time and ion energy](image-url)
Tailored voltage waveforms: Square Wave (1)

**Experiments (dashed line):** $\text{H}_3^+$ ions, 195 kHz
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 (2)

Semi-analytical model:

\[ n_e = 2 \times 10^{16} \text{ m}^3, \quad T_e = 0.15 \text{ eV}, \quad C_B = 5 \mu\text{F}, \quad A_s/A_T = 5 \]

- \( V_T \)
- \( V_{\text{bar}T} \)
- \( V_{\text{applied}} \)

![Graph showing voltage waveforms and ion flux over time and energy](image-url)
Tailored voltage waveforms: Square Wave (3)

**PIC simulation:**
\[ n_e = 2 \times 10^{16} \text{ m}^{-3}, \quad T_e = 0.15 \text{ eV}, \quad f = 13.56 \text{ MHz} \]
Tailored voltage waveforms: Square Wave (4)

Semi-analytical model:
\[ n_\alpha = 2 \times 10^{16} \text{m}^{-3}, \quad T_\alpha = 0.15 \text{ eV}, \quad C_B = 5 \ \mu\text{F}, \quad A_S/A_T = 1 \]
Tailored voltage waveforms
Square Wave with blocking capacitor (1)

Experiments (dashed line): $\text{H}_3^+$ ions, $C_B = 166 \ \text{pF}$, 27.7 kHz
P. Kudlacek et al. JAP 106 (2009) 073303
Tailored voltage waveforms: Square Wave with blocking capacitor (2)

Semi-analytical model
\[ n_e = 2 \times 10^{16} \text{ m}^{-3}, \; T_e = 0.15 \text{ eV}, \; C_B = 500 \text{ pF}, \; A_S/A_r = 1 \]
Tailored voltage waveforms: Square Wave + slope with blocking capacitor (1)

Experiments (solid line): $H_3^+$ ions, $C_B = 166$ pF, 33.3 kHz
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Tailored voltage waveforms: Square Wave + slope with blocking capacitor (2)

**Semi-analytical model**

\[ n_e = 2 \times 10^{16} \text{ m}^{-3}, \quad T_e = 0.15 \text{ eV}, \quad C_B = 1.66 \text{ nF}, \quad A_s/A_T = 1 \]
Summary

- 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 result in tailored IEDFs.
- PIC simulation is useful for verifying and fine tuning such waveforms.