PULSED PLASMAS FOR CONTROL OF REACTIVE FLUXES IN MICROELECTRONICS FABRICATION*

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AGENDA

- Overview of pulsed plasmas for microelectronics fabrication
- Description of models
- Dual Frequency – CCP: CW baseline
- Pulsing Dual-Frequency CCP – Pulsing LF, HF, LF & HF
- Pulsed ICPs for photon flux control
- Internal Pulsing – Beat Frequency of Phase Control
- Startup transients – a form of pulsing.
- Concluding Remarks
- Acknowledgements:
  - Dr. Saravanapriyan Sriraman, LAM Research
  - Prof. Steven Shannon, North Carolina State University

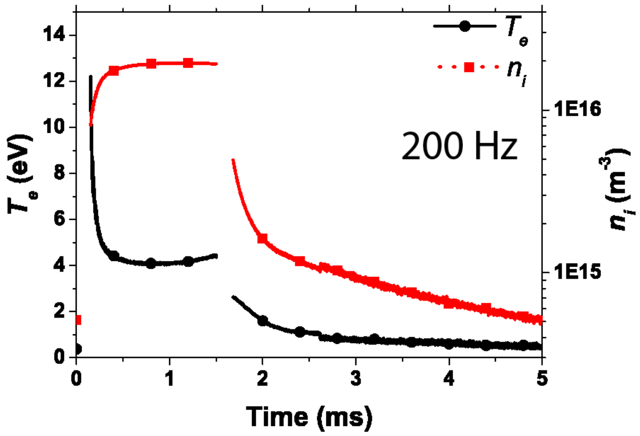
PULSED PLASMA PROCESSING

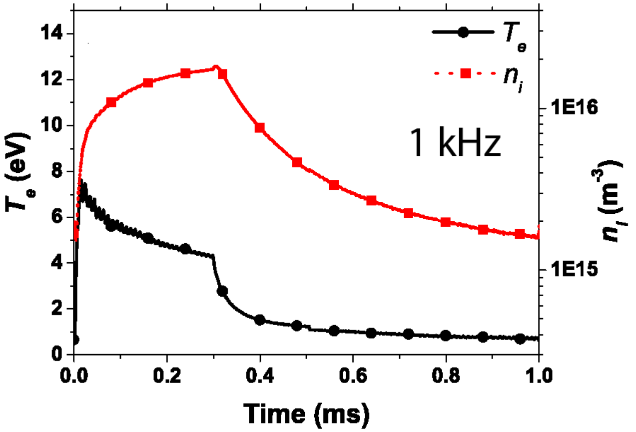
- Pulsed plasma materials processing – based on the premise that:

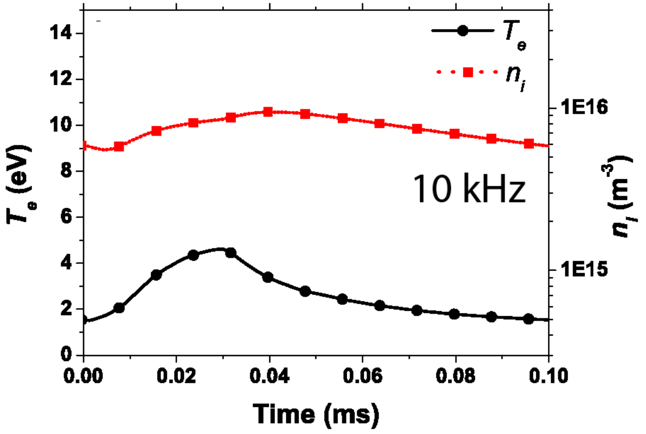
$$\frac{1}{\tau}\int_0^{\tau} R\big(P(t)\big)dt \neq R\big(\langle P(t)\rangle\big)$$

- The time average of instantaneous rates based on time varying power is not the same as the rates based on the time averaged power.

- For this premise to be valid:
    - Fluxes must respond on time scales less than the pulse period.
    - Features must "see" a statistically relevant number of particles during the sub-cycle.

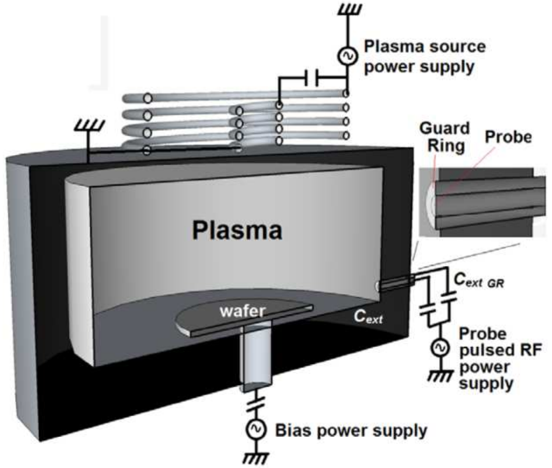






PULSED ICP-Ar

- **Ar, 10 mTorr**
- **Overshoot in T_e at beginning of low PRF cycles.**
- **Quasi-cw at high PFR**

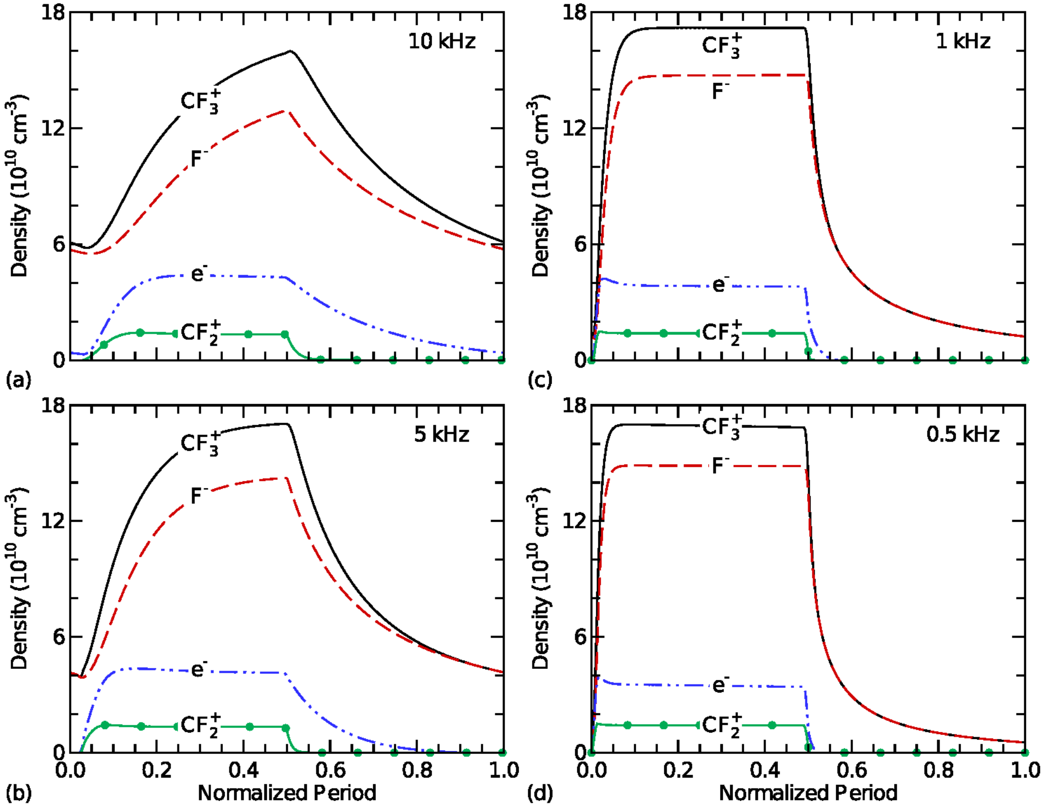


Time-resolved ion flux, electron temperature and plasma density measurements in a pulsed Ar plasma using a capacitively coupled planar probe

Maxime Darnon , Gilles Cunge and Nicholas St J Braithwaite

Plasma Sources Sci. Technol. **23** (2014) 025002 (9pp)

PULSING FOR ION-ION PLASMAS



- **Ion-ion plasmas are intended to allow negative ions to reach wafer, and remediate positive charging of features.**
- **Pulsed plasmas in electronegative mixtures transition from electron-ion to ion-ion plasmas in afterglow.**
- **Sensitive to PRF, bias**
- **CCP, 100 mTorr, CF_4, 150/14/2 MHz, 50% dc**

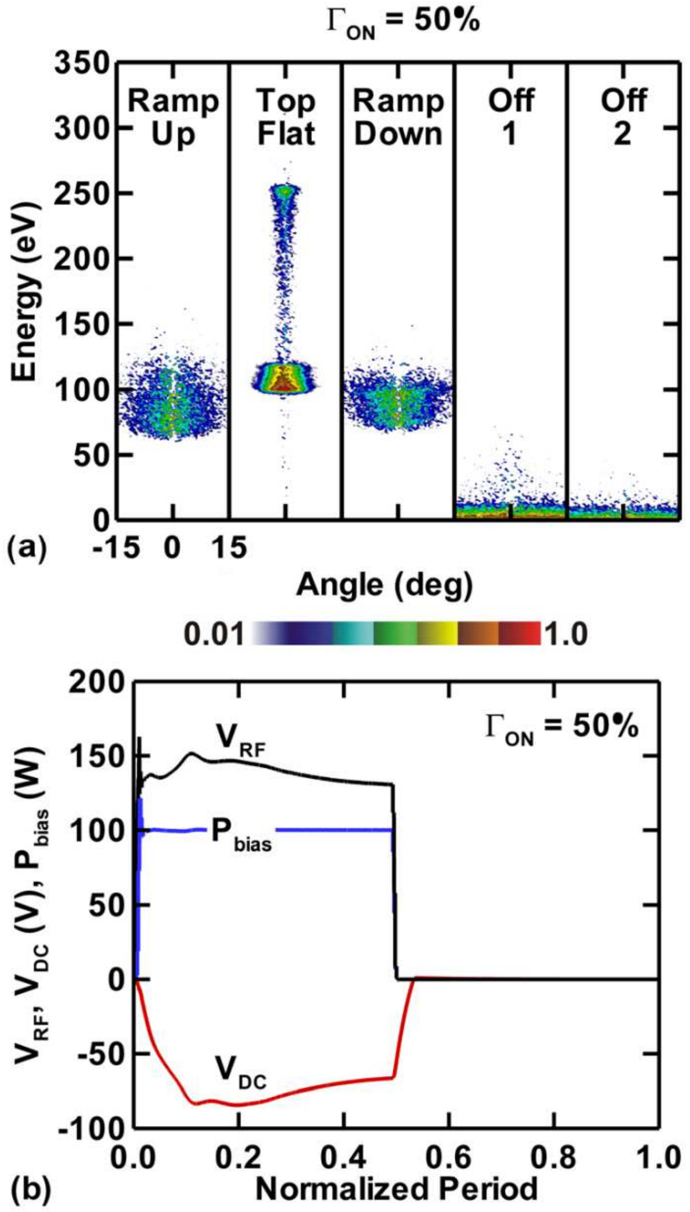
Extraction of negative ions from pulsed electronegative capacitively coupled plasmas

Ankur Agarwal,[a)] Shahid Rauf, and Ken Collins

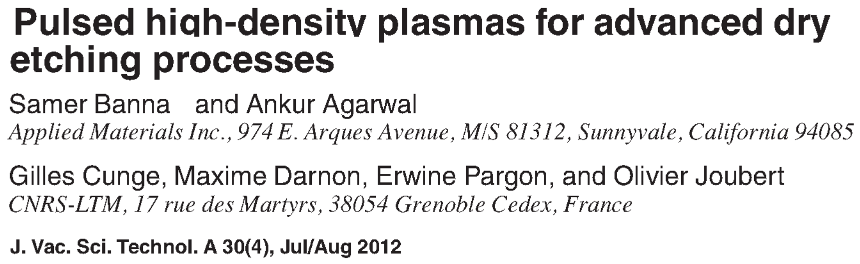
Applied Materials Inc., 974 E. Arques Avenue, M/S 81312, Sunnyvale, California 94085, USA

JOURNAL OF APPLIED PHYSICS **112**, 033303 (2012)

SYCHRONIZED PULSED ICP & BIAS



- Ar/Cl_2, 10 mTorr
- Pulsed ICP with synchronized pulsed bias. 5 kHz, 50% duty cycle.
- Ion energies have distinct sub-cycle behavior which reflects:
  - Applied Bias
  - Plasma potential (measure of T_e)
  - Interaction of circuit through dc bias.


Pulsed high-density plasmas for advanced dry etching processes

Samer Banna and Ankur Agarwal
Applied Materials Inc., 974 E. Arques Avenue, M/S 81312, Sunnyvale, California 94085

Gilles Cunge, Maxime Darnon, Erwine Pargon, and Olivier Joubert
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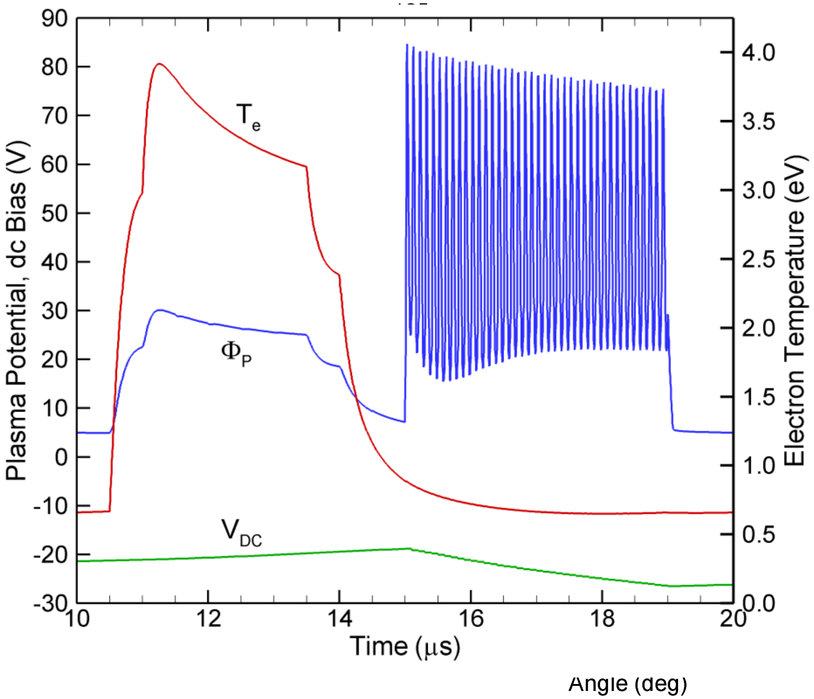
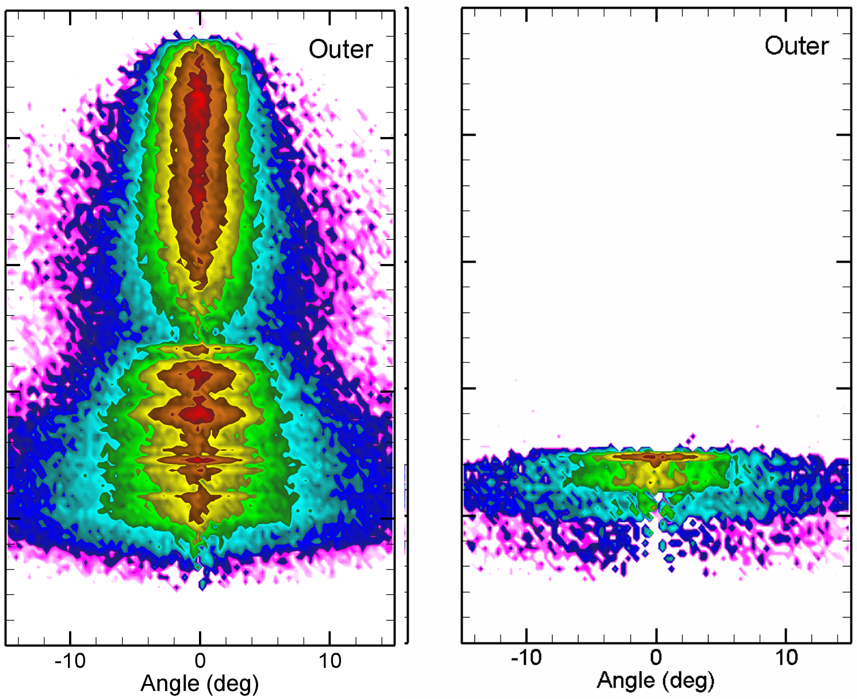
J. Vac. Sci. Technol. A 30(4), Jul/Aug 2012

PULSED ICP WITH PULSED RF BIAS IN AFTERGLOW

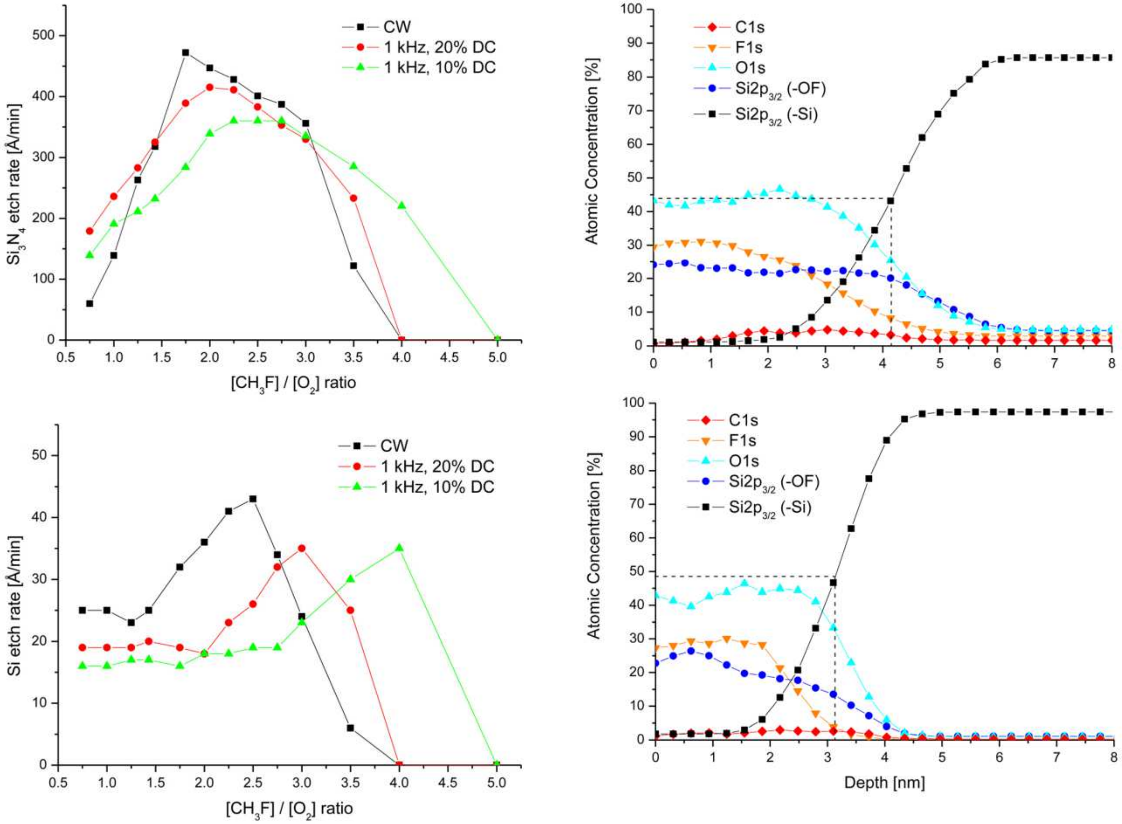




- **Addition of pulsed rf during ICP afterglow produces little change in plasma properties.**
- **RF modulation of plasma potential and DC bias (small blocking capacitor) during afterglow produce narrower, high energy IED.**
- **Cl_2, 20 mTorr, 800 W, 200 sccm, 100 kHz, 40% duty cycle, 100 V bias.**

Animation Slide

PULSING FOR SELECTIVITY



- CHF$_3$/O$_2$/He, 20 mTorr, ICP: CW and bias synchronously pulsed
- Etching of Si$_3$N$_4$ spacers with respect to Si.
- Selectivity requires Si oxidation – thickness is is reduced using pulsing.
- Obtain improvement in spacer profile with pulsing.

Patterning of silicon nitride for CMOS gate spacer technology. III. Investigation of synchronously pulsed CH$_3$F/O$_2$/He plasmas

Romuald Blanc[a)] and François Leverd
STMicroelectronics, Central R&D, 850 Rue J. Monnet, 38926 Crolles Cedex, France

Maxime Darnon, Gilles Cunge, Sylvain David, and Olivier Joubert
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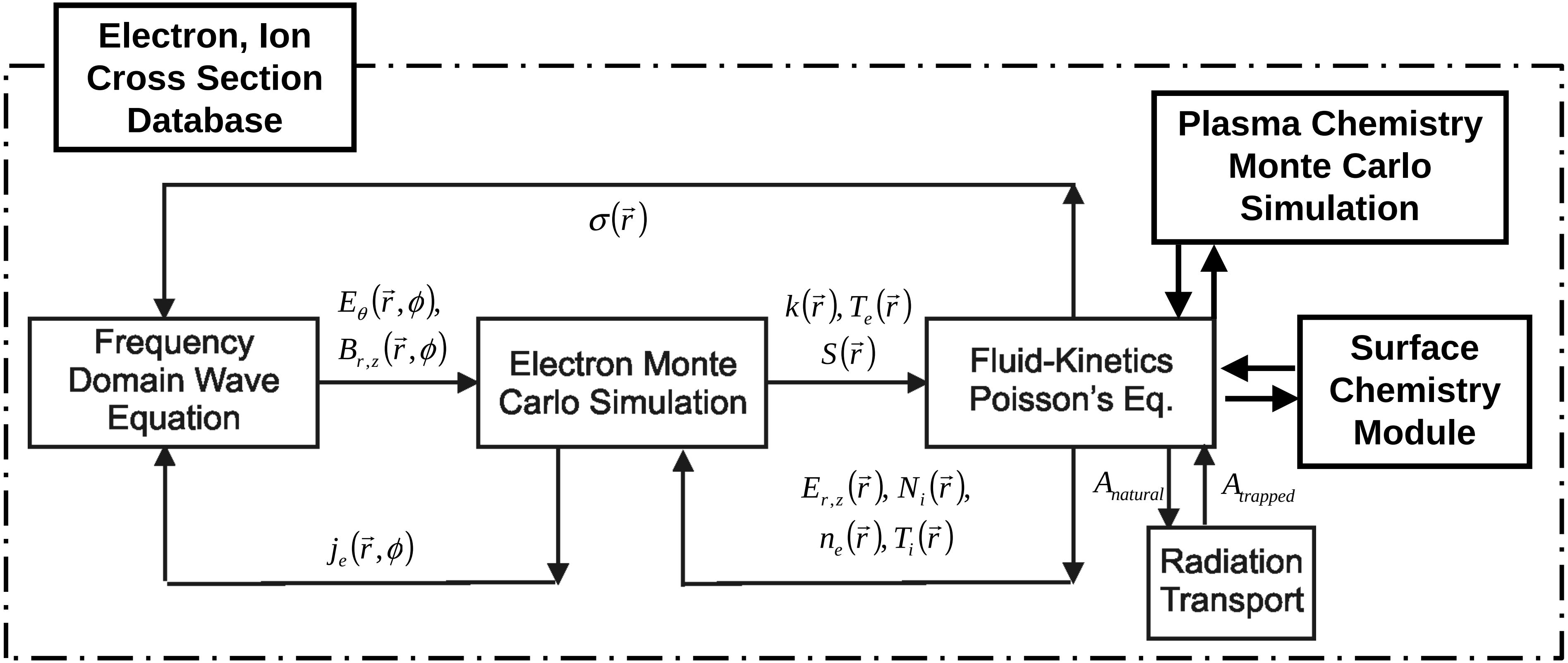
J. Vac. Sci. Technol. B 32(2), Mar/Apr 2014

CONTROL OF REACTIVE FLUXES

- **In this presentation, we discuss results from a computational investigation of controlling reactive fluxes to the substrate in pulsed systems.**
- **Several varieties of pulsing:**
    - **Pulsing power supplies**
    - **Optimizing circuit interaction**
    - **"Internal pulsing" – beat frequencies?**
    - **Pulsing during startup transients**

HYBRID PLASMA EQUIPMENT MODEL


Electron, Ion Cross Section Database

$\sigma(\vec{r})$

Frequency Domain Wave Equation

$E_\theta(\vec{r},\phi)$, $B_{r,z}(\vec{r},\phi)$

Electron Monte Carlo Simulation

$k(\vec{r}), T_e(\vec{r})$

$S(\vec{r})$

Fluid-Kinetics Poisson's Eq.

Plasma Chemistry Monte Carlo Simulation

Surface Chemistry Module

$j_e(\vec{r},\phi)$

$E_{r,z}(\vec{r}), N_i(\vec{r}),$

$n_e(\vec{r}), T_i(\vec{r})$

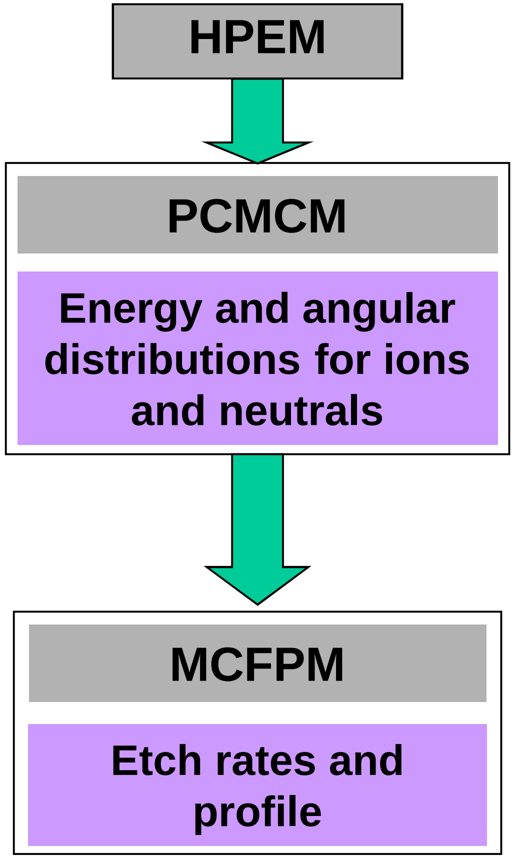
$A_{natural}$

$A_{trapped}$

Radiation Transport

- **The Hybrid Plasma Equipment Model (HPEM) is a modular simulator that combines fluid and kinetic approaches.**
- **Radiation transport is addressed using a spectrally resolved Monte Carlo simulation.**
- **Intended for smaller pd…**

MONTE CARLO FEATURE PROFILE MODEL (MCFPM)



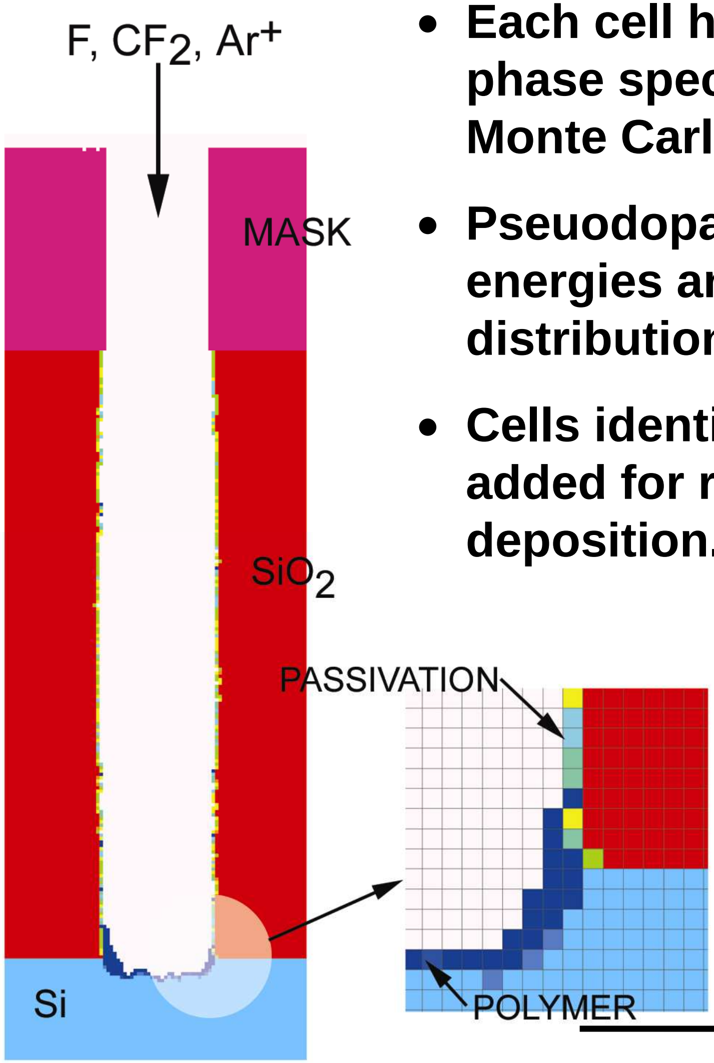
HPEM

PCMCM

Energy and angular distributions for ions and neutrals

MCFPM

Etch rates and profile

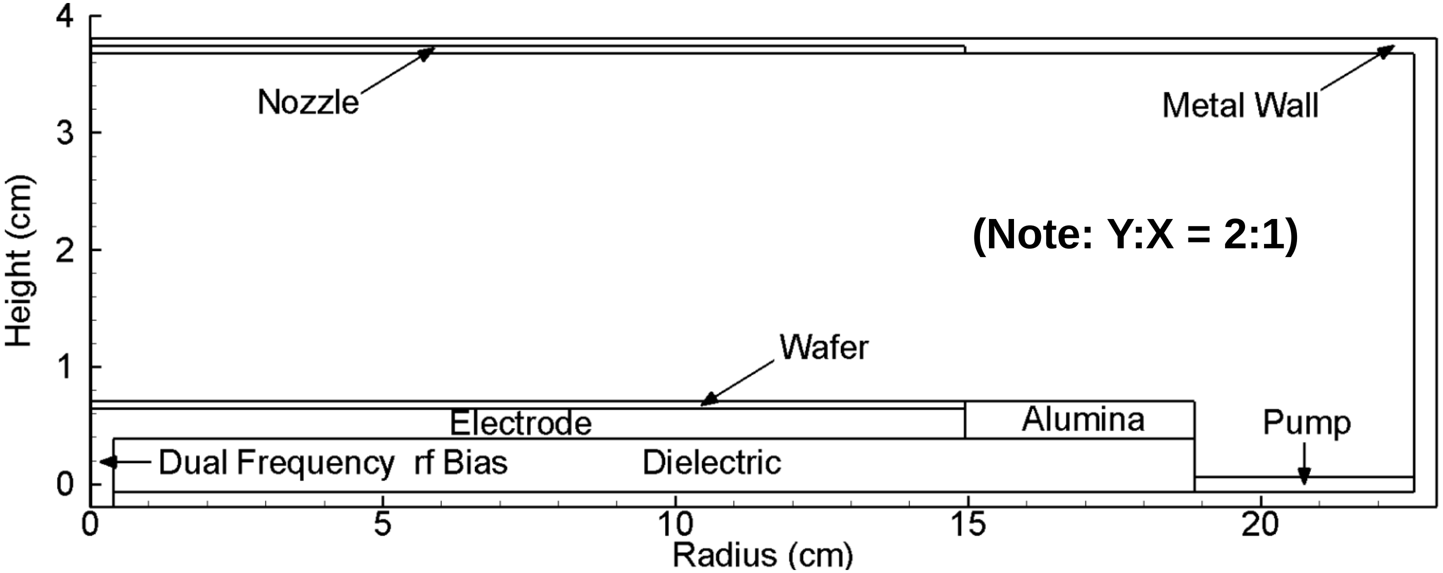


- **The MCFPM resolves the surface topology on a 2D Cartesian mesh.**
- **Each cell has a material identity. Gas phase species are represented by Monte Carlo pseudoparticles.**
- **Pseudoparticles are launched with energies and angles sampled from the distributions obtained from the HPEM**
- **Cells identities changed, removed, added for reactions, etching deposition.**
- **Poisson's equation solved for charging**

BASELINE:
IEADs in CW MULTIFREQUENCY CCPs

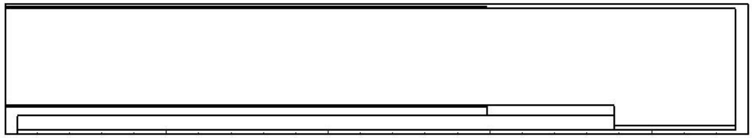
REACTOR GEOMETRY

- **Capacitively coupled plasma with multi-frequency rf biases on bottom electrode.**
- **2D, cylindrically symmetric.**
- **Ar plasma: Ar, Ar($1s_{2,3,4,5}$), Ar(4p), Ar^+, e**
- **Base case conditions:**
  - **Ar, 30 mTorr, 1000 sccm**
  - **2 MHz, 300 W; 60 MHz, 300 W**
- **Etching Chemistry:**
  - **Ar/CF_4/O_2=75/20/5, 30mTorr, 500 sccm**



(Note: Y:X = 2:1)

- **Actual aspect ratio**



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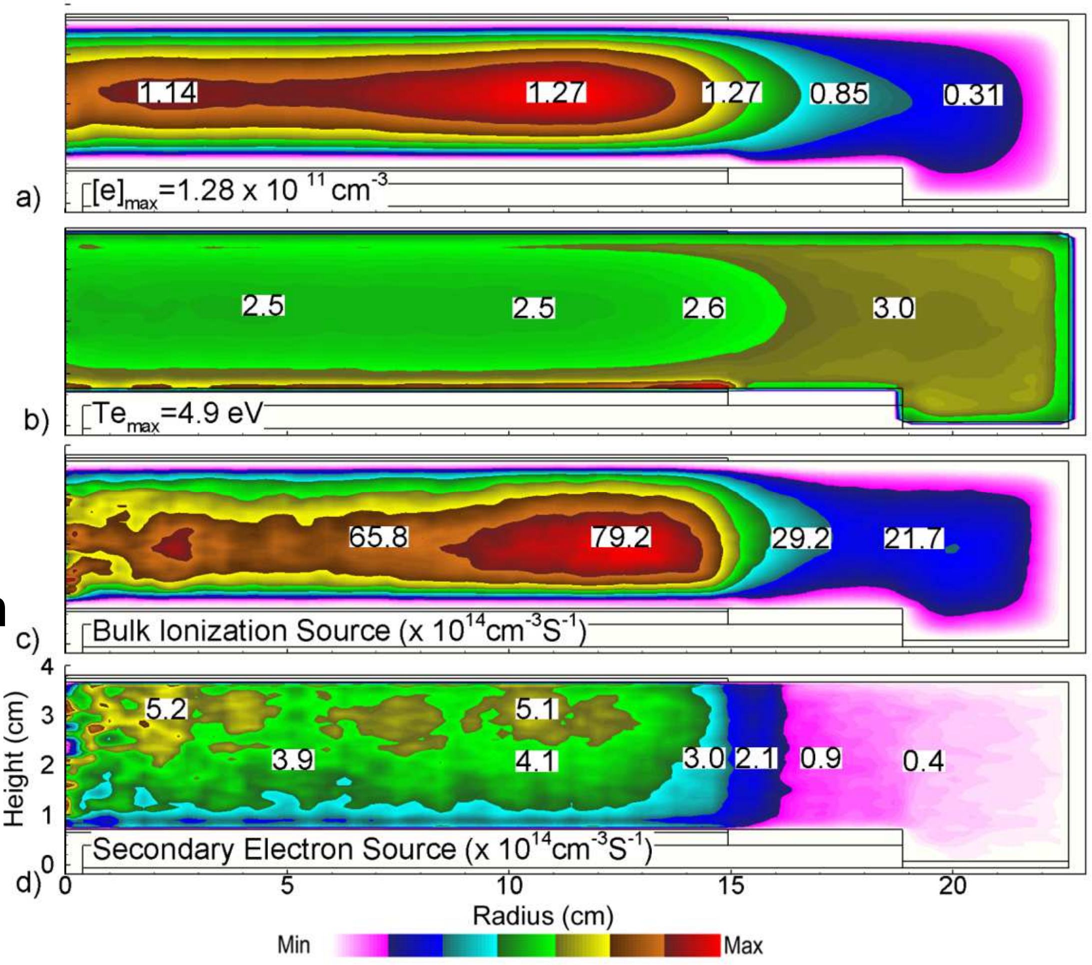
PLASMA PROPERTIES

- **Majority of power deposition that produces ions comes from HF.**
- **LF power deposition is primarily ion acceleration in the sheath.**
- **T_e is fairly uniform in the due to high thermal conductivity.**
- **Ionization by bulk and sheath accelerated secondary electrons.**
- **With large HF power, bulk ionization dominates.**

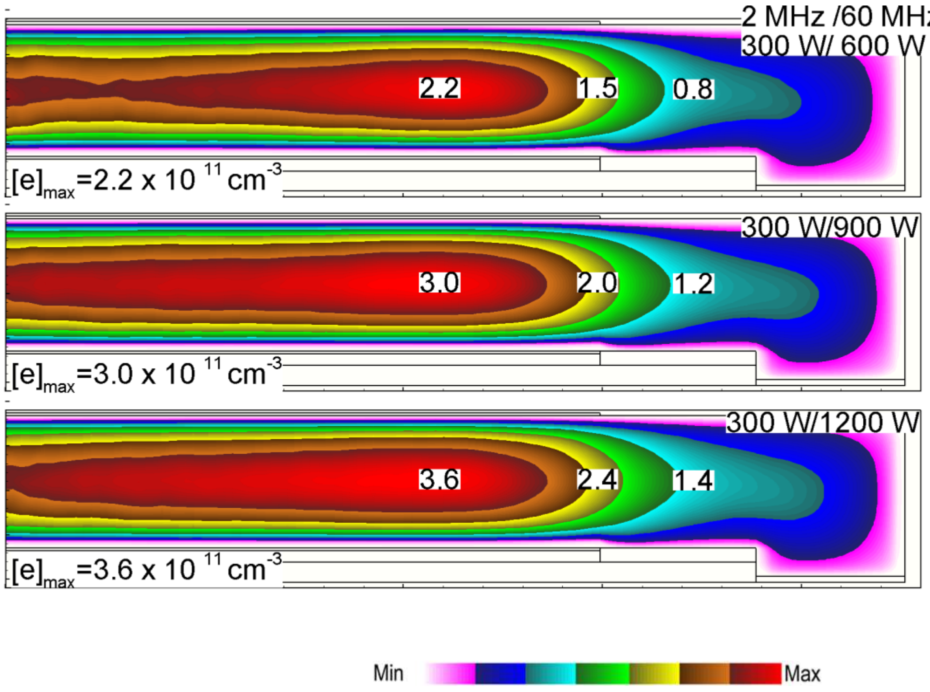


- **Ar, 30 mTorr, 1000 sccm,**
- **300 W, 2 MHz; 300 W, 60 MHz**

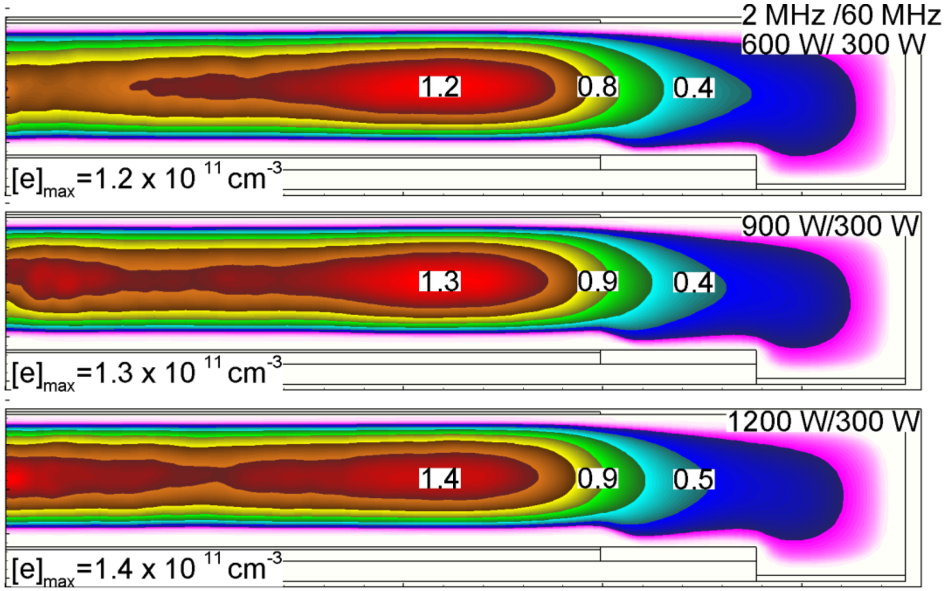
PLASMA DENSITY vs POWER

- **With larger HF power, the electron density significantly increases since HF mainly contributes to ionization and heating scales as ω^2.**
- **Increasing LF power has small effect on [e] (through ionization by secondary electrons) as majority of additional power results in ion acceleration.**
- **Uniformity increases with higher ionization.**

- **Increase HF Power**



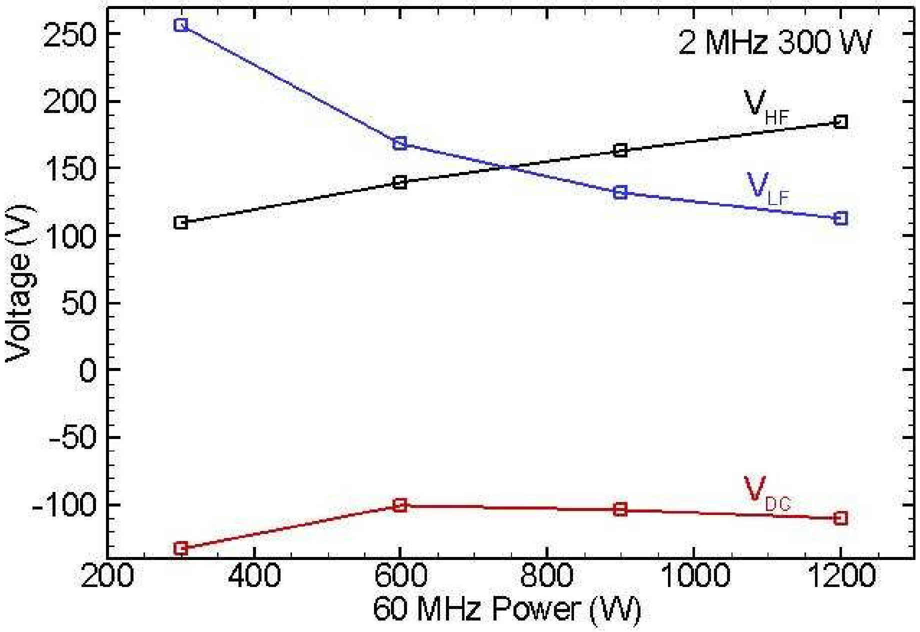
- **Increase LF Power**

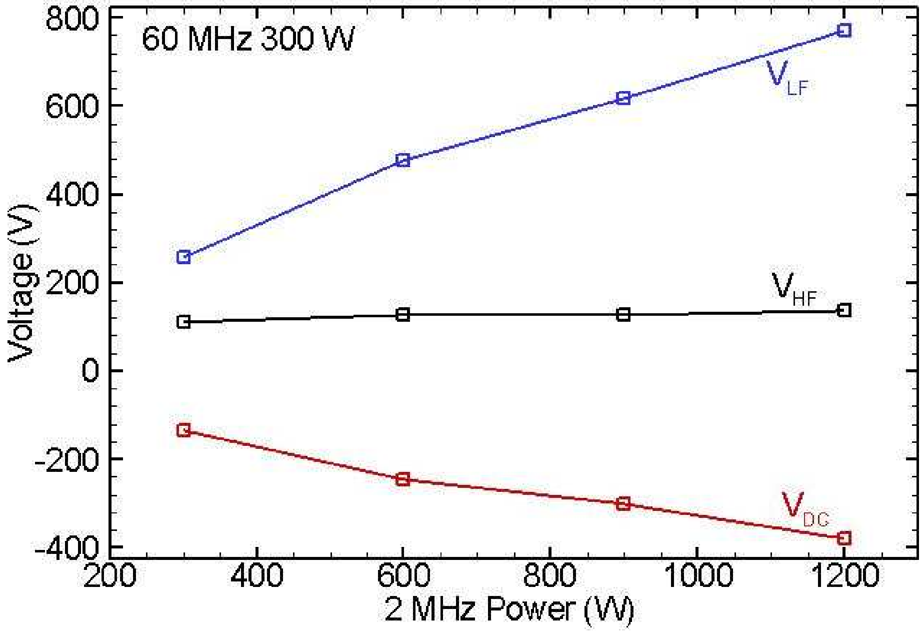


- **Ar, 30 mTorr, 1000 sccm**

VOLTAGE vs POWER

- With increase in HF power, V_{LF} decreases due to increase in ion current.
- Increase in LF power produces nominal changes in V_{HF}
- V_{dc} follows VLF and LF power (sum of V_{HF} and V_{LF}).

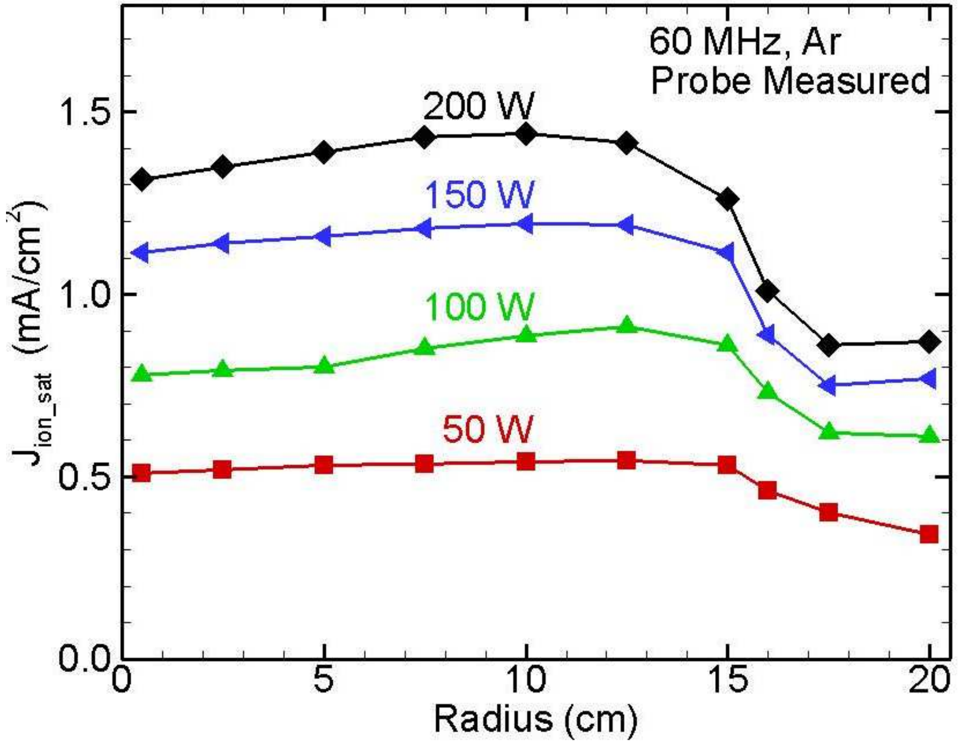


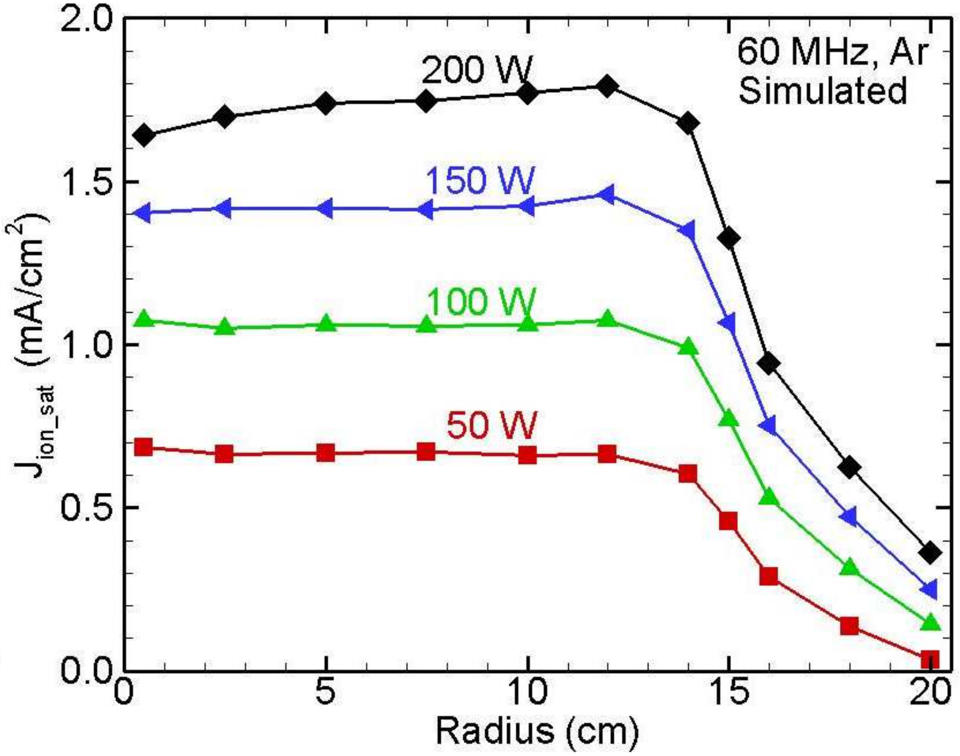


- Ar, 30 mTorr, 1000 sccm

VALIDATION: SINGLE FREQ

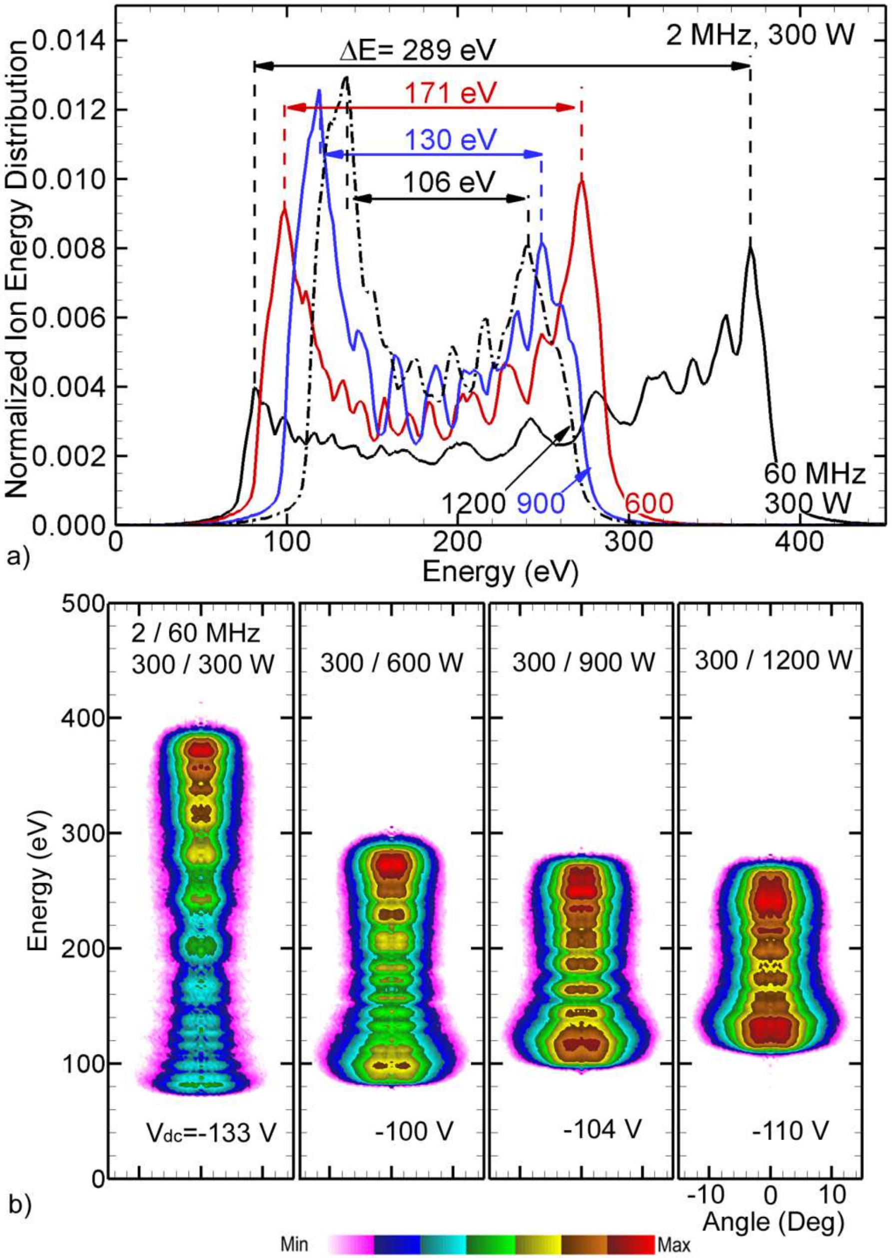
- **With HF power , both trend and magnitude of Ion saturation current density match with experiment double probe measurement.**
- **Simulated diagnostic:** $J_{ion\_sat} = \sum_{i=1}^{ion-tot} \frac{1}{4} \times q \times n_i \times \sqrt{\frac{2kT_e}{m_i}}$





- **Ar, 70 mTorr, 800 sccm**
- **Exp: Saravanapriyan Sriraman, LAM Research**

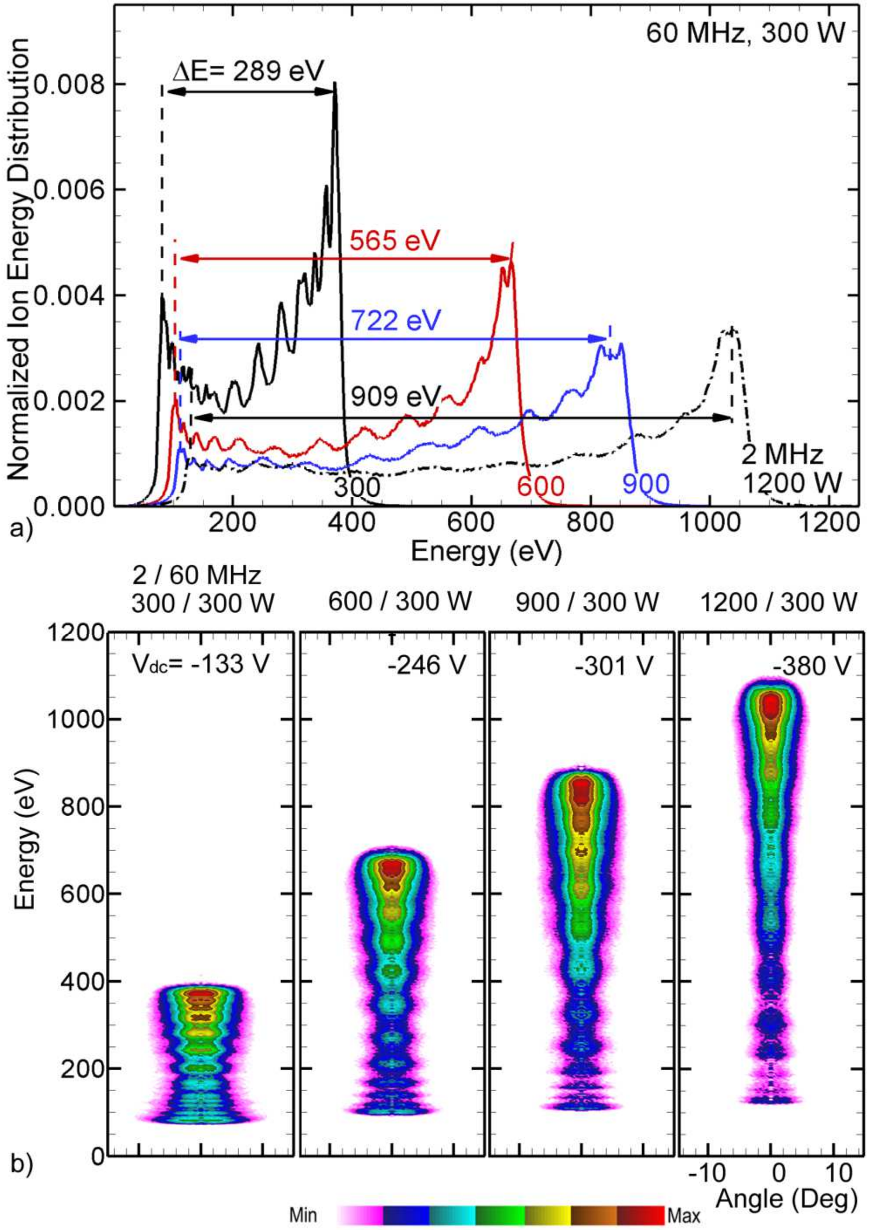
HIGH FREQUENCY POWER



- **With increase in HF power (300 W to 1200 W), the energy width ΔE shrinks and double peaks merge towards average sheath potential.**
- **Increasing in n_e produces larger current.**
- **In order to keep LF power constant, the LF voltage decreases.**
- **V_{dc} also decreases.**

- **Ar, 30 mTorr, 1000 sccm**

LOW FREQUENCY POWER

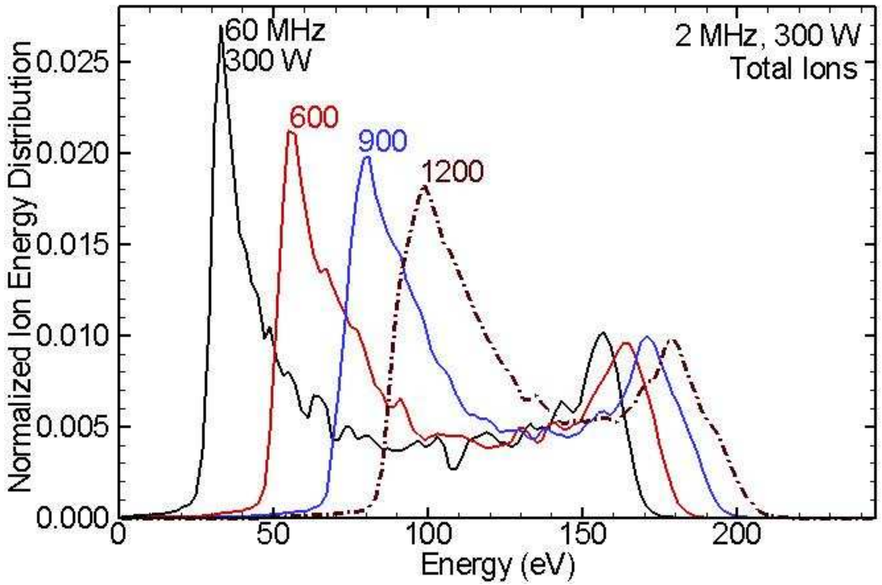


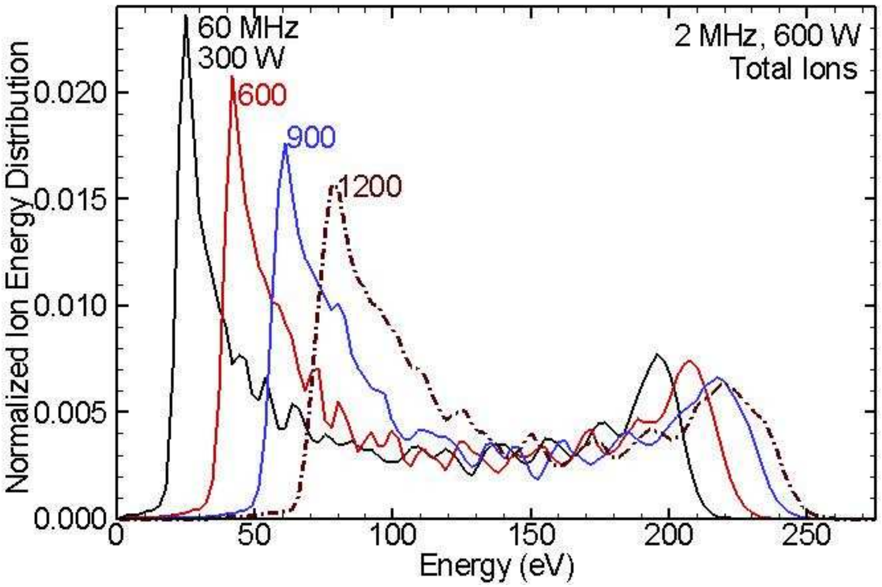
- **The LF power is mainly dissipated in the sheath – the width of IED increases with LF power.**
- **During the cathodic LF cycle, increase in sheath potential accelerates ions to higher energy.**
- **During anodic LF cycle, sheath potential is dominated by HF which is unchanged – and so modulation of IED persists.**

- **Ar, 30 mTorr, 1000 sccm**

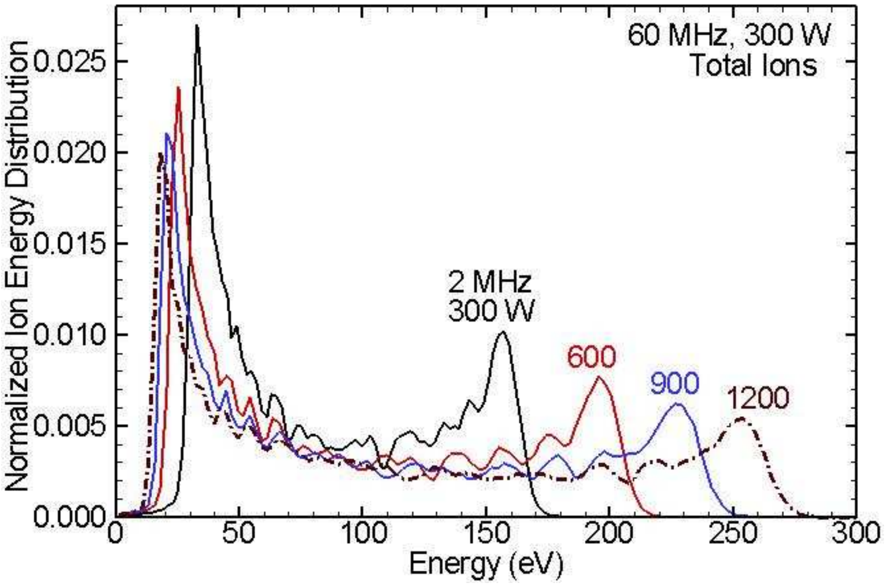
IEADs in $Ar/CF_4/O_2$ vs POWER

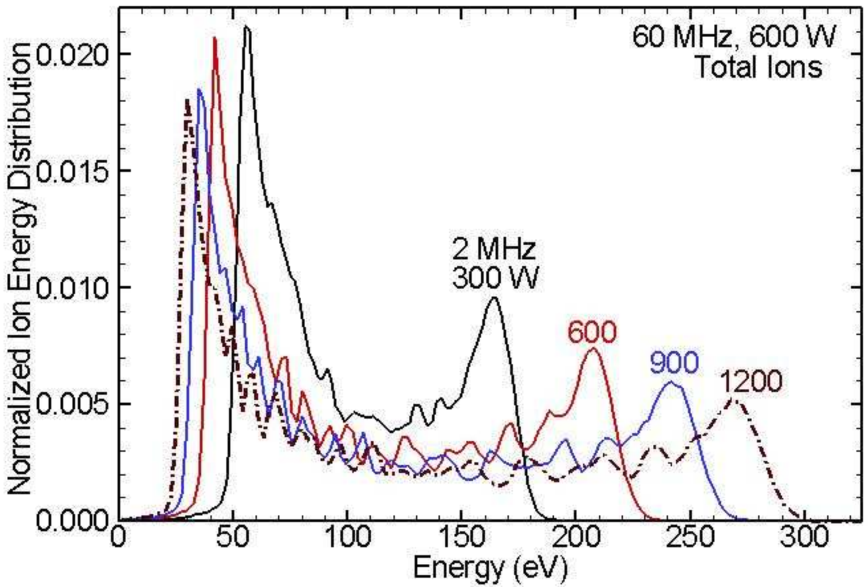
- **Increase HF Power**



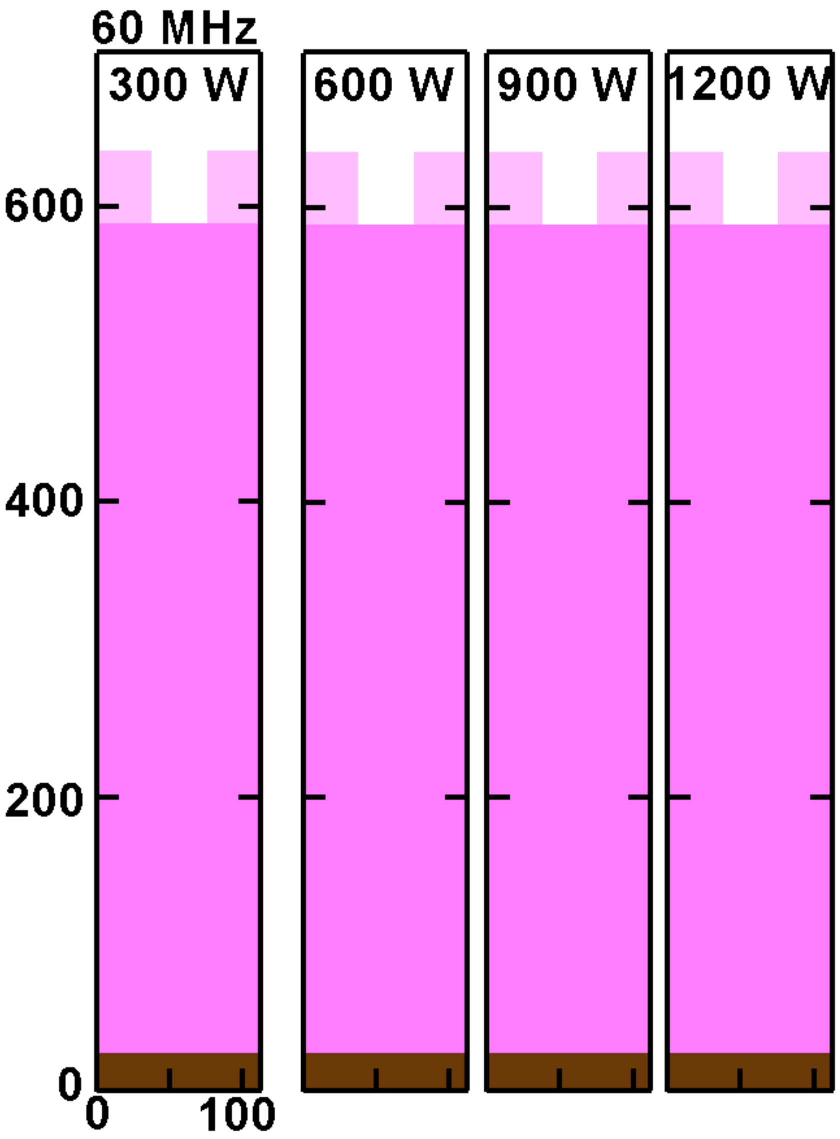


- **Increase LF Power**

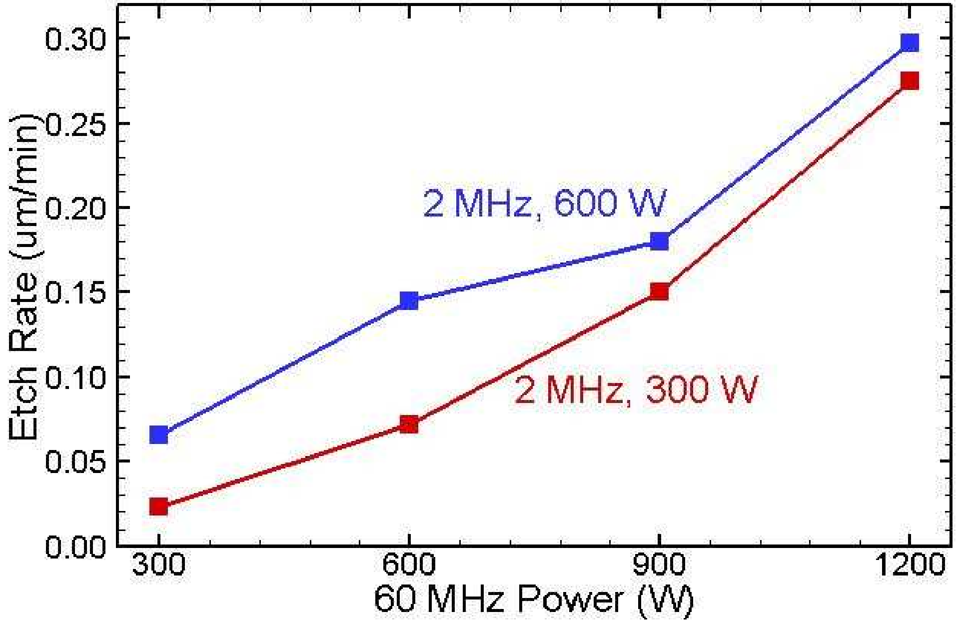




ETCH PROFILE vs HIGH FREQ POWER



- Fixed 2 MHz, 600 W.
- CD=37 nm, Aspect Ratio (AR)= 15
- Etch rate increases with HF power inspite of decrease in V_{LF}.
- Higher ion current, higher F/CF_x ratio, reduction in side-wall slope.

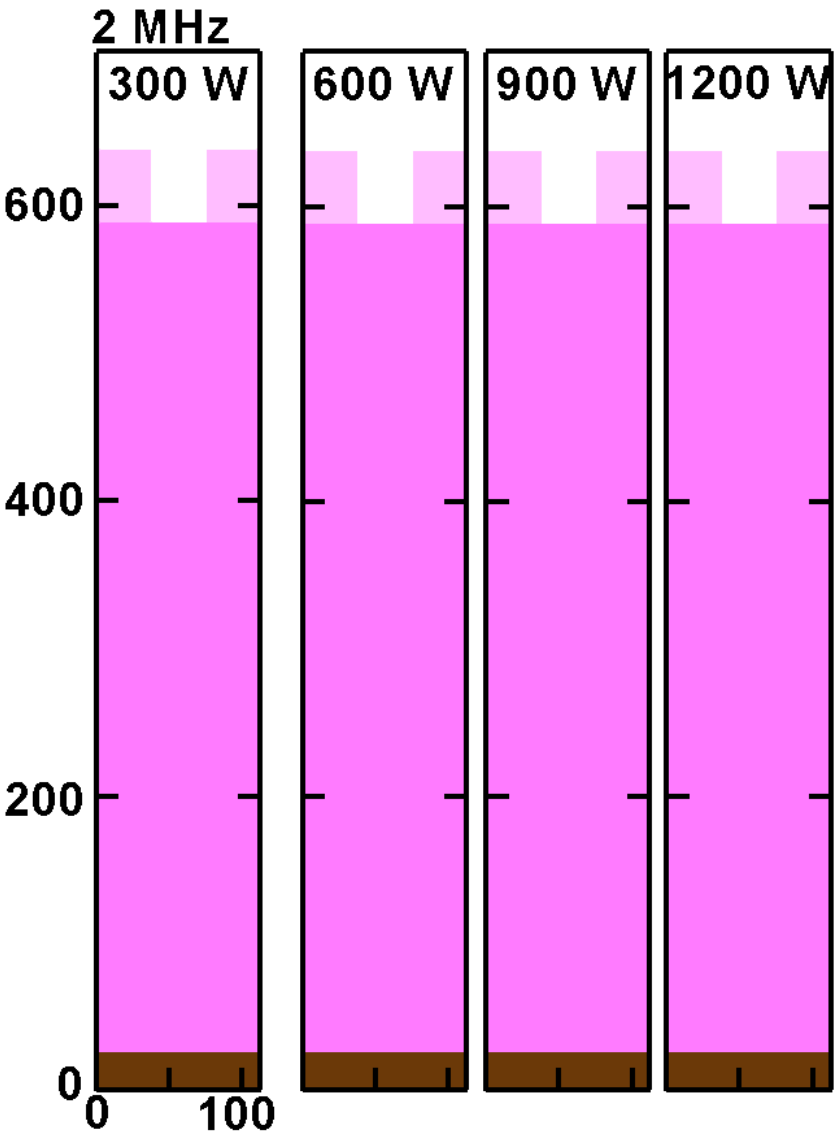


Unit: nm

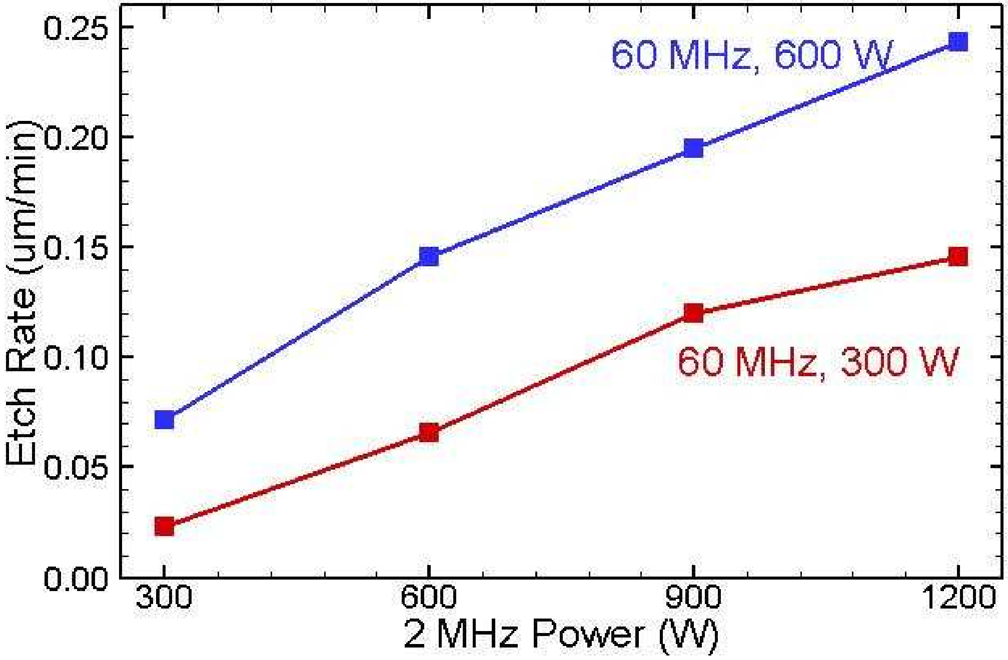
- $Ar/CF_4/O_2$=75/20/5, 30mTorr, 500 sccm

Animation Slide

ETCH PROFILE vs LOW FREQ POWER



- **Fixed 60 MHz, 600 W.**
- **Etch rate linearly increases with LF power due to average ion energy increasing.**
- **Little change in sidewall slope.**

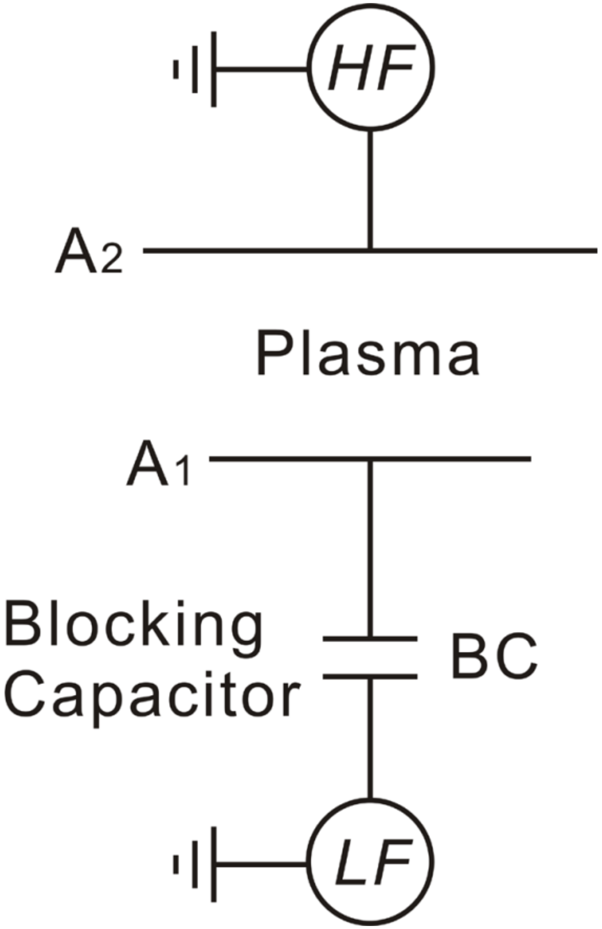


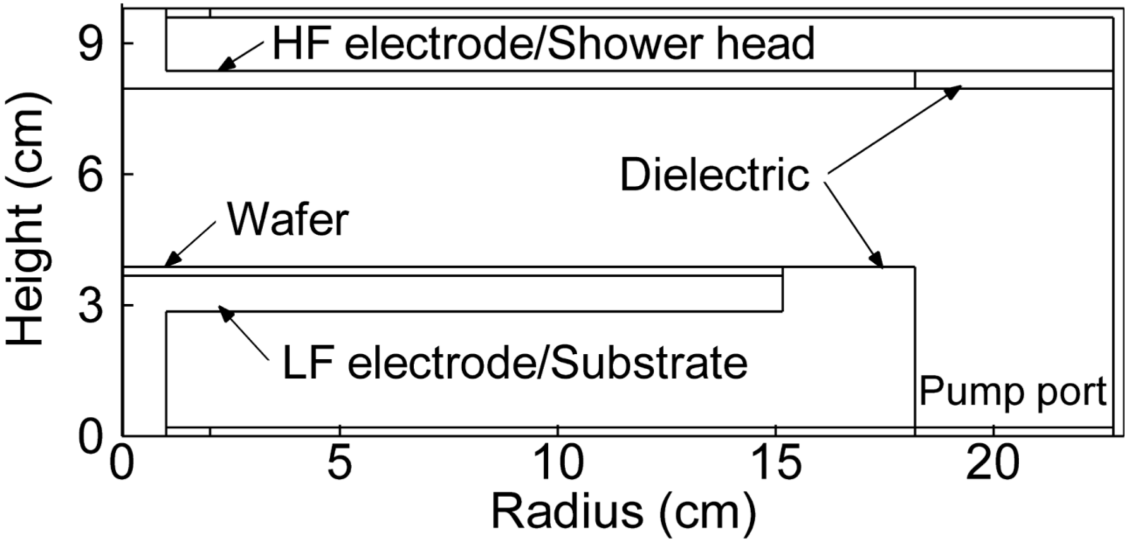
- **$Ar/CF_4/O_2$=75/20/5, 30mTorr, 500 sccm**

Animation Slide

PULSED DUAL-FREQUENCY CCPs: CIRCUIT INTERACTIONS

2 FREQUENCY CCP – BLOCKING CAPACITANCE



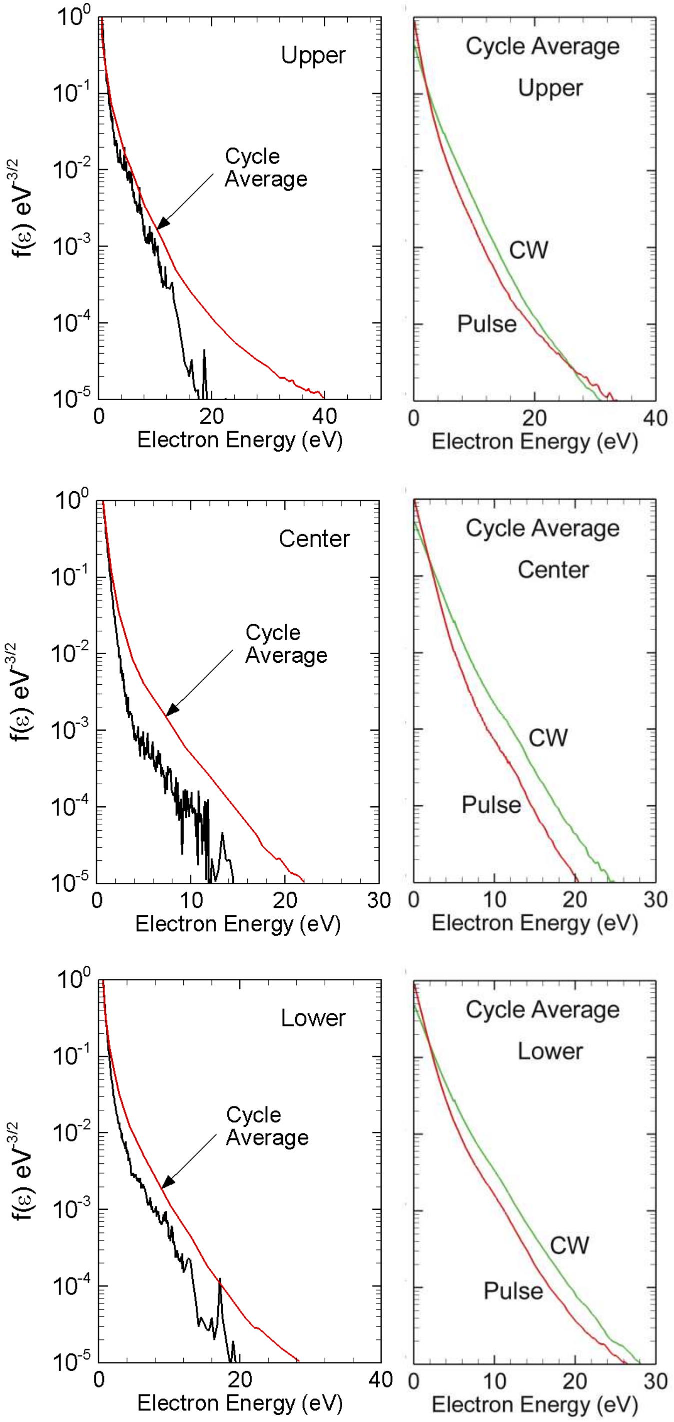


The temporal behavior of the "dc" bias during pulsing depends on the capacitance due to the RC charging time.

Ar/CF_4/O_2 = 75/20/5, /CF_4/O_2, 40 mTorr, 200 sccm

- **Lower electrode: LF = 10 MHz**
- **Upper electrode: HF = 40 MHz**

f(ε) IN PULSED CCP



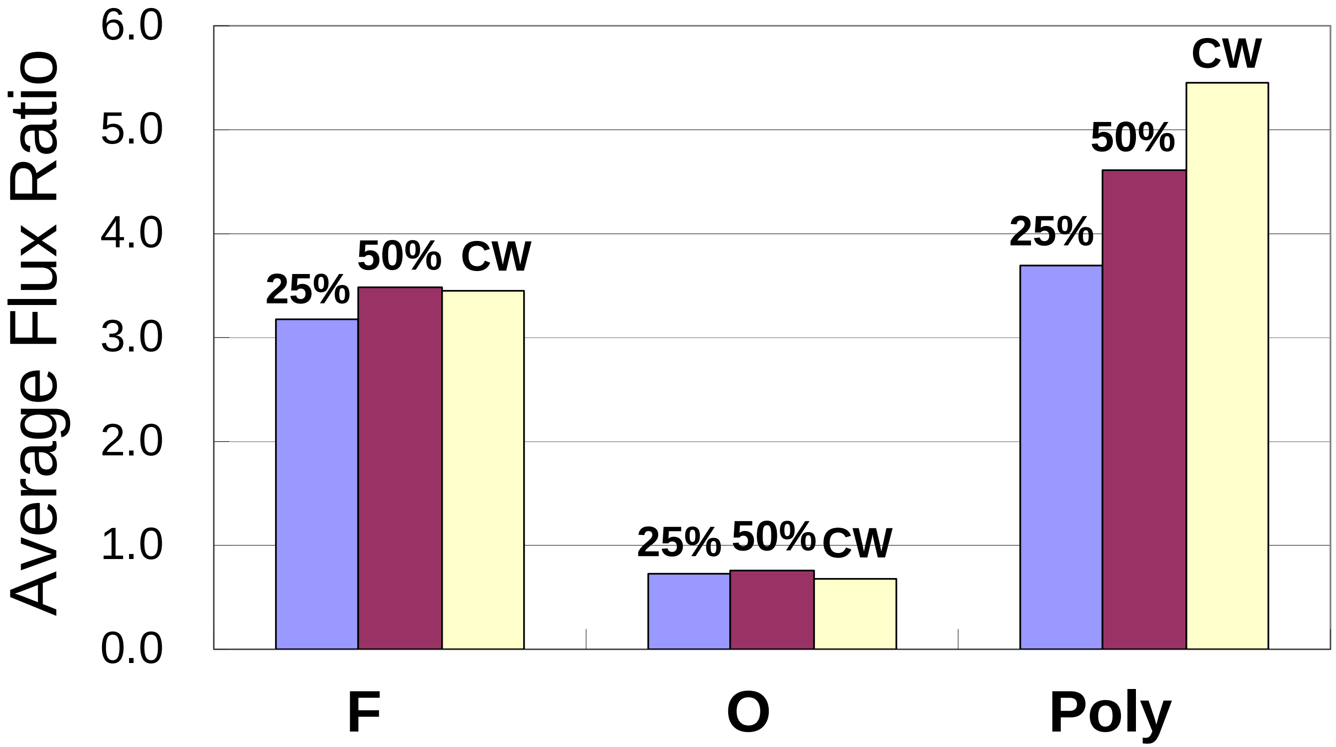
- **Pulse HF**
- **f(ε) for bulk electrons averaged over pulse cycle is distinctly different than CW for same average power.**
- **Typically more of lowest energy and highest energy electrons.**
- **Contributions of secondary electrons important in maintaining ionization balance.**
- **$Ar/CF_4/O_2$ = 75/20/5**
- **LF = 10 MHz, 500W; HF = 40 MHz, 500W**
- **PRF = 50 kHz, Duty-cycle = 25%**

Animation Slide-GIF

RATIO OF FLUXES: CF_4/O_2, DUTY CYCLE

- Flux ratio control is limited if keep power constant.
- With smaller duty cycle, polymer flux ratio is more reduced compared to the others.

- __Flux Ratios__:
  - Poly = CF_x / Ions
  - O = O / Ions
  - F = F / Ions

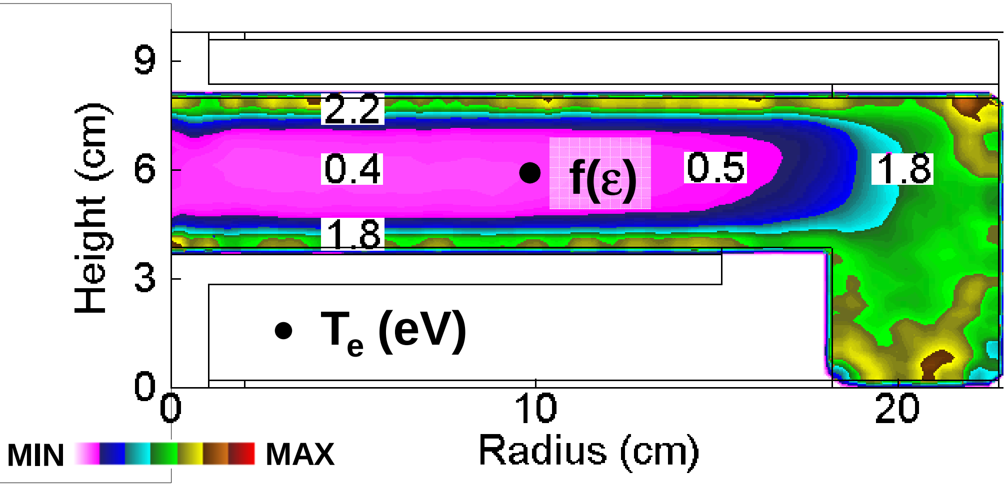


- LF 10 MHz, Pulsed HF 40 MHz, PRF = 100 kHz
- 40 mTorr, CF_4/O_2=80/20, 200 sccm

PLASMA PROPERTIES: PULSING LF

- Pulsing LF produces moderate modulation of [e] and T_e in the bulk plasma.
- Dynamics of sheath potential adjacent to the substrate are large and enable customized of ion energy distributions to the wafer
- $Ar/CF_4/O_2$ = 75/20/5, 40 mTorr, PRF = 10 kHz, Duty cycle = 25%, BC = 1 μF, %, V_{LF}=V_{HF}=250 V

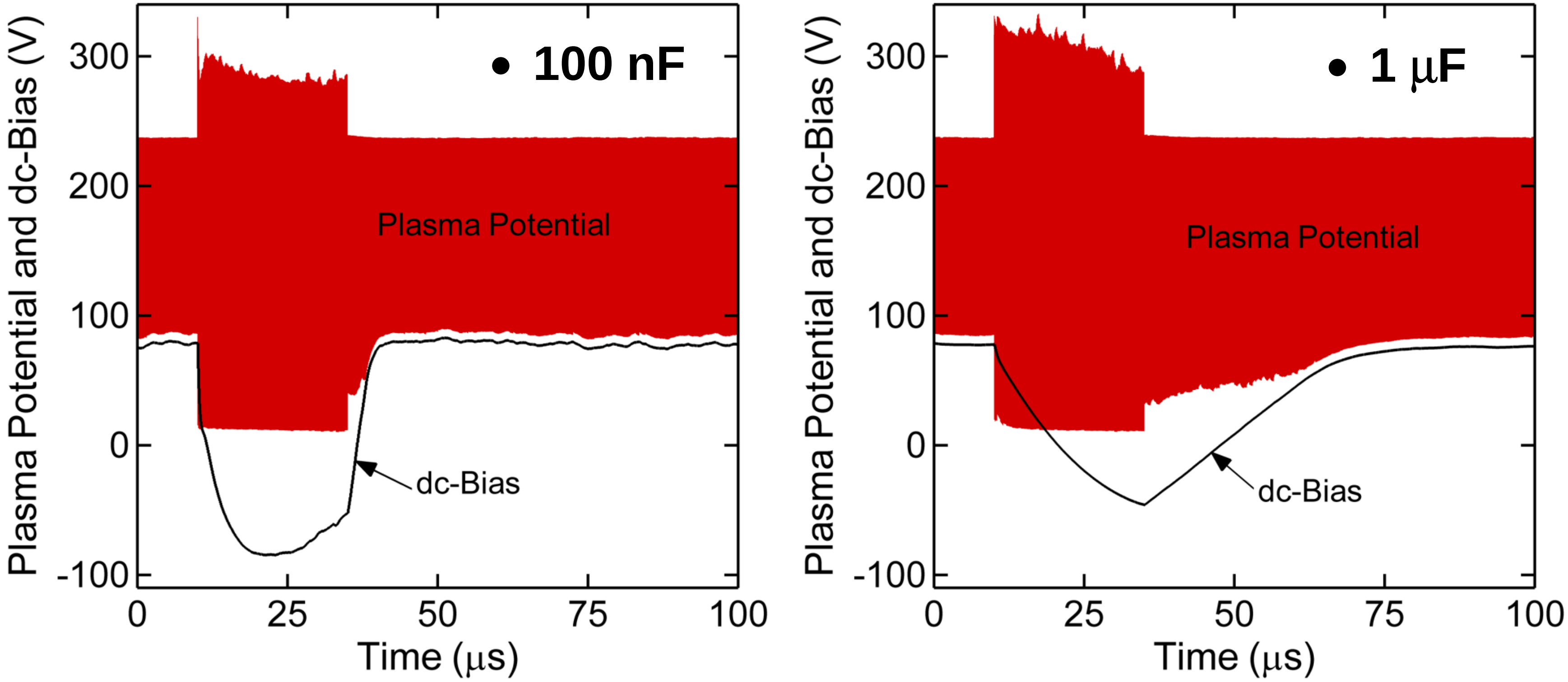
- n_e (10^{11} cm^{-3})



ANIMATION SLIDE-GIF

PLASMA POTENTIAL AND dc BIAS: LF PULSED

- A small blocking capacitor enables the “dc” bias to follow the transient currents during the pulse period.
- Maximum ion energy = Plasma Potential +V_{rf} – “dc” Bias



- $Ar/CF_4/O_2$ = 75/20/5, 40 mTorr, PRF = 10 kHz, Duty cycle = 25%, V_{LF}=V_{HF}=250 V

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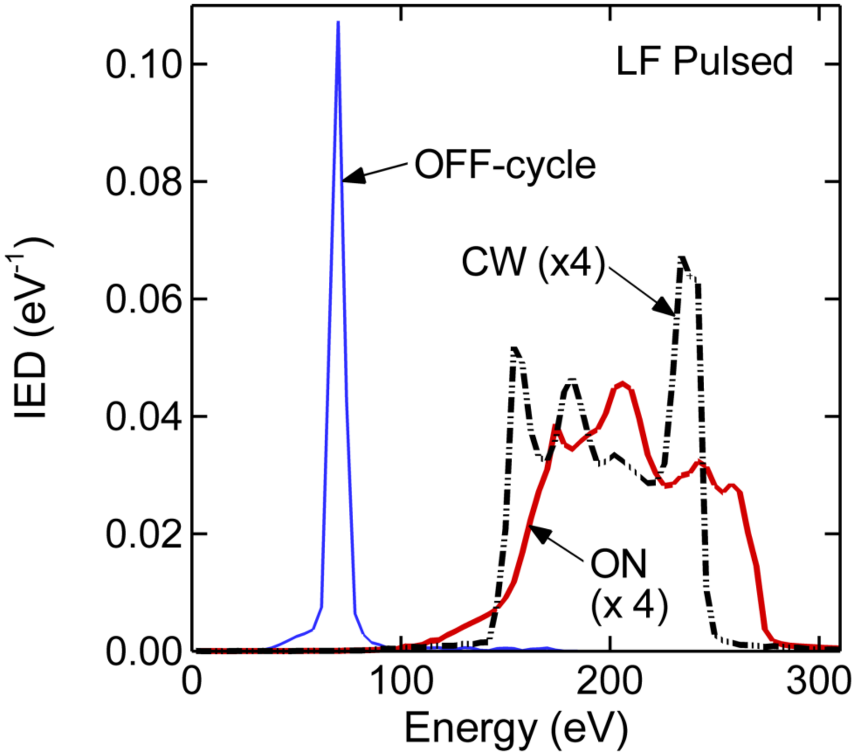
ION ENERGY DISTRIBUTION: PULSING LF

- IED consists of a low energy portion (LF off) and a high energy portion (LF on).
- Dynamics of IEADs depend on BC.



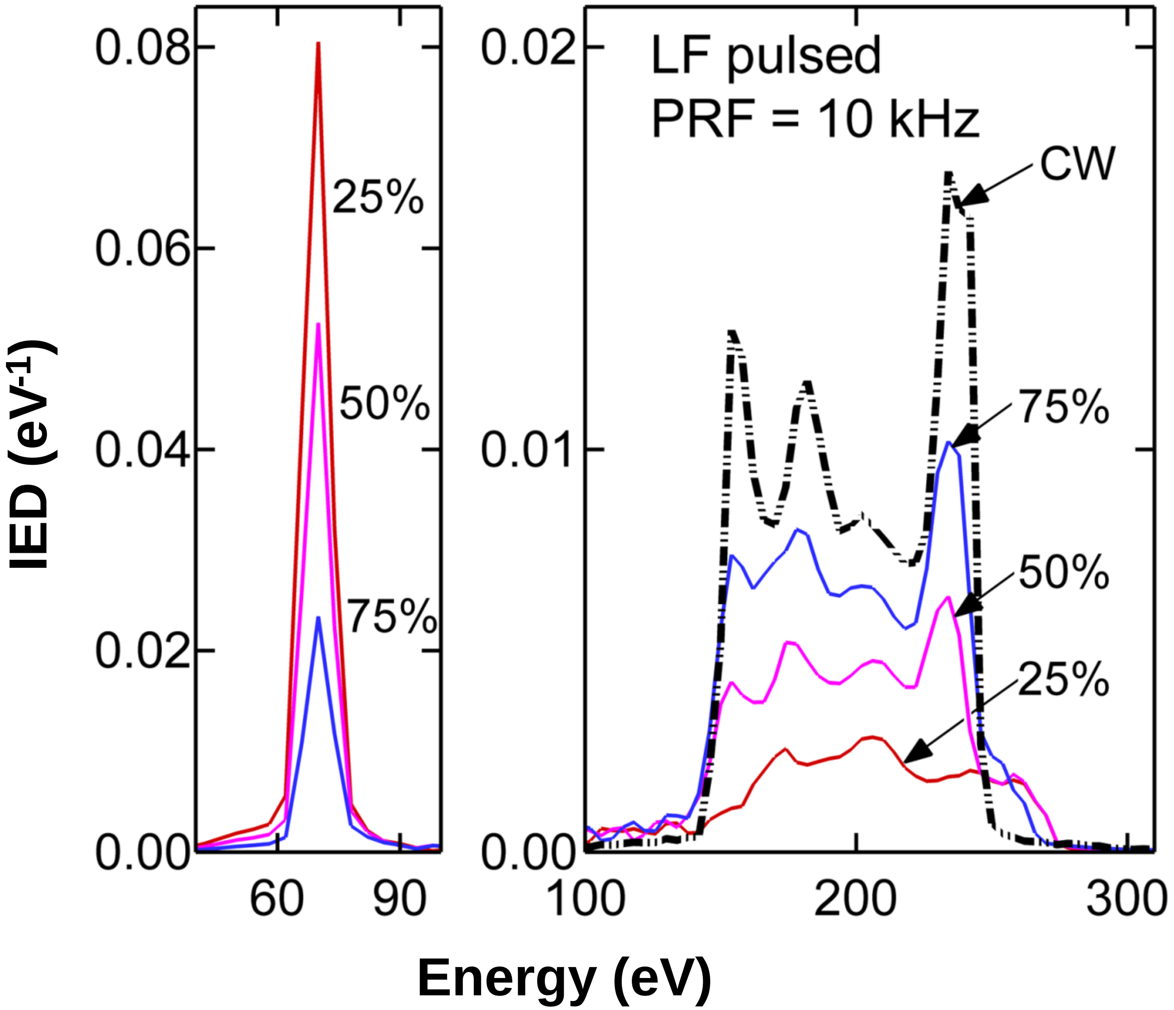
Energy (eV)

ANIMATION SLIDE-GIF

Angle (degree)

- PRF = 10 kHz, Duty cycle = 25%,
- 2 decades MIN MAX

IEDs vs DUTY CYCLE: PULSING LF

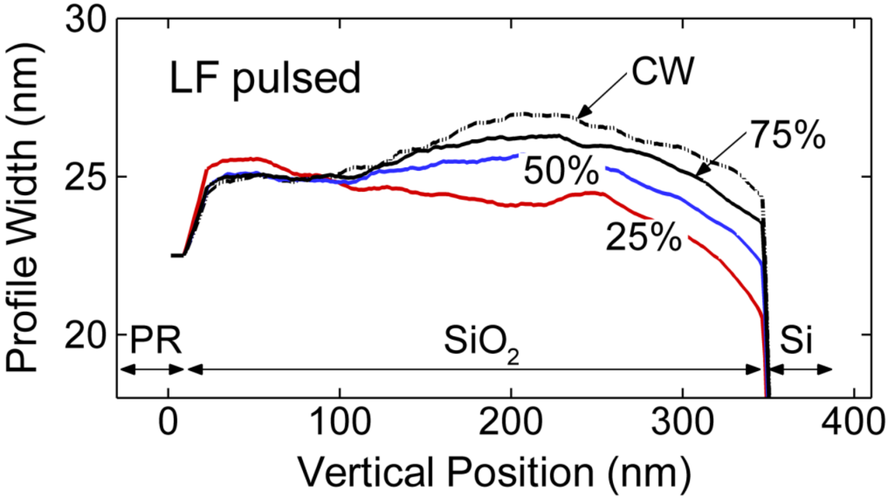


- **The high energy peak in the IED comes from the power-on stage.**
- **The low energy peak comes from the power-off stage.**
- **The amplitude of each peak can be manipulated by duty cycle.**

- **Ar/CF$_4$/O$_2$ = 75/20/5, 40 mTorr, PRF = 10 kHz, Duty cycle = 25%, BC = 100 nF**

ETCH PROFILE vs. DUTY CYCLE: PULSING LF

- **With constant voltage, lower dc produces lower etch rate.**
- **At same overetch (100%), smaller pulsed dc reduces bowing – more polymer per energetic ion.**



ANIMATION SLIDE-GIF

- **25%**
- **50%**
- **75%**
- **CW**

- **$Ar/CF_4/O_2$ = 75/20/5, 40 mTorr, PRF = 10 kHz, Duty cycle = 25%, BC = 100 nF, V_{LF}=V_{HF}=250 V, CD = 22 nm**

PLASMA PROPERTIES: PULSING HF

- **Pulsing HF produces more modulation of both electron density and temperature.**
- **In the late afterglow, T_e increases due to lower n_e, which thickens the LF sheath.**
- **CCP transitions to a self-sustained single LF.**

- ***f(ε)***

- **n_e (10^{11} cm^{-3})**
- **T_e (eV)**

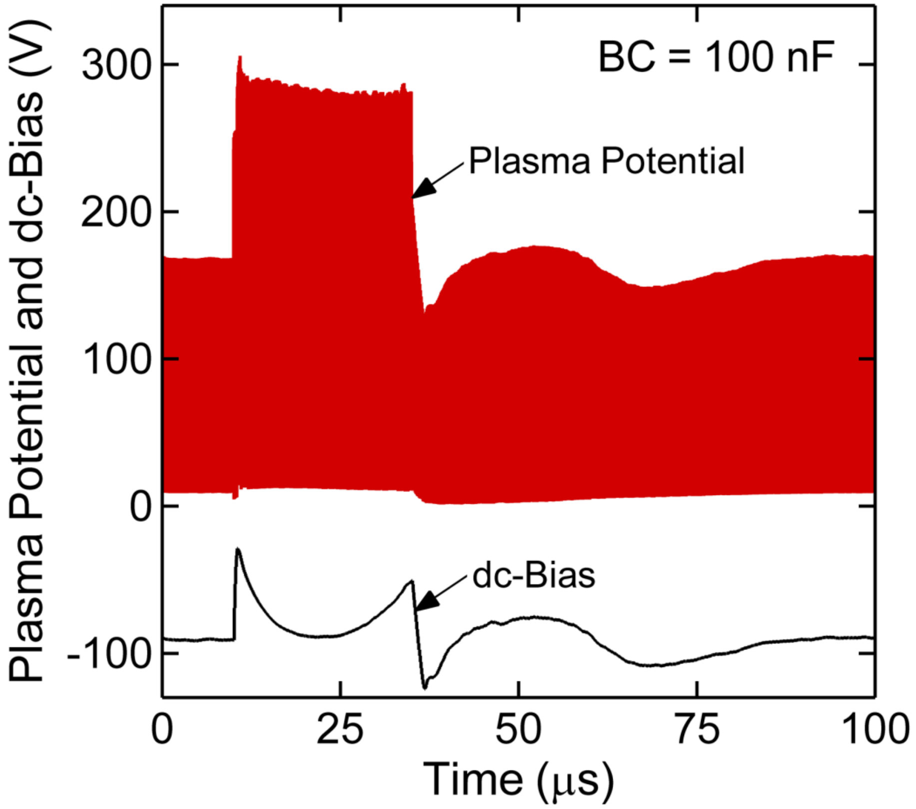
ANIMATION SLIDE-GIF

MIN **MAX**

- **$Ar/CF_4/O_2$ = 75/20/5, 40 mTorr, 10 kHz, dc= 25%, BC = 100 nF, V_{LF}=V_{HF}=250 V**

ION ENERGY: PULSING HF

- **The variation in dc bias is not as large as when pulsing LF – still some modulation due to change in ion current and spatial distribution.**



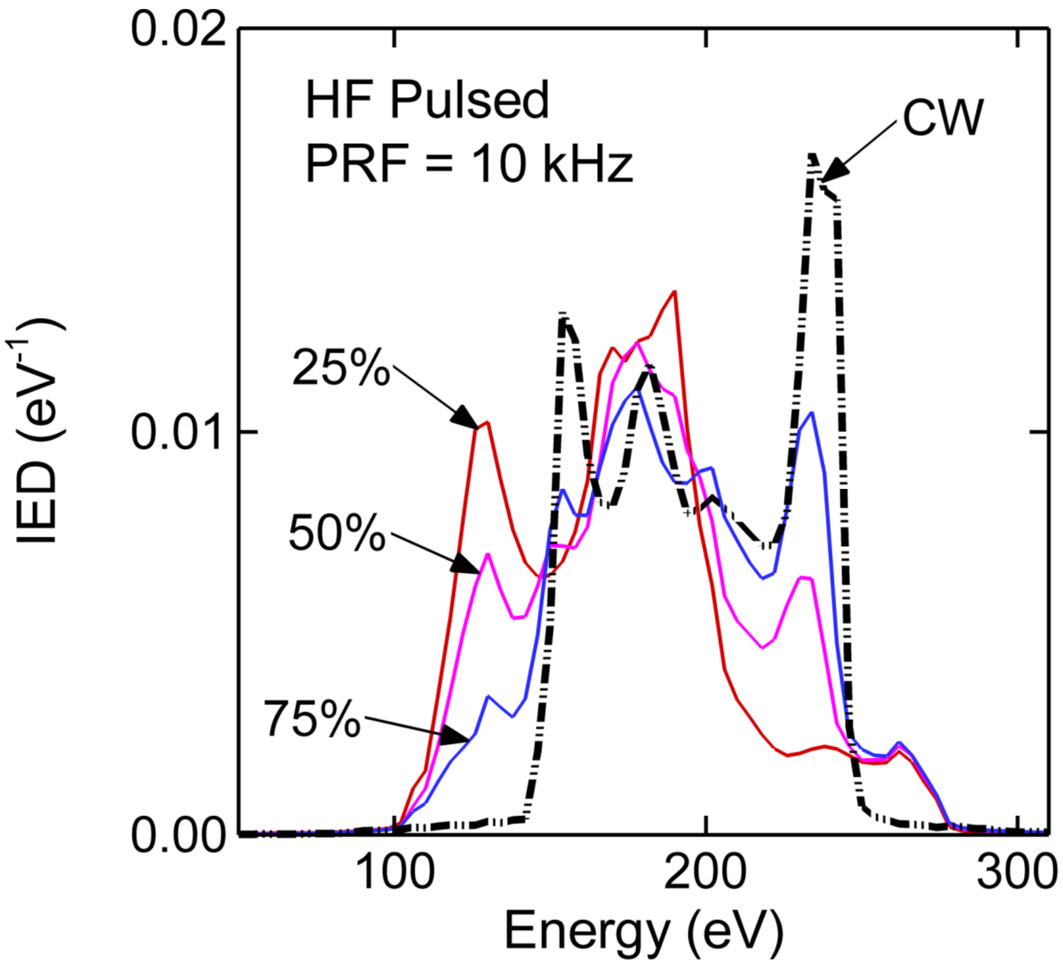
Energy (eV)

Angle (degree)

ANIMATION SLIDE-GIF

- **PRF = 10 kHz, Duty cycle = 25%**
- **2 decades** **MIN** **MAX**

IEDs vs DUTY CYCLE: PULSING HF



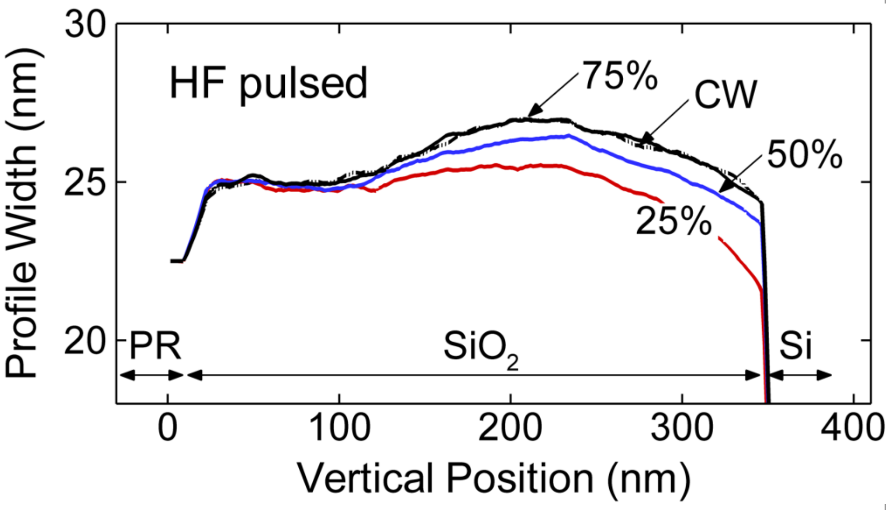
- **Unlike pulsing LF, the energy range of IED does not vary much by the duty cycle – IED is dominated by cw LF.**
- **Pulsing of plasma potential and modulation of Vdc shown in low- and high-energy components.**

- **PRF = 10 kHz, BC = 100 nF**

ETCH PROFILE vs DUTY CYCLE : PULSING HF

- 25%
- 50%
- 75%
- CW

- **The sidewall bowing tends to be suppressed by pulsed power.**
- **Duty cycles ≥ 75% resemble cw.**



- **$Ar/CF_4/O_2$ = 75/20/5, 40 mTorr, PRF = 10 kHz, Duty cycle = 25%, BC = 100 nF, V_{LF}=V_{HF}=250 V, CD = 22 nm**

ANIMATION SLIDE-GIF

PLASMA PROPERTIES: PULSING LF & HF

- Pulsing both LF & HF at the same time produces a larger dynamic range of [e] and T_e in the bulk and boundary.
- The sheath potential adjacent to the substrate is also significantly modulated by the temporal behavior of the dc-bias.
- Log scale with 2 decades

- $f(\varepsilon)$

- n_e (10^{11} cm^{-3})
- T_e (eV)

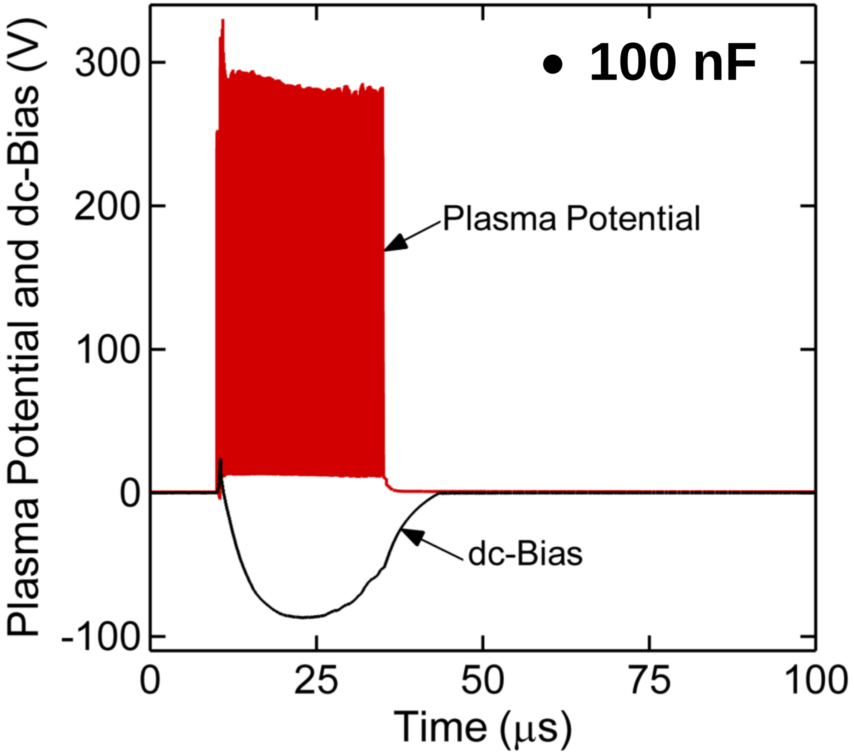
MIN MAX

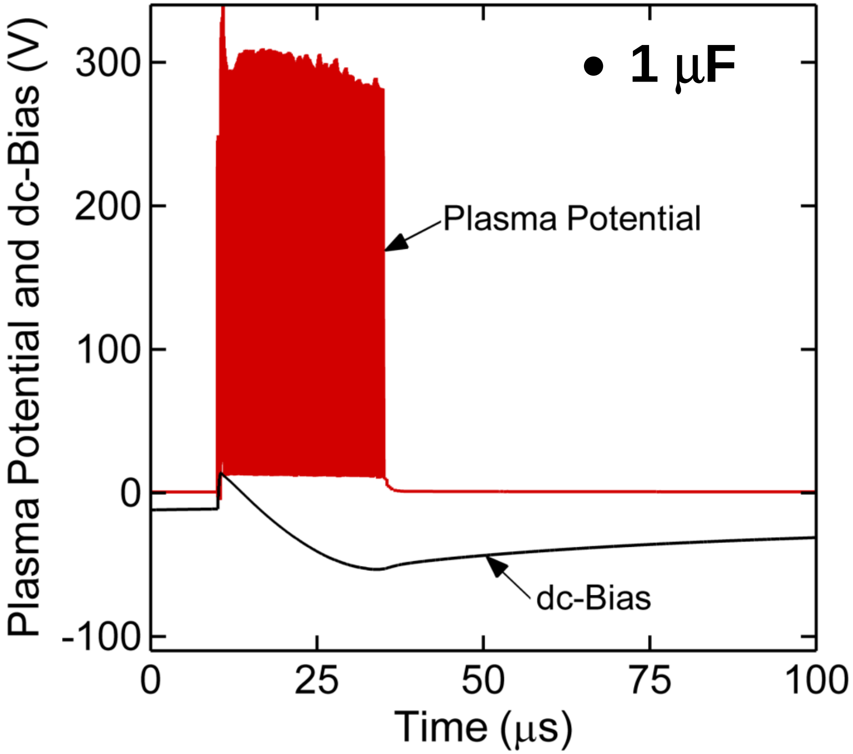
ANIMATION SLIDE-GIF

- $Ar/CF_4/O_2$ = 75/20/5, 40 mTorr, 10 kHz, dc= 25%, BC = 100 nF, V_{LF}=V_{HF}=250 V

PLASMA POTENTIAL & dc BIAS: LF & HF PULSED

- In the afterglow, the plasma potential is nearly zero. The dc-bias dissipates with the smaller blocking capacitor.
- The dc bias remains negative with the larger BC.





- PRF = 10 kHz, Duty-cycle = 25%

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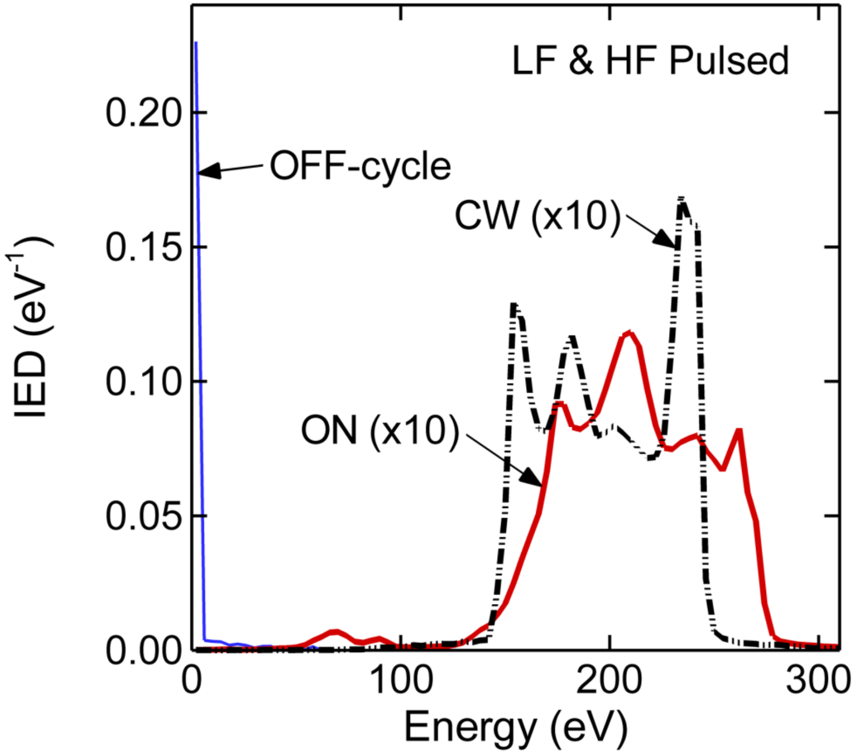
ION ENERGY DISTRIBUTION: PULSING LF & HF

- **IED thermalized in afterglow with small BC – remains at 10s eV with large BC**



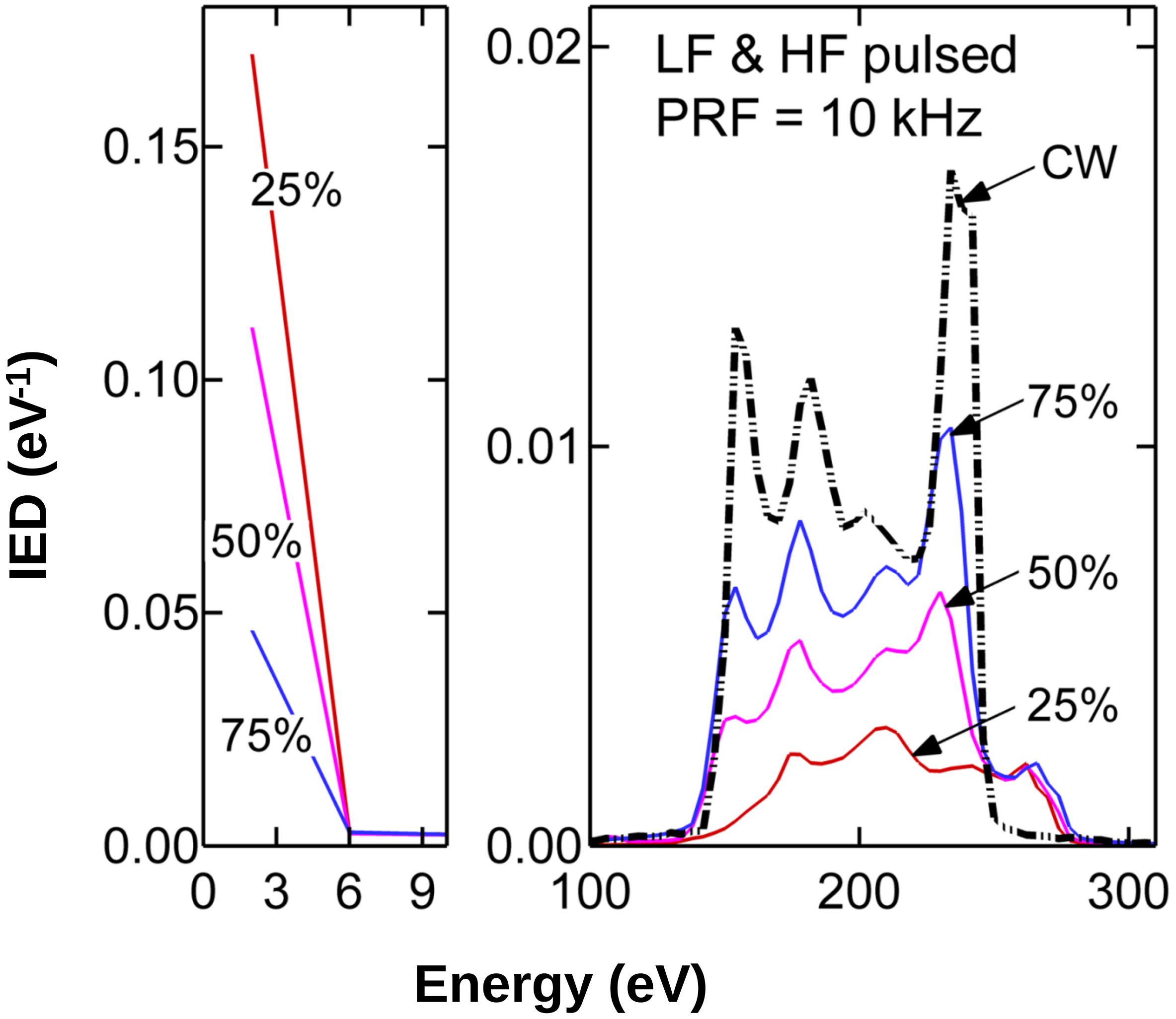
Energy (eV)

Angle (degree)

ANIMATION SLIDE-GIF

- **PRF = 10 kHz, Duty cycle = 25%,**
- **2 decades** **MIN** ▨ **MAX**

IEDs vs DUTY CYCLE: PULSING LF & HF

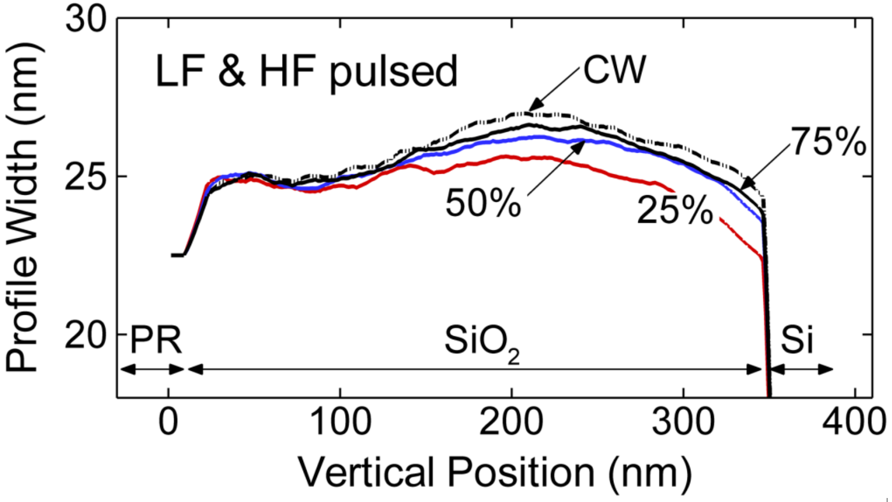


- In the afterglow, fraction of thermal ions onto the substrate increases as duty-cycle decreases.
- In the activeglow, the IEADS are similar to cw with high energy tail due to pulsing
- The relative fraction between high and low energy is controlled by duty cycle.

- PRF = 10 kHz, BC = 100 nF

ETCH PROFILE vs. DUTY CYCLE : PULSING LF & HF

- **With smaller duty cycle, the sidewall bowing tends to be suppressed.**
- **Due to ion activation of polymer deposition, effect of duty cycle is not large.**



- **25%**
- **50%**
- **75%**
- **CW**

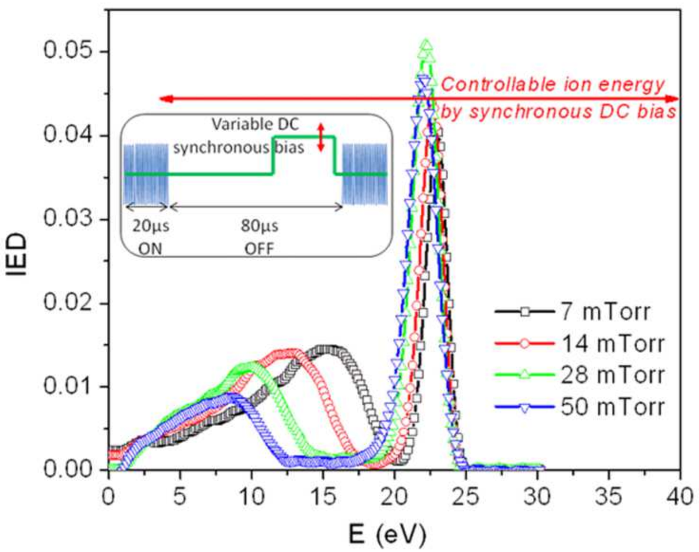
- **Ar/CF_4/O_2 = 75/20/5, 40 mTorr, PRF = 10 kHz, Duty cycle = 25%, BC = 100 nF, V_{LF}=V_{HF}=250 V, CD = 22 nm**

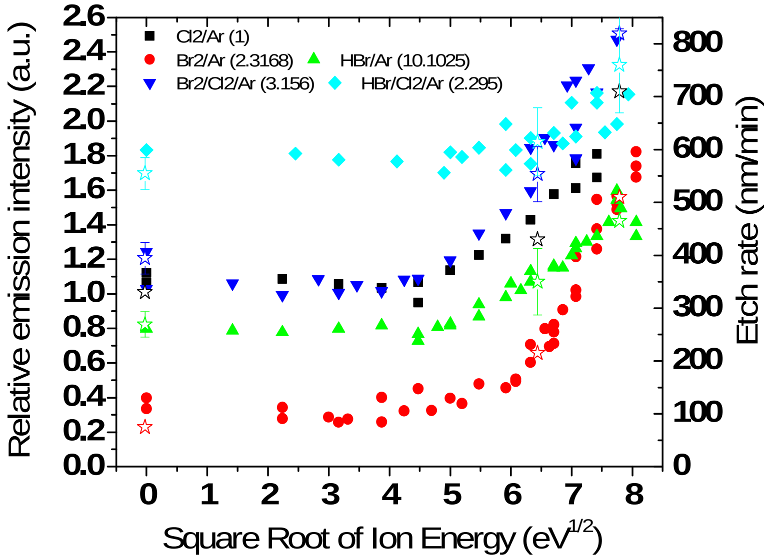
ANIMATION SLIDE-GIF

PULSING FOR CONTROL OF PHOTONS

PHOTON ASSISTED ETCHING

- **Recent observations of VUV sustained etching in Cl and HBr plasmas below accepted ion energy threshold.**

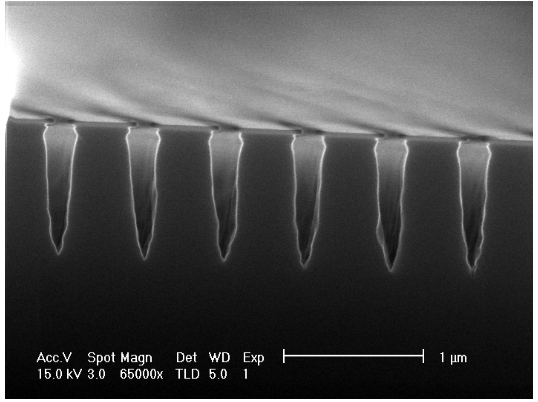




Surprising importance of photo-assisted etching of silicon in chlorine-containing plasmas

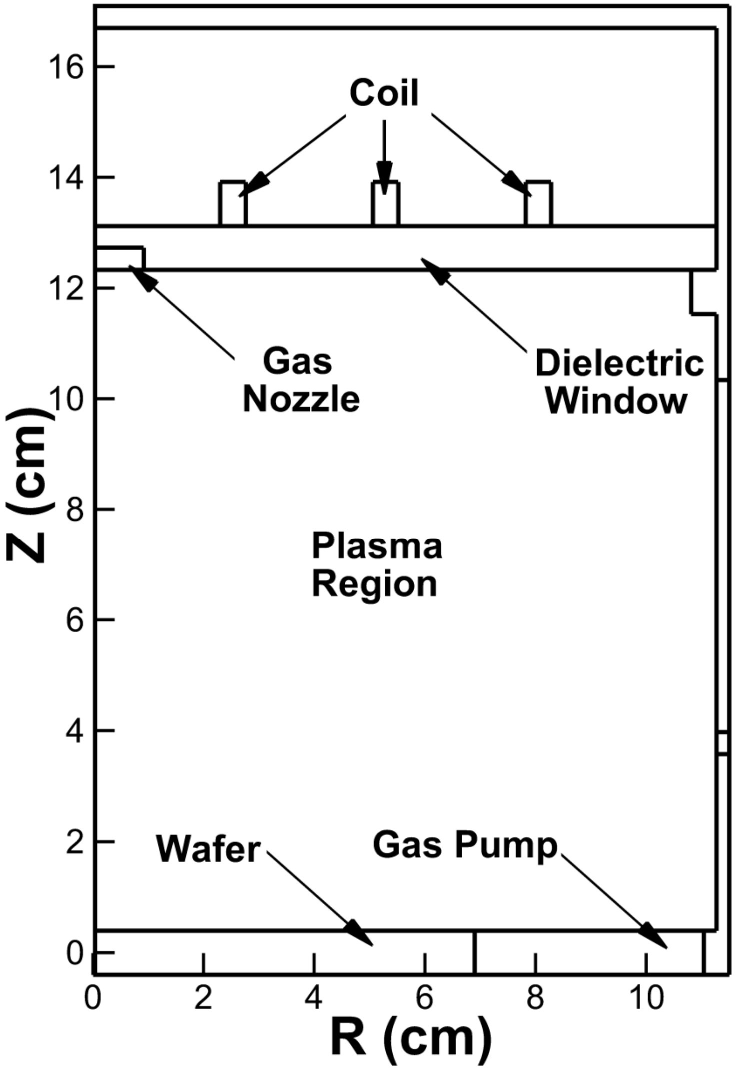
Hyungjoo Shin, Weiye Zhu, Vincent M. Donnelly, and Demetre J. Economou
Plasma Processing Laboratory, Department of Chemical and Biomolecular Engineering, University of Houston, 4800 Calhoun Road, Houston, Texas 77204

J. Vac. Sci. Technol. A 30(2), Mar/Apr 2012



- **Isolating Ion-assisted and Photon-Assisted Etching of Si in Halogen-containing ICPs with Mono-energetic ion and Energy Selected Photon Bombardment. PLSC Annual Report 2013**

MODEL GEOMETRY



- Inductively Coupled Plasma.
- RF power (10 MHz) delivered by spiral coil and coupled through dielectric (quartz) window.
- Gas injected from on axis nozzle and pumped out at the bottom.
- Grounded metallic reactor walls elsewhere.
- Cylindrically symmetric with structured mesh.
- Fluxes are collected on the wafer.

PULSED ICP: f(ε) – TIME, SPATIAL VARIATION

— = cycle average

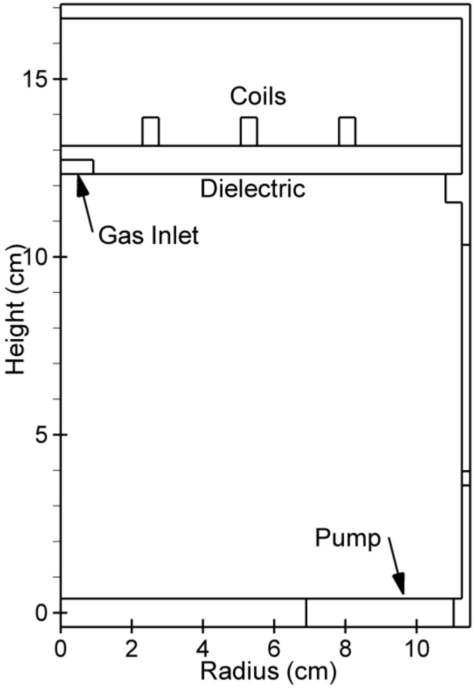
- T_e
- f(ε)

- Anomalous sheath and electron-electron collisions are efficient at convecting – conducting energy beyond power deposition zone.
- Ar/Cl_2 = 80/20, 20 mTorr, 150 W_{ave}, 50 kHz, duty cycle = 15%

Animation Slide

PULSED ICP – POWER, T_e, Φ_{VUV}

- **Investigate ability to control ratio of VUV-to-ion flux to substrate using pulsed ICP plasma.**



Power **T_e** **VUV Photon Flux**

- **Ar/Cl_2 = 80/20, 20 mTorr, 150 W_{ave}, 50 kHz, duty cycle = 15%**

MIN **MAX**

Animation Slide

PULSED ICP – [e], ION DENSITIES

- **Repetition rate and duty cycle purposely chosen so that intra-pulse variation in charged particle densities is not large (< 50%).**

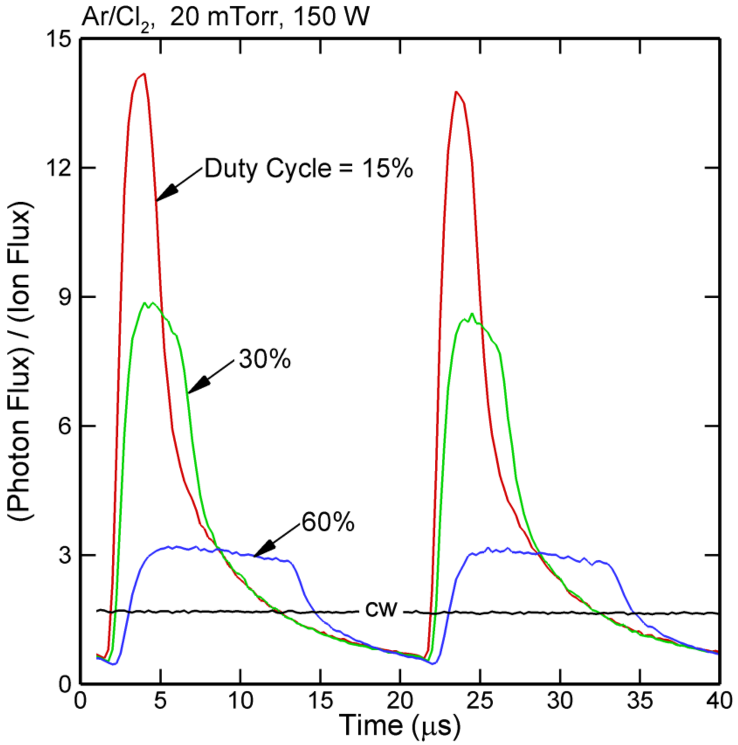
[e] **$[M^+]$** **$[Cl^-]$**

- **Ar/Cl_2 = 80/20, 20 mTorr, 150 W_{ave}, 50 kHz, duty cycle = 15%**

Animation Slide

CONTROLLABLE RATIO OF PHOTON / ION FLUX

- **Photons and ions leave plasma at different rates vs duty cycle, providing control over coincidence and ratio of photon and ion fluxes.**



- **Ar/Cl_2 = 80/20, 20 mTorr, 150 W_{ave}, 50 kHz**

Animation Slide

ASPECT RATIO – TRANSPORT OF IONS vs PHOTONS

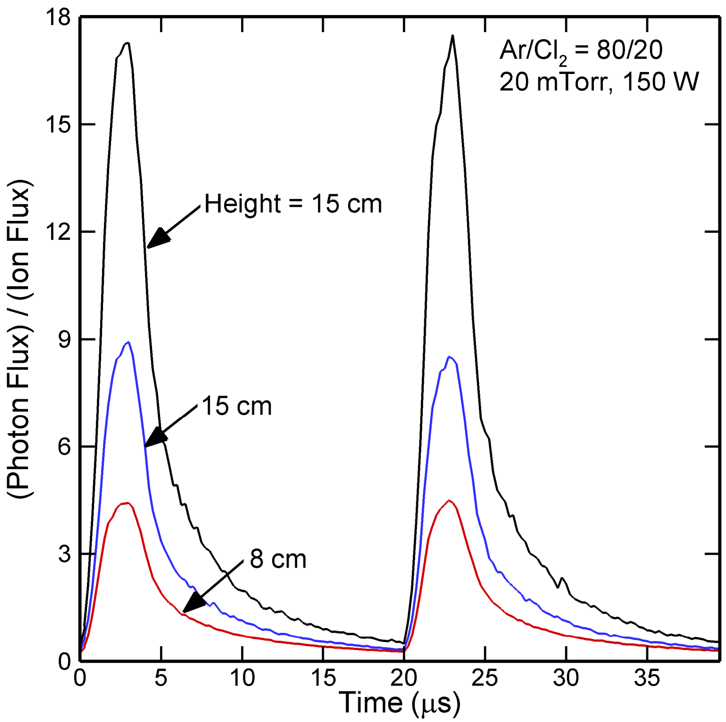
Animation Slide

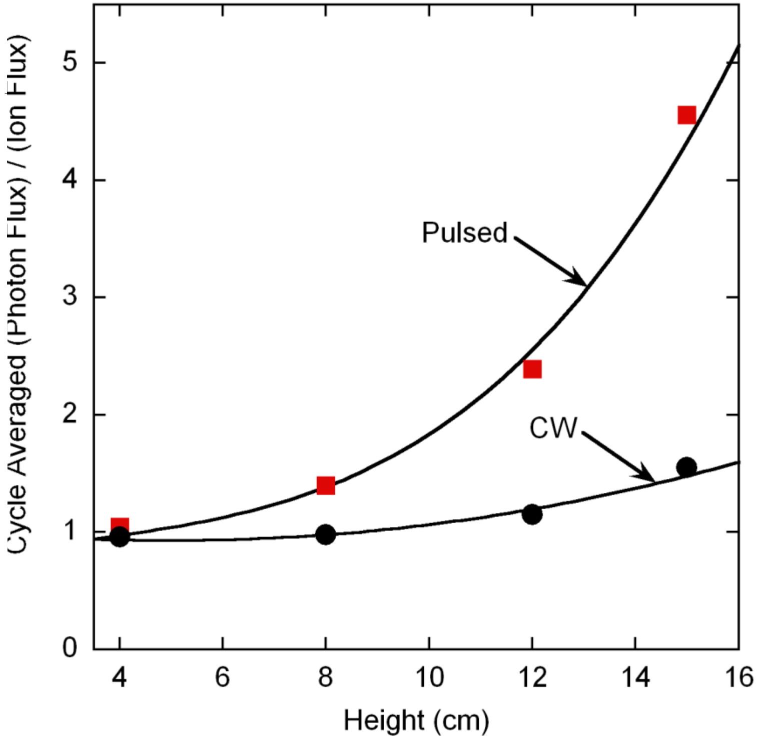
- **Although moderately trapped, the transport of Ar resonance radiation is significantly less diffusive than ions.**
- **Since sources are near the coils, aspect ratio can be used to discriminate fluxes.**
- **Ar/Cl_2 = 80/20, 20 mTorr, 150 W, 50 kHz, duty cycle = 15%**

MIN **MAX**

PHOTON / ION FLUX vs ASPECT RATIO

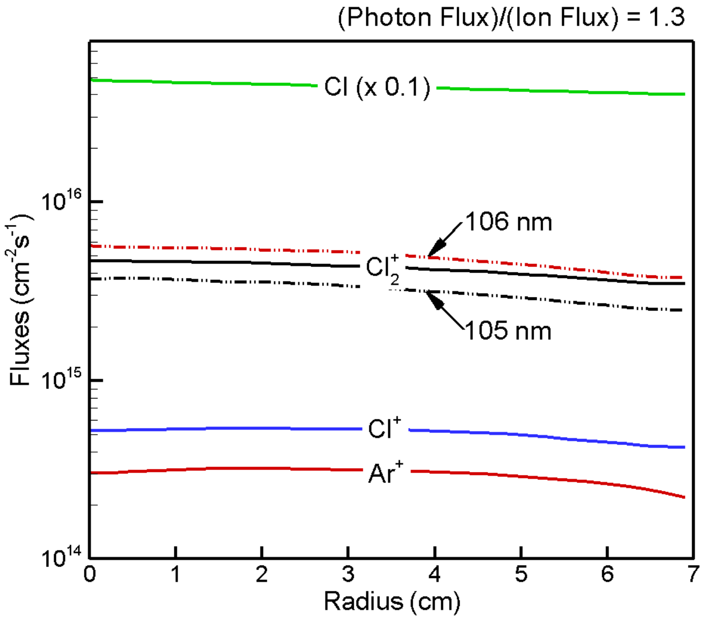
- **Varying aspect ratio (height) of reactor provides another means of controlling the ratio of photon to ion flux.**



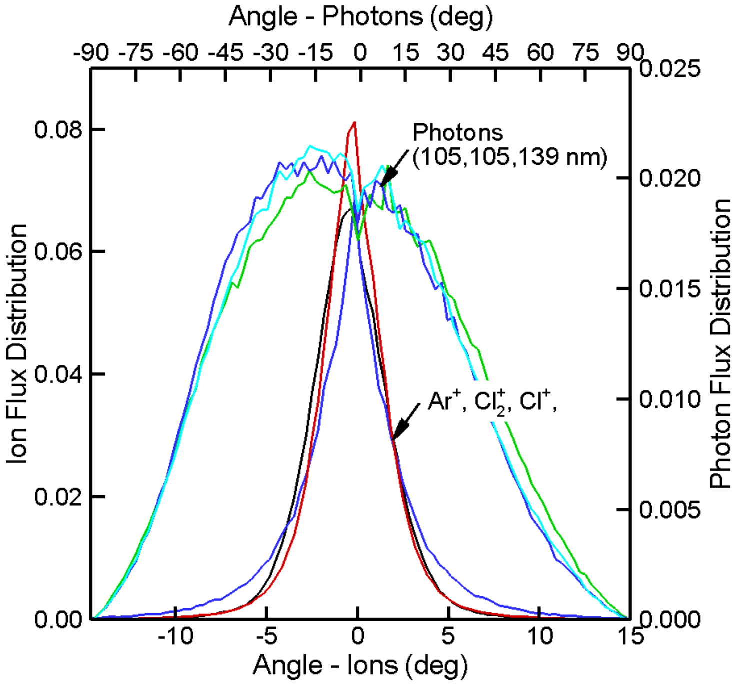


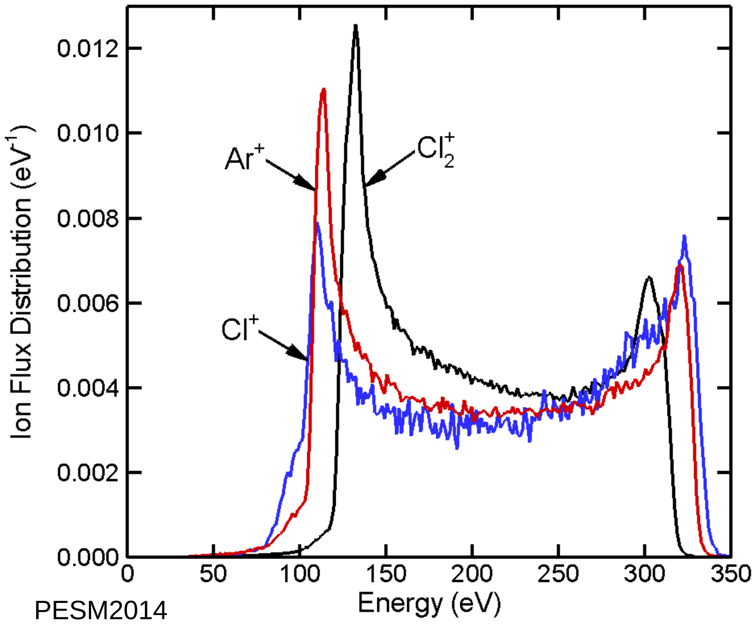
- **Flux ratios in are more sensitive to aspect ratio in pulsed plasmas due to more tight coupling between excited states and photon fluxes in cw plasmas.**
- **Ar/Cl_2 = 80/20, 20 mTorr, 150 Wave, 50 kHz**

POSSIBLE CONSEQUENCES: Ar/Cl$_2$ ETCHING OF Si



- **VUV photon fluxes are nearly isotropic.**
- **Ar/Cl$_2$ = 80/20, 20 mTorr, 150 W, 10 MHz, Bias 10 MHz**
- **Photon etch probabilities calibrated to probabilities for 40 eV ions. [H. Shin et al. JVSTA 30, 021306 (2012)]**





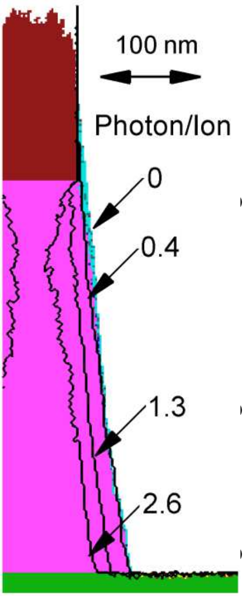
Ar/Cl_2 PLASMA ETCH OF Si WITH VUV

PR

Si

SiO_2

Without VUV



PR

Si

SiO_2

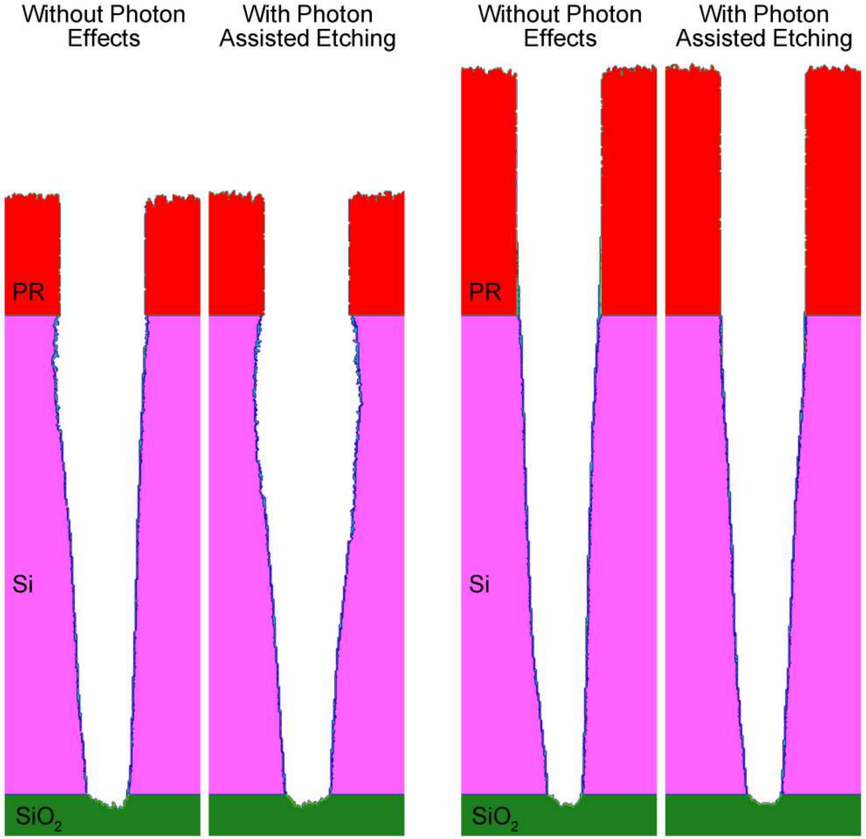
With VUV

- Nearly isotropic VUV flux reacts laterally on feature.
- Reduction in sidewall slope with slight undercut.
- PR hardening helps maintains CD.
- Photon/Ion Flux = 1.3
- Ar/Cl_2 = 80/20, 20 mTorr, 150 W, 10 MHz, Bias 10 MHz
- Symmetrized fluxes.

Animation Slide

MANAGING ISOTROPIC VUV FLUXES

- Isotropic VUV fluxes will be problematic during long over-etches when undercutting may occur.
- These fluxes may be controlled by view angle with thicker PR.



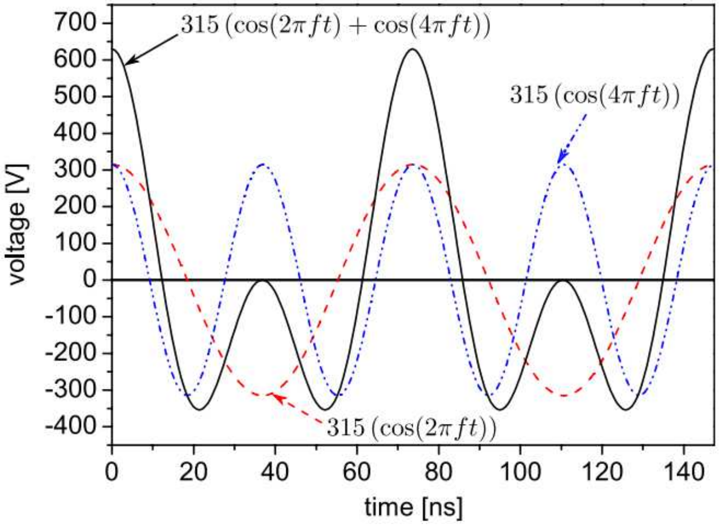
- Ar/Cl$_2$ = 80/20, 20 mTorr, 150 W, 10 MHz, Bias 10 MHz

Animation Slide

INTERNAL BEAT FREQUENCY PULSING: PHASE CONTROL BETWEEN FREQUENCIES

ELECTRICAL ASYMMETRIC EFFECT (EAE)

- **EAE is the control of the dc bias in a 2-frequency CCP through control of the phase between the applied fundamental frequency and its 2nd harmonic.**

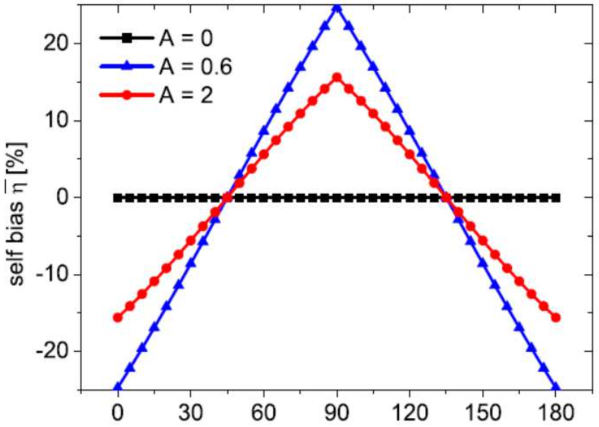


$$\Phi(t)=\Phi_1\cos(\omega t+\theta)+\Phi_2\cos(2\omega t)$$

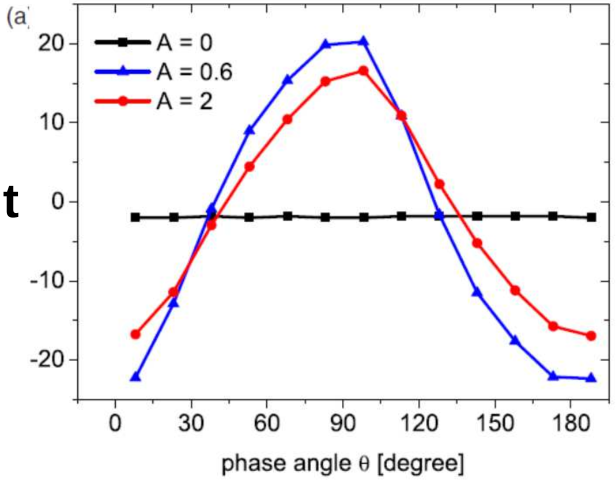
$$V_{dc}=-\frac{\tilde{\Phi}_{\max}+\varepsilon\tilde{\Phi}_{\min}}{1+\varepsilon}$$

$$\varepsilon=\left|\Phi_{sheath-ground}/\Phi_{sheath-powered}\right|$$

- **Analytic Model**



- **Experiment**

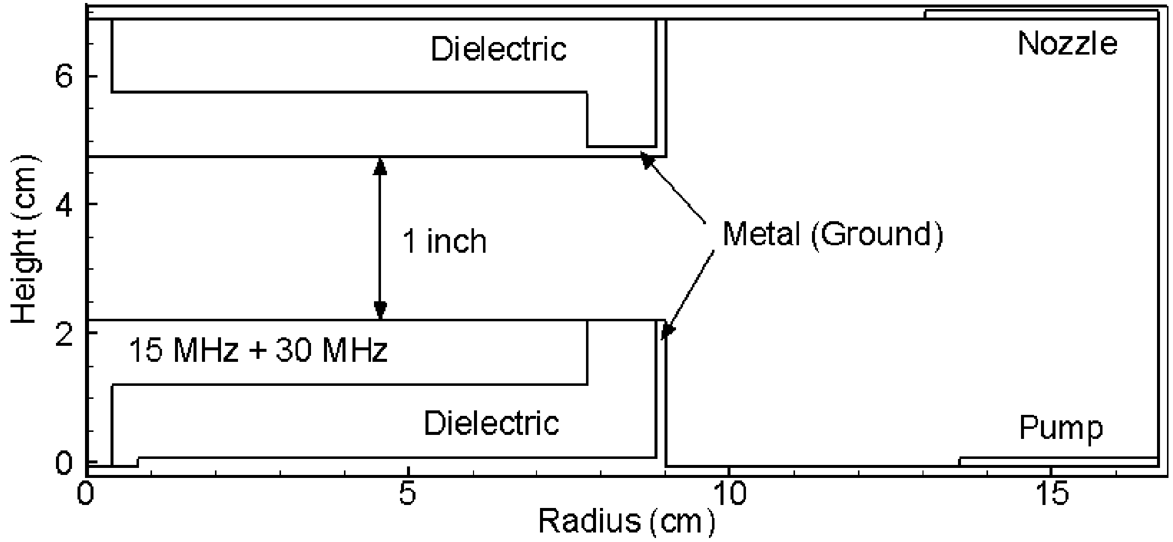


- **J. Schulze *et al*, JAP 106, 063307(2009)**
- **B. Heil *et al*, J.Phys.D 41 165202(2008)**

REACTOR GEOMETRY

- **Capacitively coupled plasma with 15 +3 0 MHz rf biases on bottom electrode.**
- **2D, cylindrically symmetric.**
- **Ar plasma: Ar, Ar(1s$_{2,3,4,5}$), Ar(4p), Ar$^+$, e**

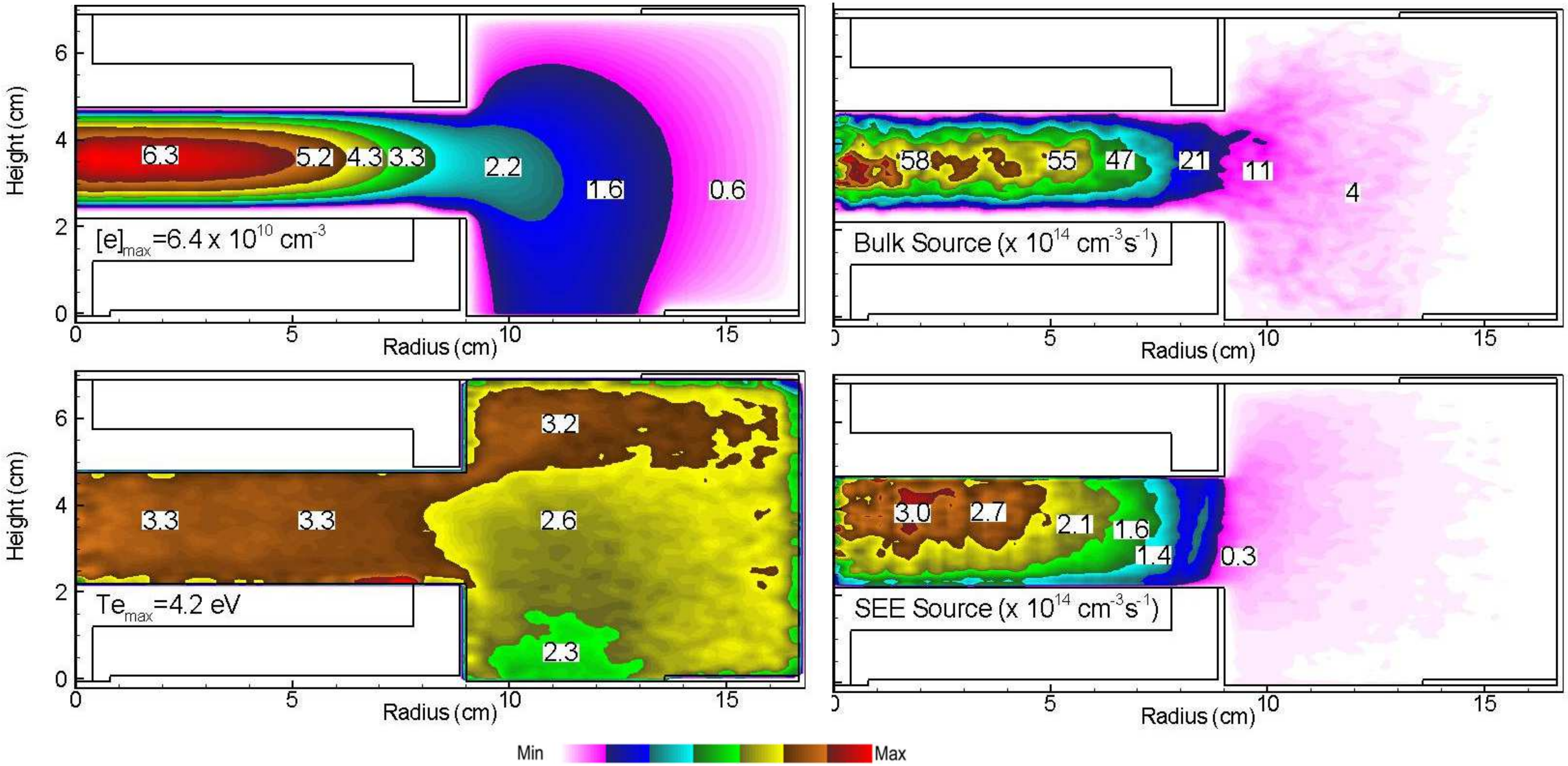
- **Base case conditions:**
  - **Ar, 20 mTorr, 50 sccm**
  - **Model: 15 MHz, 100 V; 30 MHz, 100V**
  - **Experiment: 13 MHz + 27 MHz, and voltages adjusted for constant ion saturation current.**



- **Experiments:**
  Prof. Steven Shannon, NCSU

PLASMA PROPERTIES

- **[e] ≈ 3-6 × 10^{10} cm^{-3}, T_e ≈ 3.3 eV , both are close to experiments.**
- **Nearly equal contributions from bulk ionization and sheath accelerated secondary electrons.**



- Ar, 20 mTorr, 50 sccm
- $\Delta\Phi = 0$

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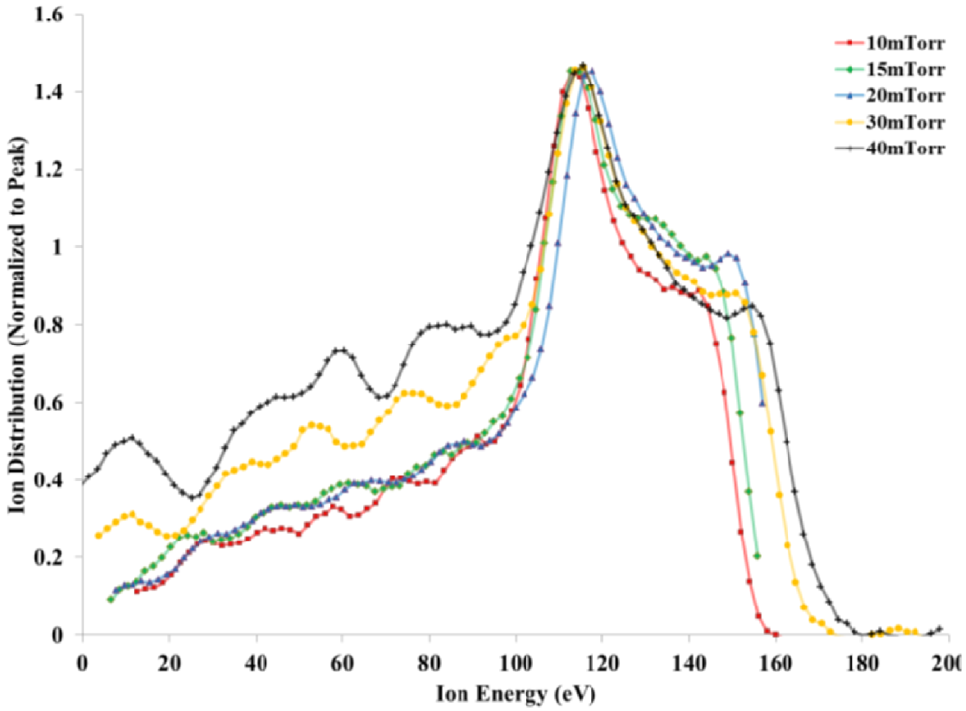
VALIDATION: SINGLE FREQ. IED vs PRES

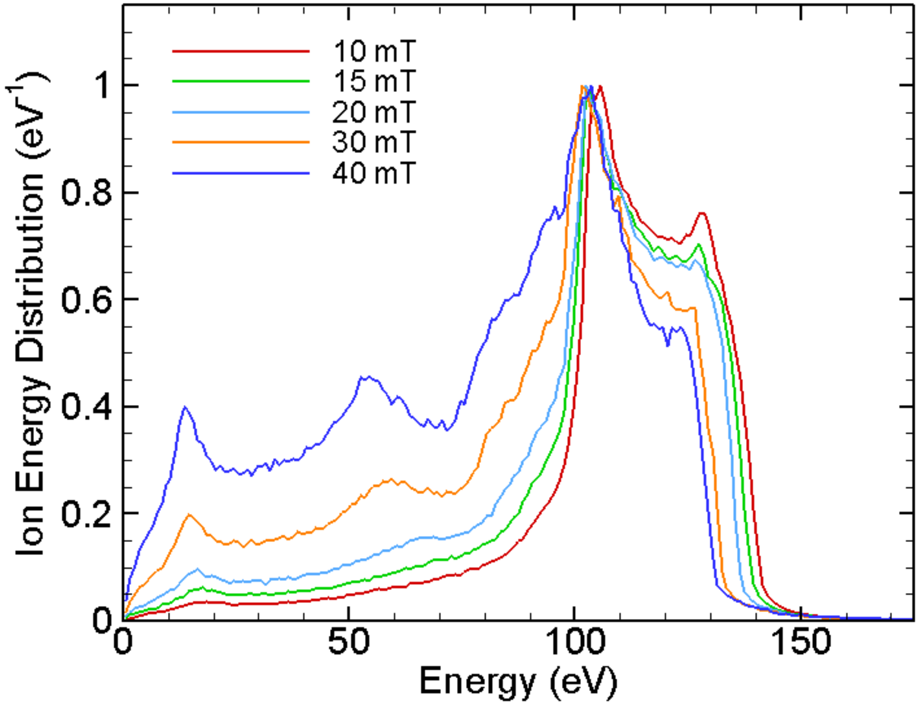
- **Sheath is collisional at 40 mTorr. Decrease in low energy tail (due to collisions) begins to saturate below 20 mTorr.**

- **Experiment**



- **Simulation**

30 MHz 125 V, Vdc -89 V

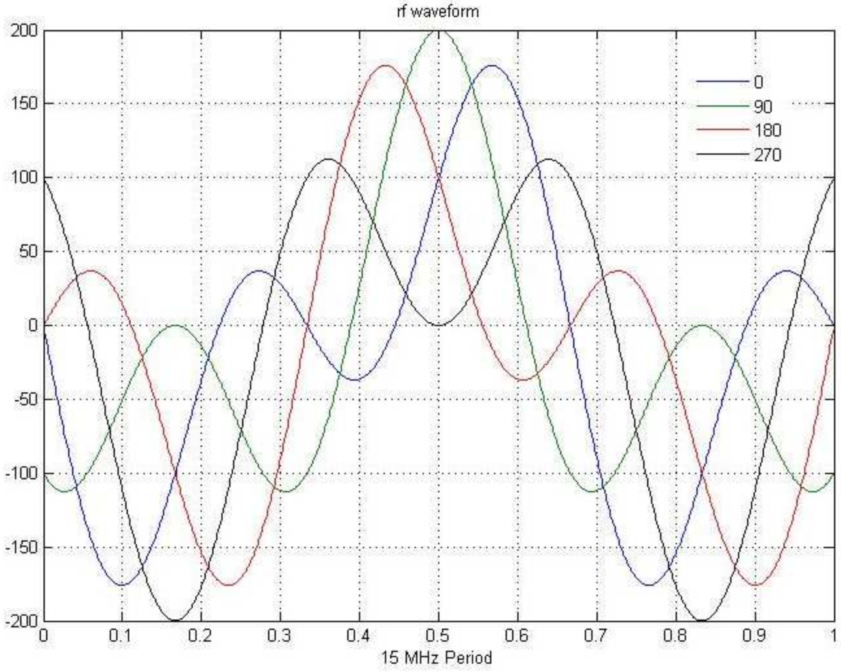


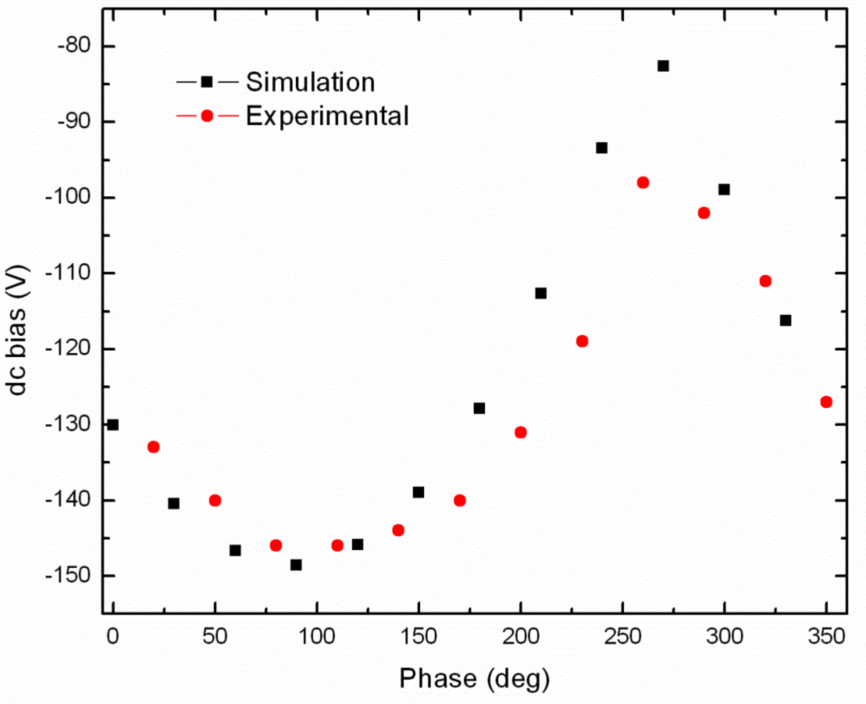
- **Ar, 50 sccm, 27 MHz**
- **Constant dc Bias = -89 V, Power varied**
- **50 W at 5 mTorr , 150 W at 40 mTorr**

- **Ar, 50 sccm, 30 MHz**
- **Constant dc Bias =-89 V.**

DC BIAS v.s. PHASE SHIFT

- **In order to match with experiment setting, the rf waveform is customized as:** $V(t) = 100\sin(\omega t + \pi) + 100\sin(2\omega t + \pi + \Delta\Phi)$
- **As phase varying, the dc bias will change according to EAE theory.**
- **The mismatch mainly due to the experimental need to keep I_{ion_sat} constant and voltages will be modified slightly.**





- **Ar, 20 mTorr, 50 sccm,**
- **Simulation 100 V, 15 MHz; 100 V, 30 MHz**
- **Experiment 13 MHz + 27 MHz**
- **Power to current ratio =0.25**

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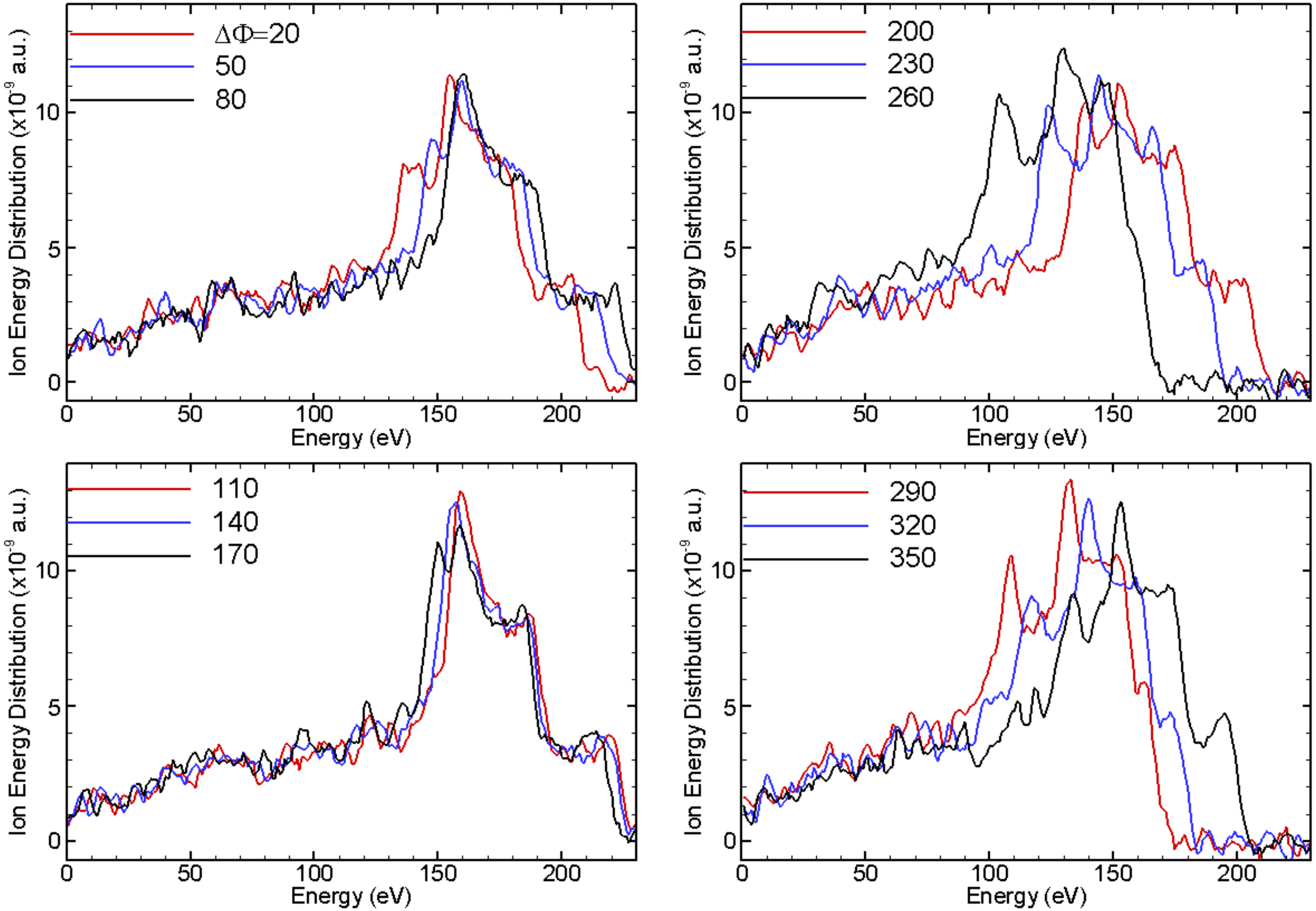
IED vs PHASE SHIFT: EXPERIMENT

- **With increasing phase difference between 15 and 30 MHz, position of maximum in IED changes from high to low to high energy.**

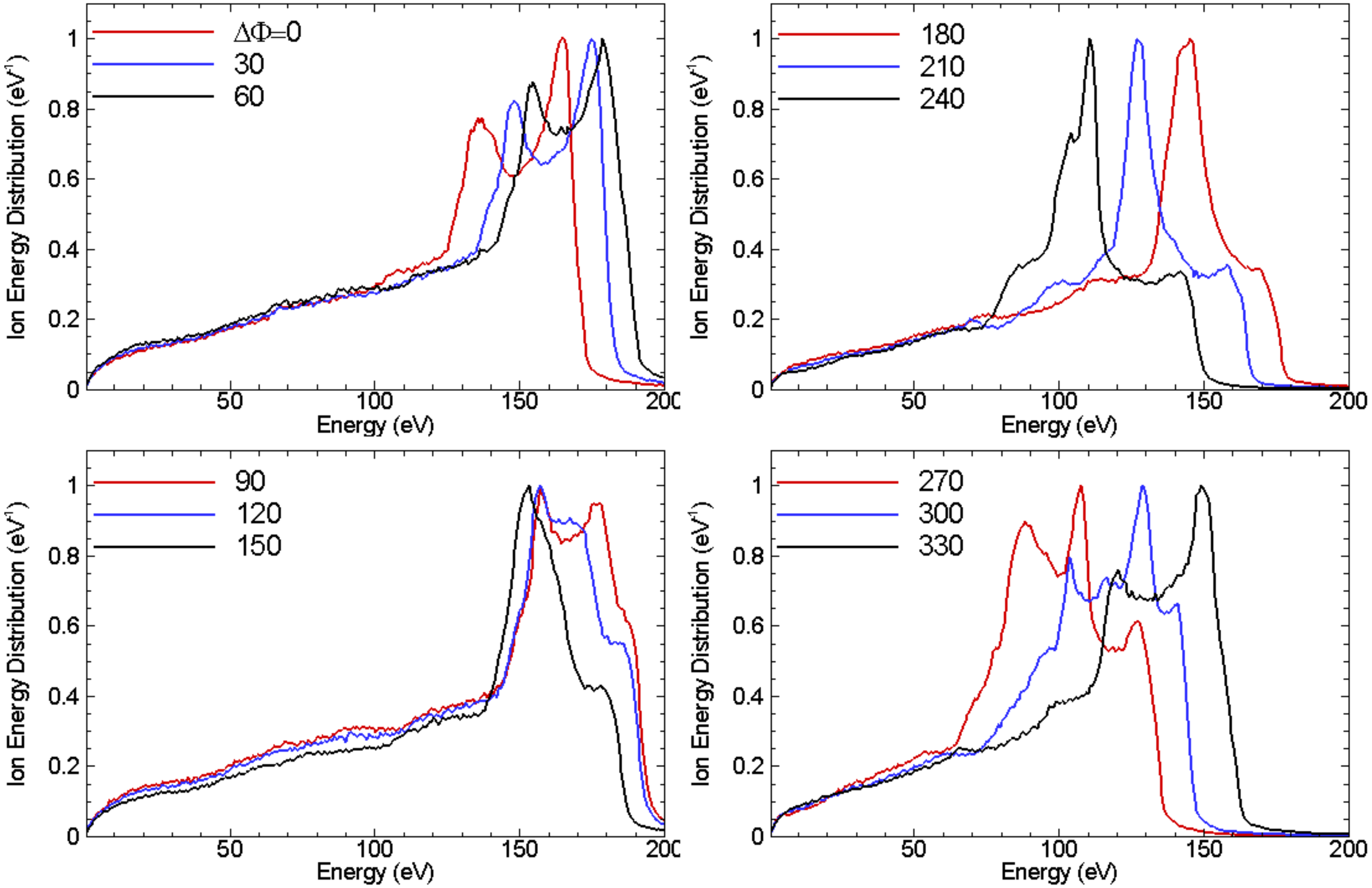
- **Exp … h $\Delta\Phi$.**



- **Ar, 20 mTorr, 50 sccm,**
- **13 + 27 MHz, Power / Current =0.25**

IED vs PHASE SHIFT: MODEL

- Model shows similar translation of the peaks in IEDs with $\Delta\Phi$.



- Ar, 20 mTorr, 50 sccm,
- 100V, 15 MHz; 100 V, 30 MHz

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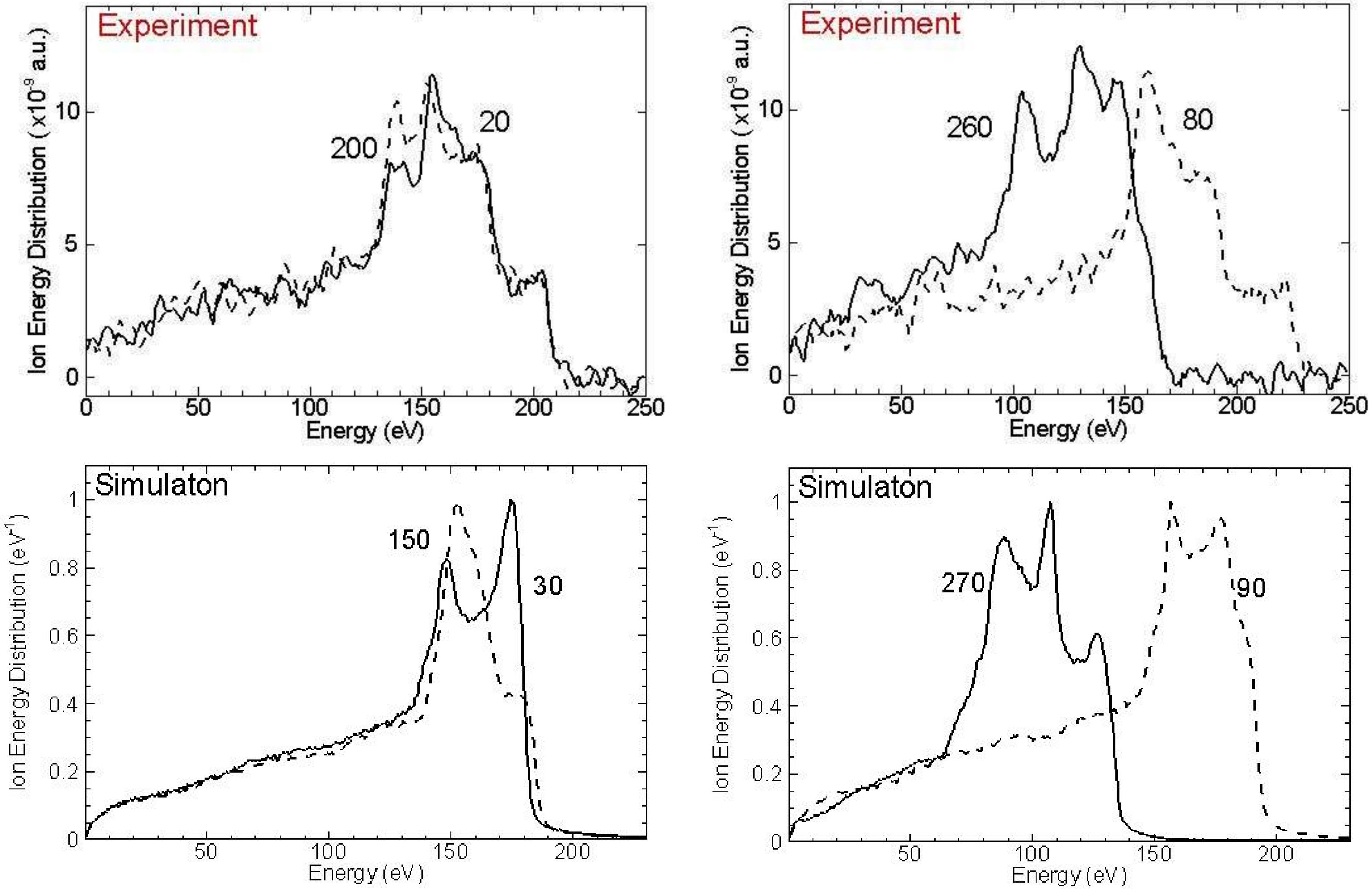
SIMULATION vs EXPERIMENT

- **The simulation predicts somewhat broader shifts of peaks than observed experimentally. Partly due to small changes in V vs $\Delta\Phi$.**



- **Model: Ar, 20 mTorr, 50 sccm,**
- **100V, 15 MHz; 100 V, 30 MHz**

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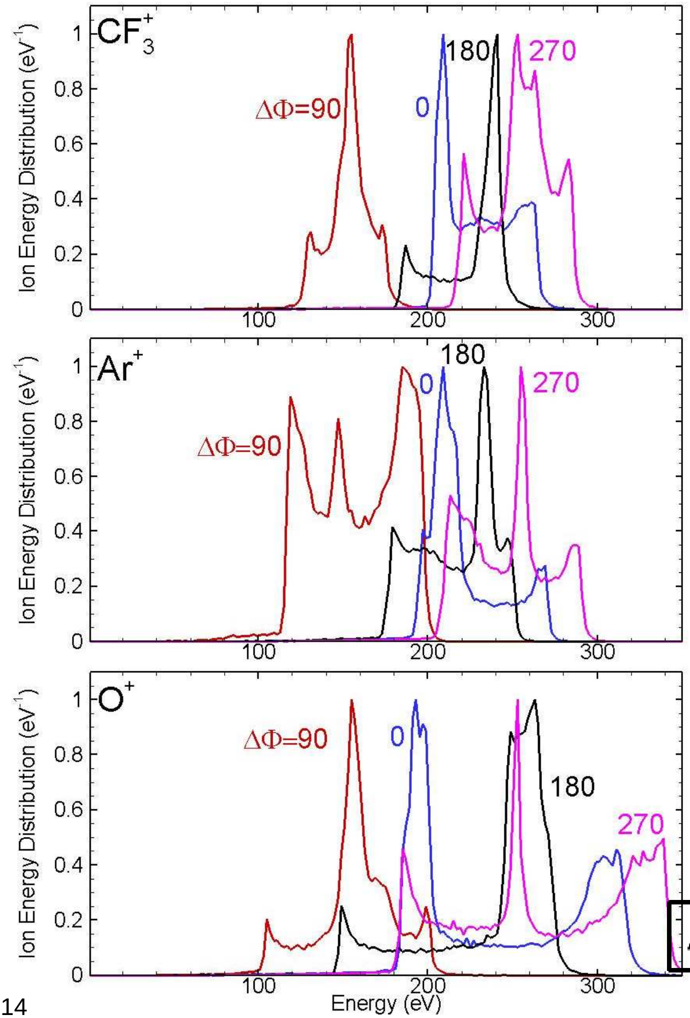
ETCH GAS MIXTURE: IED, ETCH PROFILES vs $\Delta\Phi$

- **Small changes in phase of ω and 2ω, and initial offset, produces significant changes in profile – even more subtle when considering different mass ions.**

$$bias: 150\sin(\omega_{15}t) + 150\sin(\omega_{30}t + \Delta\Phi)$$



- **$Ar/CF_4/O_2$=75/20/5, 20 mTorr, 50 sccm**

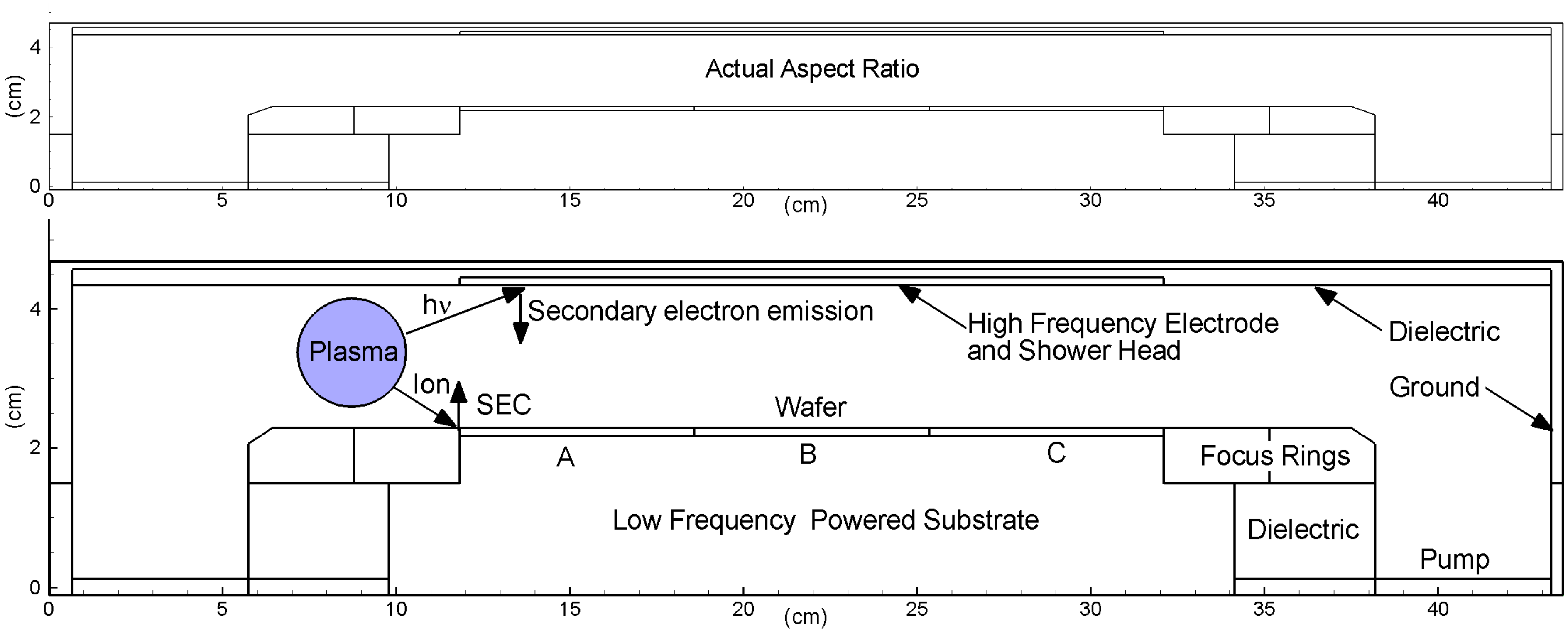
Animation Slide

PULSING – STARTUP TRANSIENT

STARTUP TRANSIENTS IN PLASMA TOOLS

- **As wafer size increases, feature size decreases, and processing time decreases, need for controllable startup (and shutdown) is more critical – a form of pulsing.**
- **Startup of plasma tool begins with "spot" of plasma, either naturally [randomly] occurring, artificially produced or, with low pulsing PRF in electronegative plasmas, left over from prior pulse.**
- **Plasma then "breaks down" and spreads across plasma tool.**
- ***Photon simulated processes likely important – secondary electron emission.***
- **In a given plasma tool, location and intensity of "spot" of plasma determines spread of plasma through tools.**
  - **Voltages, frequencies, pressures and gases that optimize breakdown and spreading of plasma are not necessarily the same as used in the process.**
  - **"Harsh" conditions that spread across wafer may produce damage.**

STARTUP IN DUAL-FREQUENCY CCP



- **Argon, 40 mTorr**
- **HF = 40 MHz, LF = 10 MHz**
- **Radiation transport, photon-and-ion secondary electron emission.**

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STARTUP IN CCP: ENHANCED BY PHOTO-ELECTRONS

- Plasma produced radiation enhances spreading of plasma by seeding secondary electrons that produce ionization.
- Ar, 40 mTorr, HF = 40 MHz – 250V, LF = 10 MHz – 275 V.

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STARTUP IN CCP: SWEEPING FLUXES AND IEADs

Ion Flux

VUV Flux

Ion Energy/Angle Distribution

- **During startup, the plasma sweeps across wafer. The ion energy distribution is highly anisotropic during this transient.**

- **Ar, 40 mTorr, HF = 40 MHz – 250V, LF = 10 MHz – 275 V.**

Animation Slide

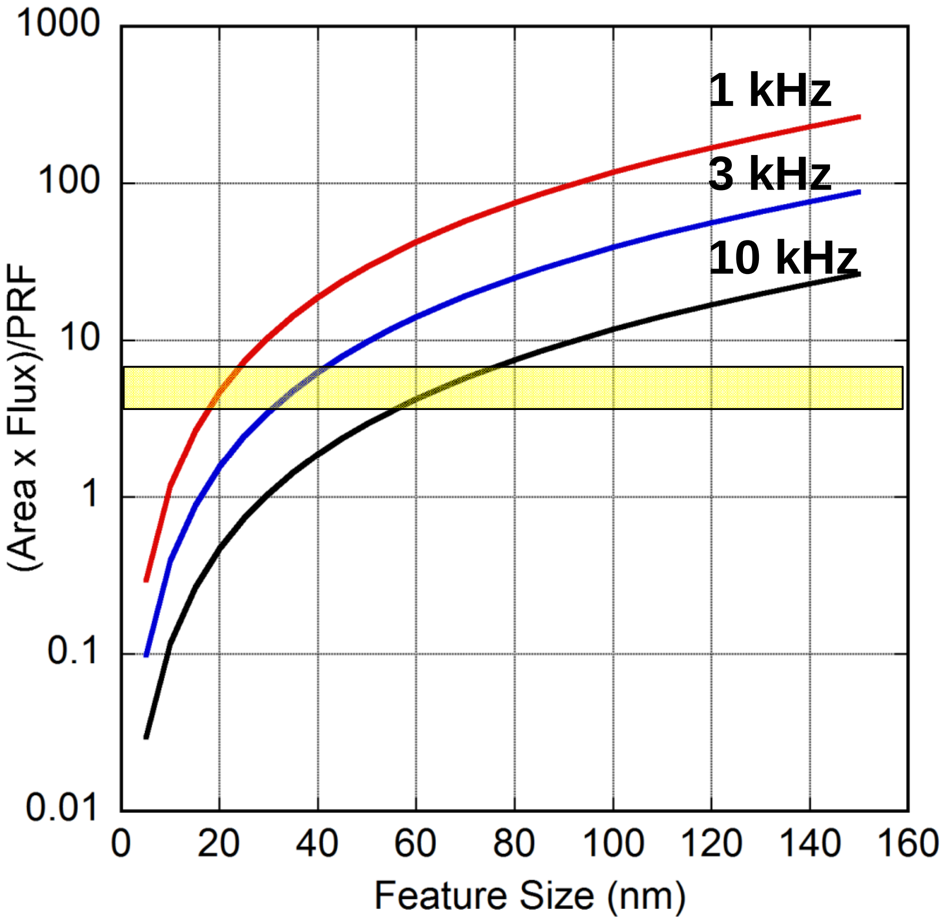
PRACTICAL MATTERS OF PULSING

- **Pulsing can be divided into two modes:**
  - **Features see pulse averaged fluxes**
  - **Features see different sets of fluxes from different parts of the pulsed cycle (e.g., sub-cycle fluxes)**
- **Neutral fluxes are, to some degree, averages over pulsed periods. Diffusion times are usually longer than inter-pulse periods for all but the lowest PRFs.**
- **The distinction between averaged and sub-cycle fluxes blurs as the feature size decreases.**
- **Ions "into the hole" per sub-cycle:**

$$N_{hole} = A \cdot \Phi \cdot d \cdot \Delta t = \frac{A \cdot \Phi \cdot d \cdot \Delta t}{f}$$

  - **A = area of feature**
  - **d = duty cycle**
  - **Φ = ion flux**
  - **Δt = period, f = PRF**

LIMIT OF PRF FOR FEATURE SIZE



- **If you need "a few" ions/feature to "know" that the ion flux is uniquely in the sub-cycle, what is the limiting feature size or PRF for “pulsing”?**
- **I_{ion} = 0.5 mA/cm^2**
- **d = 50%**
- **For sub-20 nm features, require PRFs of < 1 kHz**

CONCLUDING REMARKS

- Pulsing broadens the parameter space available for processing optimization:
    - Pulse LF, HF or both, vary BC, pulse ICP with/without synchronizing bias, PRF, dc, ….
    - R. Gottscho – “A parameter space with millions of combinations”
- The breadth and opportunity of pulsing complicates cause-and-effect analysis – synergistic effects between parameters.
- Clearly, some unambiguous trends in shaping IEDs and controlling T_e – what is less clear is on the neutral side, effects on passivation, photons (!)
- Many unappreciated examples of pulsing – beating due to phasing between LF, HF, startup transients.

HPEM-EQUATIONS SOLVED - $E_\theta(\vec{r},\phi)$

- Maxwell's Equations – Frequency Domain Wave Equation

$$-\nabla\left(\frac{1}{\mu}\nabla\cdot\vec{E}\right)+\nabla\cdot\left(\frac{1}{\mu}\nabla\vec{E}\right)=\frac{\partial^2\left(\varepsilon\vec{E}\right)}{\partial t^2}+\frac{\partial\left(\vec{J}_{plasma}+\vec{J}_{antenna}\right)}{\partial t}$$

$$\vec{E}(\vec{r},t)=E_\theta(\vec{r})\exp(i\omega t),\quad \vec{J}_{antenna}(\vec{r},t)=J_\theta(\vec{r},\phi)$$

$$\vec{J}_{plasma}(\vec{r},\phi)=\overline{\overline{\sigma}}_{ion}\cdot E_\theta(\vec{r},\phi)+\vec{J}_e(\vec{r},\phi)_{MCS}$$

- Azimuthal antenna currents – retain only E_θ, B_{rz}
- Plasma currents
  - Collisional ion currents
  - Kinetically derived non-local electron currents capture nonlocal effects.

HPEM-EQUATIONS SOLVED - $f\left(\varepsilon,\vec{r},\phi\right)$

- **Electron Energy Distributions – Electron Monte Carlo Simulation**

$$\frac{\partial f\left(\vec{v},\vec{r},t\right)}{\partial t}= -\vec{v}\nabla f\left(\vec{v},\vec{r},t\right)-\frac{q\left(\vec{E}_{rz}\left(\vec{r}\right)+\vec{E}_{\theta}\left(\vec{r},\phi\right)+\vec{v}\times\vec{B}_{rz}\left(\vec{r},\phi\right)\right)}{m}\nabla_{v} f\left(\vec{v},\vec{r},t\right)+\left(\frac{\partial f\left(\vec{v},\vec{r},t\right)}{\partial t}\right)_{c}$$

  - **Cycle dependent electrostatic fields**
  - **Phase dependent electromagnetic fields**
  - **Electron-electron collisions using particle-mesh algorithm**
  - **Phase resolved electron currents computed for wave equation solution.**
  - **Captures long-mean-free path and anomalous behavior.**

HPEM-EQUATIONS SOLVED - $N\left(\vec{r},\phi\right)$

$$Electrons, Ions, Neutrals: \quad \frac{\partial N_i}{\partial t} = -\nabla \cdot (N_i \vec{v}_i) + S_i$$

$$e, Ions, Neutrals: \frac{\partial\left(N_i \vec{v}_i\right)}{\partial t} = -\frac{1}{m_i}\nabla\left(kN_iT_i\right) - \nabla \cdot \left(N_i \vec{v}_i \vec{v}_i\right) + \frac{q_i N_i}{m_i}\left(\vec{E} + \vec{v}_i \times \vec{B}\right)$$

$$-\nabla \cdot \overline{\mu}_i - \sum_j \frac{m_j}{m_i + m_j} N_i N_j \left(\vec{v}_i - \vec{v}_j\right)\nu_{i,j}$$

$$Ions, Neutrals: \frac{\partial\left(N_i \varepsilon_i\right)}{\partial t} + \nabla \cdot Q_i + P_i \nabla \cdot U_i + \nabla \cdot (N_i U_i \varepsilon_i) = \frac{N_i q_i^2 \nu_i}{m_i(\nu_i^2 + \omega^2)} E^2$$

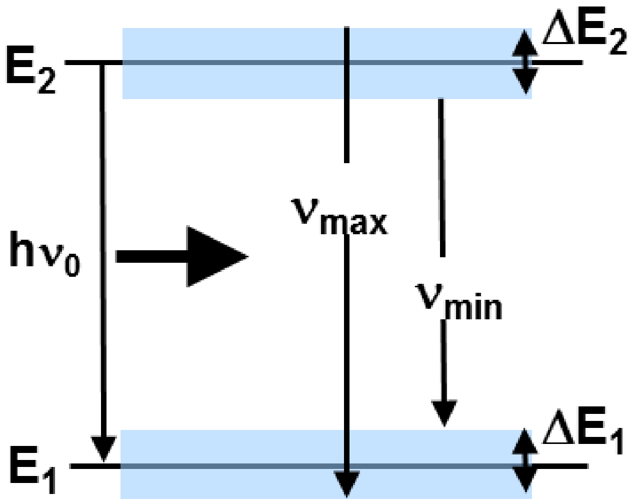
$$+\frac{N_i q_i^2}{m_i \nu_i} E_s^2 + \sum_j 3\frac{m_j}{m_i + m_j} N_i N_j R_{ij} k_B (T_j - T_i) \pm \sum_j 3 N_i N_j R_{ij} k_B T_j$$

$$Electrons: \ \vec{\phi}_e = -D_e \nabla n_e - \mu_e n_e E_{rz} \ or \ Scharfetter-Gummel \ Fluxes$$

$$Electrostatic \ \ Potential: \quad \nabla \cdot \varepsilon \nabla \Phi\left(t + \Delta t\right) = \text{-}\left(\rho_s + \sum_i q_i N_i \text{ - } \Delta t \cdot \sum_i \left(q_i \nabla \cdot \vec{\phi}_i\right)\right)$$

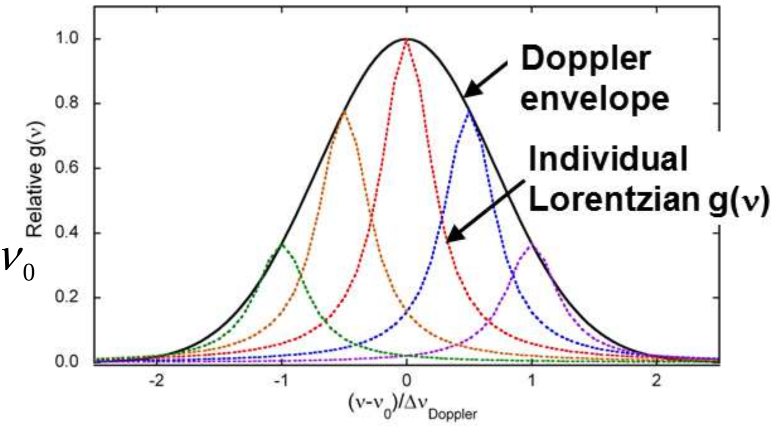
EMISSION OF RADIATION

- **Emission of line radiation in low pressure plasmas at frequencies given by lineshape function $\int_0^\infty g(\nu')d\nu' = 1$.**
- **Homogeneous (natural and pressure Lorentzian) and inhomogenous (Doppler) broadening combined into Voigt profile.**



$$g_H(\nu) = \frac{(\Delta\nu_L/2\pi)}{(\Delta\nu_L/2)^2 + (\nu-\nu_0)^2}, \ \Delta\nu_L = \frac{1}{2\pi}\left(\frac{1}{\tau_1} + \frac{1}{\tau_2} + 2\nu_c\right)$$

$$g_D(\nu) = \left(\frac{4\ln 2}{\pi\Delta\nu_D^2}\right)^{1/2} \exp\left(-4\ln 2\left(\frac{\nu-\nu_0}{\Delta\nu_D}\right)^2\right), \ \Delta\nu_D = \left(\frac{8k_BT_g\ln 2}{Mc^2}\right)^{1/2}\nu_0$$

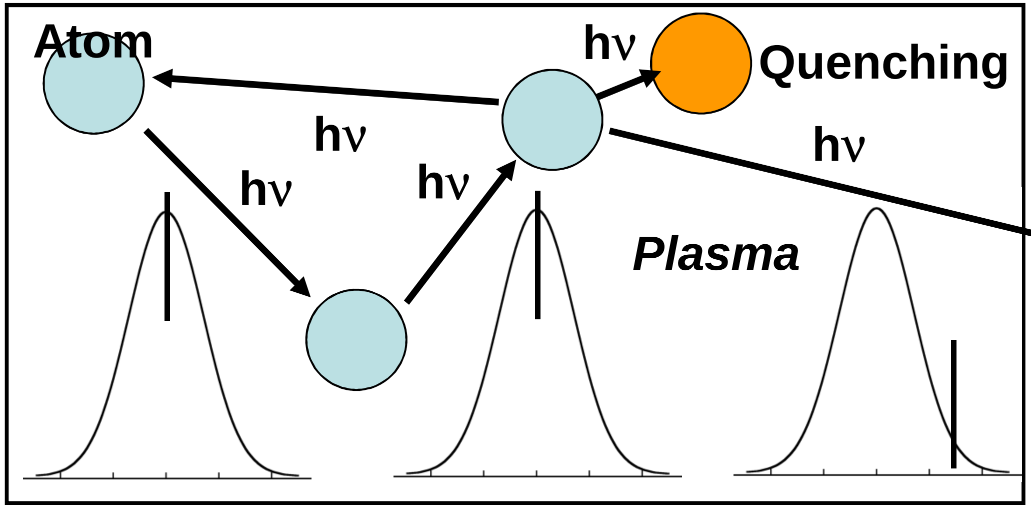


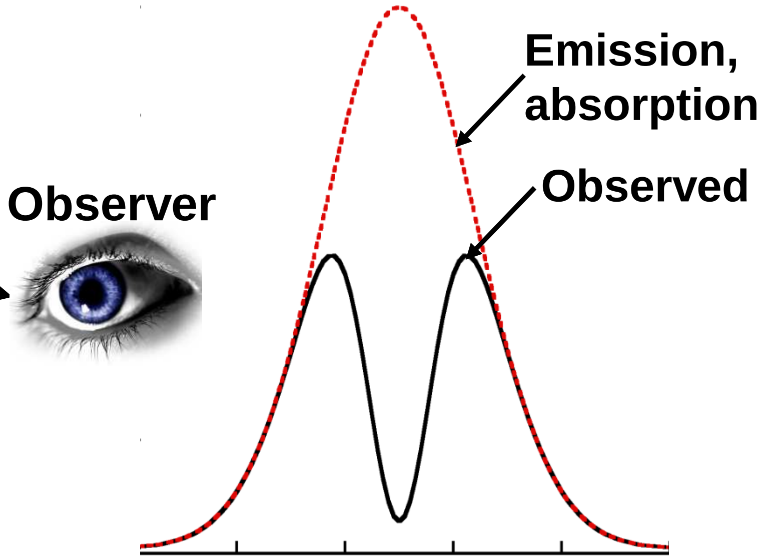
EMISSION, ABSORPTION, INVERSION, TRAPPING

- **The photon absorption cross section between levels 1 and 2 (A_{21} = Einstein A coefficient)**

$$\sigma(\nu) = A_{21}\frac{c^2}{8\pi n^2 \nu_0^2} g(\nu)$$

- **Line radiation is preferentially absorbed near line center. This leads to radiation trapping and inverted line emission.**

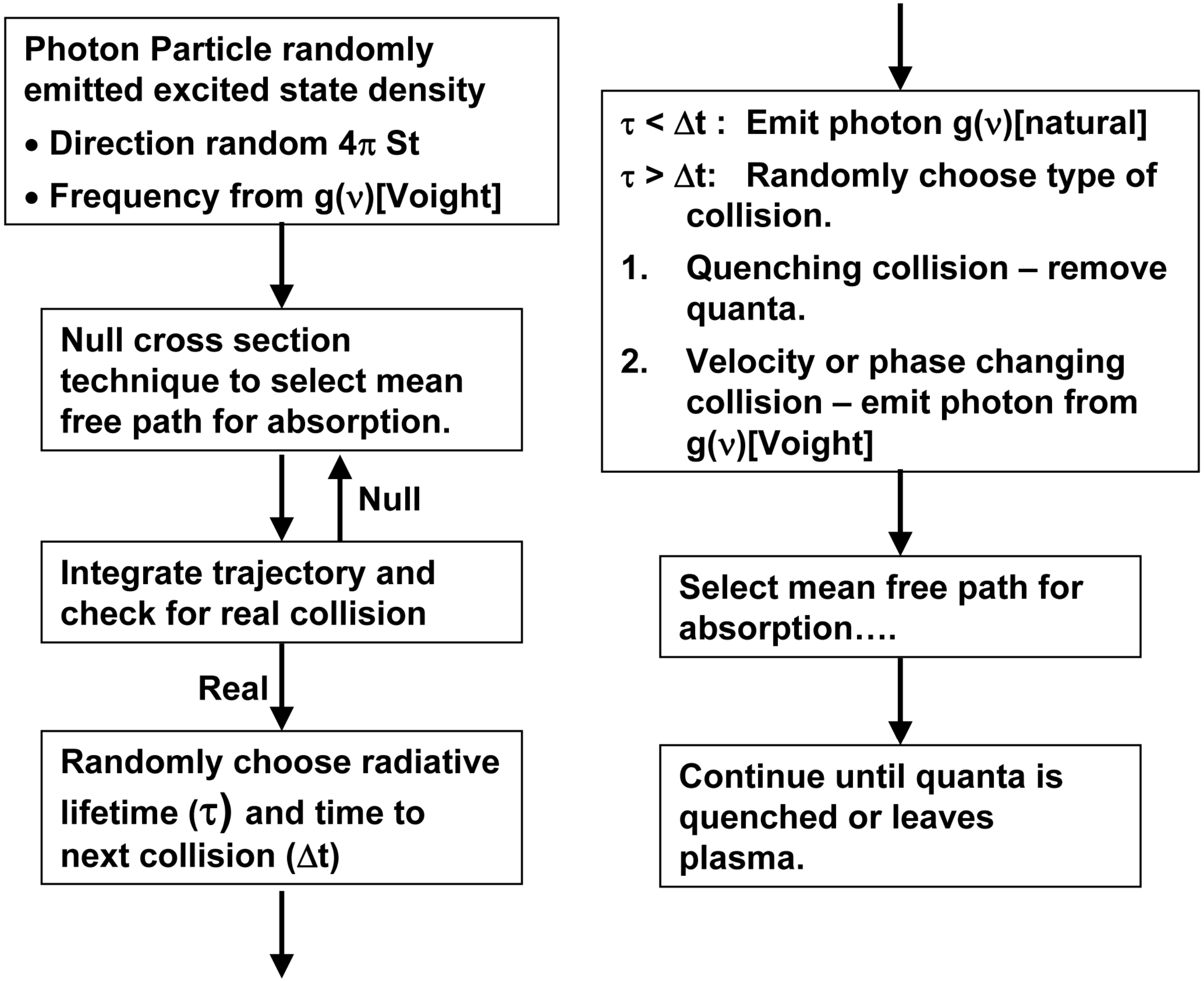




- **The number of emission/absorptions before leaving plasma is the *radiation trapping factor*, which can be 100s to 1000s, and leads to *effectively metastable* states.**

RADIATION TRANSPORT MODEL IN HPEM

- **Frequency resolved radiation transport in HPEM is modeled using a Monte Carlo simulation that accounts for partial frequency redistribution (PFR) and radiation trapping.**



Photon Particle randomly emitted excited state density

- **Direction random 4π St**
- **Frequency from g(ν)[Voight]**

Null cross section technique to select mean free path for absorption.

Integrate trajectory and check for real collision

Randomly choose radiative lifetime (τ) and time to next collision (Δt)

$\tau < \Delta t$: Emit photon g(ν)[natural]

$\tau > \Delta t$: Randomly choose type of collision.

1. **Quenching collision – remove quanta.**
2. **Velocity or phase changing collision – emit photon from g(ν)[Voight]**

Select mean free path for absorption….

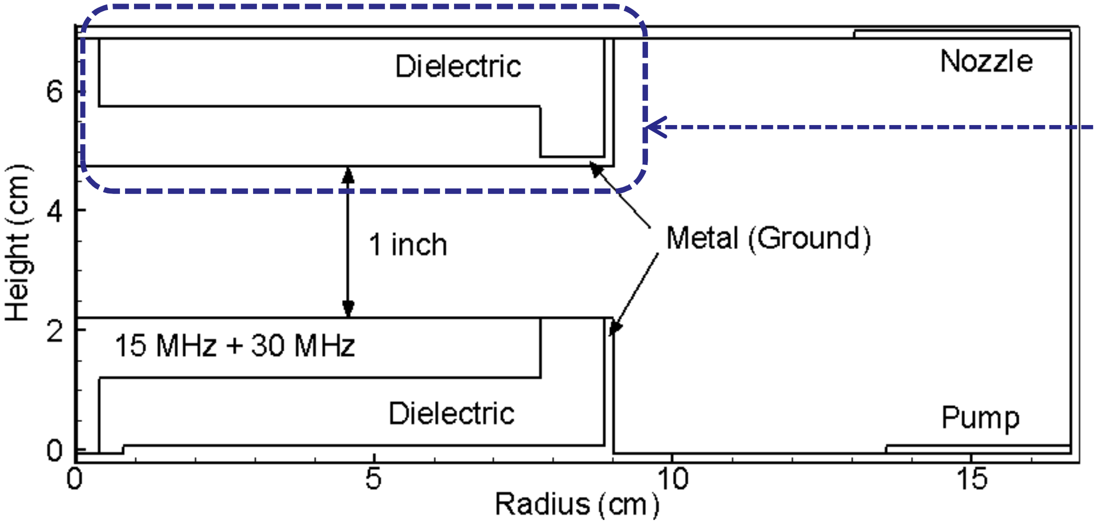
Continue until quanta is quenched or leaves plasma.

REACTOR GEOMETRY

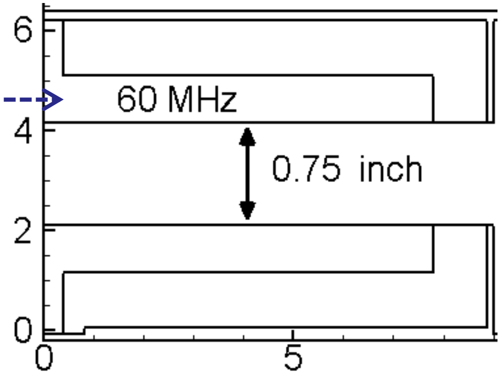
- Capacitively coupled plasma with 15 +3 0 MHz rf biases on bottom electrode, and 60 MHz on top.
- 2D, cylindrically symmetric.
- Ar plasma: Ar, Ar(1s$_{2,3,4,5}$), Ar(4p), Ar^{+}, e

- Base case conditions:
  - Ar, 20 mTorr, 50 sccm
  - Model: 15 MHz, 100 V; 30 MHz, 100V
  - Experiment: 13 MHz + 27 MHz, and voltages adjusted for constant ion saturation current.

- Dual-frequency set up



- Tri-frequency set up

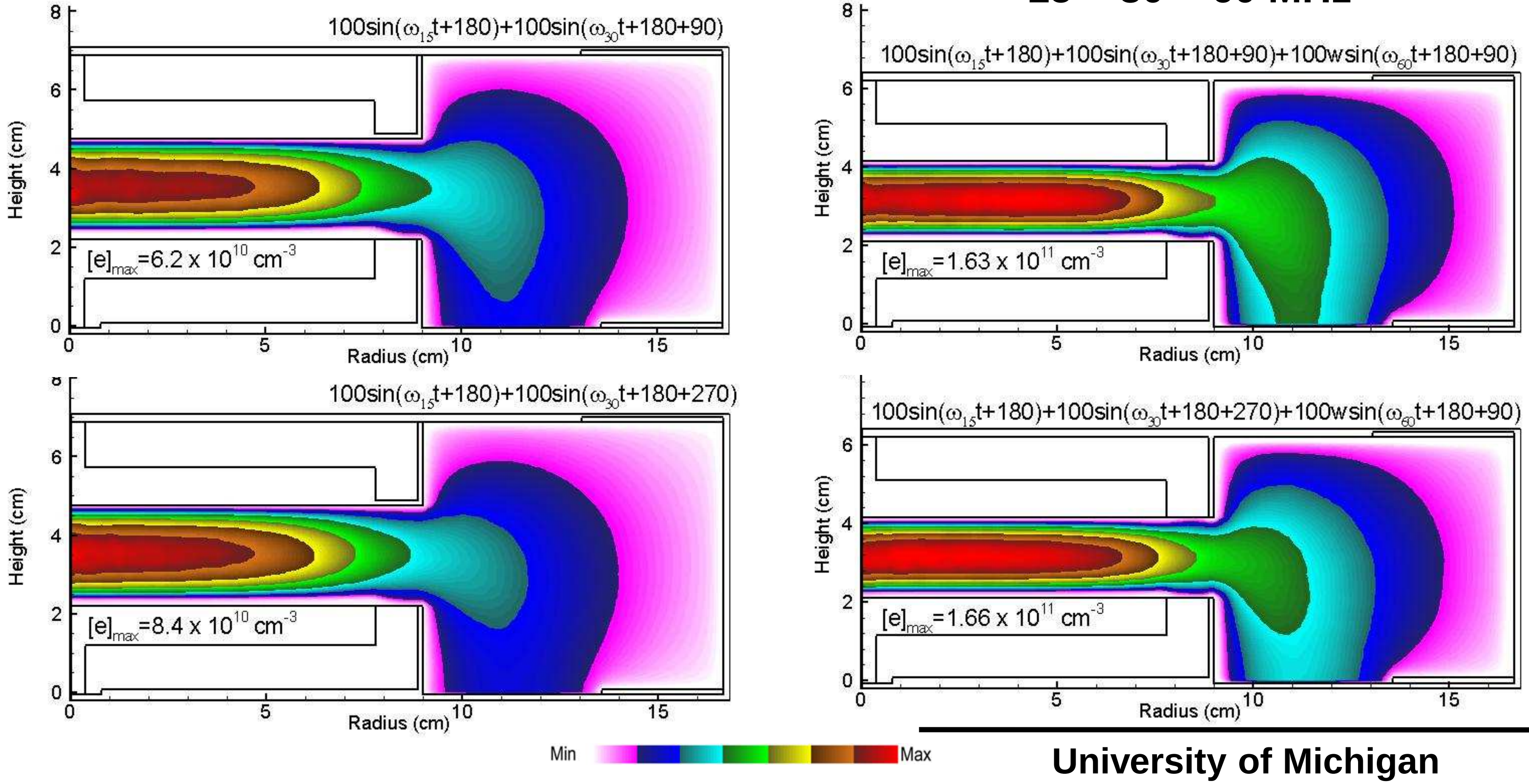


- **Experiments:**
  Prof. Steven Shannon, NCSU

MULTI FREQ-CCP PLASMA PROPERTIES

- **Changing ΔΦ in DF-CCP may modify plasma density.**
- **With addition of 60 MHz, plasma density is stabilized. With electron heating scale with ω^2, high frequency can dominate ionization.**

- **15 + 30 MHz**
- **15 + 30 + 60 MHz**



- **Ar, 20 mTorr, 50 sccm**

University of Michigan
Institute for Plasma Science & Engr.

IEDs in TRI-FREQ CCP

- **DC bias EAE effect still occurs with 60 MHz. At min and max dc bias phases, same general trend of change in IEDs is seen.**

$$\mathit{Simulaton}\ :100\sin(\omega_{15}t+\pi)+\ldots$$

$$100\sin(\omega_{30}t+\pi+\Phi_1)+100\sin(\omega_{60}t+\pi+\Phi_2)$$