Control of the Ion Energy Distribution on a Plasma Electrode

<u>P. Diomede</u>, D. J. Economou and V. M. Donnelly
Plasma Processing Laboratory, University of Houston

Outline

- **Introduction**
- **PIC-MCC simulation of tailored bias on boundary electrode**
- **Semi-analytic model**
- **Comparison with data**
- **Summary**

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* (not just the average ion energy) becomes increasingly important.**

Goal and Approach

Goal:

Develop methodologies to achieve "tailored" ion energy distributions[1] (IEDs).

Approach:

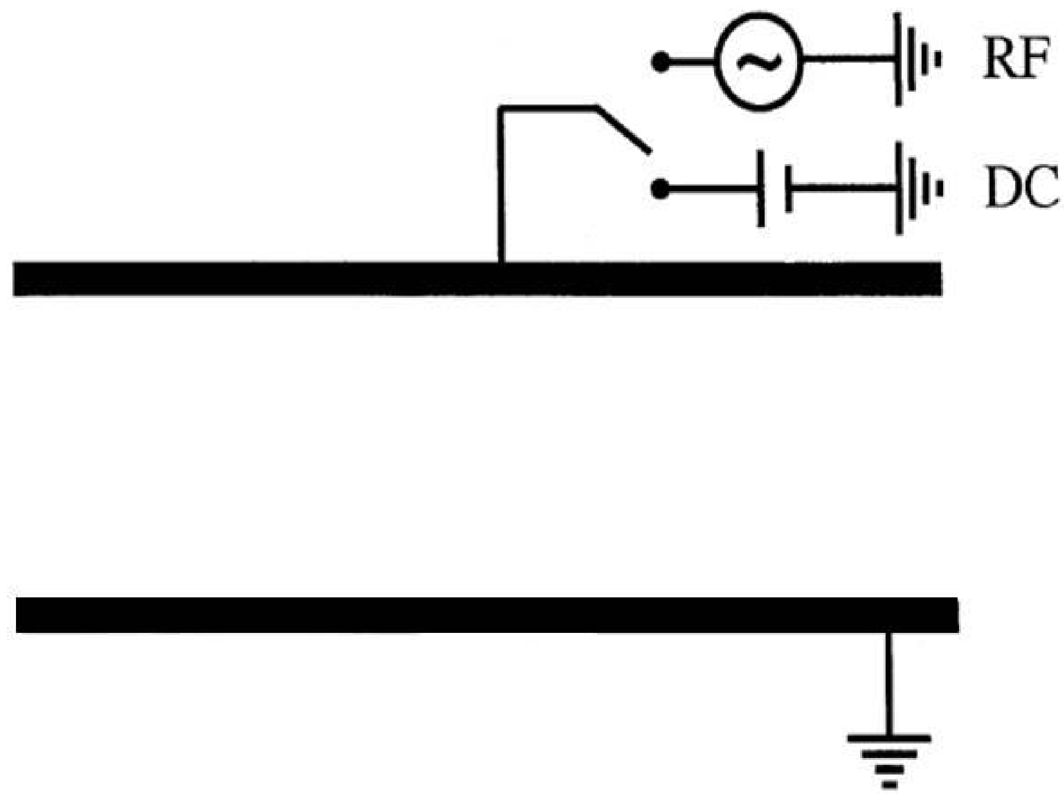
- Use combination of modeling/simulation and experiments.
- Particle-In-Cell simulation with Monte Carlo Collisions (PIC-MCC).[2]
- Semi-analytic model[3].

[1]P. Diomede et al., *J. Appl. Phys*., **109**, 083302 (2011); X.V. Quin, Y.-H. Ting and A.E. Wendt, *Plasma Sources Sci. Technol.,* **19**, 065014 (2010).

[2]S. K. Nam, D. J. Economou and V. M. Donnelly, *IEEE Trans. Plasma Sci.*, **35**, 1370 (2007); V. Vahedi, G. DiPeso, C. K. Birdsall, M. A. Lieberman, and T. D. Rognlien, *Plasma Sources Sci. Technol*. , **2**, 261 (1993); J. Verboncoeur, M. Alves, V. Vahedi, and C. K. Birdsall, *J. Comp. Phys*., **104**, 321 (1993); P. Diomede et al. *PSST*, 14, 459 (2005)

[3]P. Diomede et al., *PSST*, **20**, 045011 (2011).

PIC-MCC Simulation of Pulsed CCP Reactor with DC Bias in Afterglow

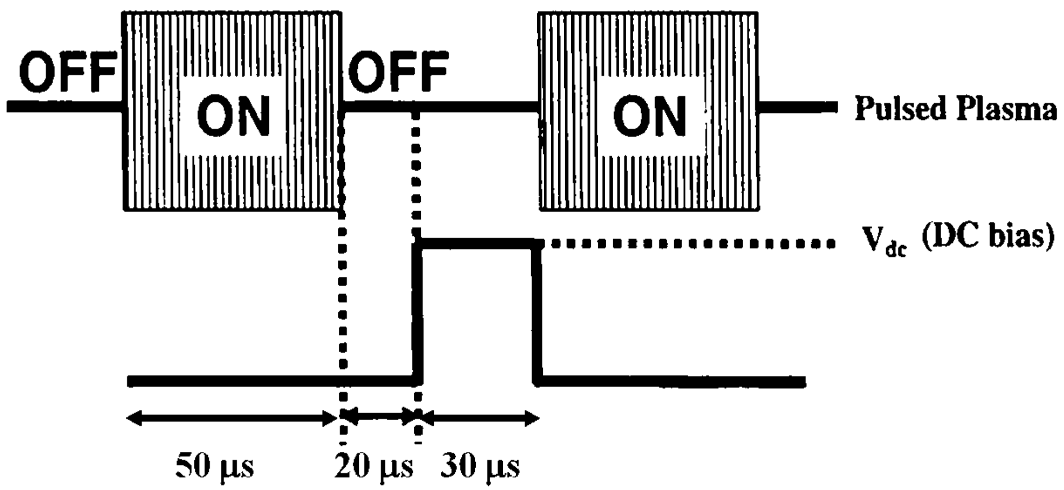


Argon plasma
V_{RF} = 300 V
ν_{RF} = 13.56 MHz
p = 10 mTorr
d = 6 cm

10 kHz pulse
50% duty ratio

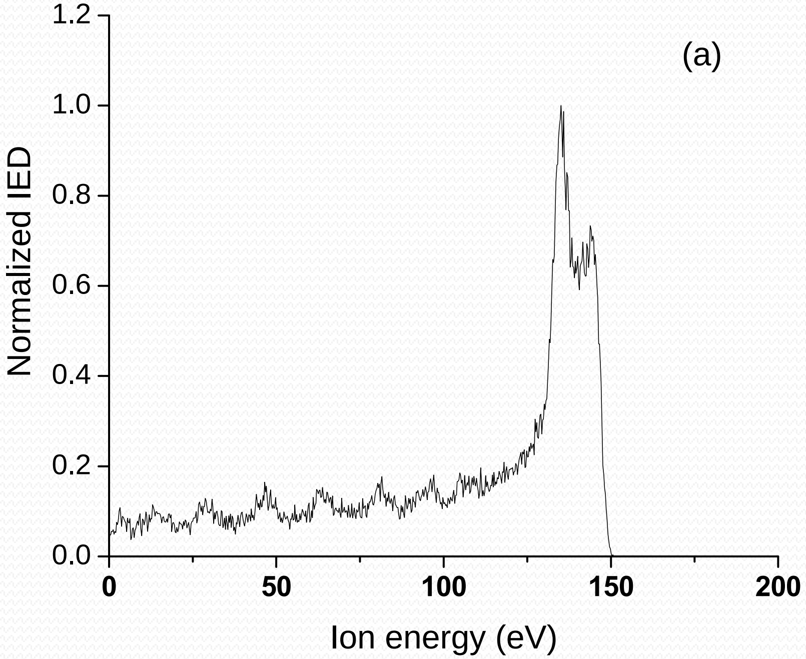
- Pulsed plasma is sustained in capacitively coupled plasma (CCP) reactor.
- DC bias is applied on the upper (boundary) electrode in the afterglow to modify the IED on the lower (substrate) electrode.

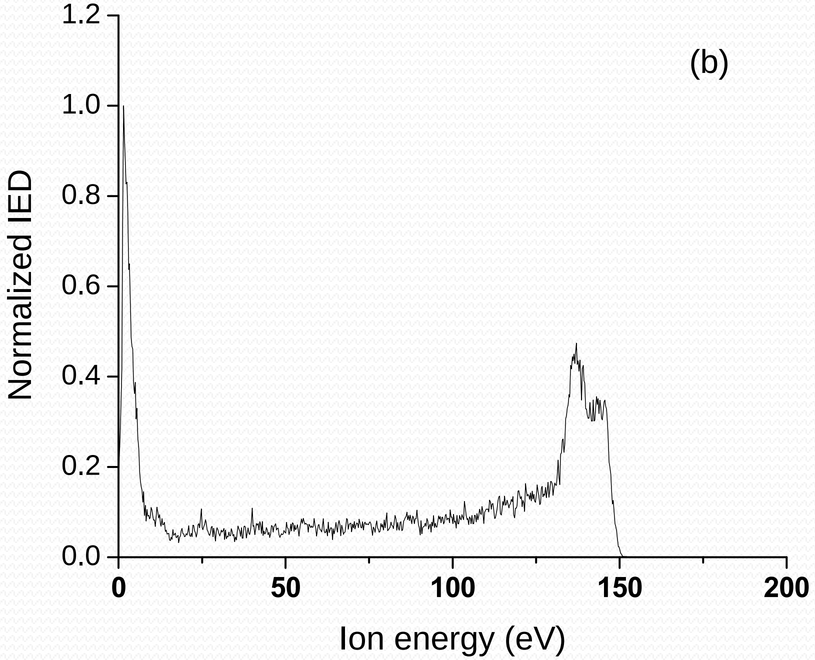
Application of DC Bias in the Afterglow of a Pulsed Plasma



- After plasma power turn off (afterglow), T_e and V_p decay rapidly.
- Apply synchronously tailored positive bias voltage V_{dc} during specified time window in the afterglow.
- Bias raises plasma potential, modifying the IED on the wafer.

IED without Bias

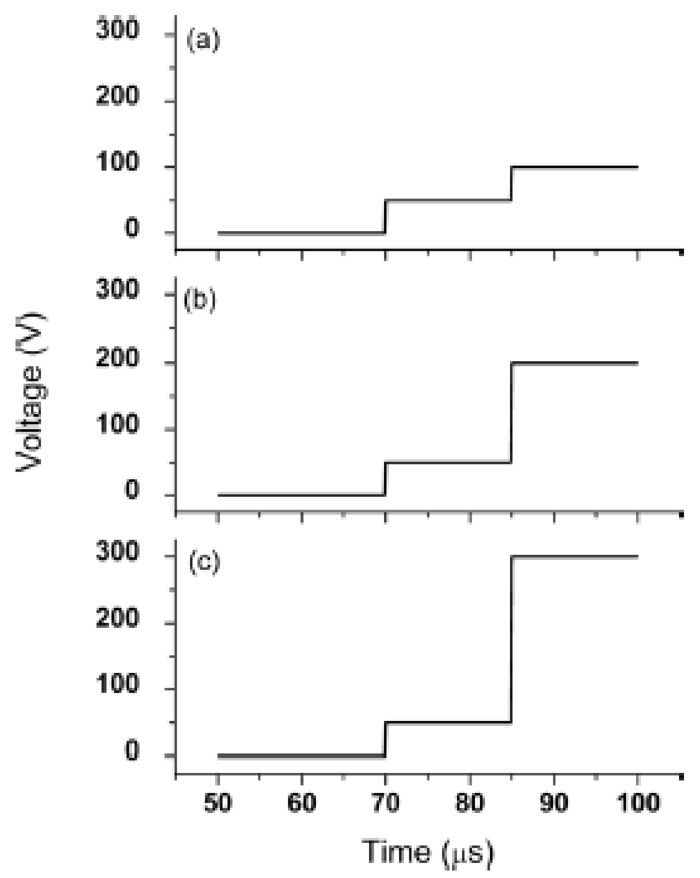


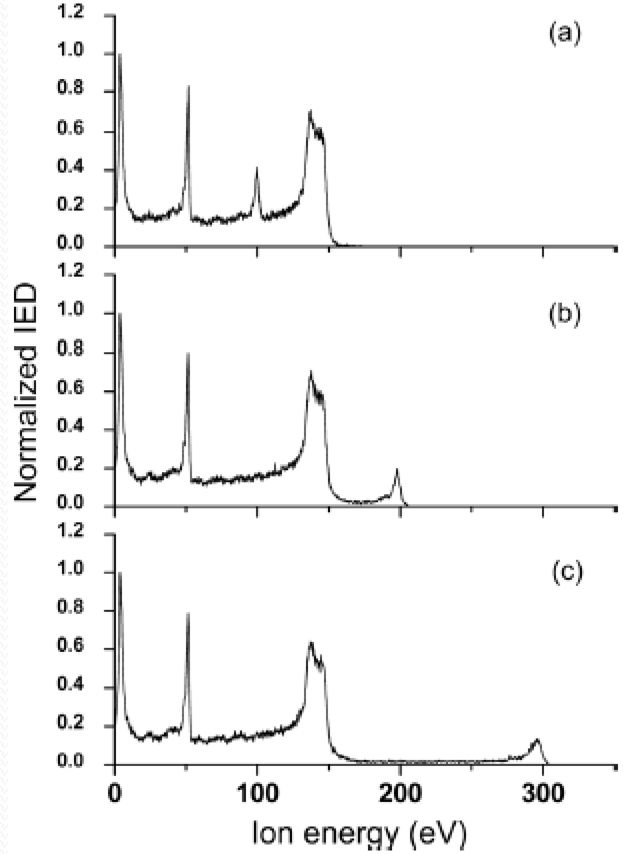


(a) IED for continuous wave (cw) plasma w/o bias

(b) IED for pulsed plasma (10 kHz, 50% duty cycle) w/o bias

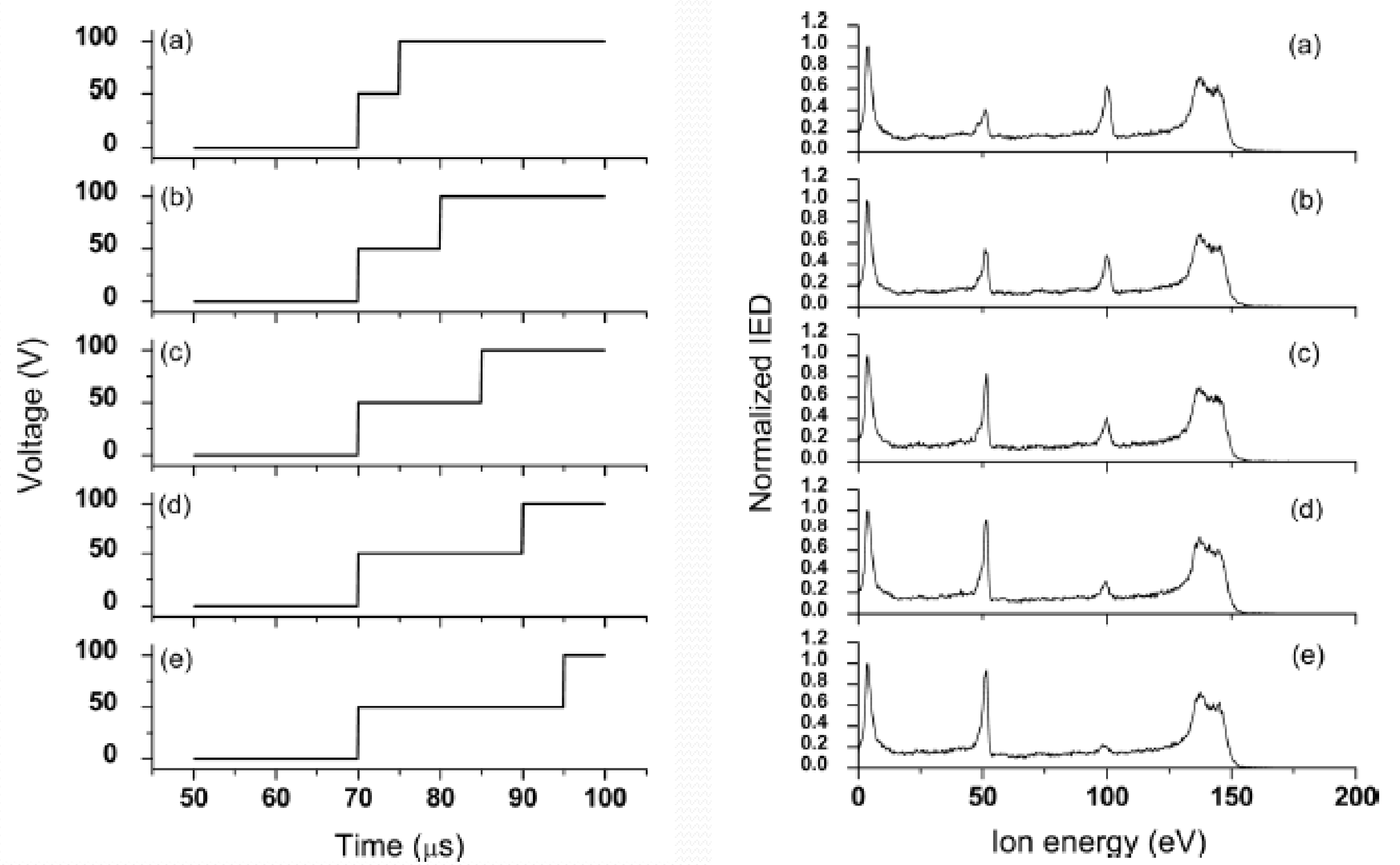
IEDs with Staircase DC Bias Applied in Afterglow





- Afterglow starts at time t = 50 μs.
- Additional peaks appear in the IED.
- Peak location can be controlled by the value of the applied bias voltage.

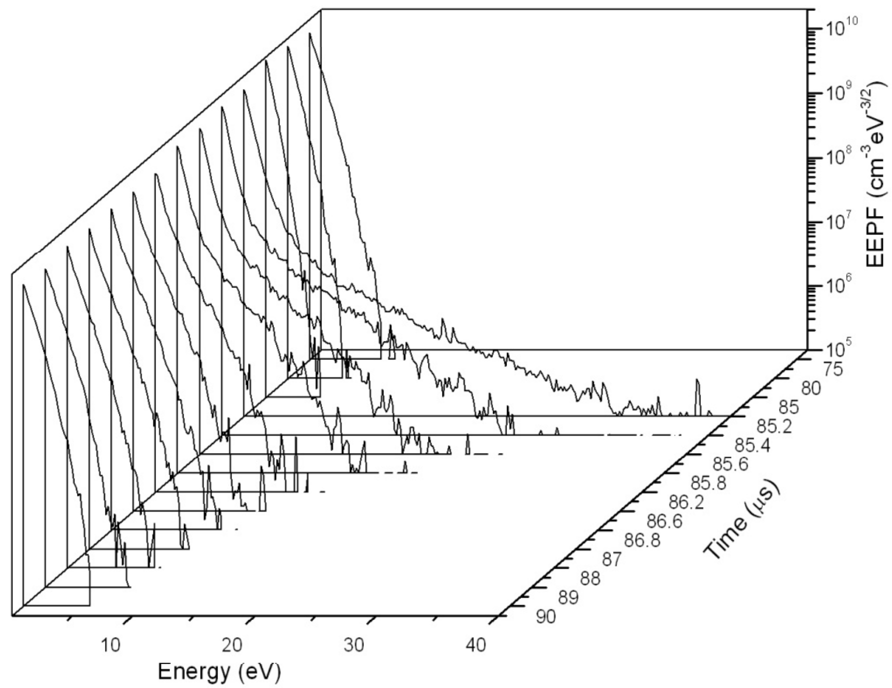
IEDs with Staircase DC Bias Applied in Afterglow (2)

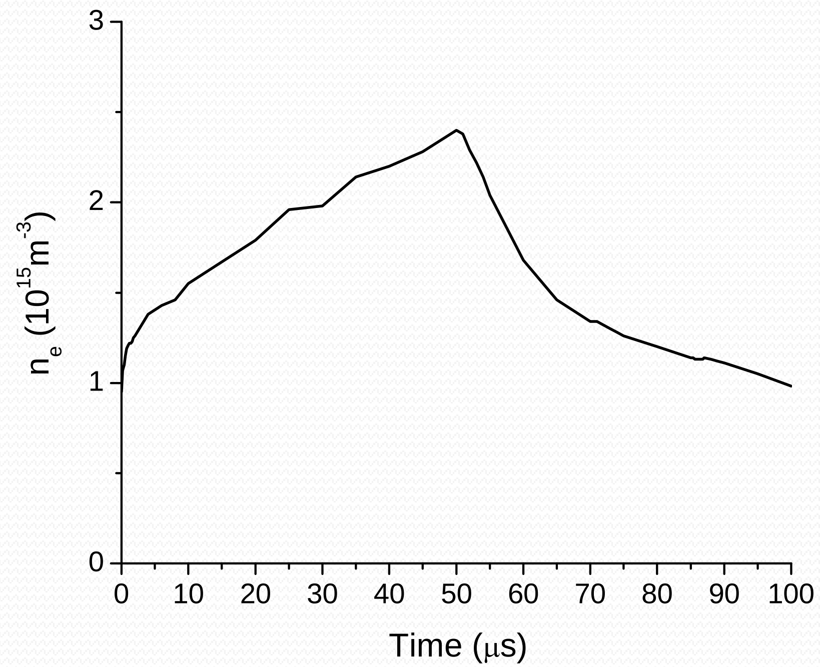


Peak strength can be controlled by the duration of the respective DC bias voltage.

P. Diomede et al., *J. Appl. Phys.*, **109**, 083302 (2011)

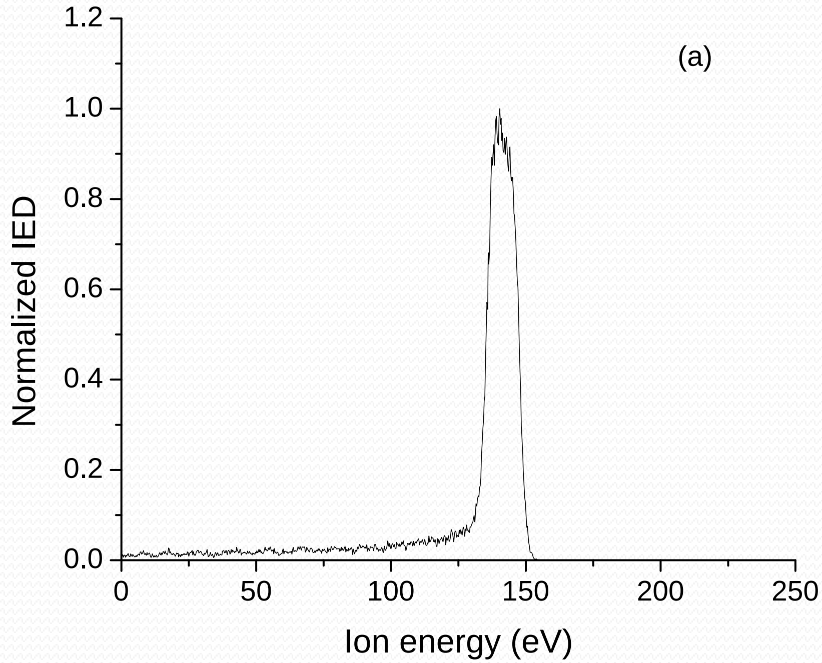
EEPF and Electron Density Evolution



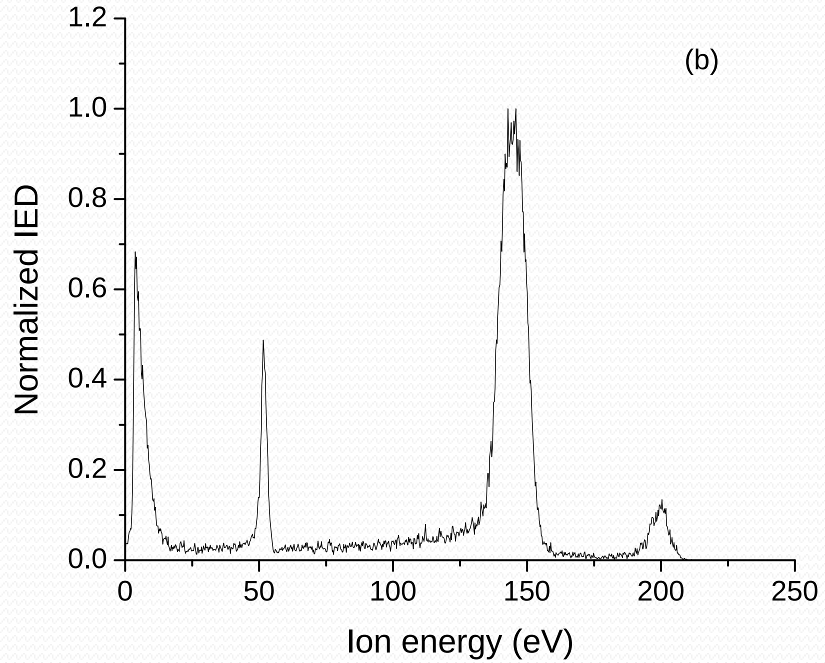


- In the afterglow of pulsed CCP, apply 50 V DC during t = 70-85 μs, followed by 300 V DC during t = 85-100 μs.
- EEPF is temporarily heated when the bias is applied but the electron density evolution is hardly affected.

Plasma Excitation Frequency of 60 MHz



IED for cw plasma w/o bias



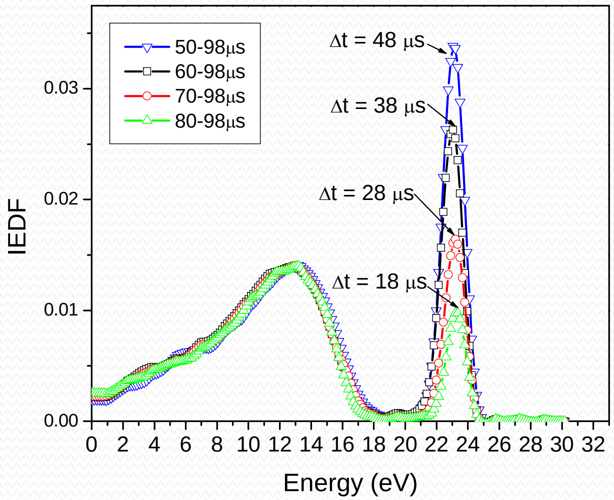
IED for pulsed plasma with staircase DC bias applied in afterglow (50 V during 70-85 μs, 200 V during 85-100 μs).

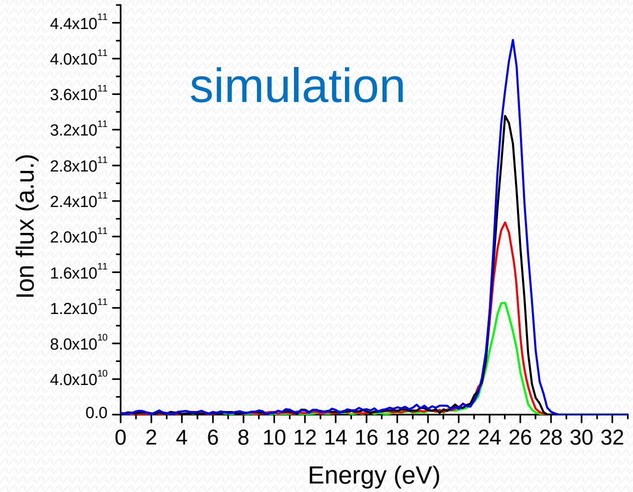
- Increasing frequency to 60 MHz boosts the electron density (n_e~f^2), yields thinner sheath, reduces the collisionality of the sheath, and results in sharper IEDs.
- Ion energy peak location and fraction of ions under each peak can be controlled.

Comparison of PIC Simulation with Experimental Data (1)

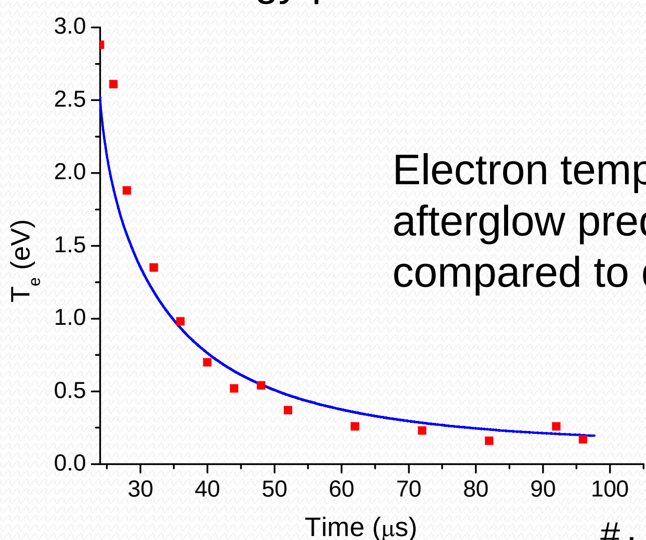
PS2-TuA9

PS+SS-WeM6





IEDs predicted by the PIC simulation of the afterglow (right) compared to data# (left). The low energy peak of the data is due to the active glow (not simulated by PIC).

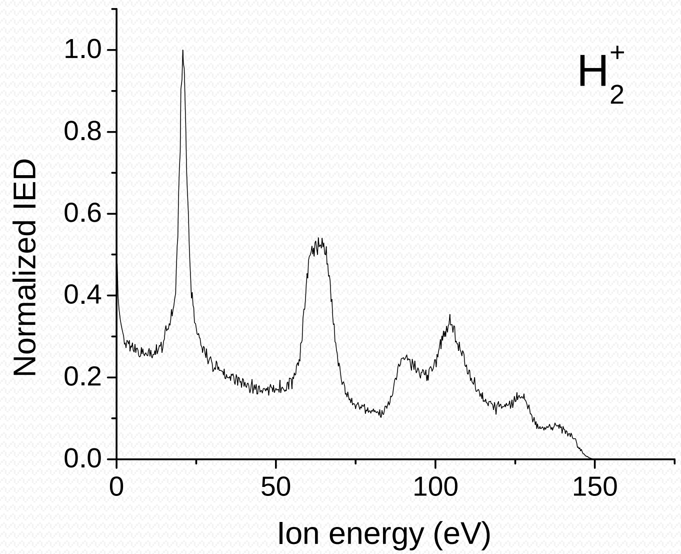


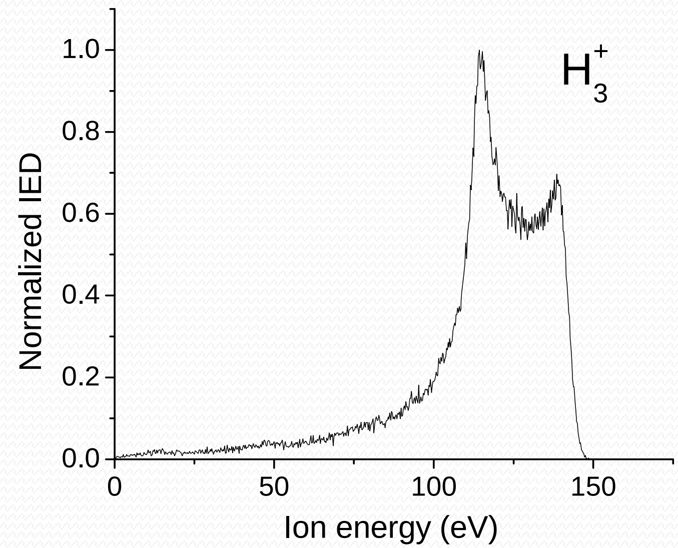
Electron temperature in the afterglow predicted by PIC (line), compared to data# (points).

Pulsed plasma, 10 KHz modulation, 20% duty, 14 mTorr, 120 W average power, 24.4 V DC bias applied in afterglow during time windows shown above.

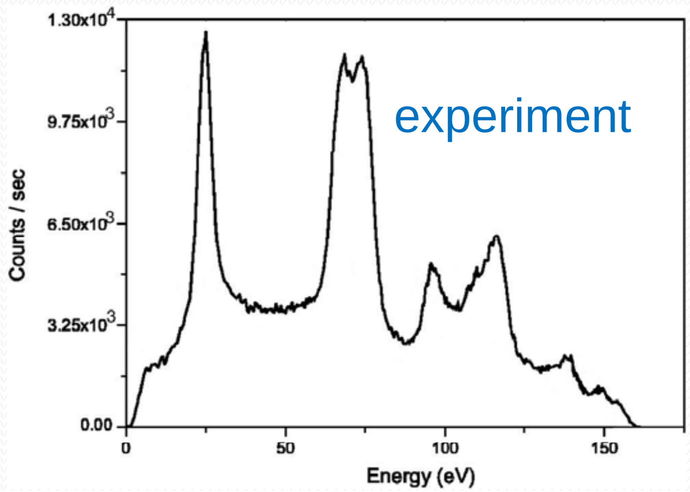
H. Shin et al., *PSST,* **20** 055001 (2011).

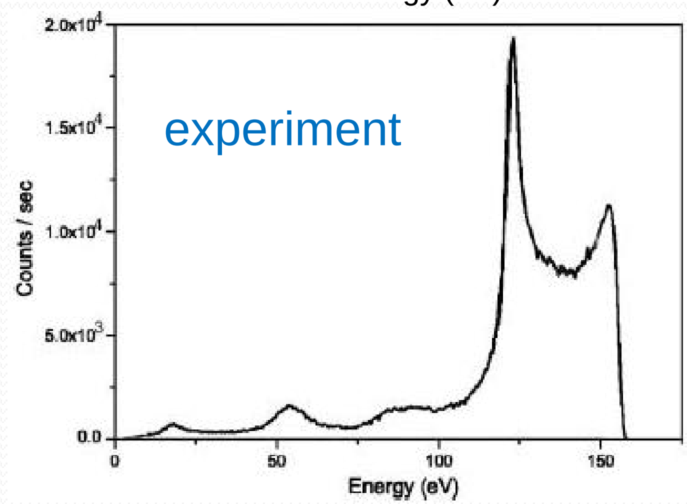
Comparison of PIC Simulation with Experimental Data (2)





Hydrogen plasma
V_{RF} = 300 V
ν_{RF} = 13.56 MHz
p = 50 mTorr
d = 6 cm

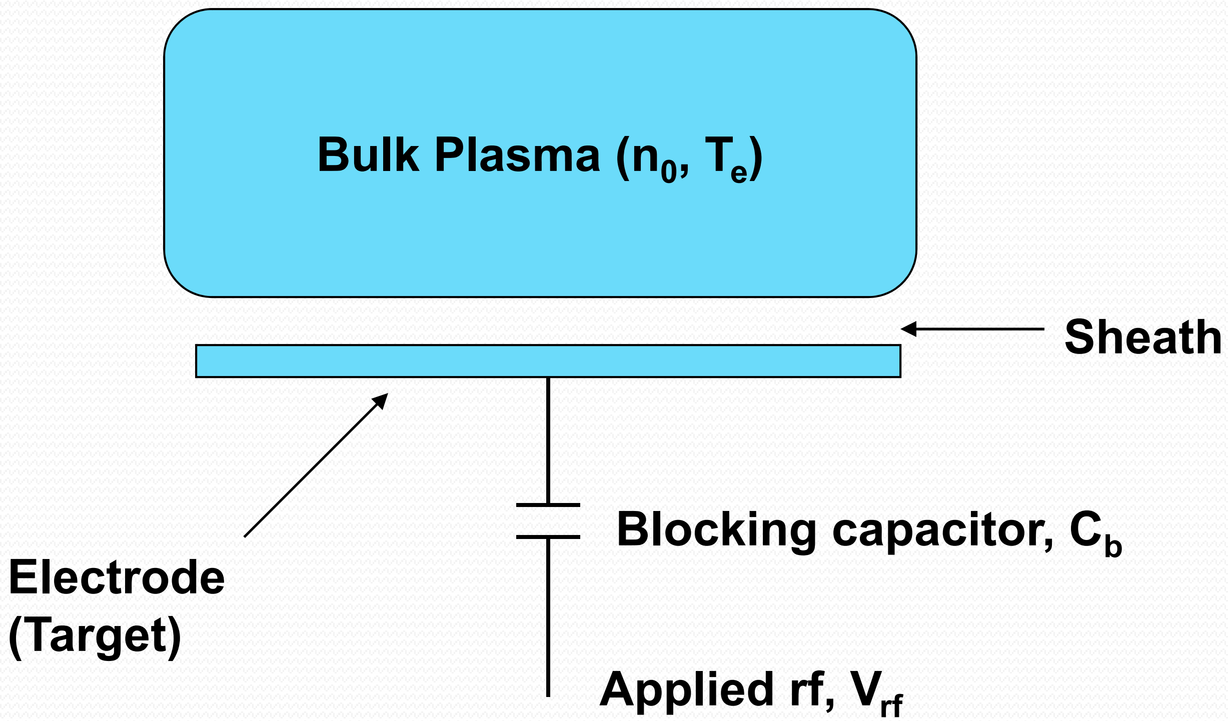




IEDs for cw plasma w/o bias

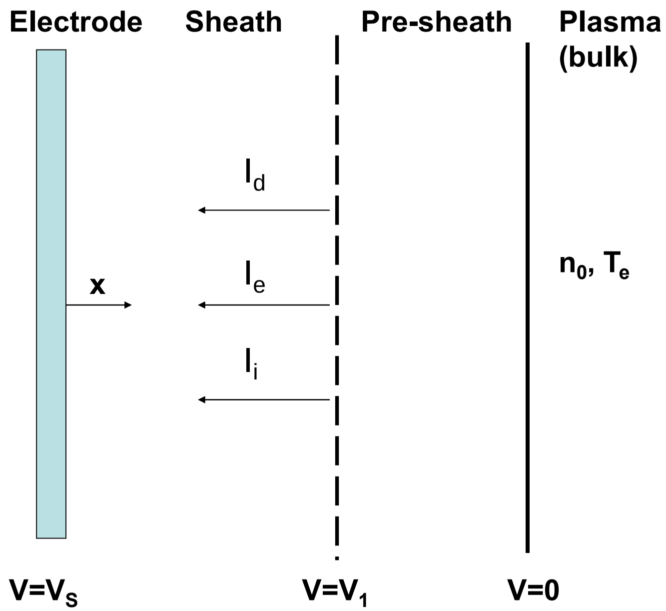
Experiments: D. O'Connell et al. *Phys. Plasmas* **14**, 103510 (2007)
Model: P. Diomede et al. *PSST*, **14**, 459 (2005)

Electrode in Contact with Plasma



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.

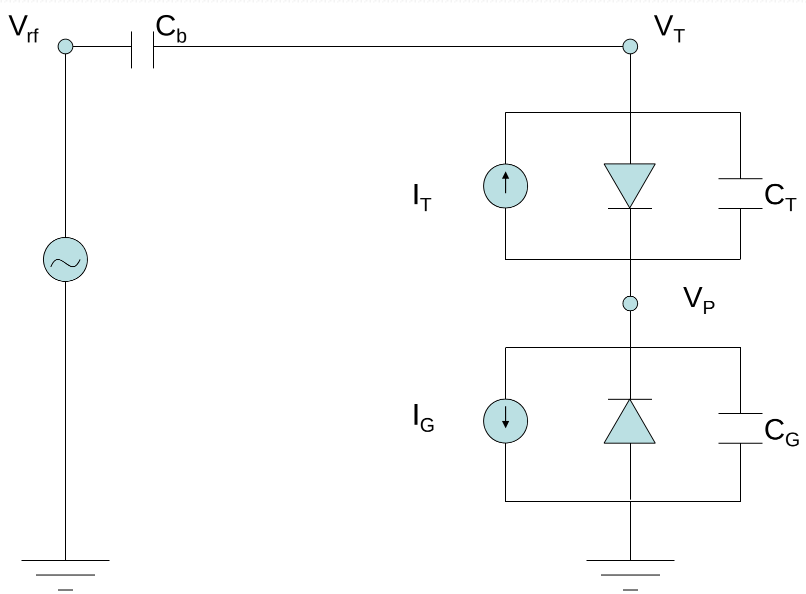
$$C_s = -\varepsilon_0 A \frac{\partial E}{\partial V_s}$$

$$E = -\sqrt{\frac{2n_1 kT_e}{\varepsilon_0}}[exp(\frac{e(V_s - V_1)}{kT_e}) + \frac{V_s}{V_1} - 2]^{1/2}$$

A. Metze et al., *J. Appl. Phys.*, **60**, 3081 (1986).
P. Miller and M. Riley, *J. Appl. Phys.*, **82**, 3689 (1997).
T. Panagopoulos and D. Economou, *JAP*, **85**, 3435 (1999).

Semi-analytic Model (2)

Equivalent circuit model, A. Metze et al., *J. Appl. Phys*., **60**, 3081 (1986).



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

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

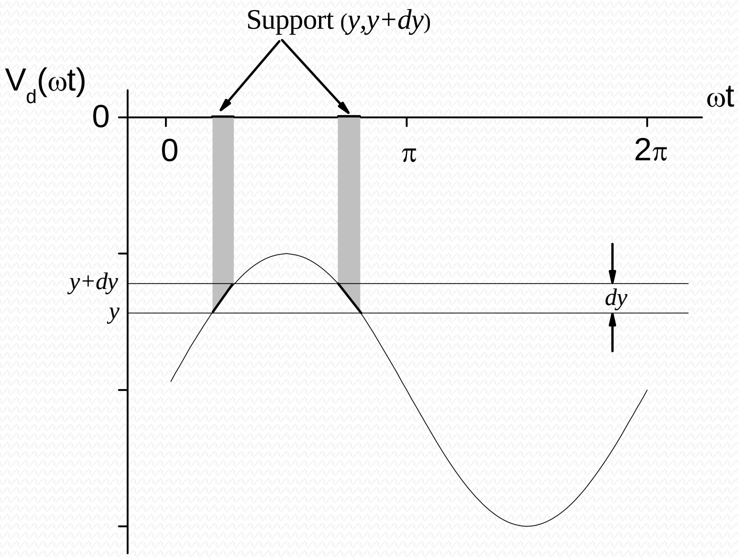
$$C_T \frac{d}{dt}(V_P - V_T) + C_G \frac{d}{dt} V_P + I_T + I_G = 0$$

$$\frac{dV_d}{dt} = -\frac{V_d - (V_T - V_p)}{\tau_i}$$

Ions respond to a "damped" potential V_d

Voltage V_{rf} is applied through blocking capacitor, C_b.
Given n_0, T_e, V_{rf} and C_b, calculate V_T , V_p, and **V_d.**

Ion Energy Distribution



$$f(y)=\frac{1}{2\pi}\sum_{\substack{\#\text{ of points in } 0<\omega t<2\pi \\ \text{such that} \\ V_d(\omega t)=y}}\frac{1}{\left|\frac{dV_d}{d(\omega t)}\right|}$$

$$f(y)=IED$$

$$V_d=V_d(\omega t)=\text{"damped" sheath voltage}$$

Sample damped sheath potential waveform

$$y=V_d(\omega t)\Rightarrow \omega t=V_d^{-1}(y)$$

$$f(y)=\frac{1}{2\pi}\sum_{\substack{\#\text{ of points in } 0<\omega t<2\pi \\ \text{such that } V_d(\omega t)=y}}\left|\frac{dV_d^{-1}(y)}{dy}\right|$$

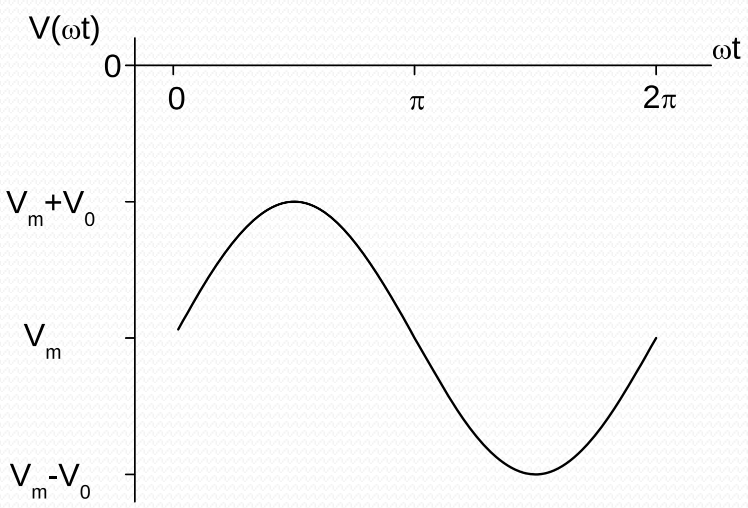
P. Diomede et al., *Plasma Sources Sci. Technol.*, **20**, 045011 (2011).

E. Kawamura et al., *Plasma Sources Sci. Technol.*, **8**, R45 (1999).

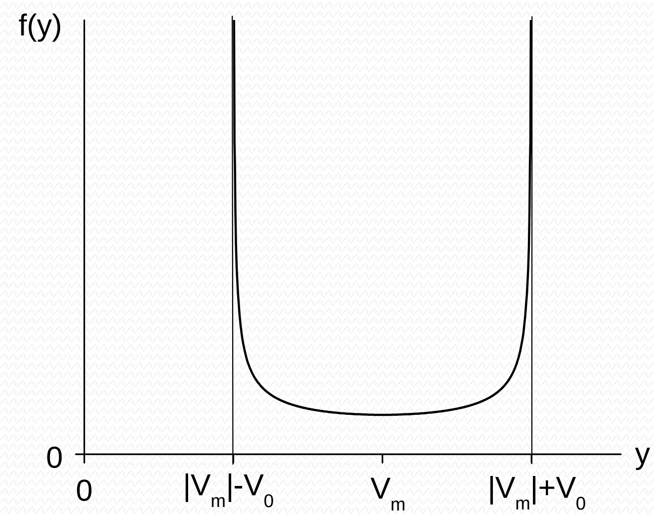
IED for a sinusoidal sheath voltage

(Forward problem)

Damped sheath potential



Resulting IED



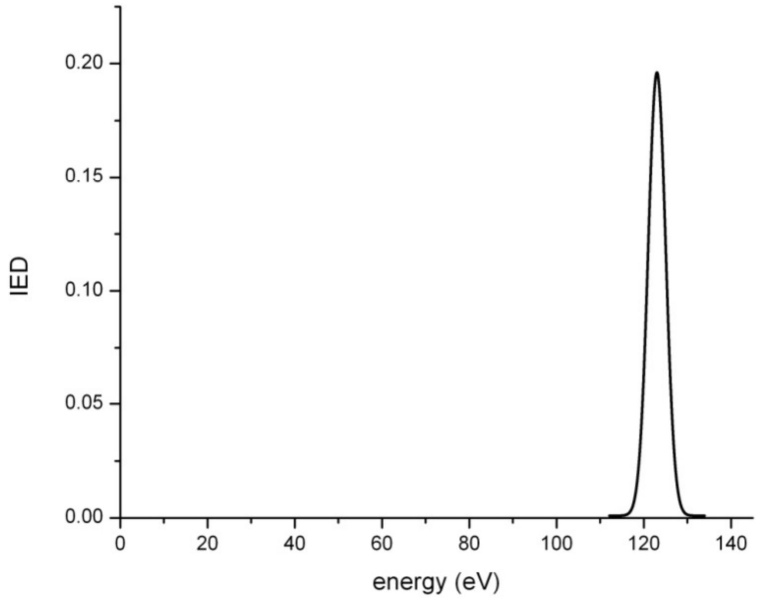
$$y = V_d(\omega t) = V_m + V_0 \sin \omega t$$

$$|V_m| > V_0, \quad V_m < 0, \quad 0 < \omega t < 2\pi$$

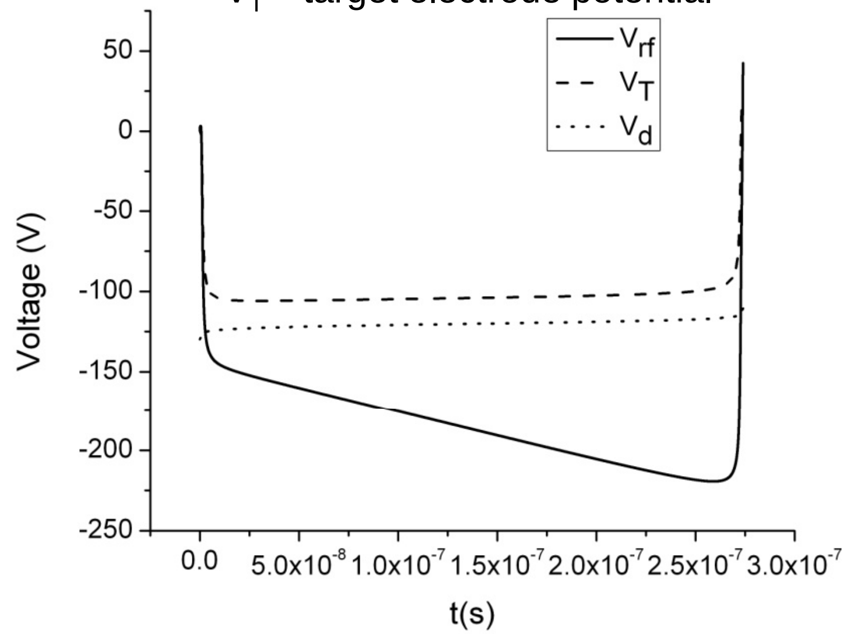
$$f(y) = \frac{1}{\pi} \frac{1}{V_0 \sqrt{1 - \left(\frac{y - |V_m|}{V_0} \right)^2}}$$

Voltage Waveform Required to Obtain Desired IED (Inverse problem)

C_b = 500 pF, $n_0 = 2{\times}10^{10}$ cm^{-3}, T_e = 3 eV,
M = 40 amu (Ar^+), A_G/A_T = 20, $\omega\tau_i = 1$



V_{rf} = rf voltage before blocking cap
V_d = "damped" sheath potential
V_T = target electrode potential



Desired IED is Gaussian with specified peak and standard deviation.

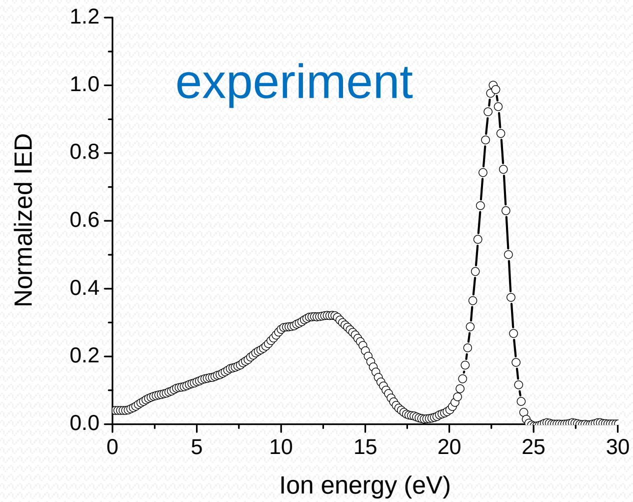
Required voltage waveform V_{rf} is a "rectangular" pulse with a slope. Slope is needed because of blocking capacitor charging.

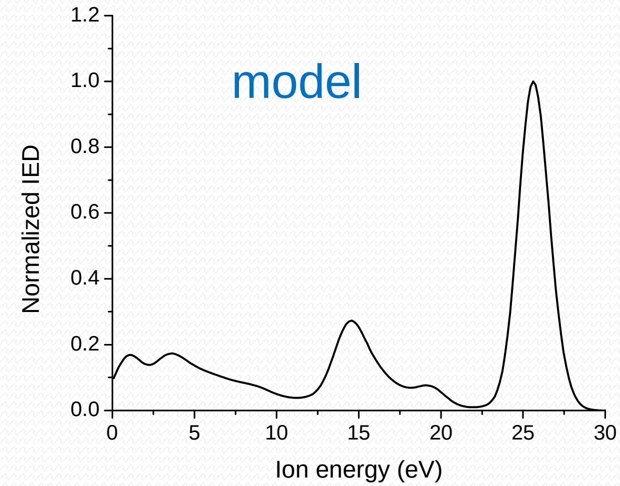
P. Diomede et al., *Plasma Sources Sci. Technol.*, **20**, 045011 (2011).

Comparison of Semi-analytic Model with Experimental Data
Argon Plasma

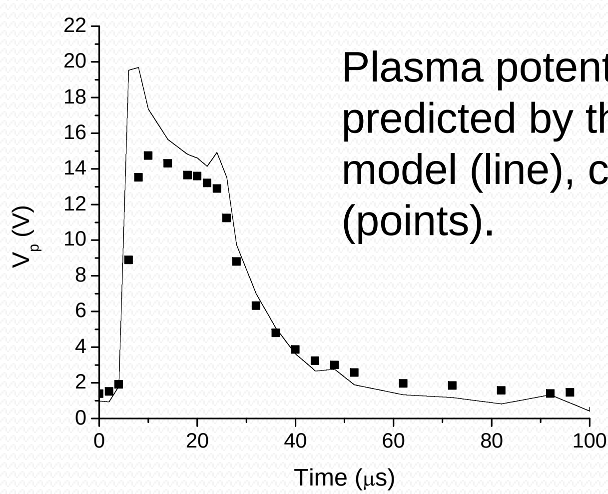
PS2-TuA9

PS+SS-WeM6





IEDs predicted by the semi-analytical model (right) compared to data# (left).



Plasma potential w/o DC bias predicted by the semi-analytical model (line), compared to data# (points).

Pulsed plasma, 10 KHz modulation, 20% duty, 14 mTorr, 120 W average power, 24.4 V DC bias applied in afterglow during Δt_b = 45-95 μs.

H. Shin et al., *PSST,* **20** 055001 (2011).

Summary

- The energy distribution of ions bombarding the wafer can be tailored by applying voltage waveforms with special shapes (square wave, staircase, etc.).
- Both the location of the peak(s) of the IED and the fraction of ions under each peak can be controlled.
- Semi-analytic model can identify voltage waveforms that result in desired IED (inverse problem).
- Semi-analytic model executes much faster, but PIC simulation provides detailed information about both the IED and the EEDF upon application of bias.
- Experimental measurements were in good agreement with model and simulation predictions.

Acknowledgements

Prof. M. Nikolaou, University of Houston
Dr. H. Shin, University of Houston
PhD candidate W. Zhu, University of Houston

Prof. S. Longo, University of Bari and CNR/IMIP, Italy
Prof. M. Capitelli, University of Bari and CNR/IMIP, Italy

Funding:
DoE Plasma Science Center
NSF