MODELING OF INTEGRATED PLASMA PROCESSING: PLASMA PHYSICS, PLASMA CHEMISTRY AND SURFACE KINETICS

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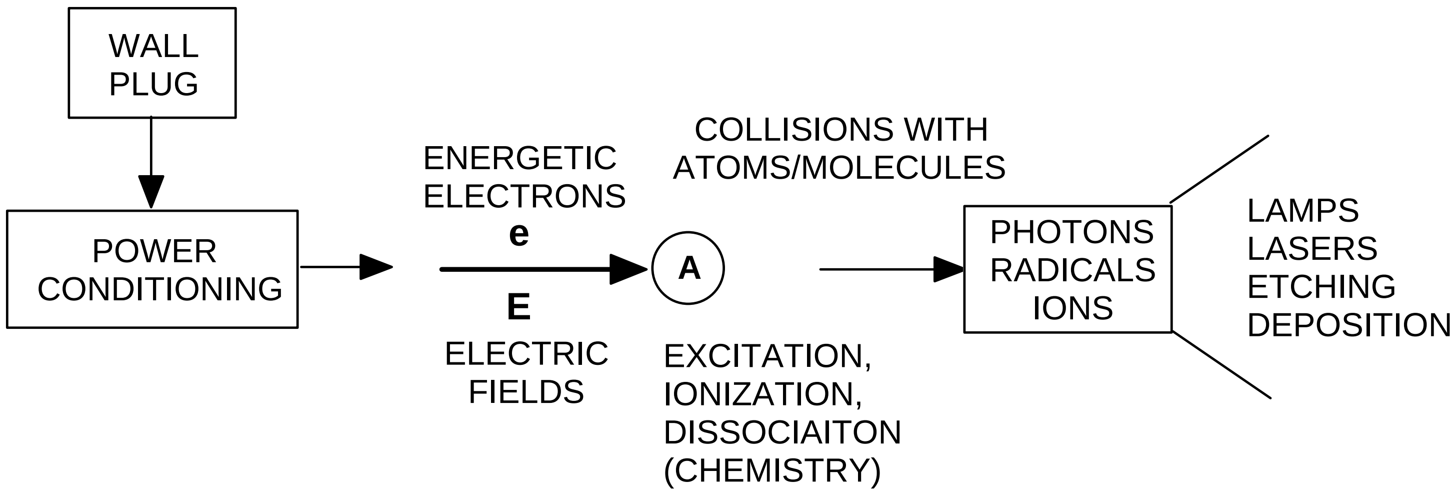
May 2003

AGENDA

- Integration in Plasma Processing
- Modeling Requirements:
    - Plasma Physics
    - Plasma Chemistry
    - Surface Kinetics
- Integrated process modeling of etching and cleaning of porous silica; and metal deposition for interconnect wiring.
- Concluding Remarks

COLLISIONAL LOW TEMPERATURE PLASMAS

- **Partially ionized plasmas are gases containing neutral atoms and molecules, electrons, positive ions and negative ions. These systems are the plasmas of every day technology.**

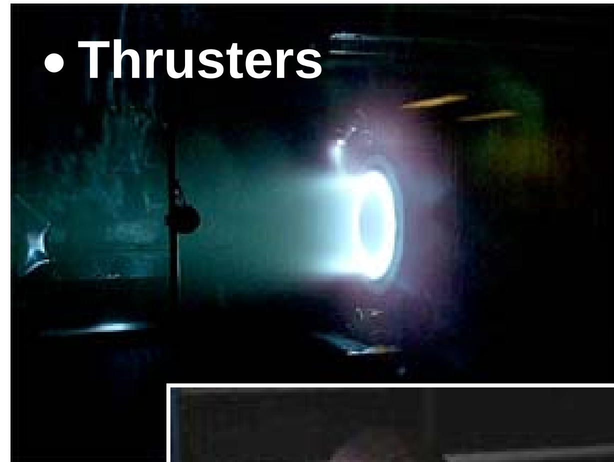


- **Electrons transfer power from the "wall plug" to internal modes of atoms / molecules to "make a product", very much like combustion.**

- **The electrons are "hot" (several eV or 10-30,000 K) while the gas and ions are cool, creating"non-equilibrium" plasmas.**

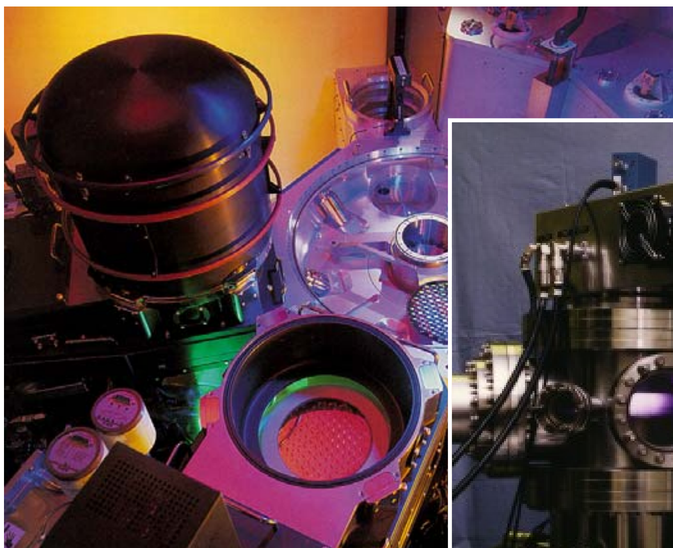
COLLISIONAL LOW TEMPERATURE PLASMAS

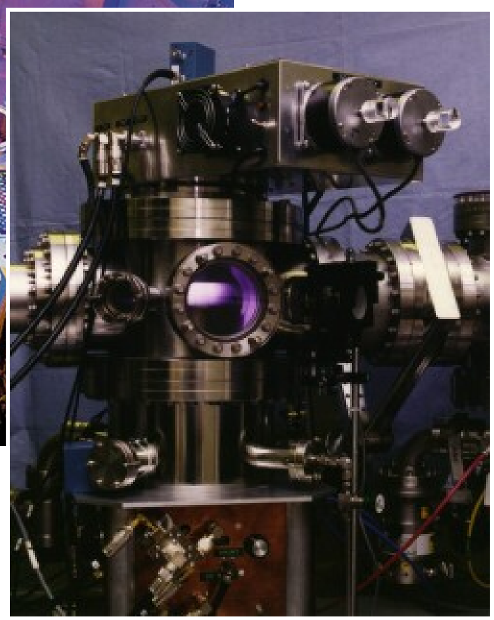
- Lighting



- Thrusters

- Spray Coatings





- Materials Processing

- Displays

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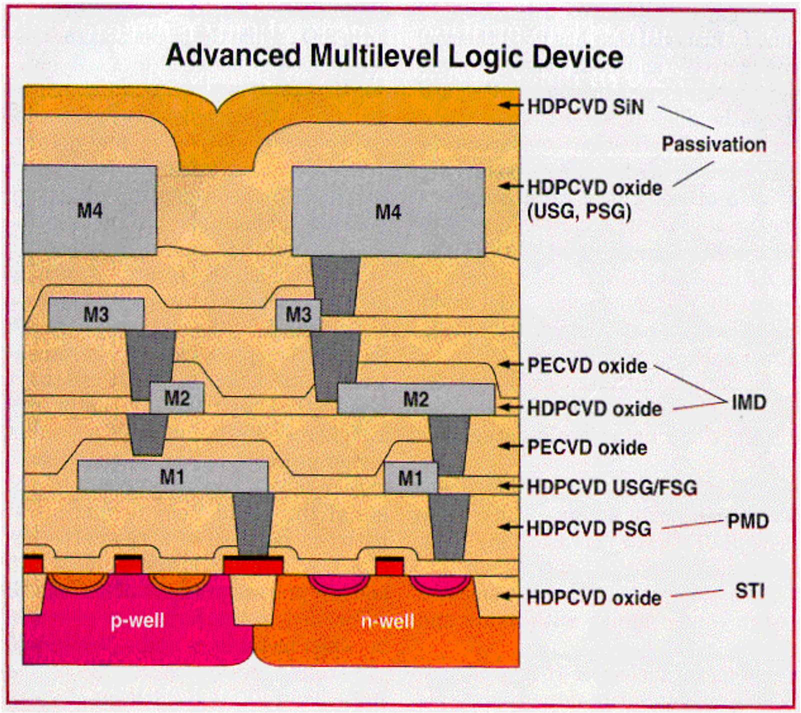
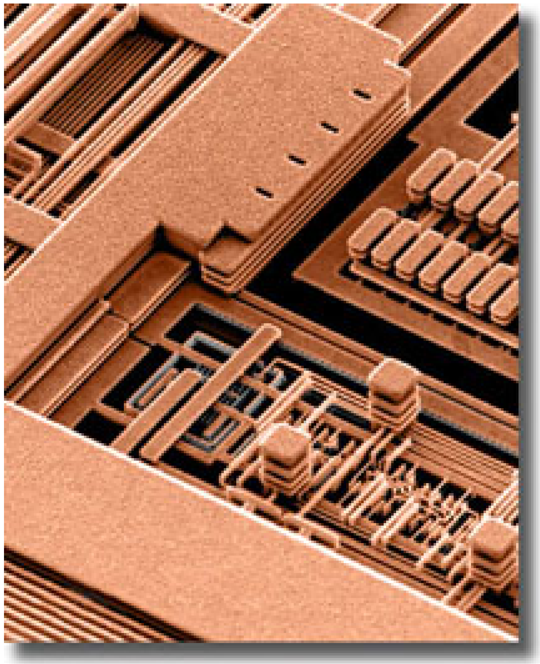
PLASMAS IN MICROELECTRONICS FABRICATION

- The striking improvement in the functionality of microelectronics devices results from shrinking of individual components and increasing complexity of the circuitry





Ref: IBM Microelectronics

- Plasmas are absolutely essential to the fabrication of microelectronics.

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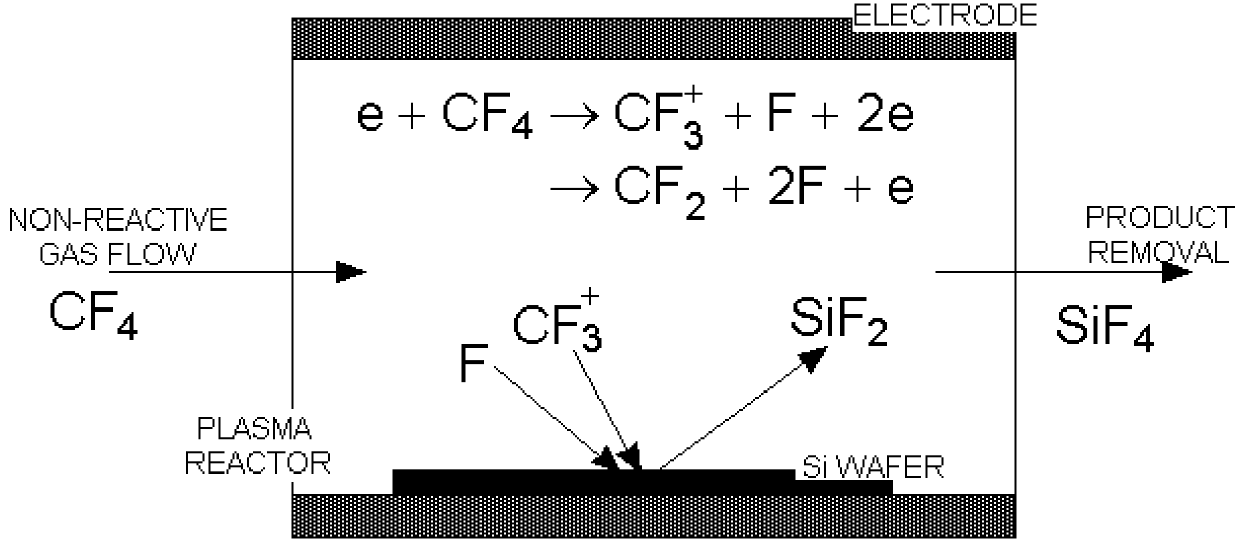
PLASMAS IN MICROELECTRONICS FABRICATION

- Plasmas play a dual role in microelectronics fabrication.

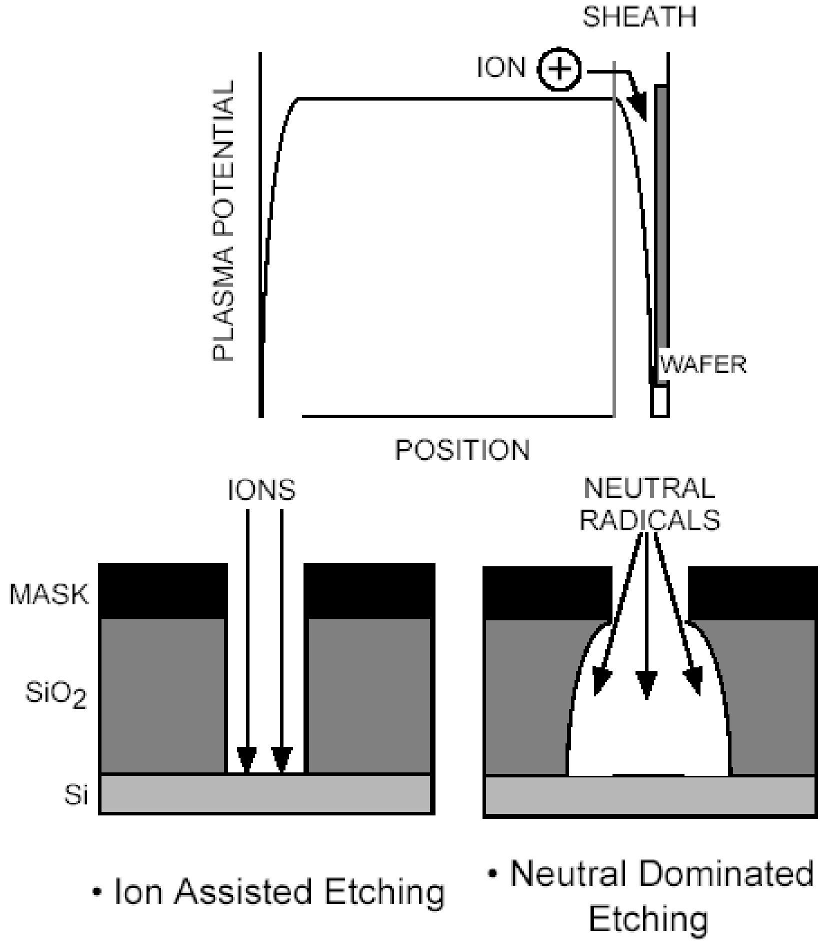
- First, electron impact on otherwise unreactive gases produces neutral radicals and ions.

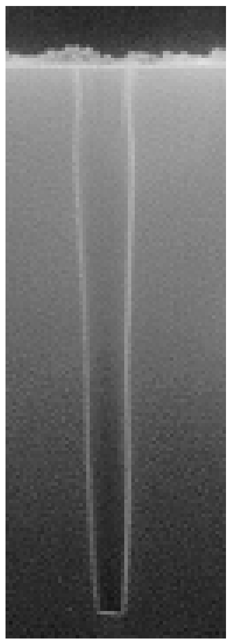


- These species then drift or diffuse to surfaces where they add, remove or modify materials.

PLASMAS IN MICROELECTRONICS FABRICATION

- Second, ions deliver directed activation energy to surfaces fabricating fine having extreme and reproducable tolerances.





- 0.25 μm Feature (C. Cui, AMAT)

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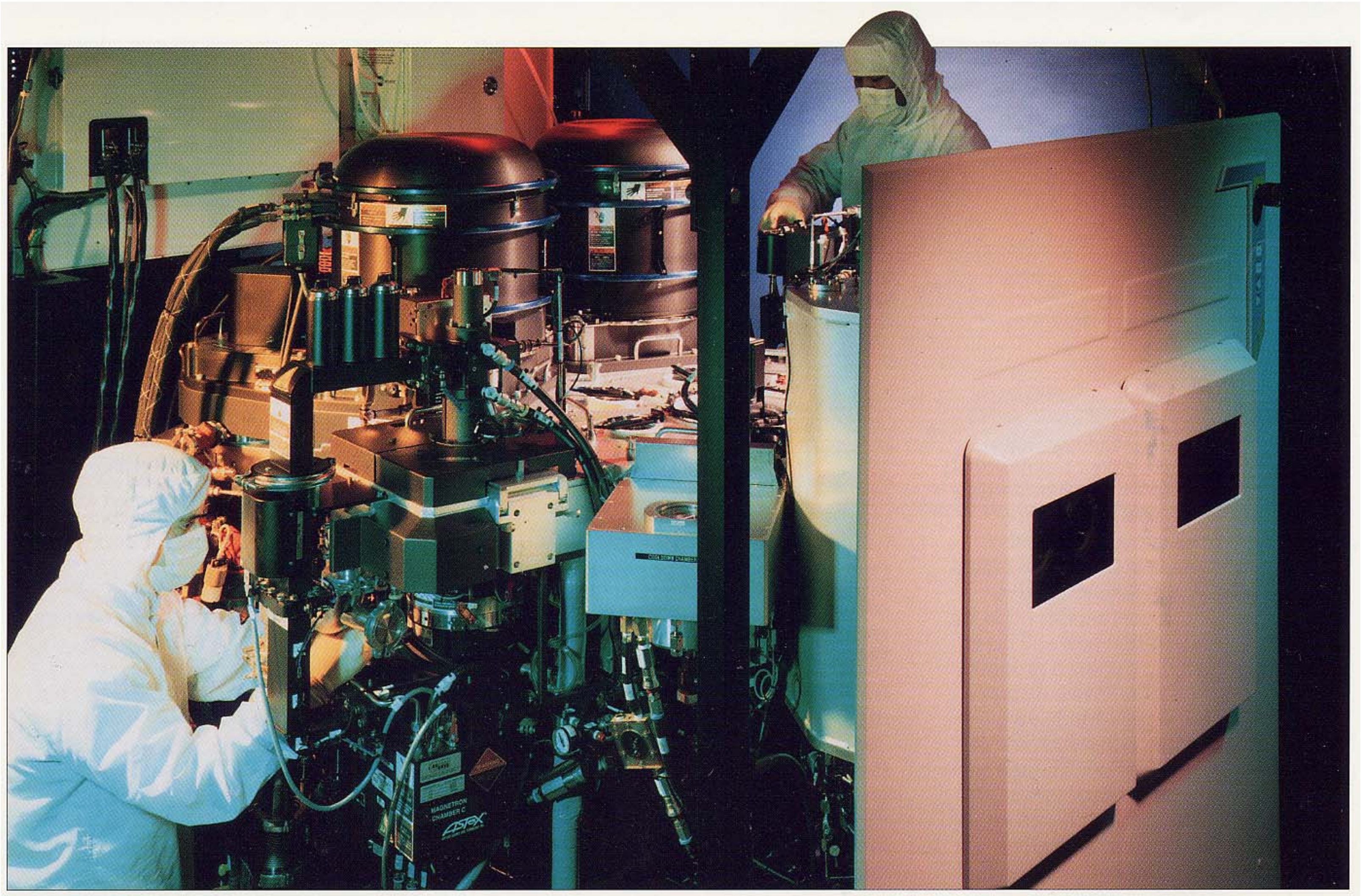
APPLIED MATERIALS DECOUPLED PLASMA SOURCES (DPS)



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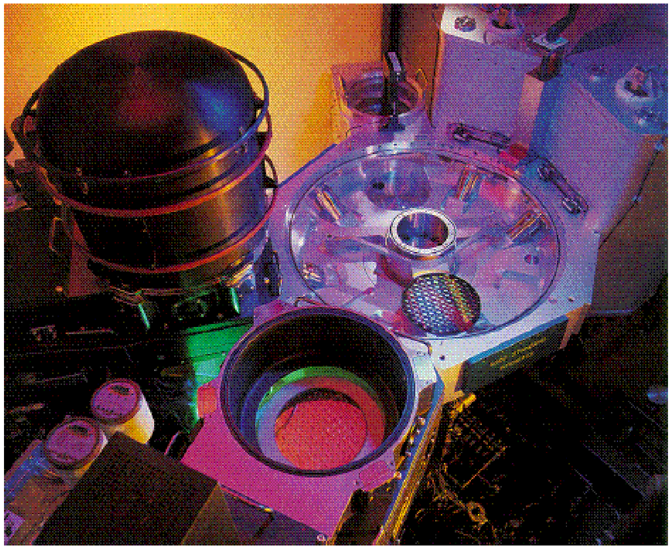
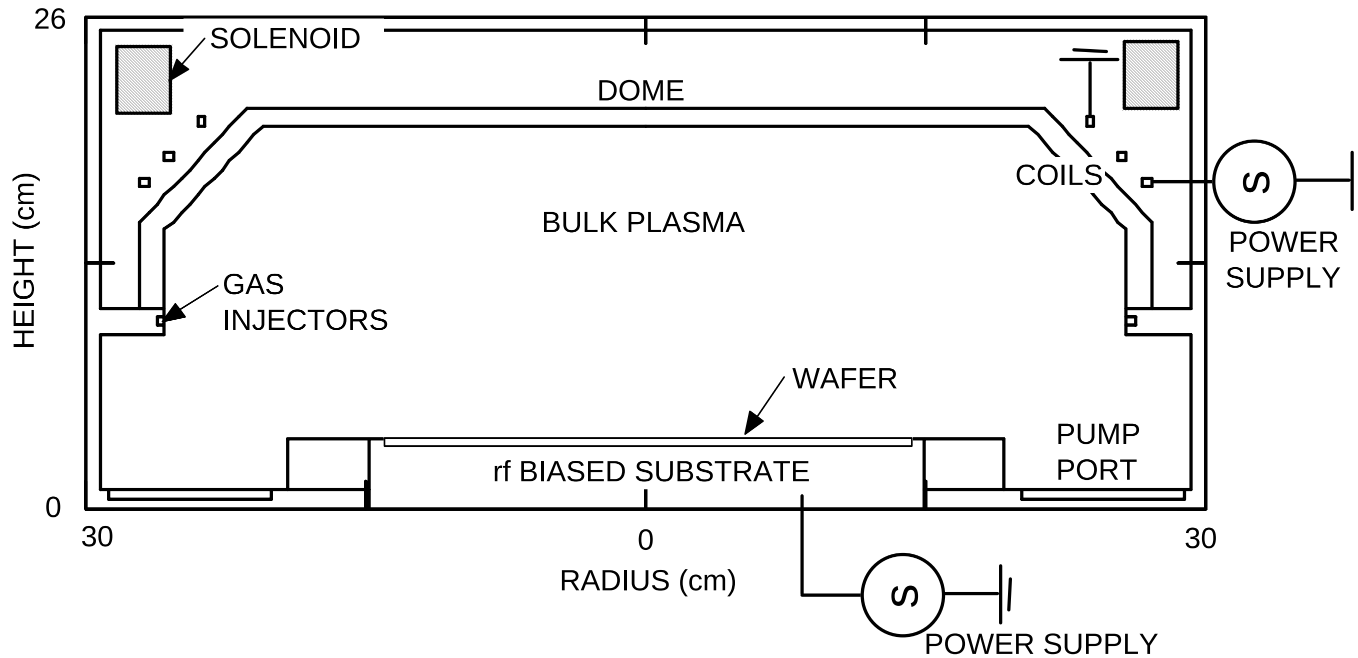


rf BIASED INDUCTIVELY COUPLED PLASMAS

- **Inductively Coupled Plasmas (ICPs) with rf biasing are used here.**
- **< 10s mTorr, 10s MHz, 100s W – kW, electron densities of 10^{11}-10^{12} cm^{-3}.**



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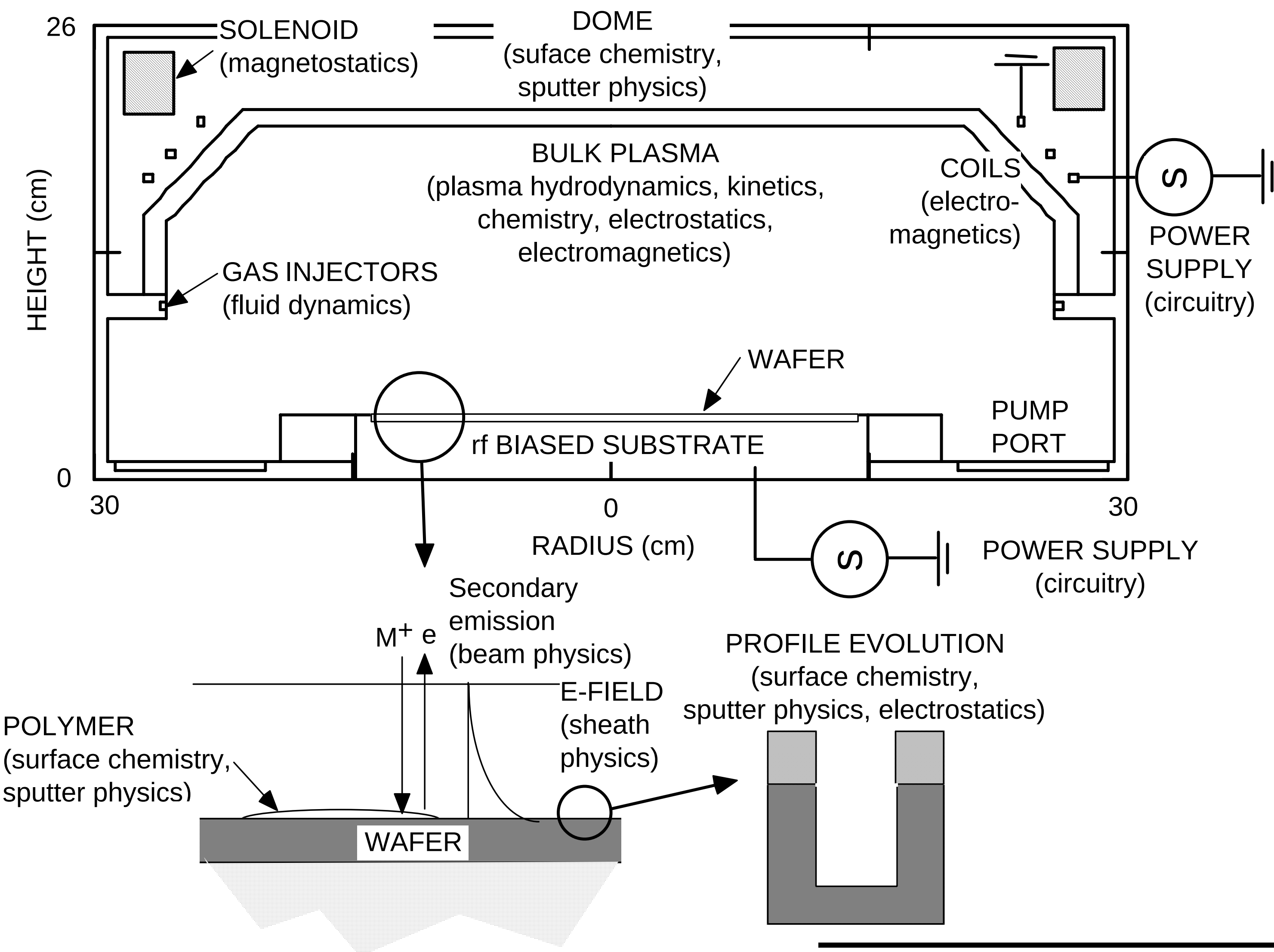
PHYSICAL PROCESSES IN REACTOR



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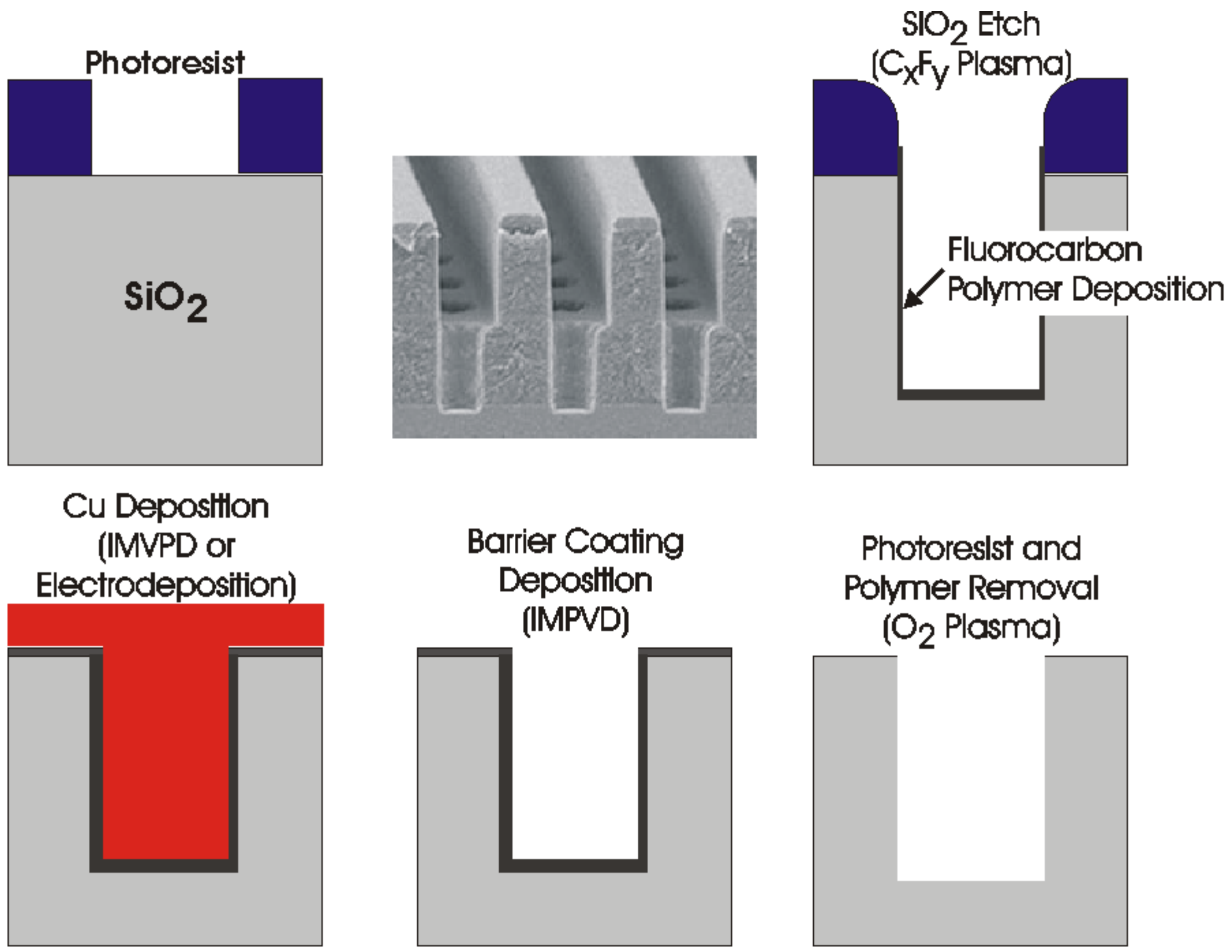
GOAL FOR PROCESS MODELING: INTEGRATION

- **Plasma processing involves an integrated sequence of steps, each of which depends on the quality of the previous steps.**



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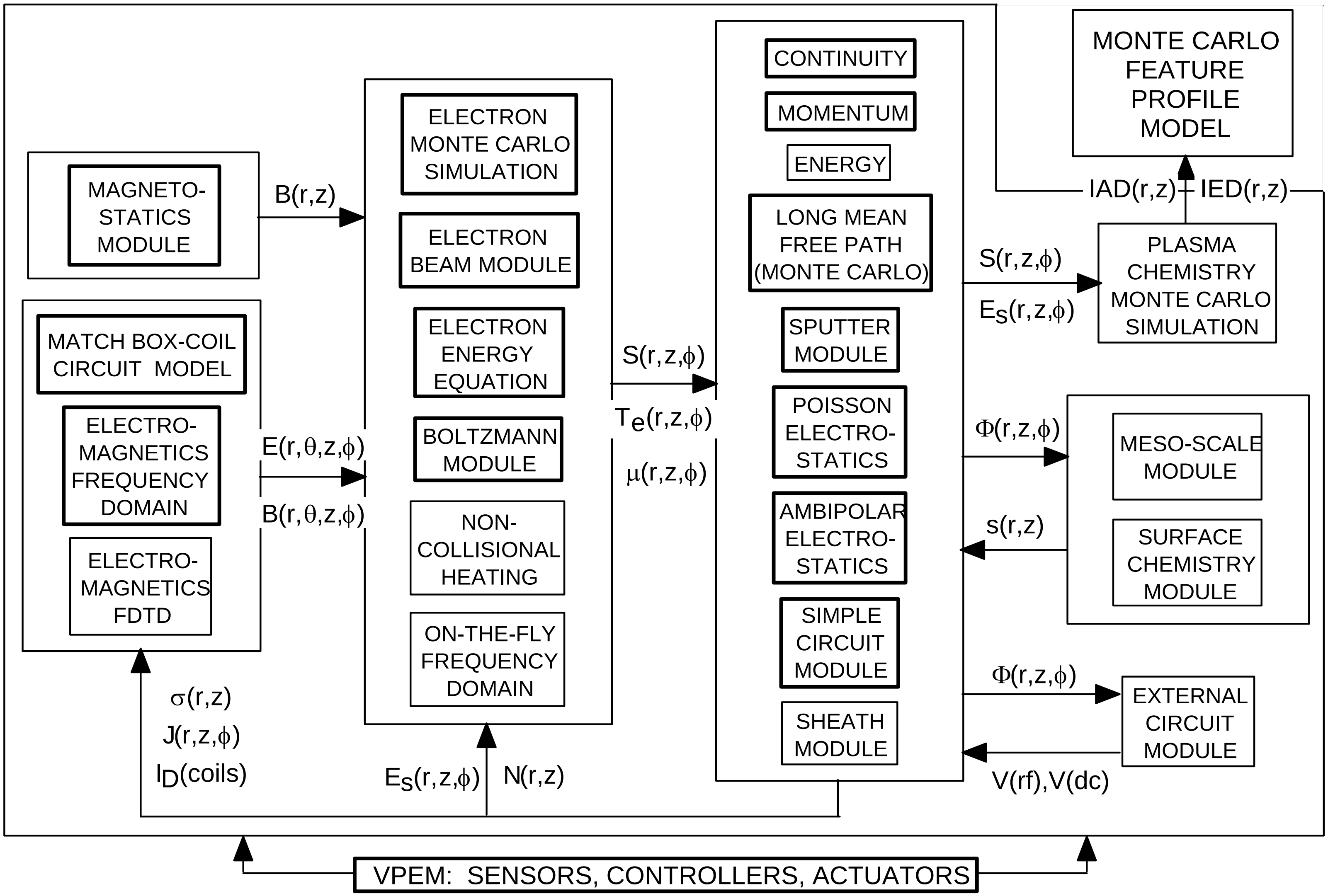
GOAL FOR PROCESS MODELING: INTEGRATION

- **To address these complexities, modeling platforms must integrate:**

  - ***Plasma Physics***
  - ***Plasma Chemistry***
  - ***Surface Kinetics***

HYBRID PLASMA EQUIPMENT MODEL



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ELECTROMAGNETICS MODEL

- **The wave equation is solved in the frequency domain using sparse matrix techniques (2D,3D):**

$$-\nabla\left(\frac{1}{\mu}\nabla\cdot\overline{E}\right)+\nabla\cdot\left(\frac{1}{\mu}\nabla\overline{E}\right)=\frac{\partial^2\left(\varepsilon\overline{E}\right)}{\partial t^2}+\frac{\partial\left(\overline{\overline{\sigma}}\cdot\overline{E}+\overline{J}\right)}{\partial t}$$

$$\vec{E}(\vec{r},t)=\vec{E}'(\vec{r})\exp(-i(\omega t+\varphi(\vec{r})))$$

- **Conductivities are tensor quantities (2D,3D):**

$$\overline{\overline{\sigma}}=\sigma_o\frac{m\nu_m}{q\alpha}\frac{1}{\left(\alpha^2+\left|\vec{B}\right|^2\right)}\begin{pmatrix}\alpha^2+B_r^2 & \alpha B_z+B_rB_\theta & -\alpha B_\theta+B_rB_z\\ -\alpha B_z+B_rB_\theta & \alpha^2+B_\theta^2 & \alpha B_r+B_\theta B_z\\ -\alpha B_\theta+B_rB_z & -\alpha B_r+B_\theta B_z & \alpha^2+B_z^2\end{pmatrix}$$

$$\vec{j}=\overline{\overline{\sigma}}\cdot\vec{E}\qquad\qquad \alpha=\frac{\left(i\omega+\nu_m\right)}{q/m},\quad \sigma_o=\frac{q^2n_e}{m\nu_m}$$

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ELECTROMAGNETICS MODEL (cont.)

- The electrostatic term in the wave equation is addressed using a perturbation to the electron density (2D).

$$\nabla \cdot \overline{E} = \frac{\rho}{\varepsilon} = \frac{q \Delta n_e}{\varepsilon}, \quad \Delta n_e = -\nabla \cdot \left(\frac{\overline{\overline{\sigma}} \cdot \overline{E}}{q} \right) / \left(\frac{1}{\tau} + i\omega \right)$$

- Conduction currents can be kinetically derived from the Electron Monte Carlo Simulation to account for non-collisional effects (2D).

$$\mathrm{J}_{\mathrm{e}}(\vec{r},t) = J_o(\vec{r}) \exp(i(\omega t + \phi_v(\vec{r}))) = -q n_e(\vec{r}) \vec{v}_e(\vec{r}) \exp\left(i\left(\omega t + \vec{\phi}_v(\vec{r})\right)\right)$$

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ELECTRON ENERGY TRANSPORT

- **Continuum (2D,3D):**

$$\partial\left(\frac{3}{2}n_e k T_e\right)/\partial t = S(T_e) - L(T_e) - \nabla\cdot\left(\frac{5}{2}\Phi k T_e - \overline{\overline{\kappa}}(T_e)\cdot\nabla T_e\right) + S_{EB}$$

where	**$S(T_e)$**	**=**	**Power deposition from electric fields**
	$L(T_e)$	**=**	**Electron power loss due to collisions**
	Φ	**=**	**Electron flux**
	$\kappa(T_e)$	**=**	**Electron thermal conductivity tensor**
	S_{EB}	**=**	**Power source source from beam electrons**

- **Power deposition has contributions from wave and electrostatic heating.**

- **Kinetic (2D,3D): A Monte Carlo Simulation is used to derive** $f(\varepsilon,\vec{r},t)$ **including electron-electron collisions using electromagnetic fields from the EMM and electrostatic fields from the FKM.**

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PLASMA CHEMISTRY, TRANSPORT AND ELECTROSTATICS

- **Continuity, momentum and energy equations are solved for each species (with jump conditions at boundaries) (2D,3D).**

$$\frac{\partial N_i}{\partial t} = -\nabla \cdot (N_i \vec{\mathrm{v}}_i) + S_i$$

$$\frac{\partial (N_i \vec{v}_i)}{\partial t} = \frac{1}{m_i} \nabla (k N_i T_i) - \nabla \cdot (N_i \vec{v}_i \vec{v}_i) + \frac{q_i N_i}{m_i} \left(\vec{E} + \vec{v}_i \times \vec{B} \right) - \nabla \cdot \overline{\mu}_i - \sum_j \frac{m_j}{m_i + m_j} N_i N_j \left(\vec{v}_i - \vec{v}_j \right) \nu_{ij}$$

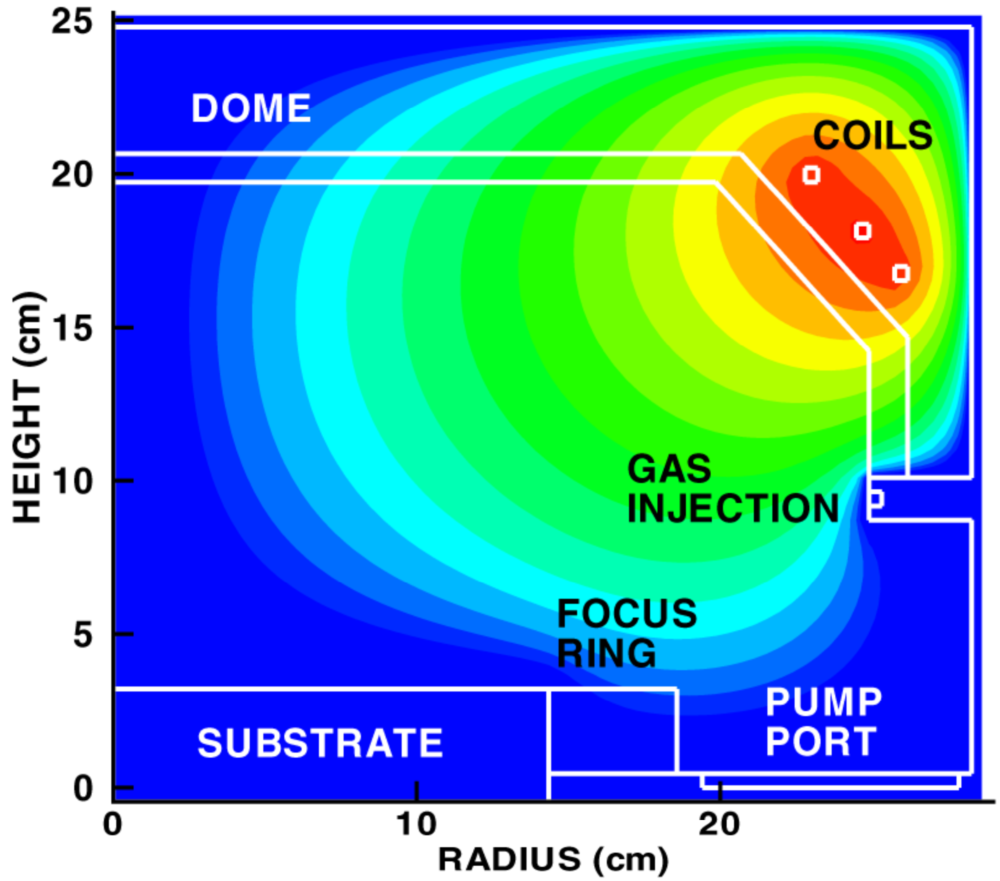
$$\frac{\partial (N_i \varepsilon_i)}{\partial t} + \nabla \cdot \mathrm{Q}_i + P_i \nabla \cdot \mathrm{U}_i + \nabla \cdot (N_i \mathrm{U}_i \varepsilon_i) = \frac{N_i q_i^2 \nu_i}{m_i (\nu_i^2 + \omega^2)} E^2 + \frac{N_i q_i^2}{m_i \nu_i} E_s^2 + \sum_j 3 \frac{m_{ij}}{m_i + m_j} N_i N_j R_{ij} k_B (T_j - T_i) \pm \sum_j 3 N_i N_j R_{ij} k_B T_j$$

- **Implicit solution of Poisson's equation (2D,3D):**

$$\nabla \cdot \varepsilon \nabla \Phi (t + \Delta t) = -\left(\rho_s + \sum_i q_i N_i - \Delta \mathrm{t} \cdot \sum_{\mathrm{i}} \left(\mathrm{q_i} \nabla \cdot \vec{\phi}_i \right) \right)$$

WALK THROUGH: Ar/Cl_2 PLASMA FOR p-Si ETCHING

- **The inductively coupled electromagnetic fields have a skin depth of 3-4 cm.**
- **Absorption of the fields produces power deposition in the plasma.**
- **Electric Field (max = 6.3 V/cm)**
  - **Ar/Cl_2 = 80/20**
  - **20 mTorr**
  - **1000 W ICP 2 MHz**
  - **250 V bias, 2 MHz (260 W)**



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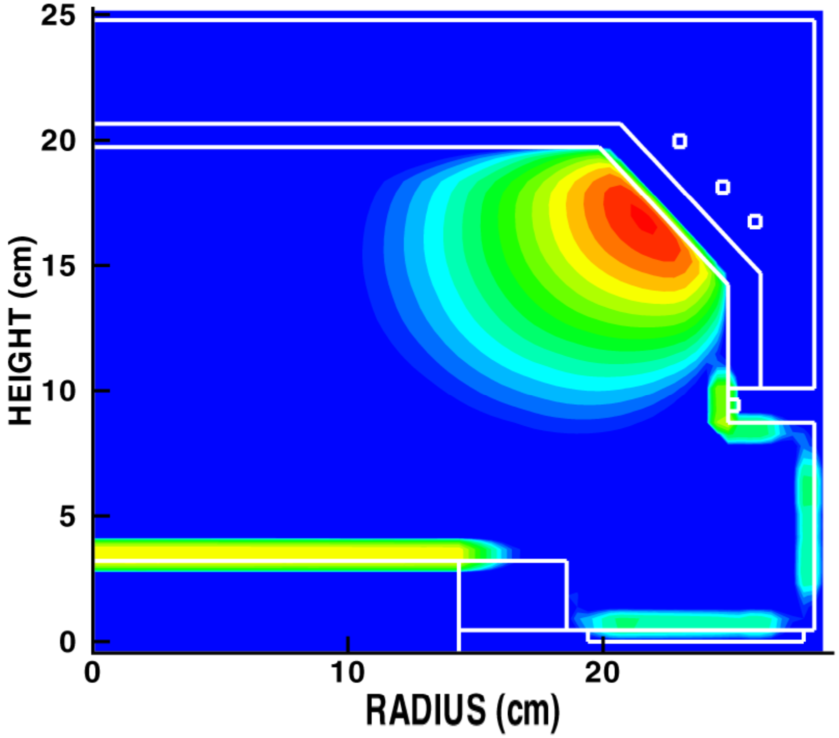
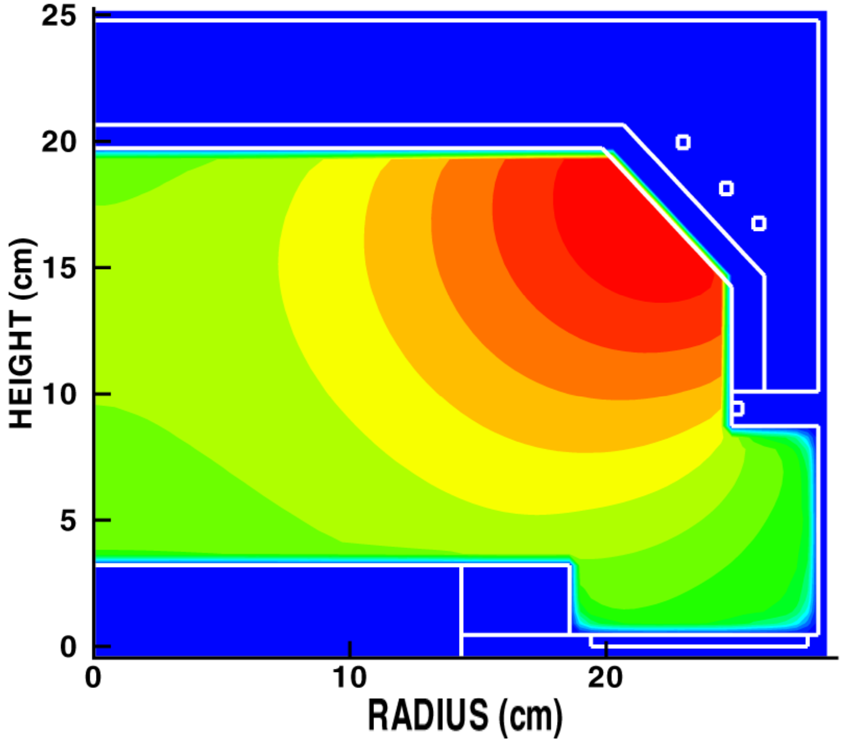
Ar/Cl_2 ICP: POWER AND ELECTRON TEMPERATURE

- ICP Power heats electrons, capacitively coupled power dominantly accelerates ions.





- <u>Power Deposition (max = 0.9 W/cm^3)</u>
- <u>Electron Temperature (max = 5 eV)</u>

- Ar/Cl_2 = 80/20, 20 mTorr, 1000 W ICP 2 MHz, 250 V bias, 2 MHz (260 W)

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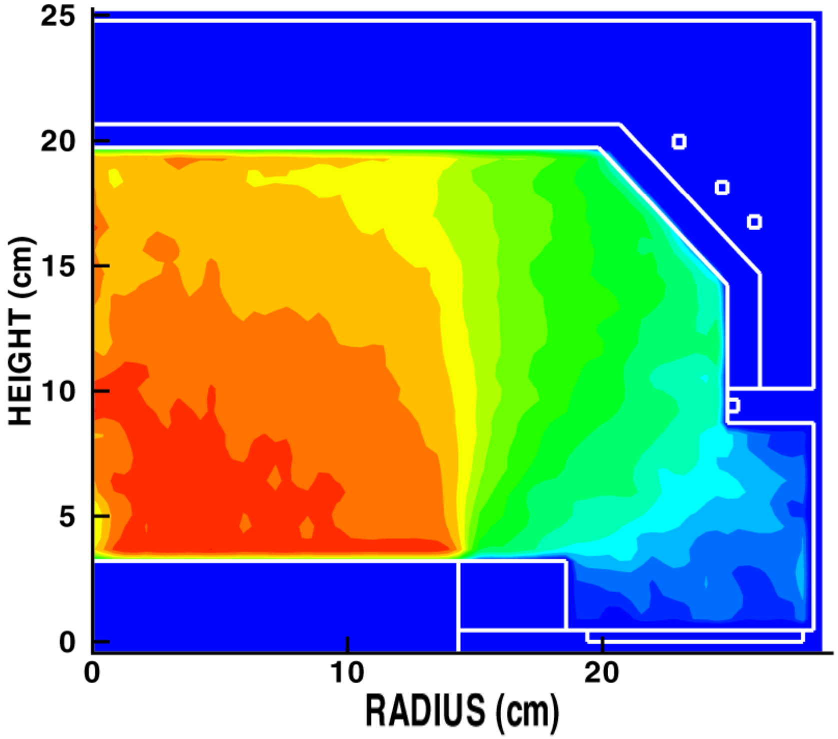
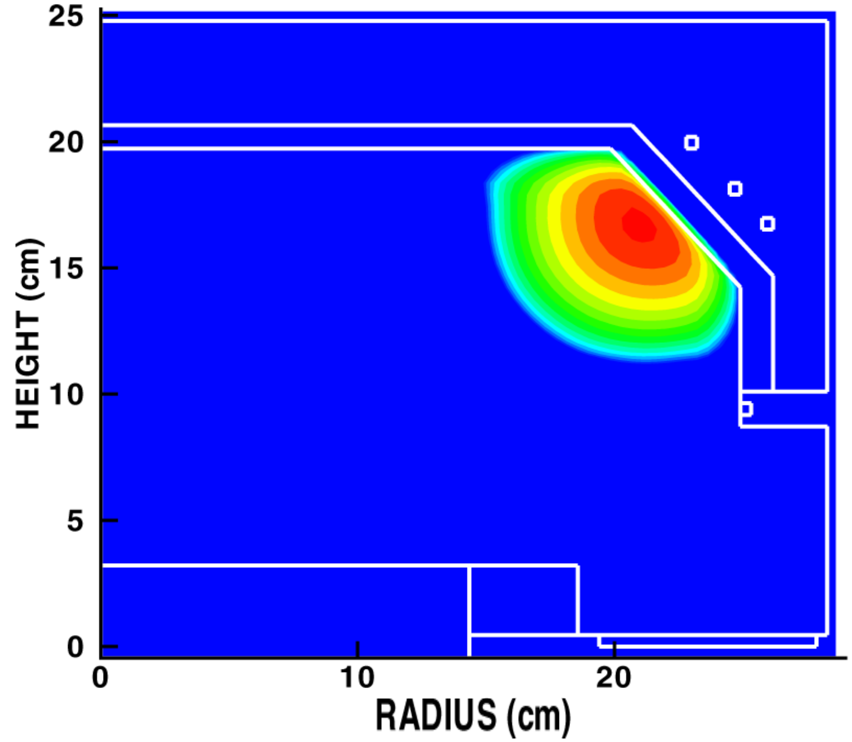
Ar/Cl_2 ICP: IONIZATION

- Ionization is produced by bulk electrons and sheath accelerated secondary electrons.



- **Beam Ionization**
(max = 1.3 x 10^{14} $cm^{-3}s^{-1}$)



- **Bulk Ionization**
(max = 5.4 x 10^{15} $cm^{-3}s^{-1}$)

- Ar/Cl_2 = 80/20, 20 mTorr, 1000 W ICP 2 MHz, 250 V bias, 2 MHz (260 W)

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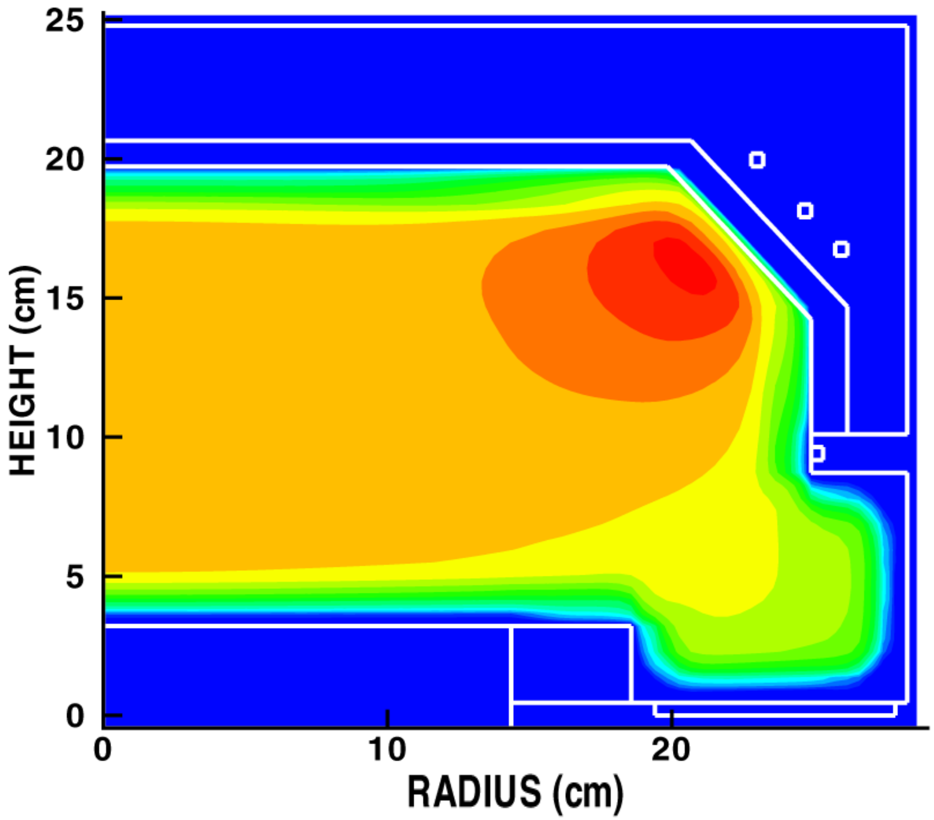
Ar/Cl_2 ICP: POSITIVE ION DENSITY

- **Diffusion from the remote plasma source produces uniform ion densities at the substrate.**



- **<u>Positive Ion Density (max = 1.8 x 10^{11} cm^{-3})</u>**

- **Ar/Cl_2 = 80/20, 20 mTorr, 1000 W ICP 2 MHz, 250 V bias, 2 MHz (260 W)**

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•*PLASMA PHYSICS*
(Are we getting it right?)

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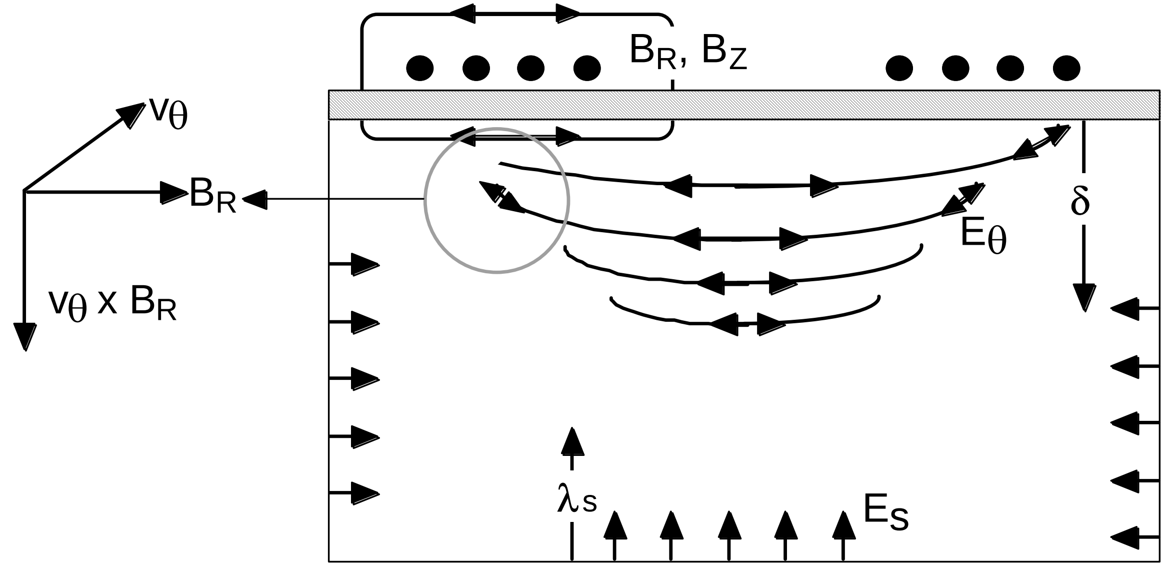
FORCES ON ELECTRONS IN ICPs



- **Inductive electric field provides azimuthal acceleration; penetrates** $\delta = \left(m_e / \left(e^2 \mu_o n_e\right)\right)^{1/2}$ **(1-3 cm)**
- **Electrostatic (capacitive); penetrates** $\lambda_S \approx 10\lambda_D,\ \lambda_D = \left(kT_e / \left(8\pi n_e e^2\right)\right)^{1/2}$ **(100s μm to mm)**
- **Non-linear Lorentz Force** $\vec{F} = v_\theta \times \vec{B}_{rf}$

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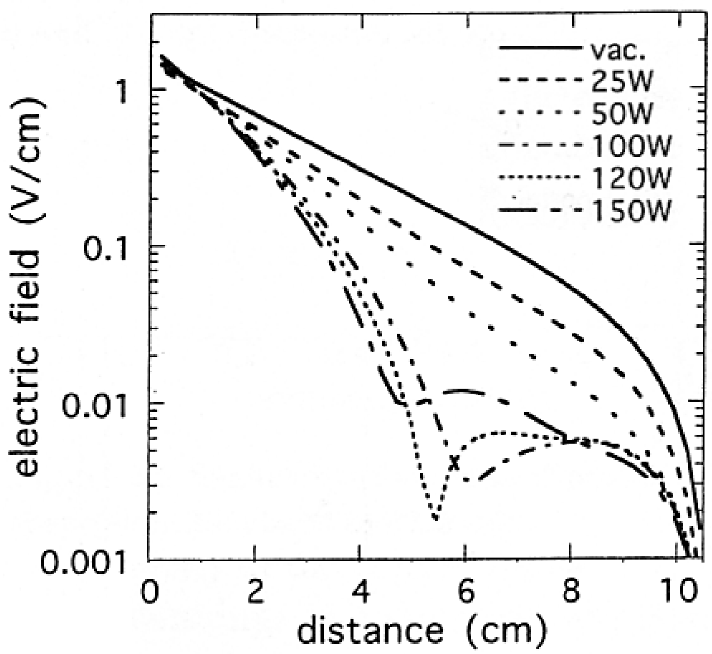
ANAMOLOUS SKIN EFFECT AND POWER DEPOSITION



- Ref: V. Godyak, “Electron Kinetics of Glow Discharges”

- **Collisional heating:**

$$\lambda_{mfp} < \delta_{skin}, \quad \vec{J}_e(\vec{r},t) = \sigma(\vec{r},t)\vec{E}(\vec{r},t)$$

- **Anomalous skin effect:**

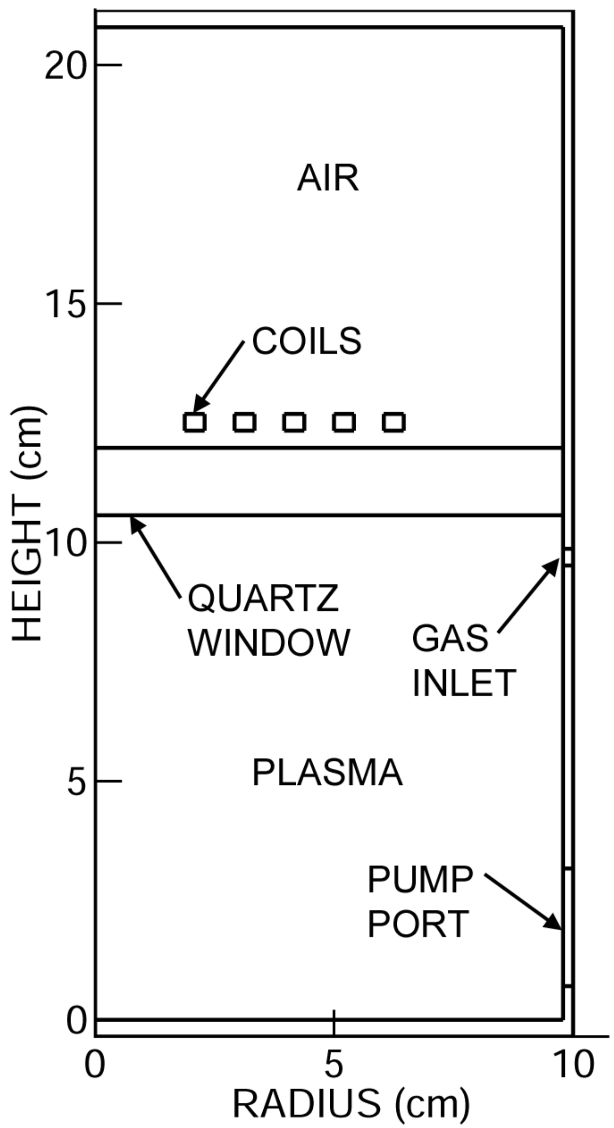
$$\lambda_{mfp} > \delta_{skin}$$

$$\vec{J}_e(\vec{r},t) = \iint \sigma(\vec{r},\vec{r}',t,t')\vec{E}(\vec{r}',t')d\vec{r}'dt'$$

$$\vec{F} = \vec{v} \times \vec{B}$$

- **Electrons receive (positive) and deliver (negative) power from/to the E-field.**
- **E-field is non-monotonic.**

ICP CELL FOR VALIDATION



- **Experiments by Godyak et al are used for validation.**
- **The experimental cell is an ICP reactor with a Faraday shield to minimize capacitive coupling.**

  - **V. Godyak et al, J. Appl. Phys. 85, 703 (1999)**

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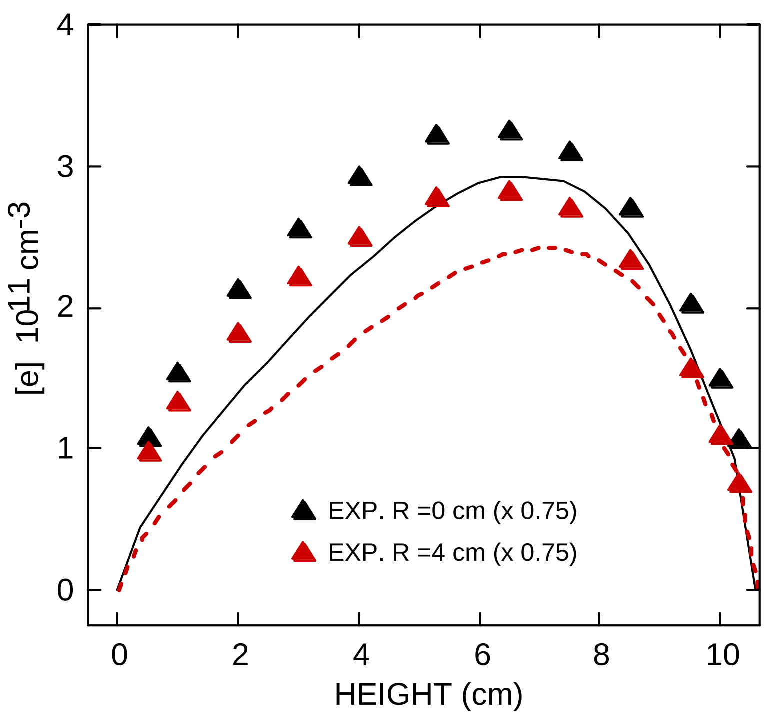
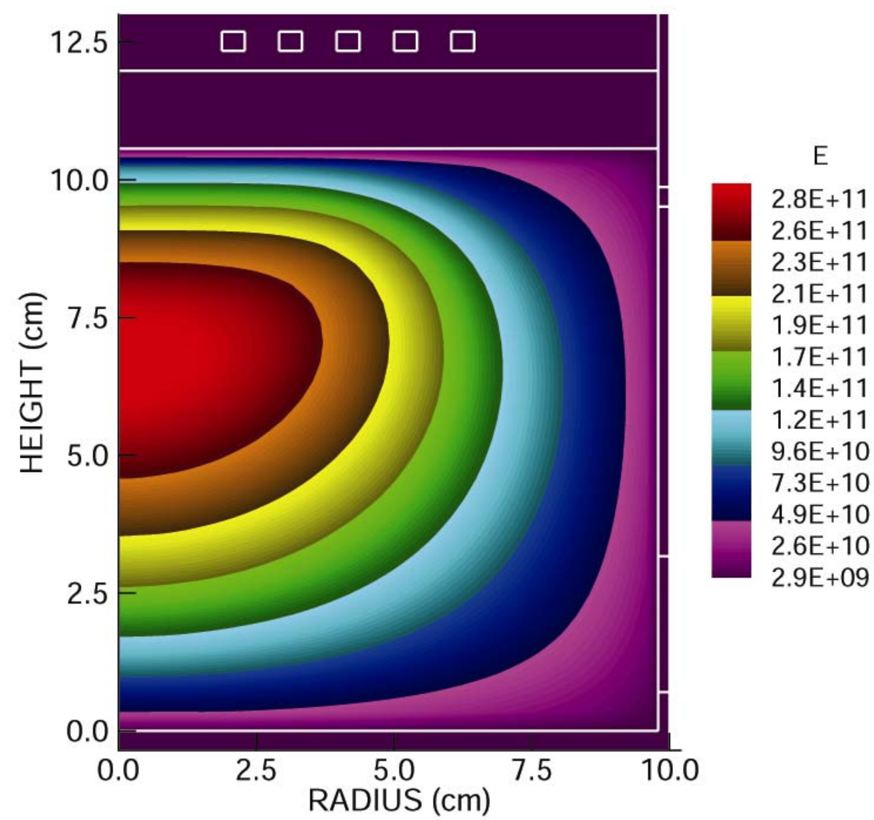
ELECTRON DENSITY: Ar, 10 mTorr, 200 W, 7 MHz

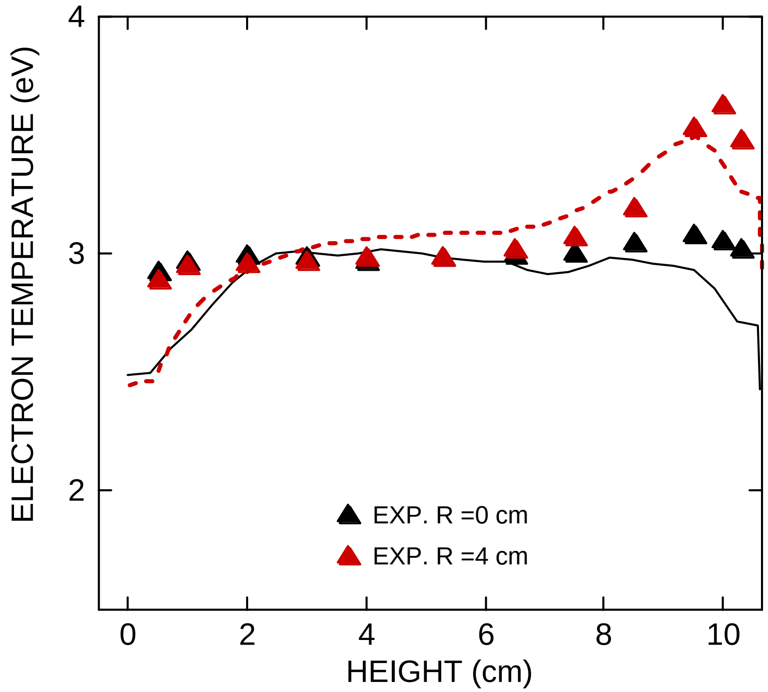


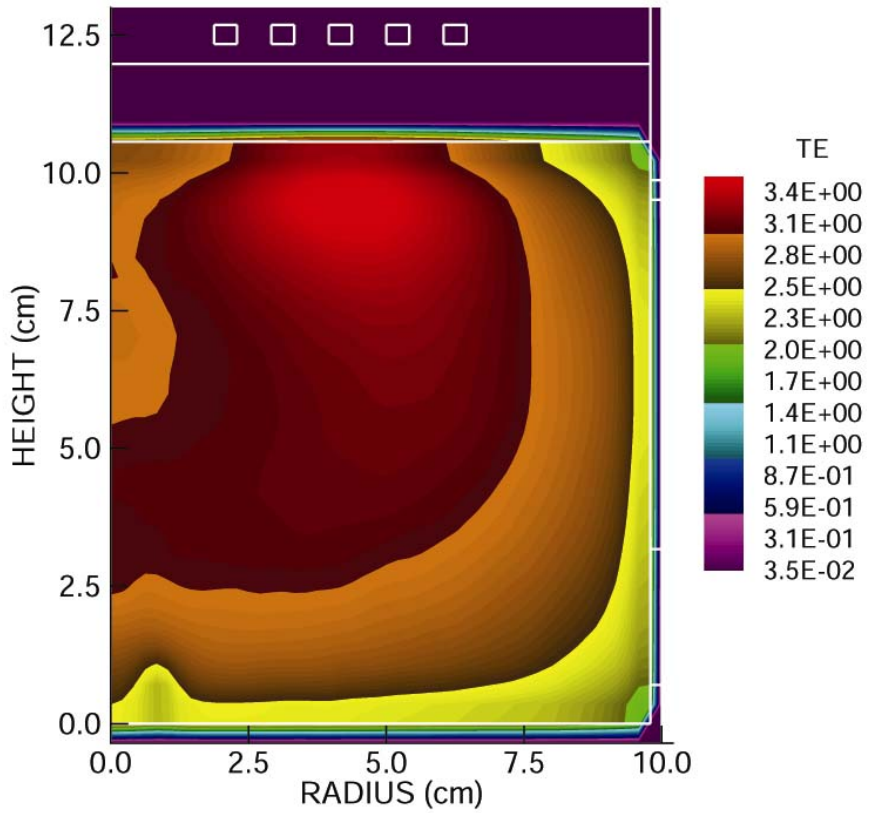
- **Ref: V. Godyak, Private Comm.**



- **On axis peak in [e] occurs inspite of off-axis power deposition.**
- **Model is about 30% below experiments. This likely has to do with details of the sheath model.**

ELECTRON TEMPERATURE: Ar, 10 mTorr, 200 W, 7 MHz



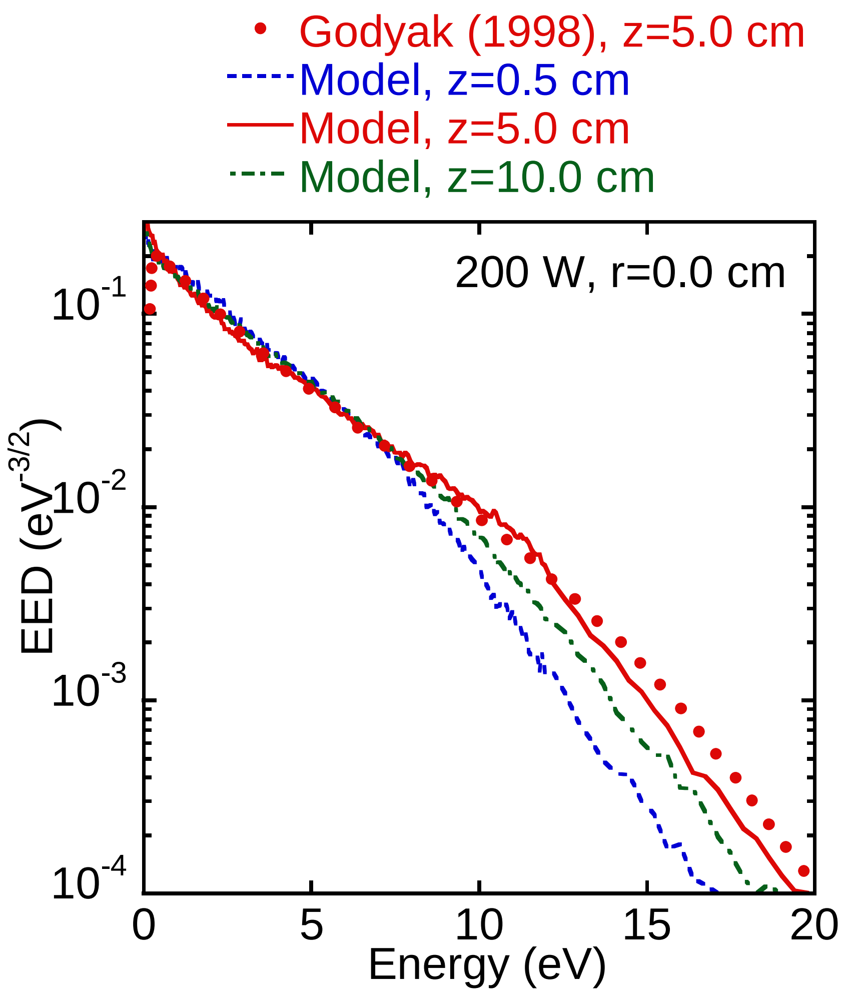


- **Ref: V. Godyak, Private Comm.**

- **The high thermal conductivity and redistribution of energy by e-e collisions produces nearly uniform temperatures.**

- **T_e peaks under the coils where power deposition is largest.**

EEDs ALONG THE CENTERLINE OF THE REACTOR



- The electron energy distributions show a bi-Maxwellian form, which is typical for low-pressure inductively coupled plasmas.

- Ar, 10 mTorr, 6.78 MHz, 200 W

COLLISIONLESS TRANSPORT ELECTRIC FIELDS

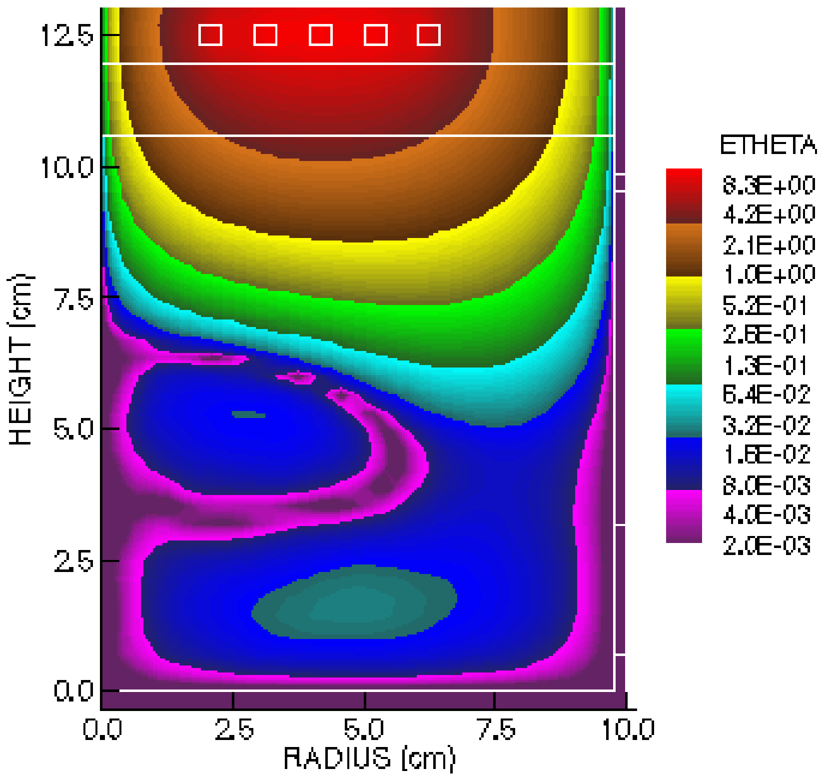
- **We couple electron transport to Maxwell's equations by kinetically deriving electron current.**

$$\oint \vec{j}(\vec{r})\exp(i\omega(t-t_o))\cdot dA = \sum_k q_k \vec{v}_k(\vec{r})\exp(i\omega(t_k-t_o))$$

- **E_θ during the rf cycle exhibits extrema and nodes resulting from this non-collisional transport.**

- **"Sheets" of electrons provide current sources interfering or reinforcing E_θ for the next sheet.**

- **Axial transport results from $\vec{v}\times\vec{B}_{rf}$ forces.**



ANIMATION SLIDE

- **Ar, 10 mTorr, 7 MHz, 100 W**

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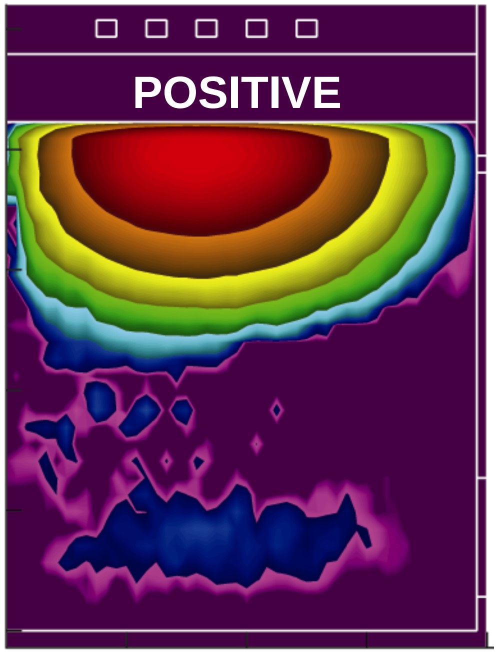
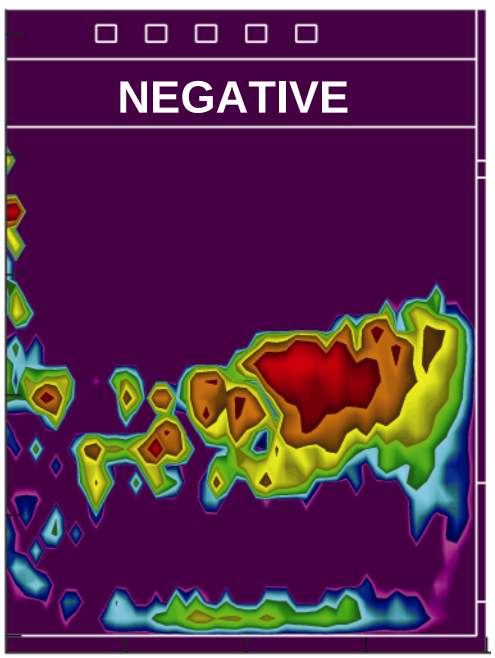
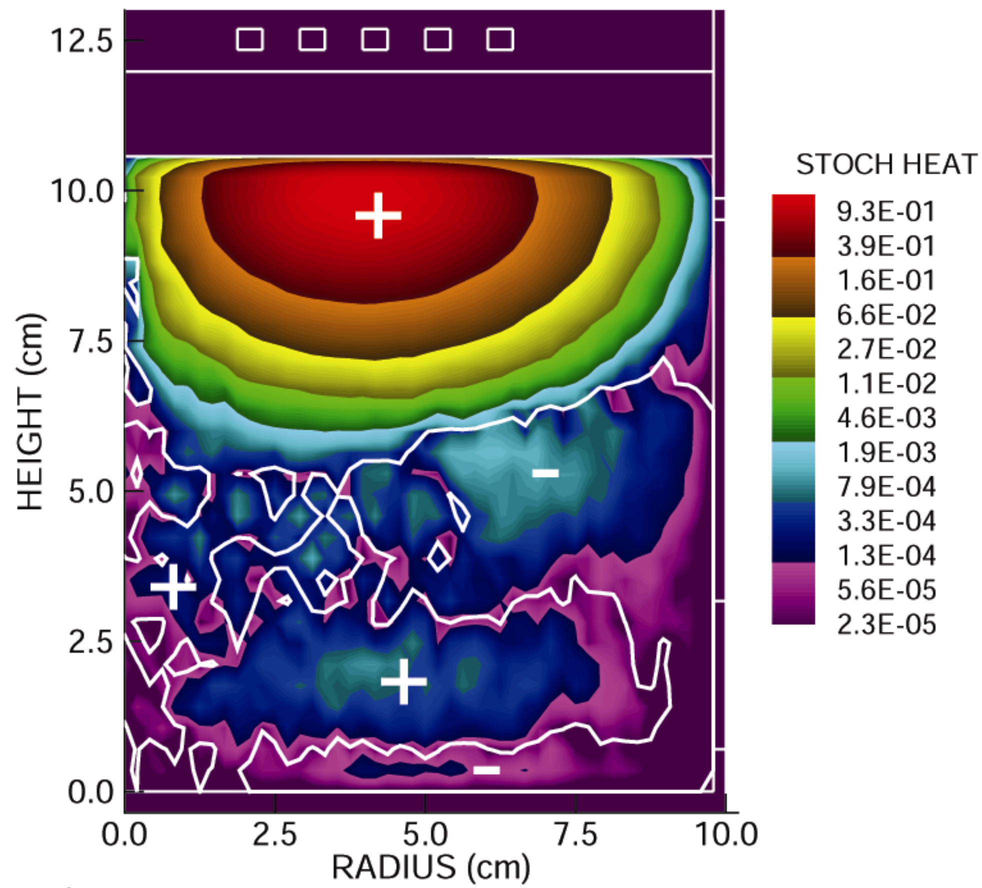
POWER DEPOSITION: POSITIVE AND NEGATIVE





- The end result is regions of positive and negative power deposition.



- Ar, 10 mTorr, 7 MHz, 100 W

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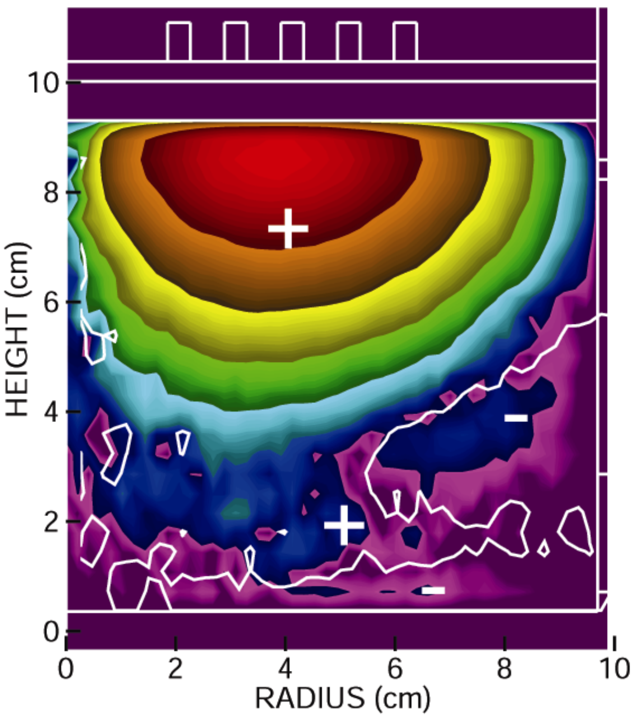
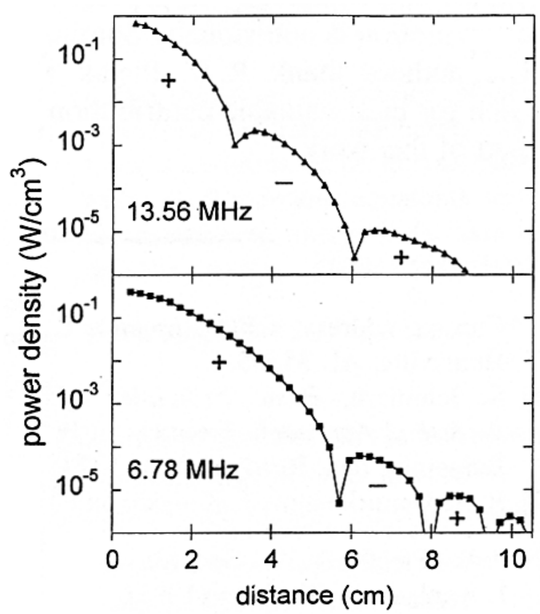
POWER DEPOSITION vs FREQUENCY

- **The shorter skin depth at high frequency produces more layers of negative power deposition of larger magnitude.**

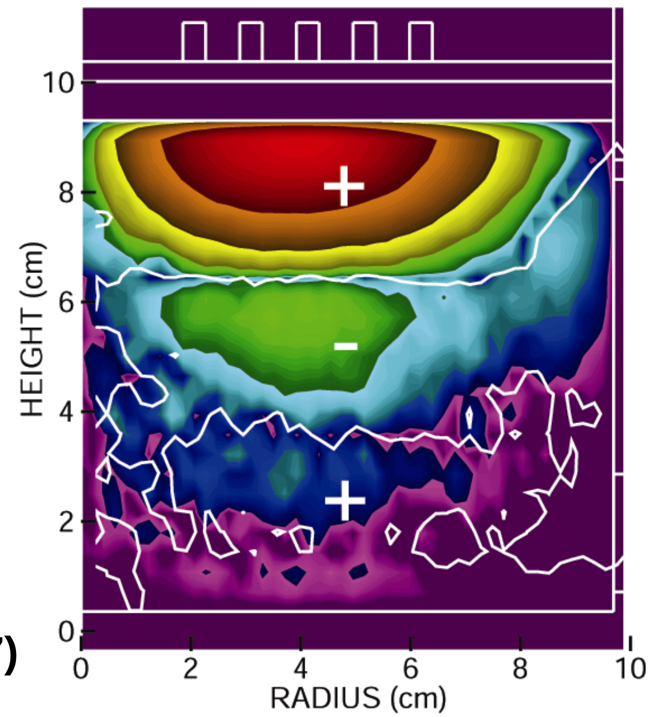


- **6.7 MHz**

(5x10^{-5} – 1.4 W/cm^3)



- **Ref: Godyak, PRL (1997)**
- **Ar, 10 mTorr, 200 W**



- **13.4 MHz**

(8x10^{-5} – 2.2 W/cm^3)

MIN **MAX**

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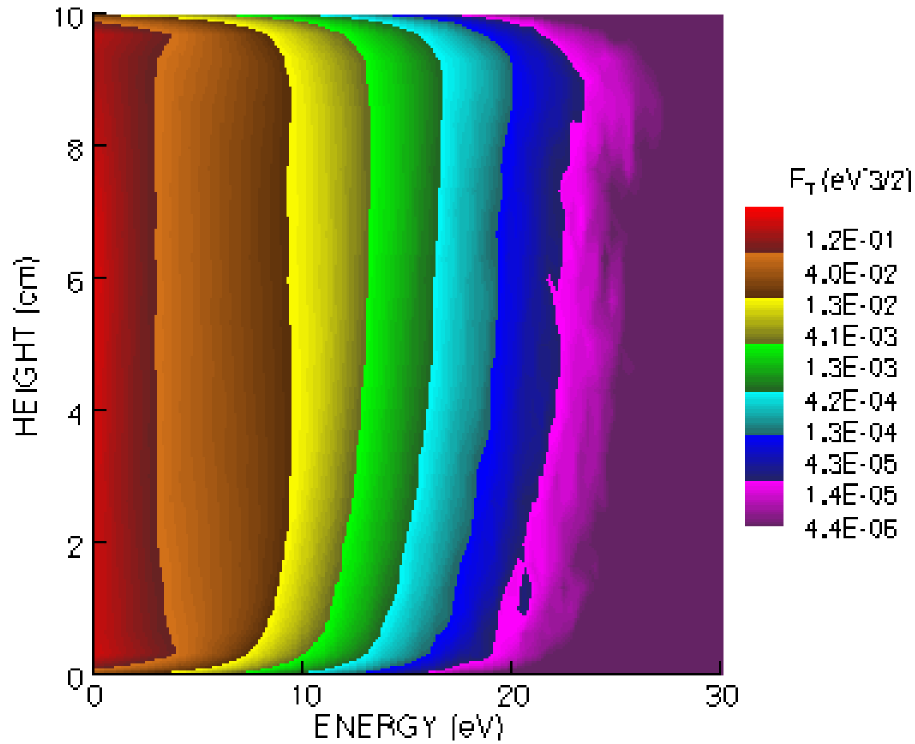
TIME DEPENDENCE OF THE EED

- **Time variation of the EED is mostly at higher energies where electrons are more collisional.**
- **Dynamics are dominantly in the electromagnetic skin depth where both collisional and non-linear Lorentz Forces) peak.**
- **The second harmonic dominates these dynamics.**

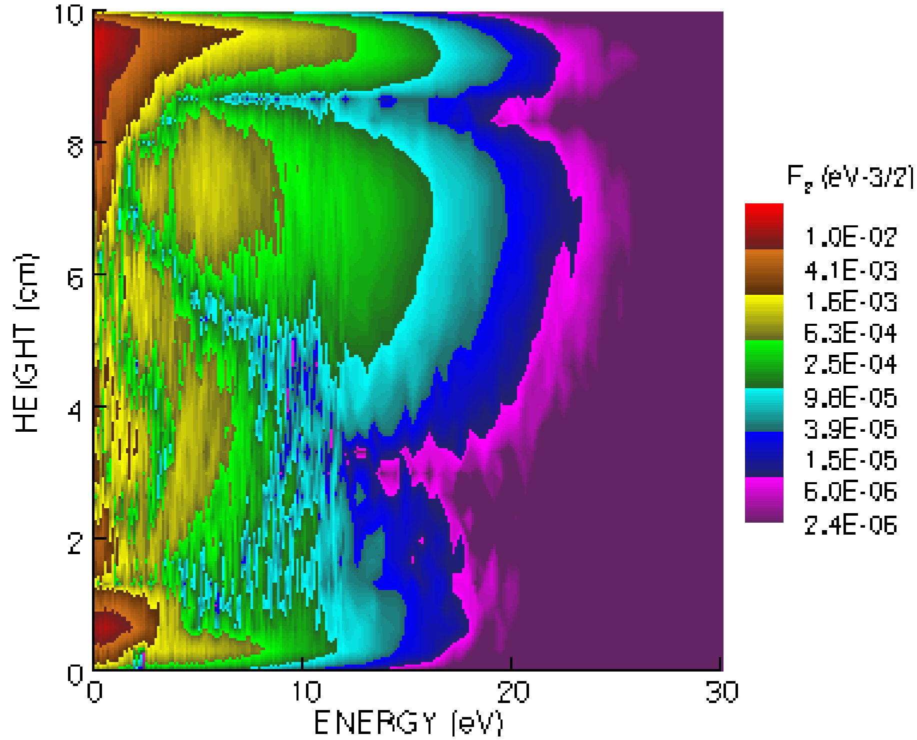


- **Ar, 10 mTorr, 100 W, 7 MHz, r = 4 cm**

ANIMATION SLIDE

TIME DEPENDENCE OF THE EED: 2nd HARMONIC

- **Electrons in skin depth quickly increase in energy and are "launched" into the bulk plasma.**
- **Undergoing collisions while traversing the reactor, they degrade in energy.**
- **Those surviving "climb" the opposite sheath, exchanging kinetic for potential energy.**
- **Several "pulses" are in transit simultaneously.**



- **Amplitude of 2nd Harmonic**

ANIMATION SLIDE

- **Ar, 10 mTorr, 100 W, 7 MHz, r = 4 cm**

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CONSEQUENCES OF ELECTRON DYNAMICS IN ICPs

- **The consequences of electron dynamics were investigated for Ar/N_2 gas mixtures.**

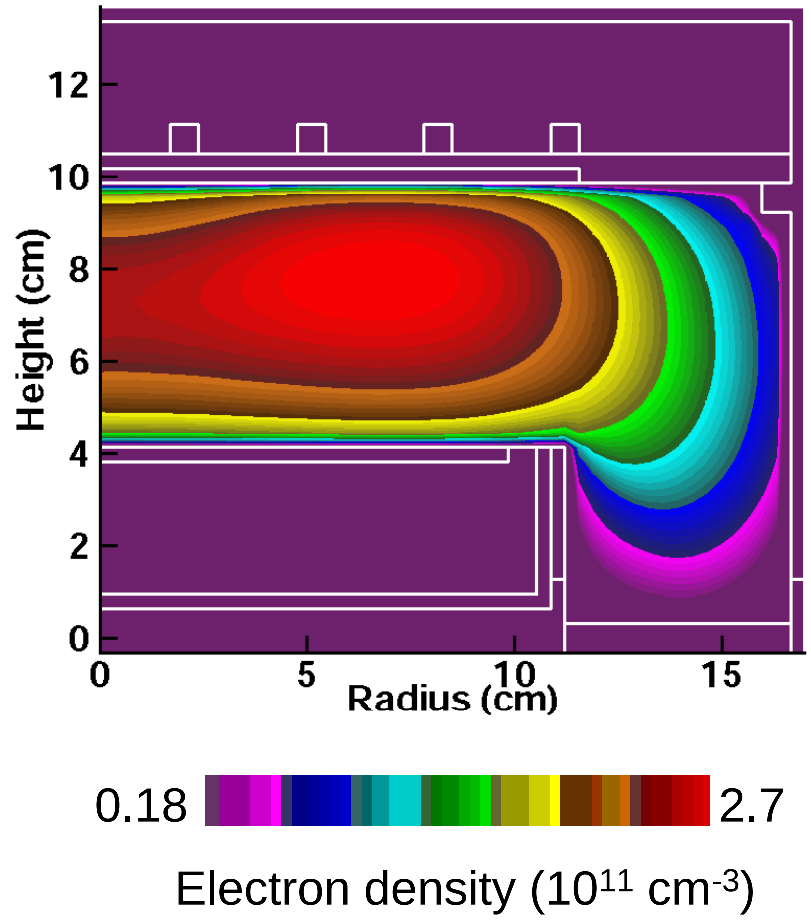
- **$e^- + Ar \rightarrow Ar^+ + e^- + e^-$, $\Delta\varepsilon = 16$ eV**

  High threshold reactions capture modulation in the tail of the EED.

- **$e^- + N_2 \rightarrow N_2\,(vib) + e^-$, $\Delta\varepsilon = 0.29$ eV**

  Low threshold reactions capture modulation of the bulk of the EED.

- **Base case conditions:**
  - **Pressure: 5 mTorr**
  - **Frequency: 13.56 MHz**
  - **Ar / N_2: 90 / 10**
  - **Power : 650 W**



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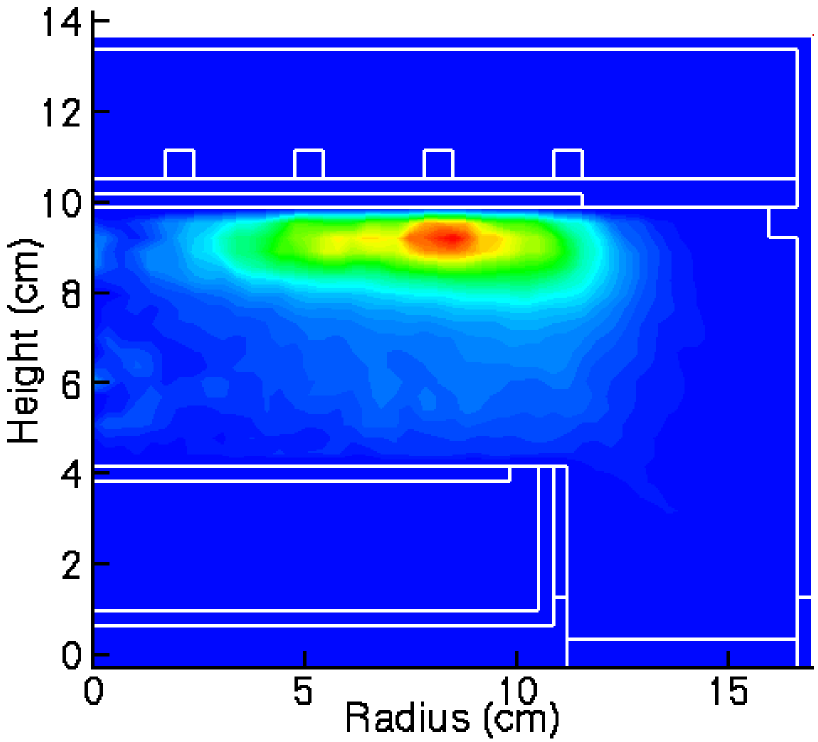
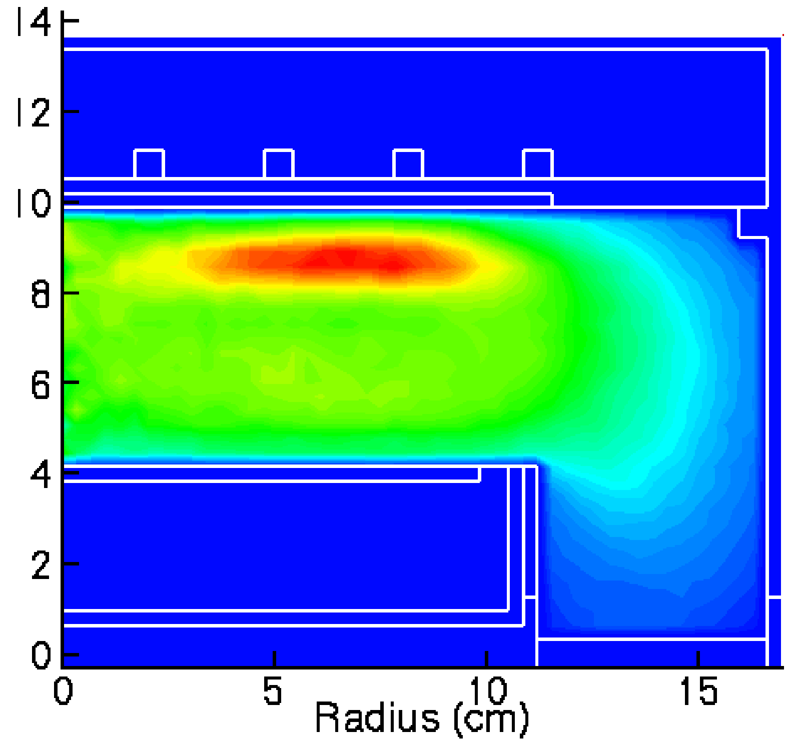
SOURCES FUNCTION vs TIME: THRESHOLD

- Ionization of Ar has more modulation than vibrational excitation of N_2 due to modulation of the tail of the EED.

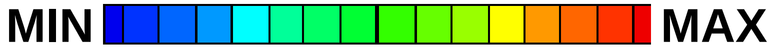


- Ionization of Ar
$6 \times 10^{14} – 3 \times 10^{16}$ $cm^{-3}s^{-1}$



- Excitation of $N_2(v)$
$1.4 \times 10^{14} – 8 \times 10^{15}$ $cm^{-3}s^{-1}$

ANIMATION SLIDE



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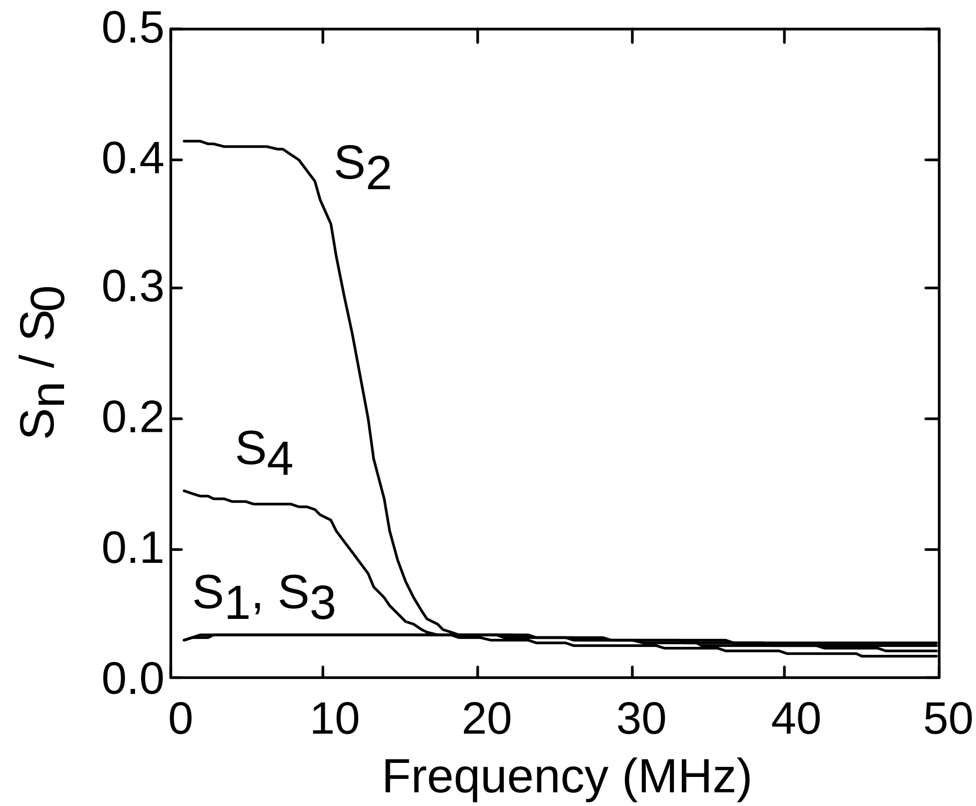
HARMONICS OF Ar IONIZATION: FREQUENCY

- At large ω, non-linear Lorentz forces are small, and so harmonic content is also small.

- At small ω, both non-linear Lorentz forces and harmonic excitation by the electric field are large.

- Ar/N_2=90/10, 5 mTorr



- Harmonic Amplitude/Time Average

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•*PLASMA CHEMISTRY*
(Are we getting this right?)

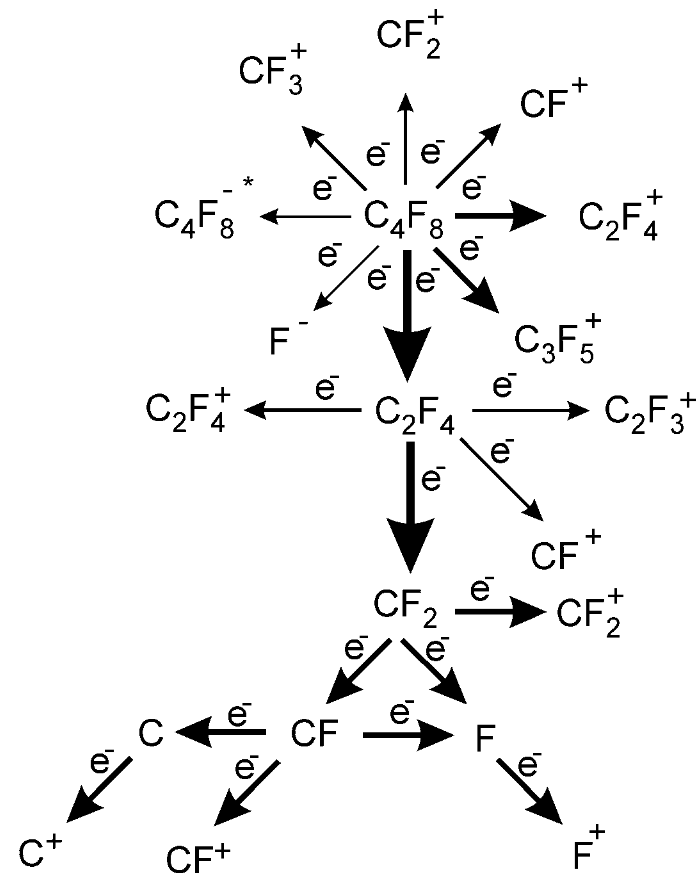
REACTION MECHANISMS FOR PLASMA ETCHING

- Recipes for plasma etching of dielectric materials (e.g., SiO_2, Si_3N_4) often contain mixtures of many gases such as:

  Ar , C_4F_8 , O_2 , N_2 , CO

- The fluorocarbon donors are often highly dissociated, thereby requiring databases for both feedstocks and their fragments.

- For predictive modeling, reaction mechanisms must be developed for arbitrary mixtures and wide ranges of pressures.



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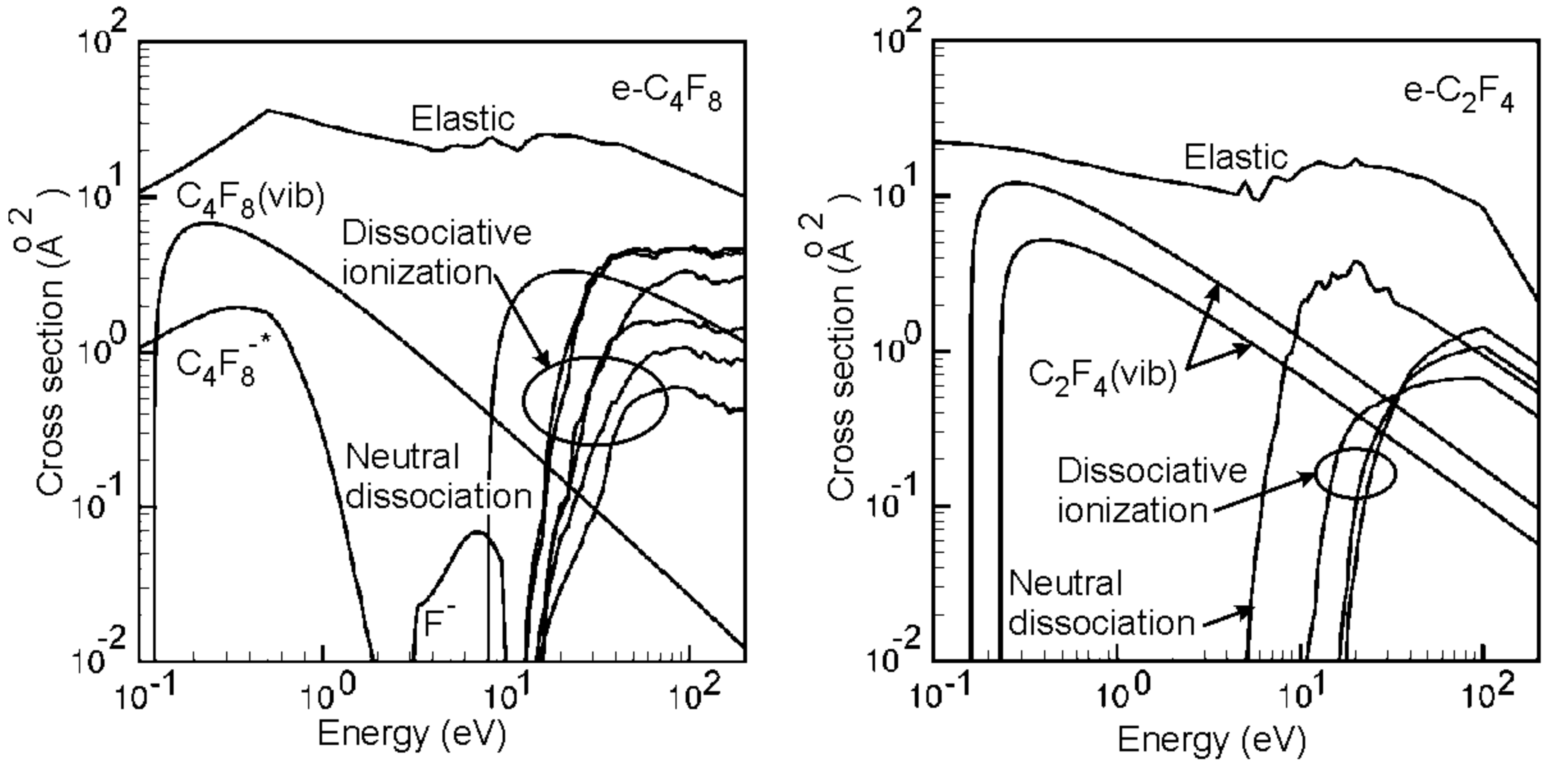
C_4F_8, C_2F_4 CROSS SECTION SETS

- **The first step in developing a reaction mechanism is compilation of electron impact cross section sets.**



- **Ref: V. McKoy and W. L. Morgan**

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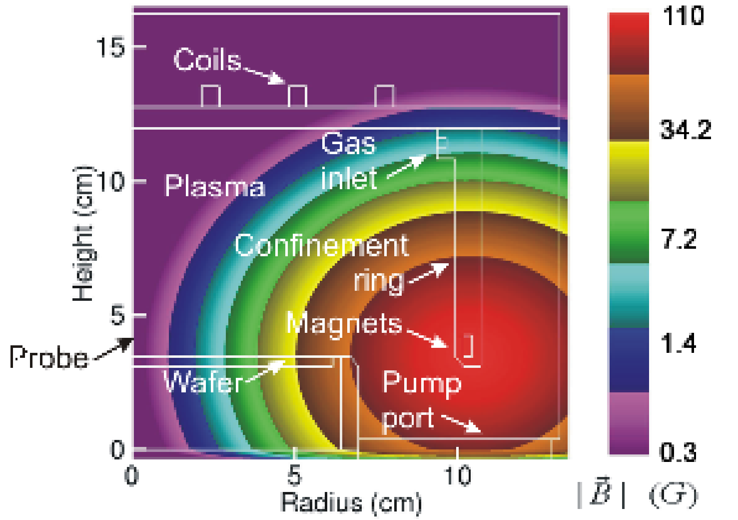
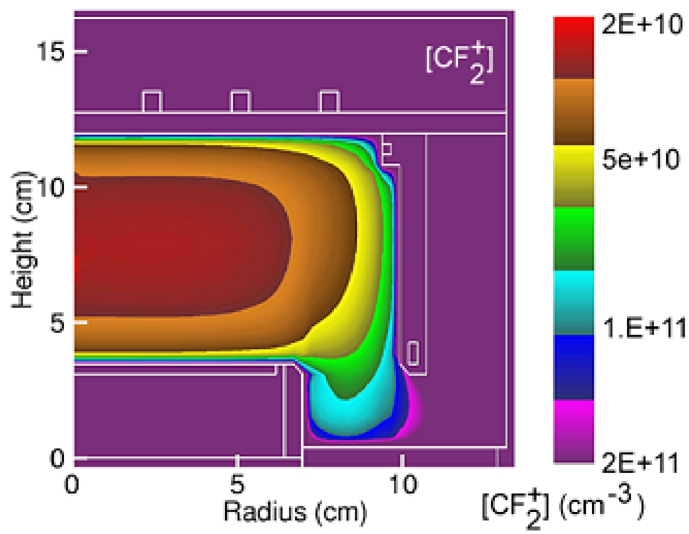
ICP CELL AND [CF_2^+] FOR C_4F_8, 10 mTorr



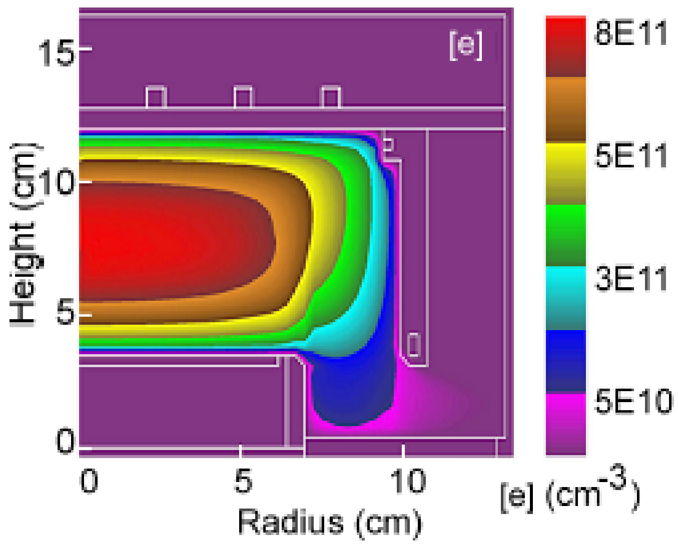


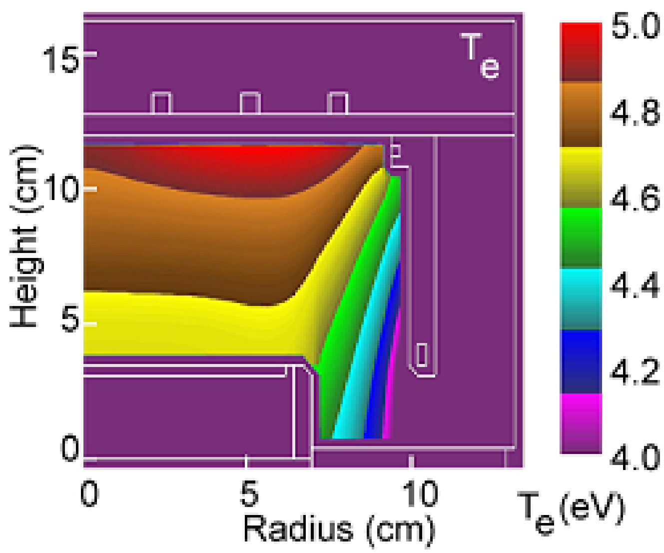
- C_4F_8, 10 mTorr, 1.4 kW, 13.56 MHz

- An ICP reactor patterned after Oeherlein, et al. was used for validation.
- Reactor has a metal ring with magnets to confine plasma.
- CF_2^+ is one of the dominant ions in C_4F_8 plasmas due to large dissociation.
- The major path for the CF_2^+ is:
- $C_4F_8 + e \rightarrow C_2F_4 + C_2F_4 + e$
- $C_2F_4 + e \rightarrow CF_2 + CF_2 + e$
- $CF_2 + e \rightarrow CF_2^+ + e + e$

SRC_2003_AVV_2

$[n_e]$ and T_e FOR C_4F_8, 10 mTorr





- **Electron density peaks at ≈10^{12} cm^{-3}.**
- **The peak in T_e occurs in the skin layer due to collisionless electron heating by the large electric field.**
- **T_e is rather uniform in the bulk plasma where electrons thermalize through e-e collisions.**

- **C_4F_8, 10 mTorr, 1.4 kW, 13.56 MHz**

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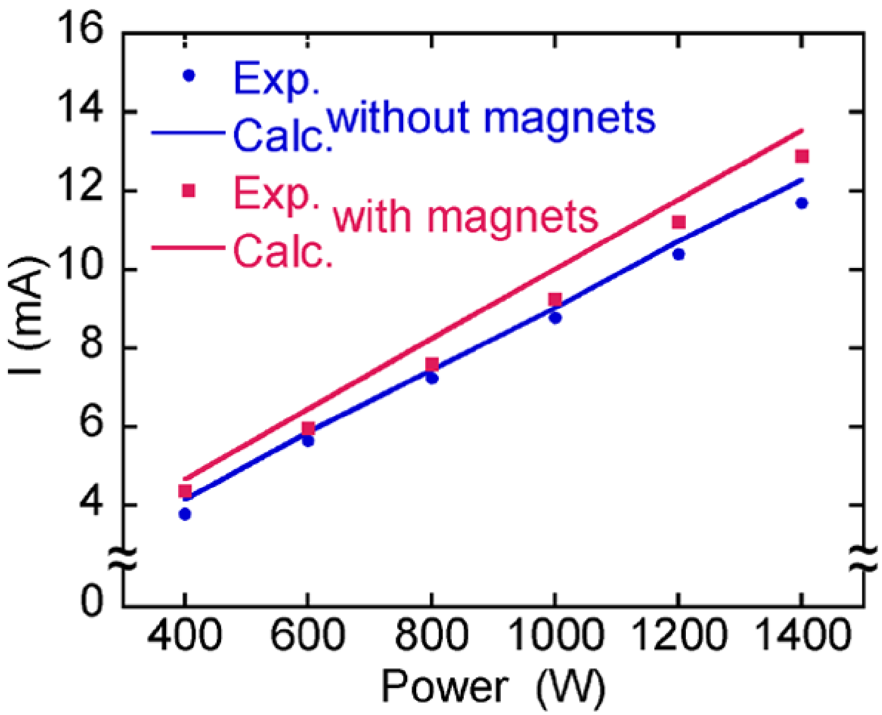
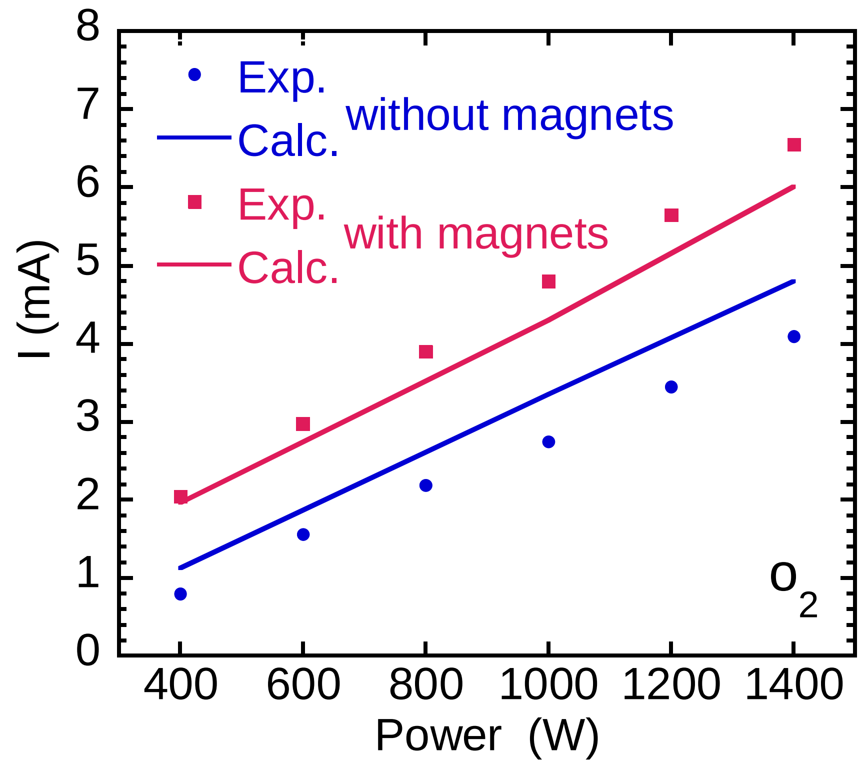
I_P (PROBE CURRENT) IN ICPs SUSTAINED IN Ar, O_2





- **Ar, 10 mTorr**
- **O_2, 10 mTorr**

- **Magnetic confinement is generally more effective in electronegative plasmas with a larger variety of ions.**

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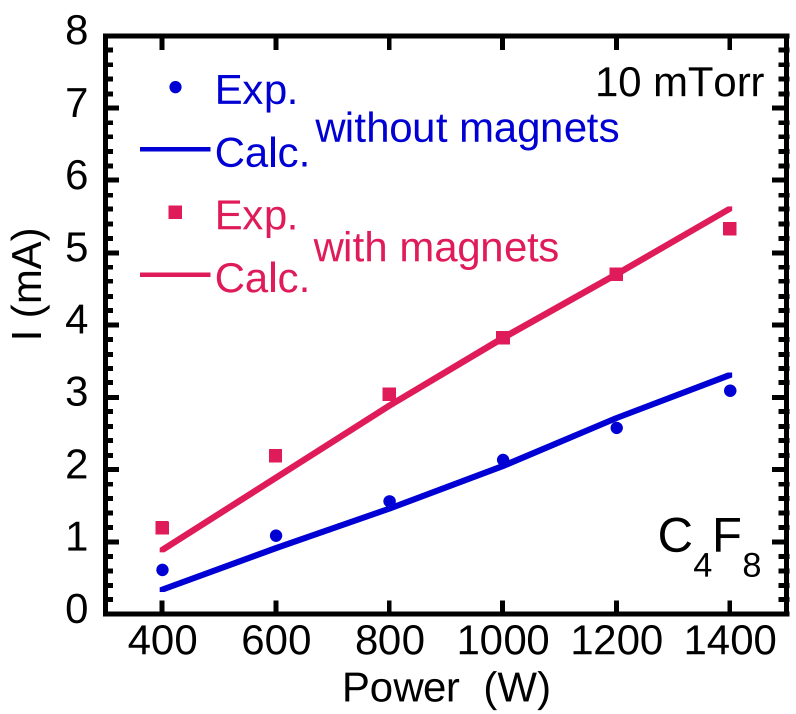
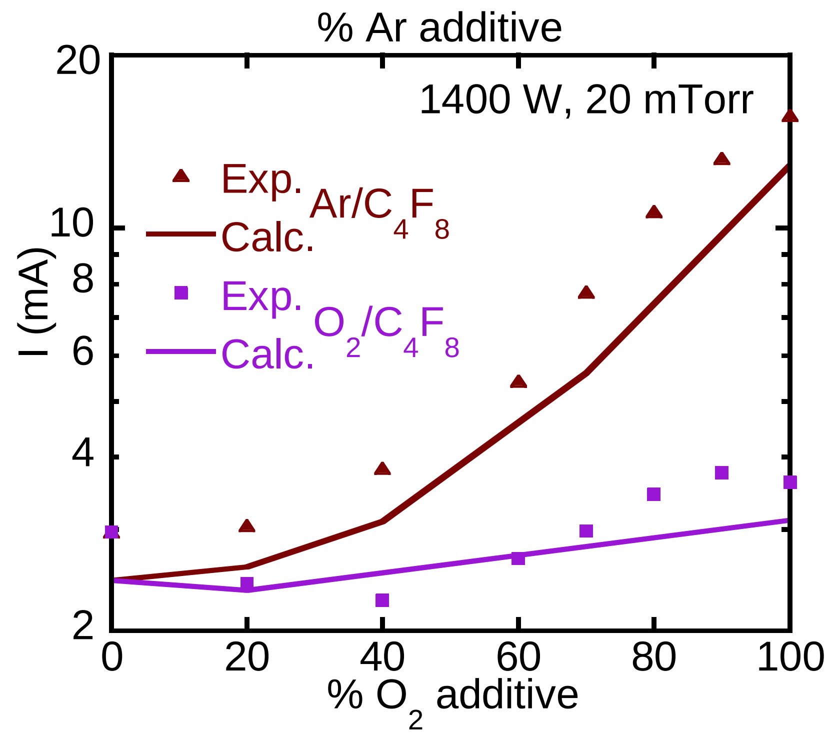
I_P VERSUS POWER FOR ICPs IN C_4F_8, Ar/C_4F_8, O_2/C_4F_8





- **The differences in I_P with and without magnets increases with power due to increased non-linear Lorentz force.**
- **I_P increases with Ar addition in Ar/C_4F_8 compared to Ar/O_2 due to higher dissociation of C_4F_8 and lower electronegativity.**

  - **13.56 MHz, -100 V probe bias.**

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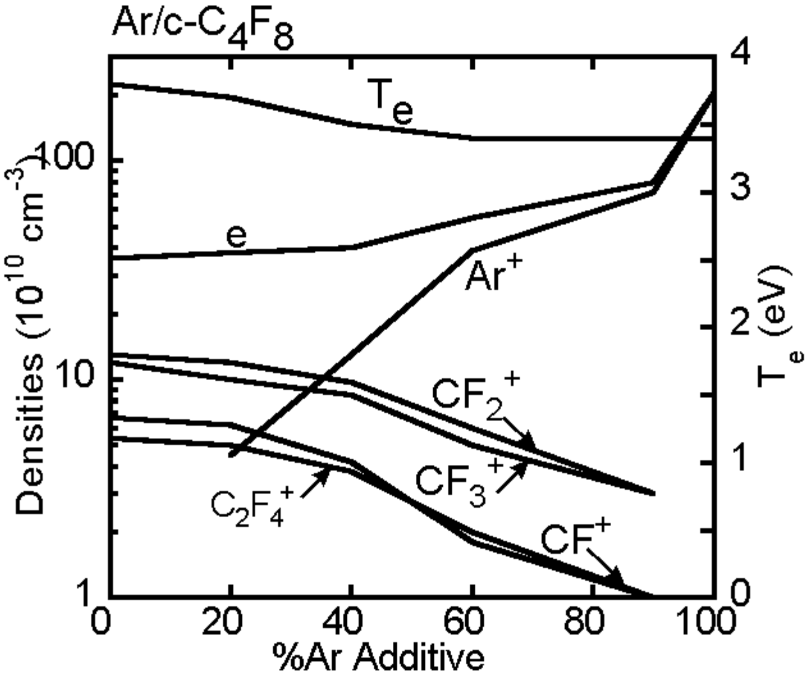
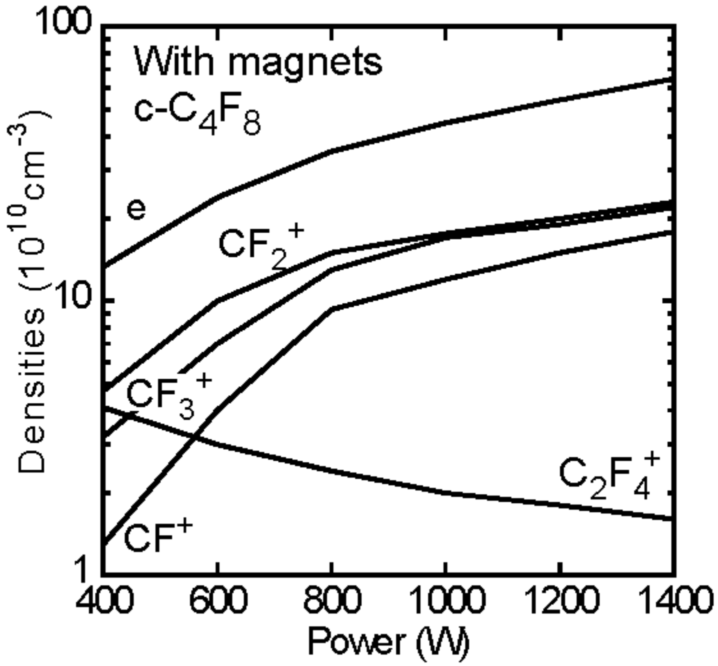
ION COMPOSITION IN C_4F_8, Ar/C_4F_8



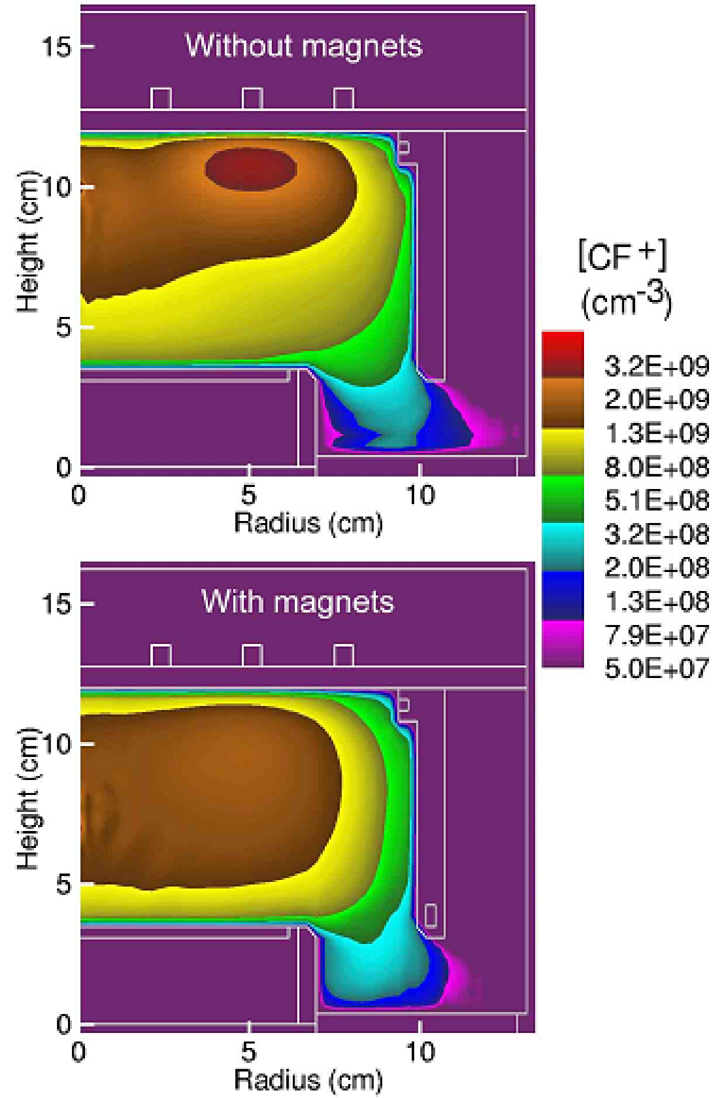


- **Optimization of processing conditions on, for example, power critically depends on the composition of the radical and ion fluxes.**

- **10 mTorr, 13.56 MHz**

EFFECT OF MAGNETS ON [CF^+]

- **Without magnets [CF^+] has a maximum at the edge of the classical skin depth where the electron impact ionization is the largest.**
- **The static magnetic fields broaden the production of [CF^+] in the radial direction.**



- **Ar/C_4F_8=20/80, 3 mTorr, 13.56 MHz, 400 W.**

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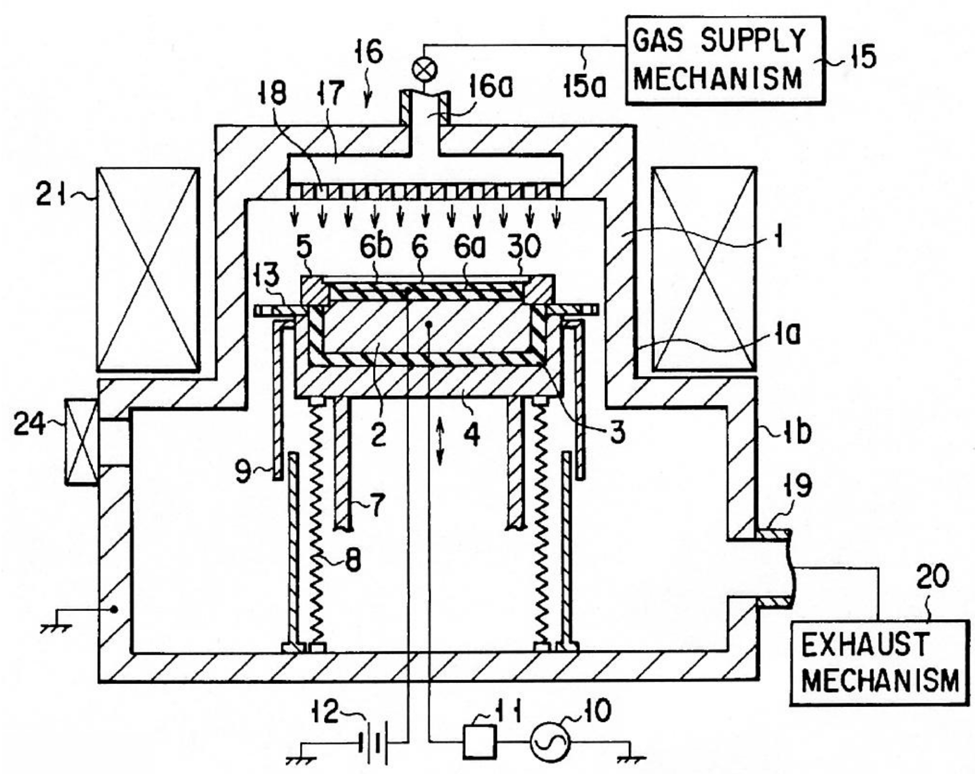
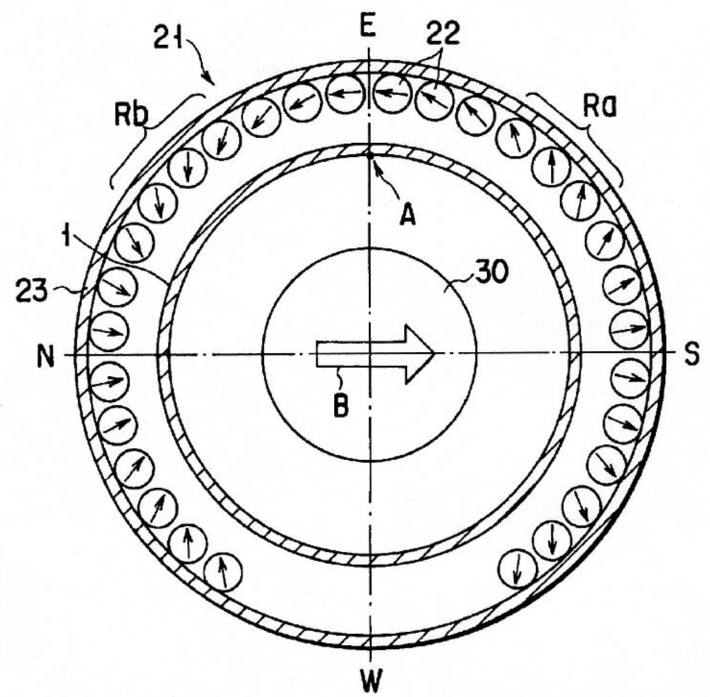
MERIE REACTOR

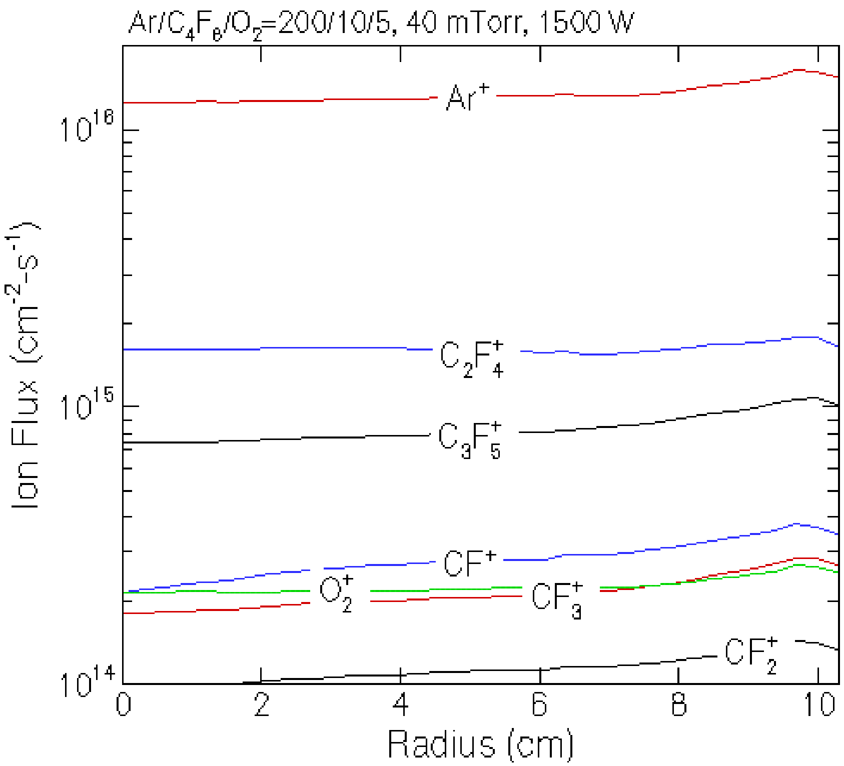
- **The model reactor is based on a TEL Design having a transverse magnetic field.**

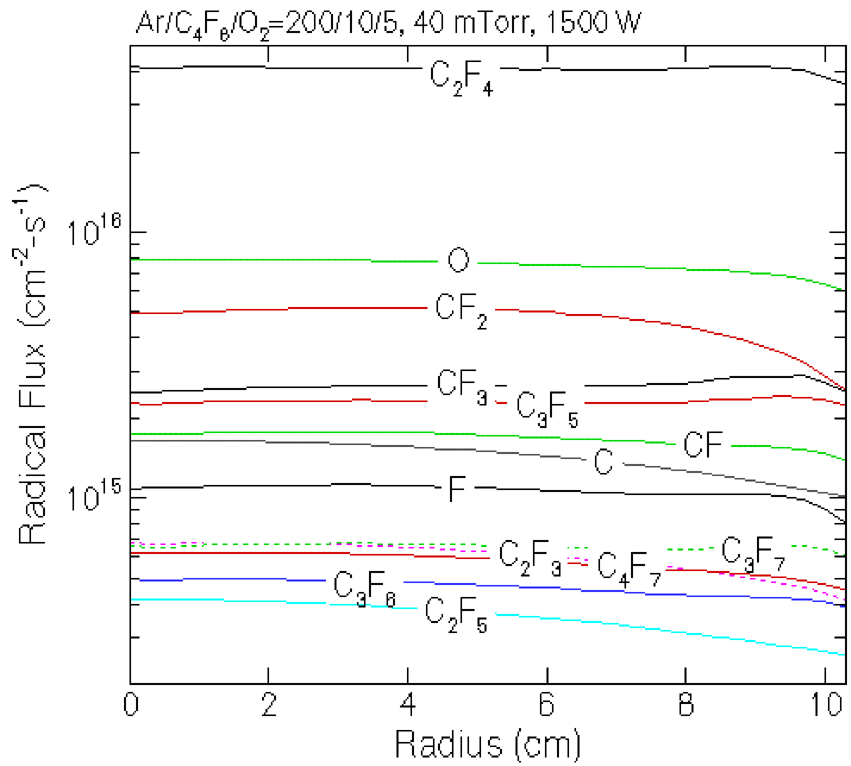




- **K. Kubota et al, US Patent 6,190,495 (2001)**

TEL-DRM: Ar / C_4F_8 / O_2





- **With reaction mechanisms developed for Ar / C_4F_8 / O_2 and improved ability to model MERIE systems, parameterizations were performed for TEL-DRM like conditions.**
- **Ar / C_4F_8 / O_2 = 200/10/5 sccm, 40 mTorr, 1500 W.**

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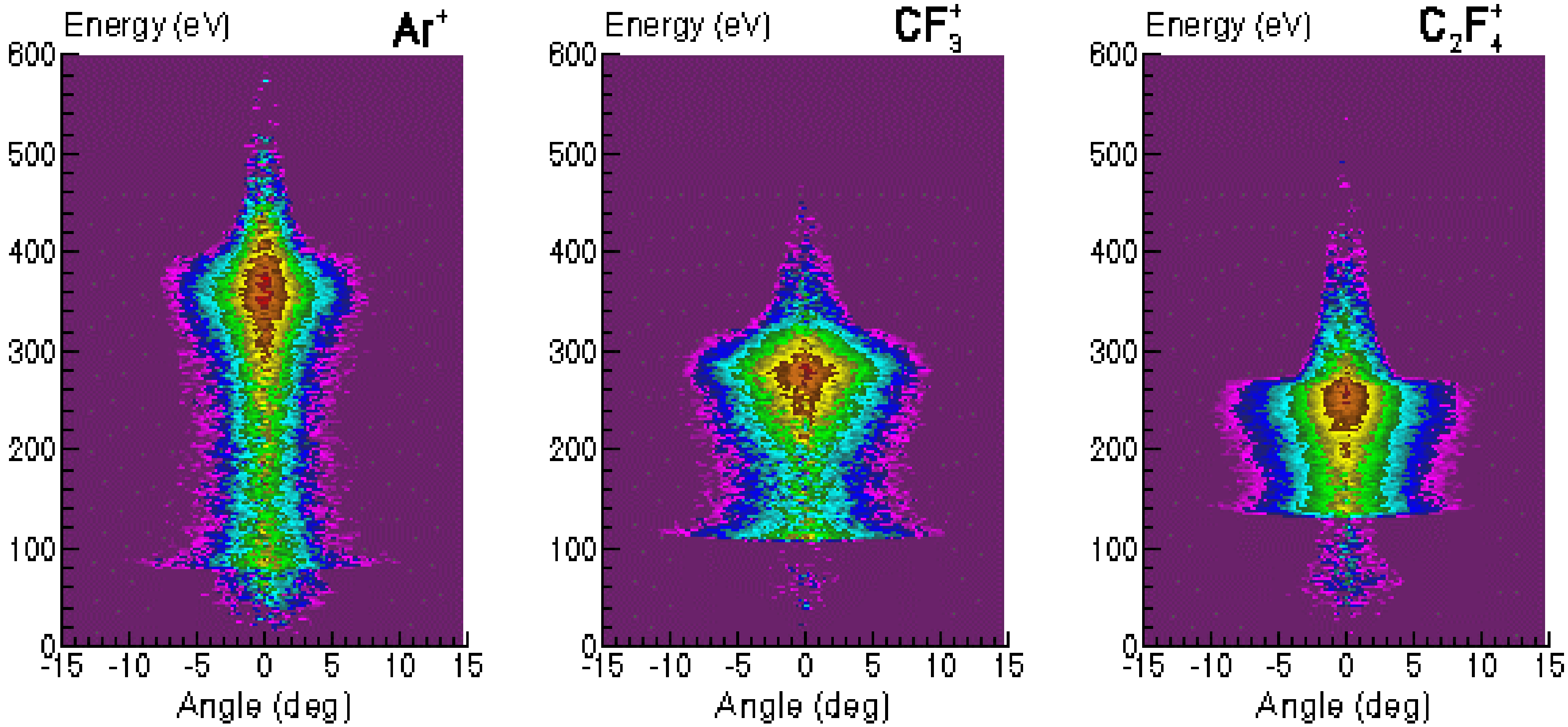
TEL-DRM: Ar / C_4F_8 / O_2



- **The large variety of ion masses produces vastly different IEADs.**
- **Ar / C_4F_8 / O_2 = 200/10/5 sccm, 40 mTorr, 1500 W.**

•*SURFACE CHEMISTRY*
(The most ill defined but perhaps most important step.)

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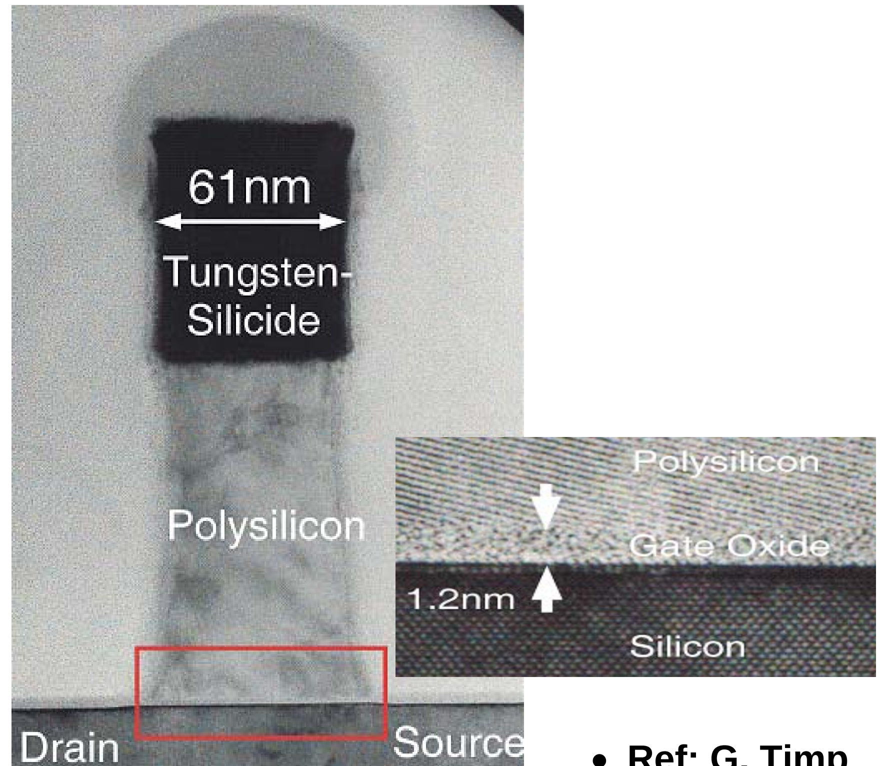
SELECTIVITY IN MICROELECTRONICS FABRICATION: PLASMAS AND POLYMERS

- Fabricating complex microelectronic structures made of different materials requires extreme *selectivity* in, for example, etching Si with respect to SiO_2.

- Monolayer selectivity is required in advanced etching processes.

- These goals are met by the unique plasma-polymer interactions enabled in fluorocarbon chemistries.



- Ref: G. Timp

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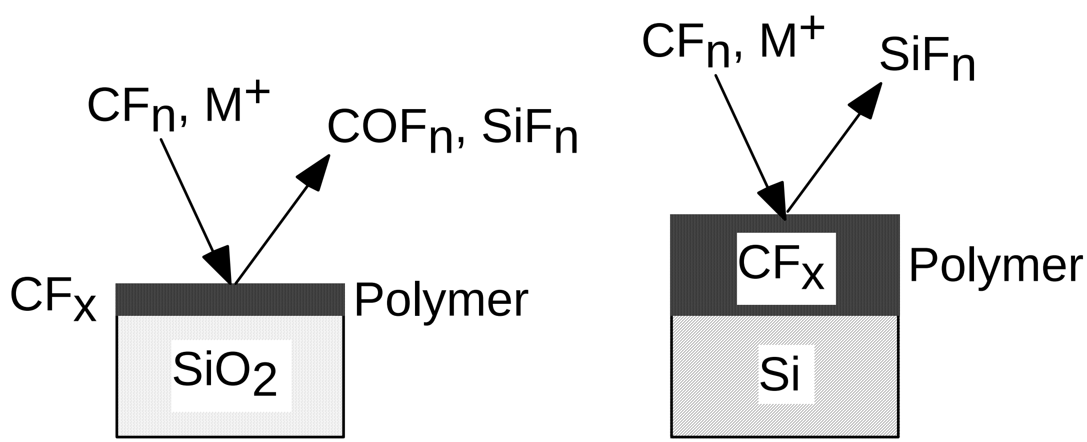
FLUORCARBON PLASMA ETCHING: SELECTIVITY

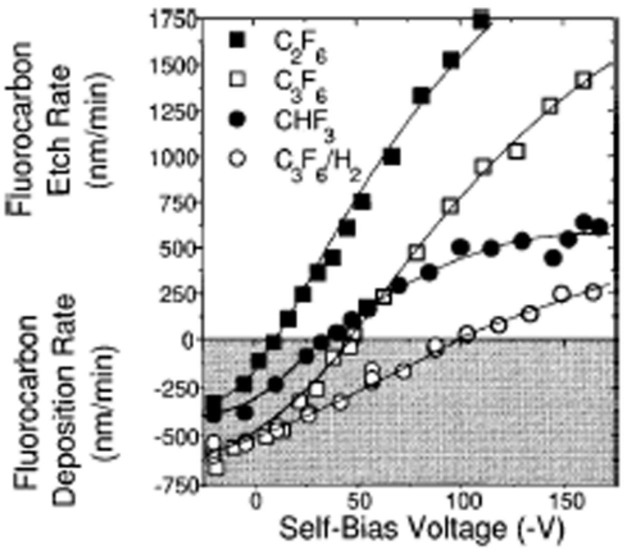
- **Selectivity in fluorocarbon etching relies on polymer deposition.**
- **Electron impact dissociation of feedstock fluorocarbons produce polymerizing radicals and ions, resulting in polymer deposition.**

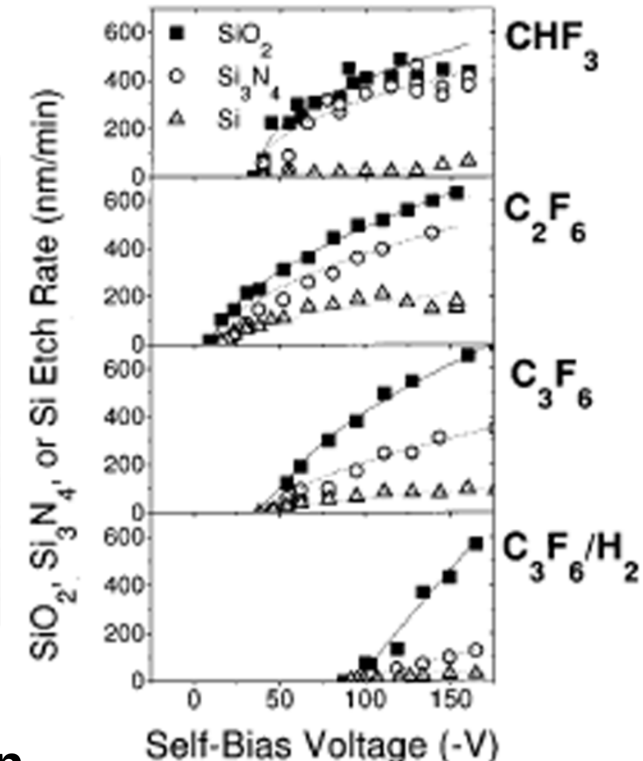
$$e + Ar/C_4F_8 \longrightarrow CF_n, M^+$$

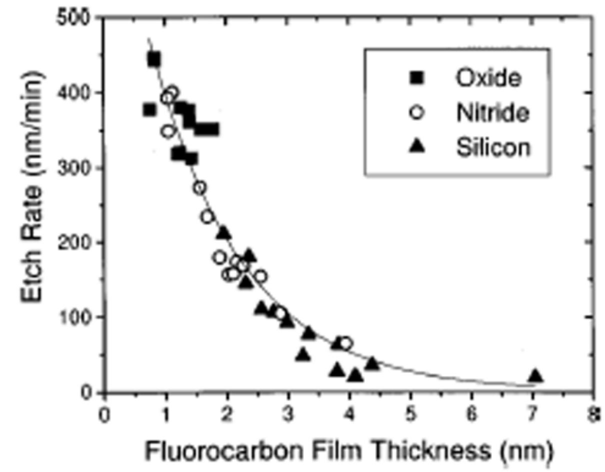


- **Compound dielectrics contain oxidants which consume the polymer, producing thinner polymer layers.**
- **Thicker polymer on non-dielectrics restrict delivery of ion energy (lower etching rates).**

FLUORCARBON PLASMA ETCHING: SELECTIVITY







- Low bias: Deposition
- High bias: etching
- Etch Rate (SiO_2 > Si)
- Polymer Thickness (SiO_2 < Si)

- G. Oerhlein, et al., JVSTA 17, 26 (1999)

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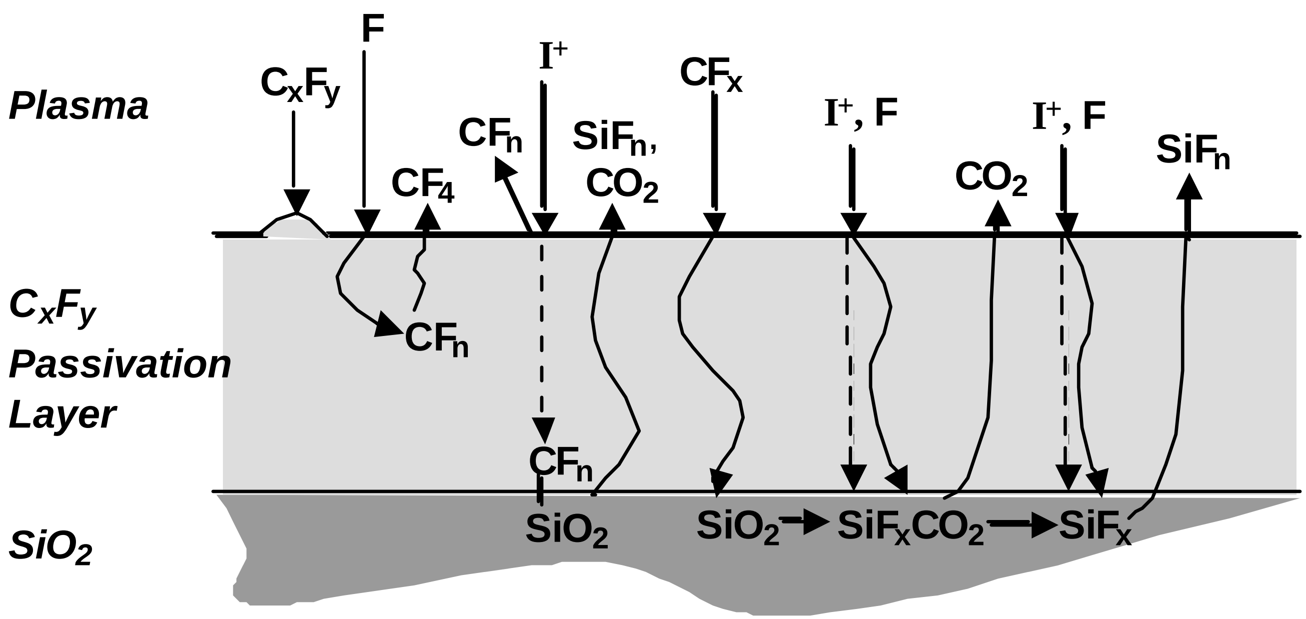
SURFACE KINETICS: FLUOROCARBON PLASMA ETCHING Si/SiO_2

- C_xF_y passivation regulates delivery of precursors and activation energy.
- Chemisorption of CF_x produces a complex at the oxide-polymer interface.
- 2-step ion activated (through polymer layer) etching of the complex consumes the polymer. Activation scales inversely with polymer thickness.
- Etch precursors and products diffuse through the polymer layer.



- In Si etching, CF_x is not consumed, resulting in thicker polymer layers.

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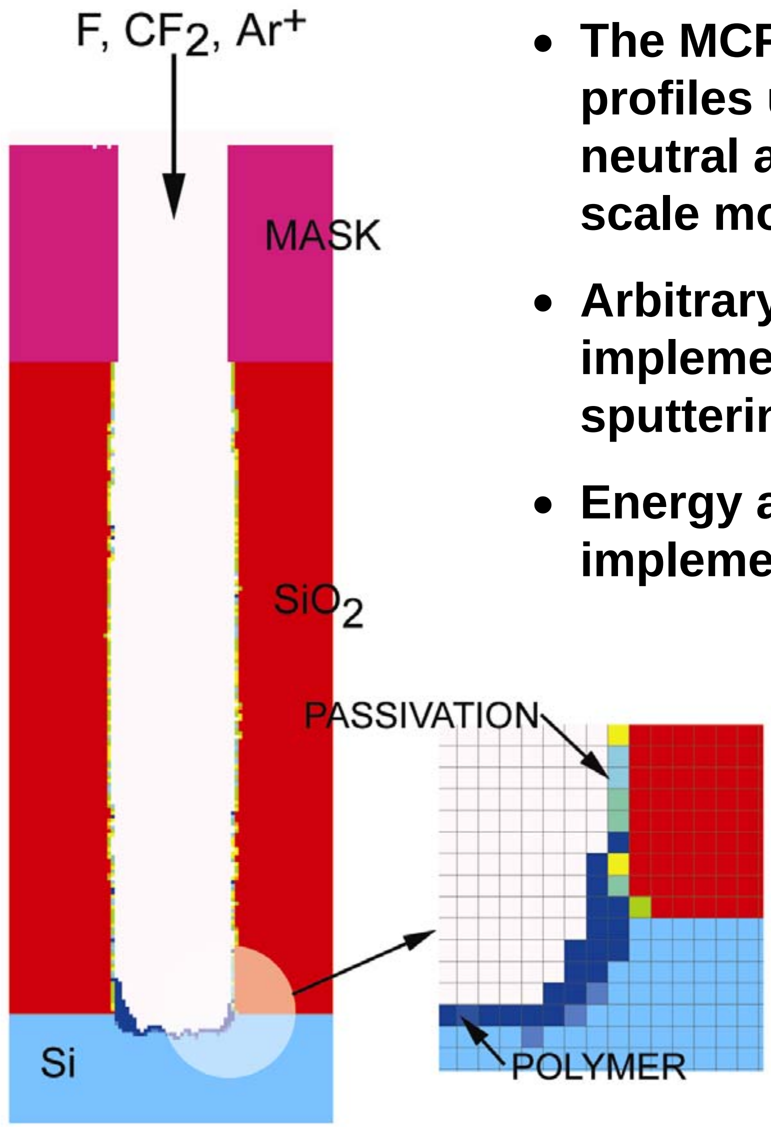
MONTE CARLO FEATURE PROFILE MODEL (MCFPM)



- The MCFPM predicts time and spatially dependent profiles using energy and angularly resolved neutral and ion fluxes obtained from equipment scale models.
- Arbitrary chemical reaction mechanisms may be implemented, including thermal and ion assisted, sputtering, deposition and surface diffusion.
- Energy and angular dependent processes are implemented using parametric forms.
- Mesh centered identify of materials allows “burial”, overlayers and transmission of energy through materials.

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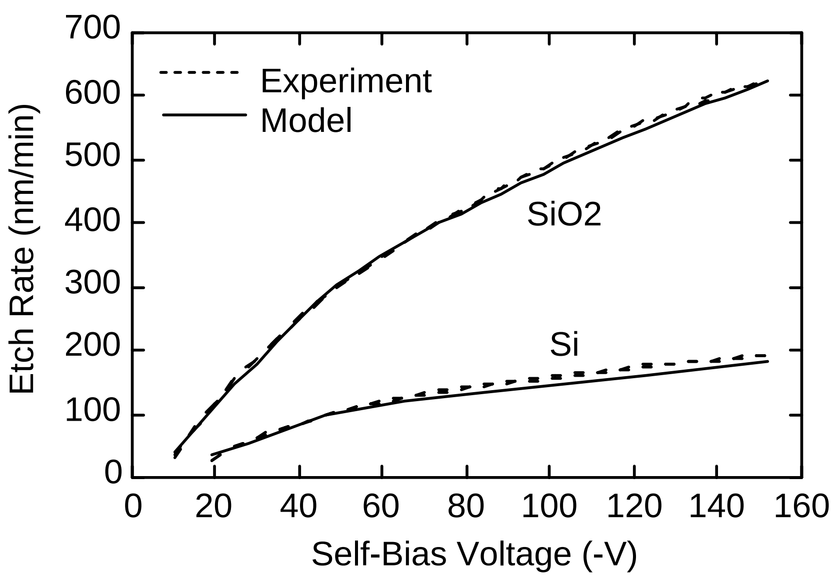
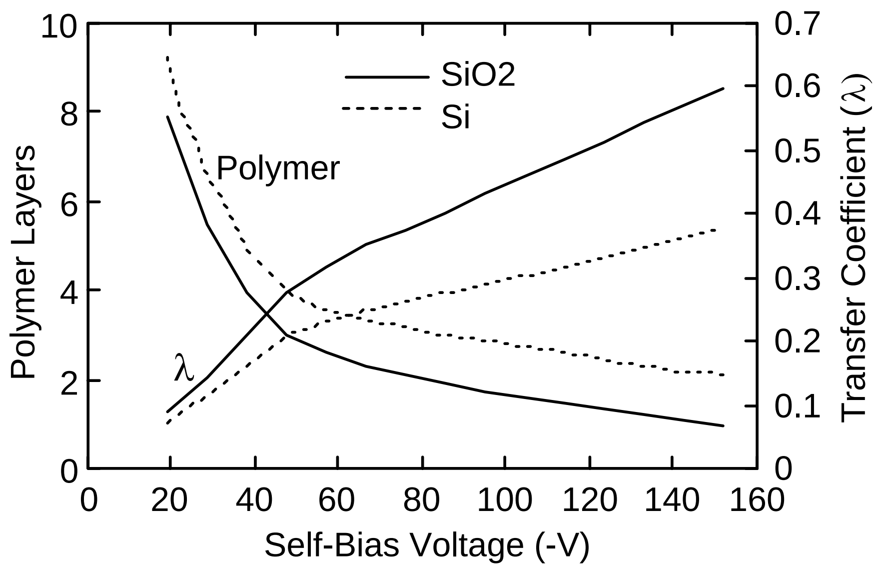
ETCH RATES AND POLYMER THICKNESS

- **Etch rates for Si and SiO_2 increase with increasing bias due, in part, to a decrease in polymer thickness.**
- **The polymer is thinner with SiO_2 due to its consumption during etching, allowing for more efficient energy transfer through the layer and more rapid etching.**





- **C_2F_6, 6 mTorr, 1400 W ICP, 40 sccm**
- **Exp. Ref: T. Standaert, et al.**
  J. Vac. Sci. Technol. A 16, 239 (1998).

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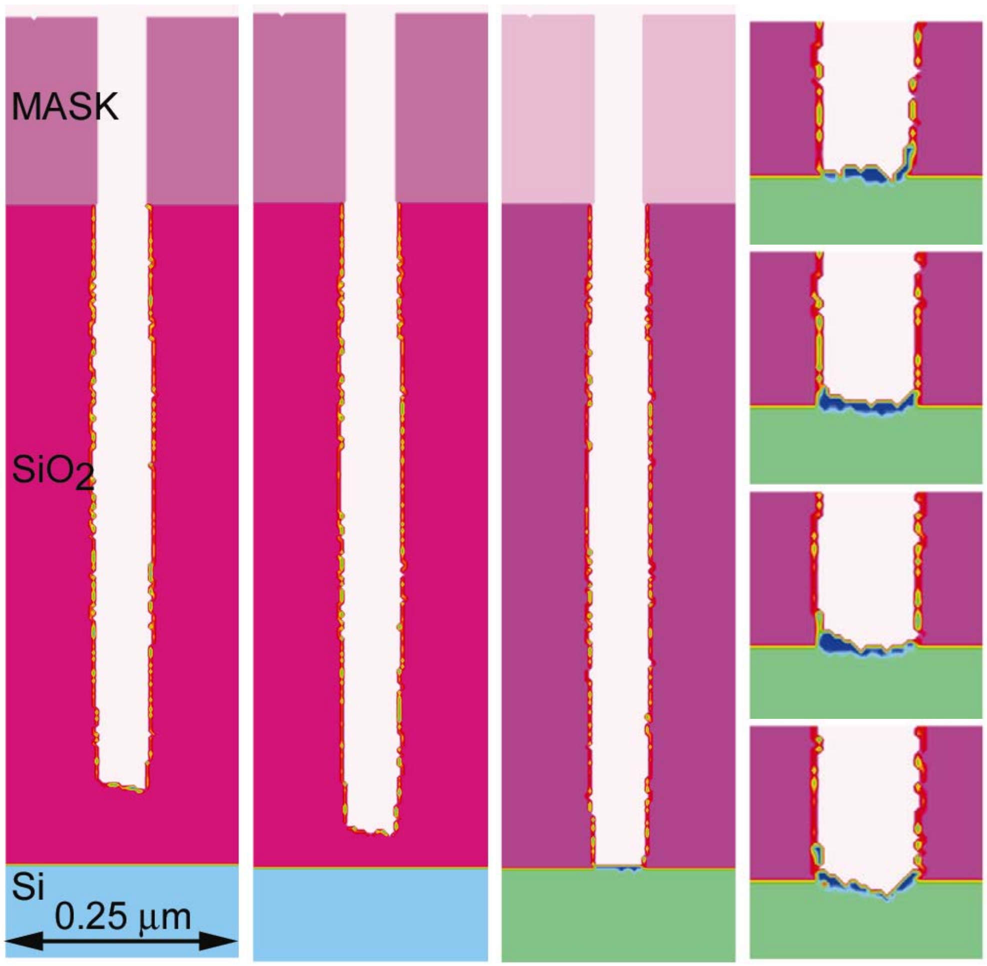
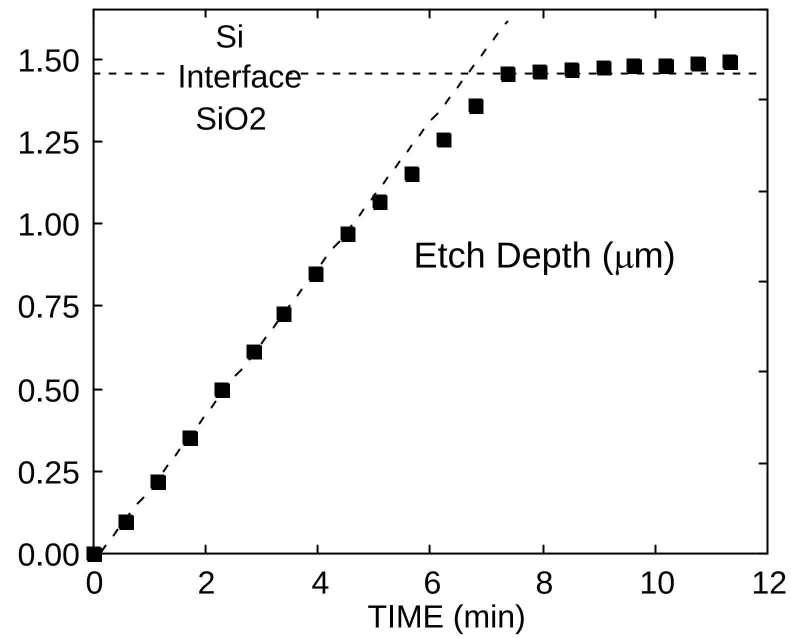
POLYMERIZATION AIDS SELECTIVITY

- Less consumption of polymer on Si relative to SiO_2 slows and, in some cases, terminates etching, providing high selectivity.





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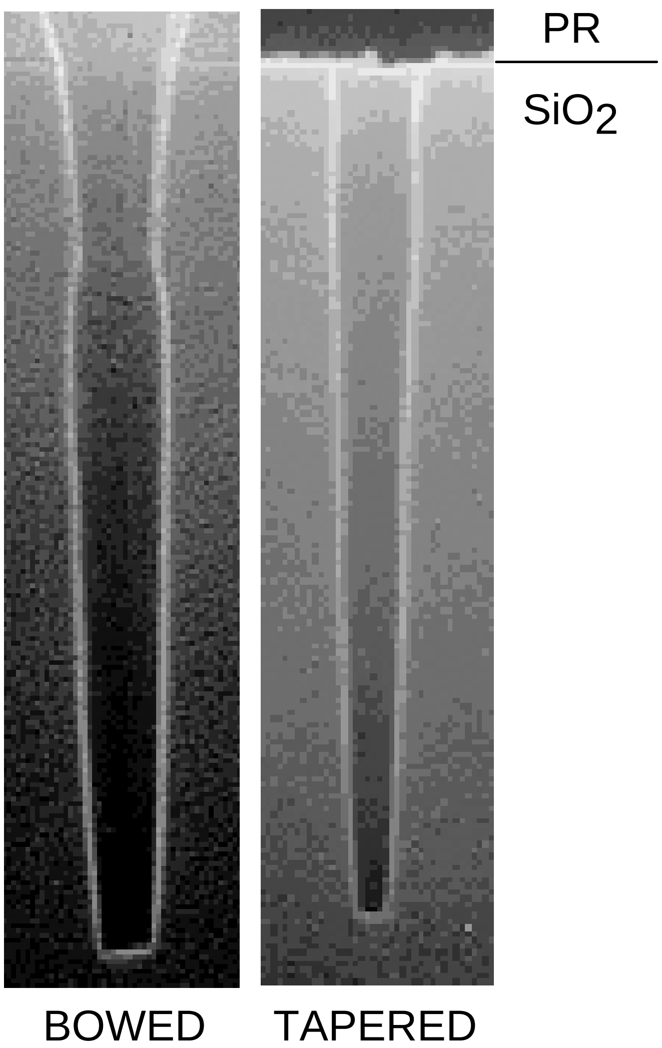
TAPERED AND BOWED PROFILES

- **In high aspect ratio (HAR) etching of SiO_2 the sidewall of trenches are passivated by neutrals (CF_x, $x \leq 2$) due to the broad angular distributions of neutral fluxes.**

- **Either tapered or bowed profiles can result from a non-optimum combination of processing parameters including:**

  - **Degree of passivation**
  - **Ion energy distribution**
  - **Radical/ion flux composition.**



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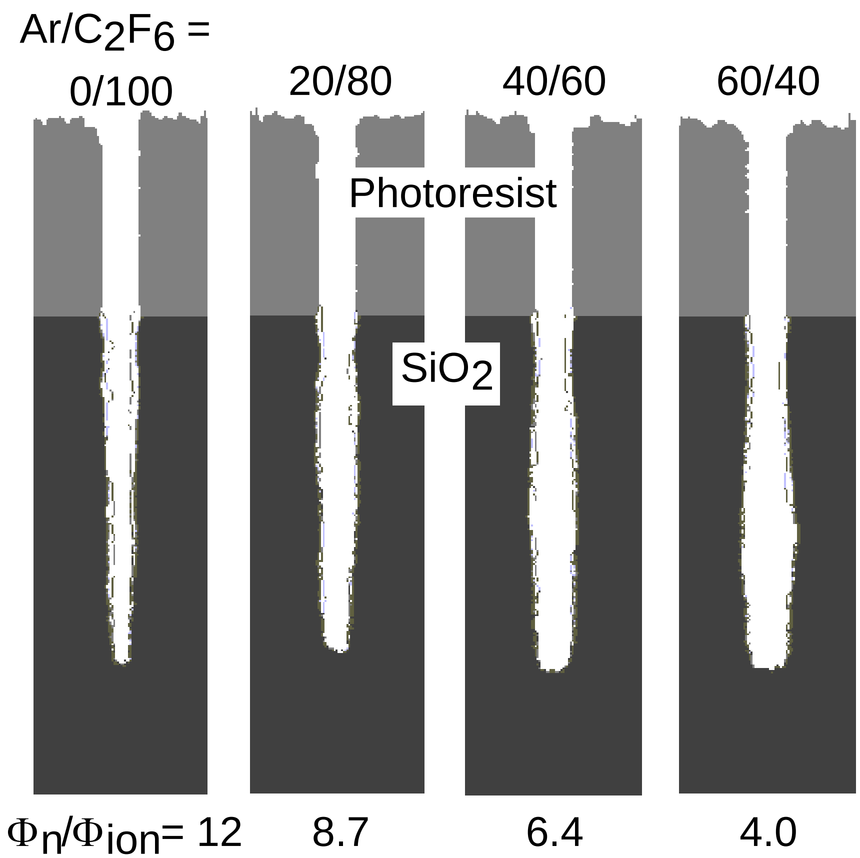
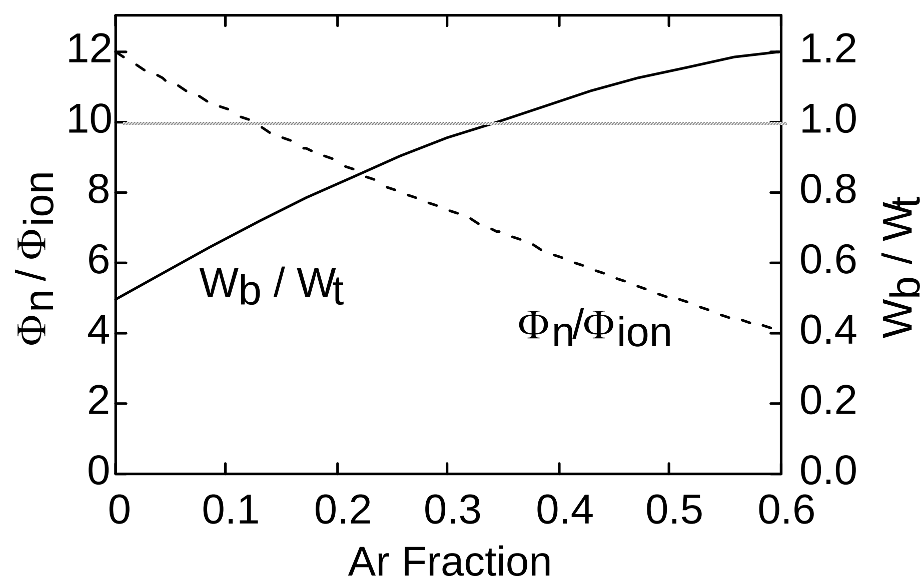
PROFILE TOPOLOGY: NEUTRAL TO ION FLUX RATIO

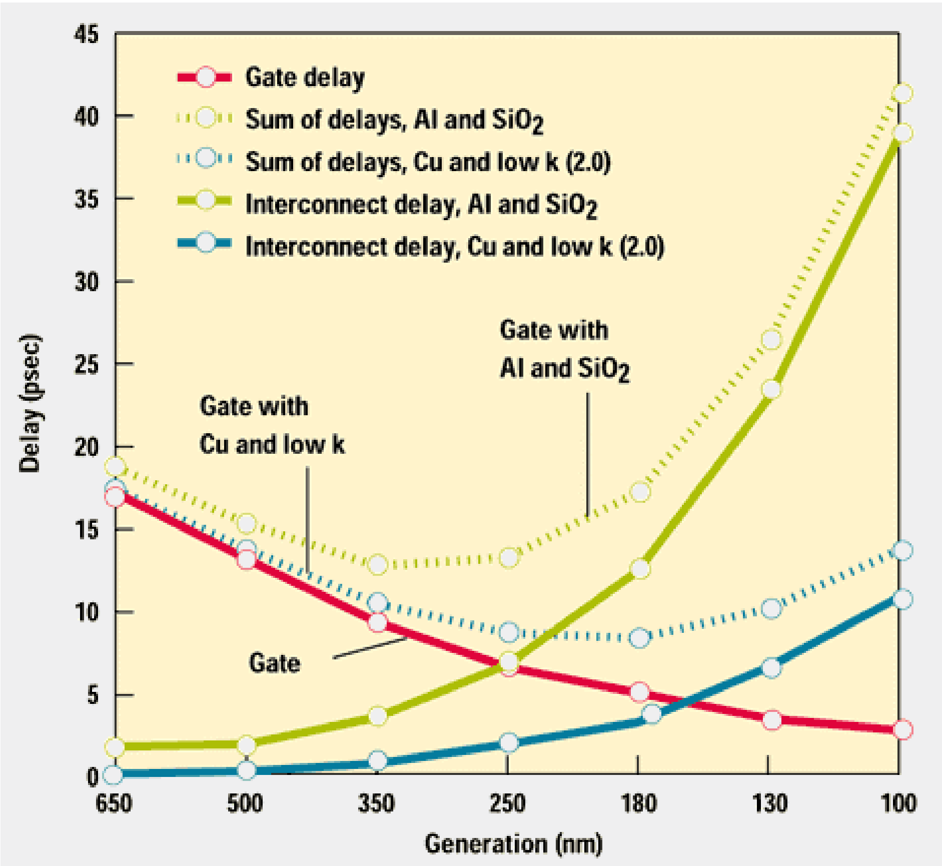
- **Profiles depend on ratio of polymer forming fluxes to energy activating fluxes. Small ratios produce bowing, large ratios tapering.**
- **Controlling this ratio through gas mixture (e.g., Ar/C_2F_6) enables specification of profile topology.**





LOW-K DIELECTRICS

- **As feature sizes decrease and device count increases, the diameter of interconnect wires shrinks and path length increases.**



- **Large RC-delay limits processor performance.**

- **To reduce RC-delay, low dielectric constant (low-k) materials are being investigated.**

- **L. Peters, *Semi. Intl.*, 9/1/1998**

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POROUS SILICON DIOXIDE

- Porous SiO_2 (xerogels) have low-k properties due to their lower mass density resulting from (vacuum) pores.

    - Typical porosities: 30-70%
    - Typical pore sizes: 2-20 nm

- Porous SiO_2 (P-SiO_2) is, from a process development viewpoint, an ideal low-k dielectric.

    - Extensive knowledge base for fluorocarbon etching of conventional non-porous (NP-SiO_2).

    - No new materials (though most P-SiO_2 contains some residual organics)

    - Few new integration requirements

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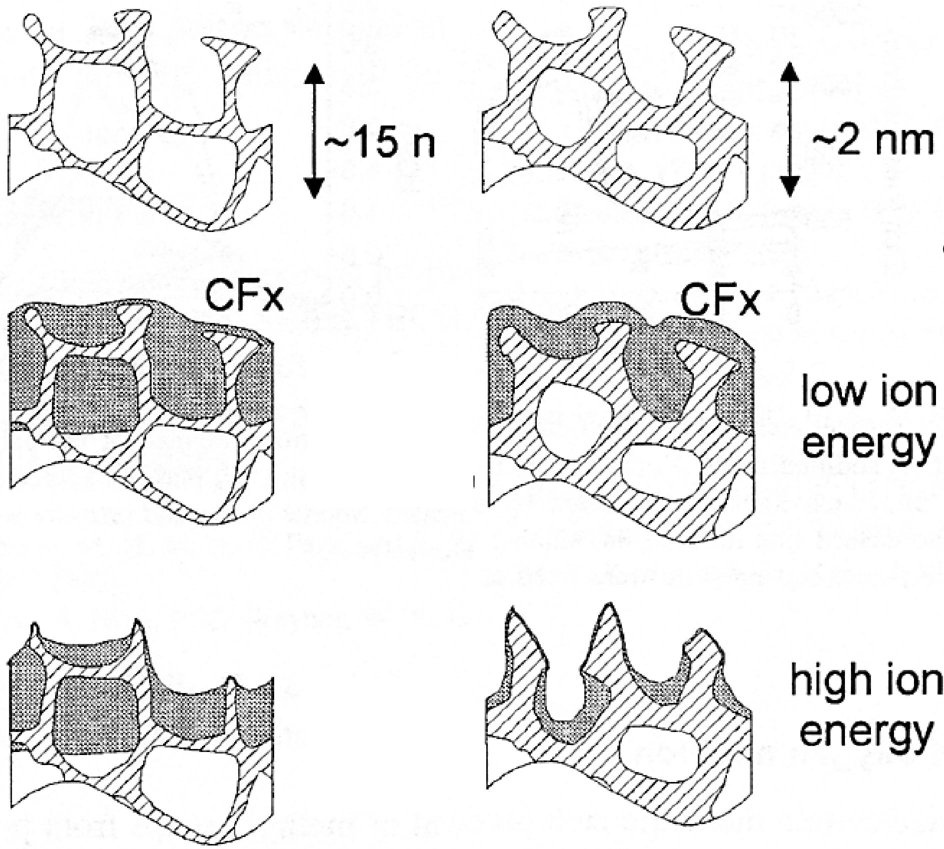
WHAT CHANGES WITH POROUS SiO_2?

- The "opening" of pores during etching of P-SiO_2 results in the filling of the voids with polymer, creating thicker layers.
- Ions which would have otherwise hit at grazing or normal angle now intersect with more optimum angle.



- An important parameter is L/a (polymer thickness / pore radius).

- Adapted: Standaert, JVSTA 18, 2742 (2000)

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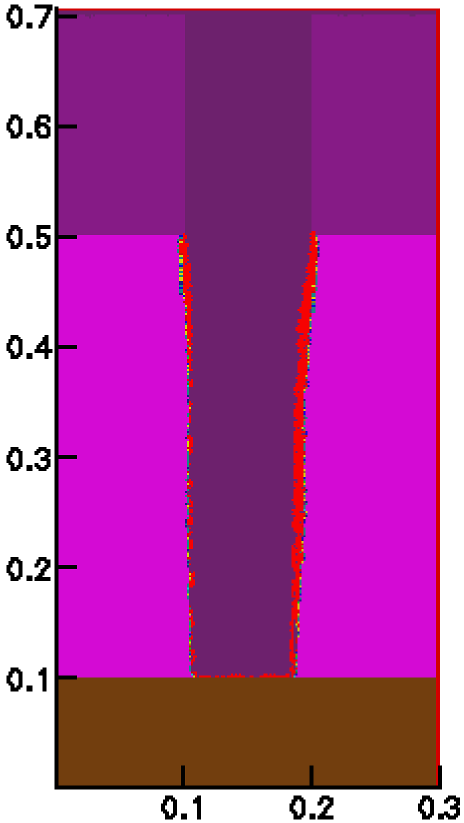
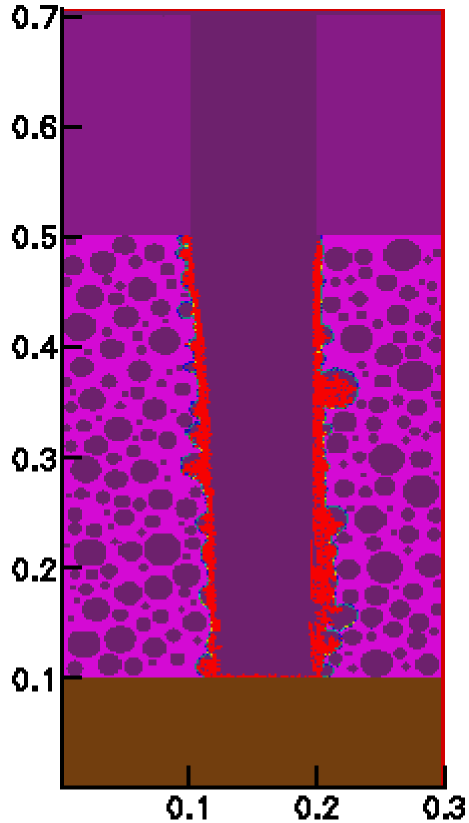
ETCH PROFILES IN SOLID AND POROUS SiO_2



- Position (μm)

- Solid



- Position (μm)

- Porosity = 45 %
  Pore radius = 10 nm

- Porous SiO_2 is being investigated for low-permittivity dielectrics for interconnect wiring.

- In polymerizing environments with heavy sidewall passivation, etch profiles differ little between solid and porous silica.

- The “open” sidewall pores quickly fill with polymer.

ANIMATION SLIDE

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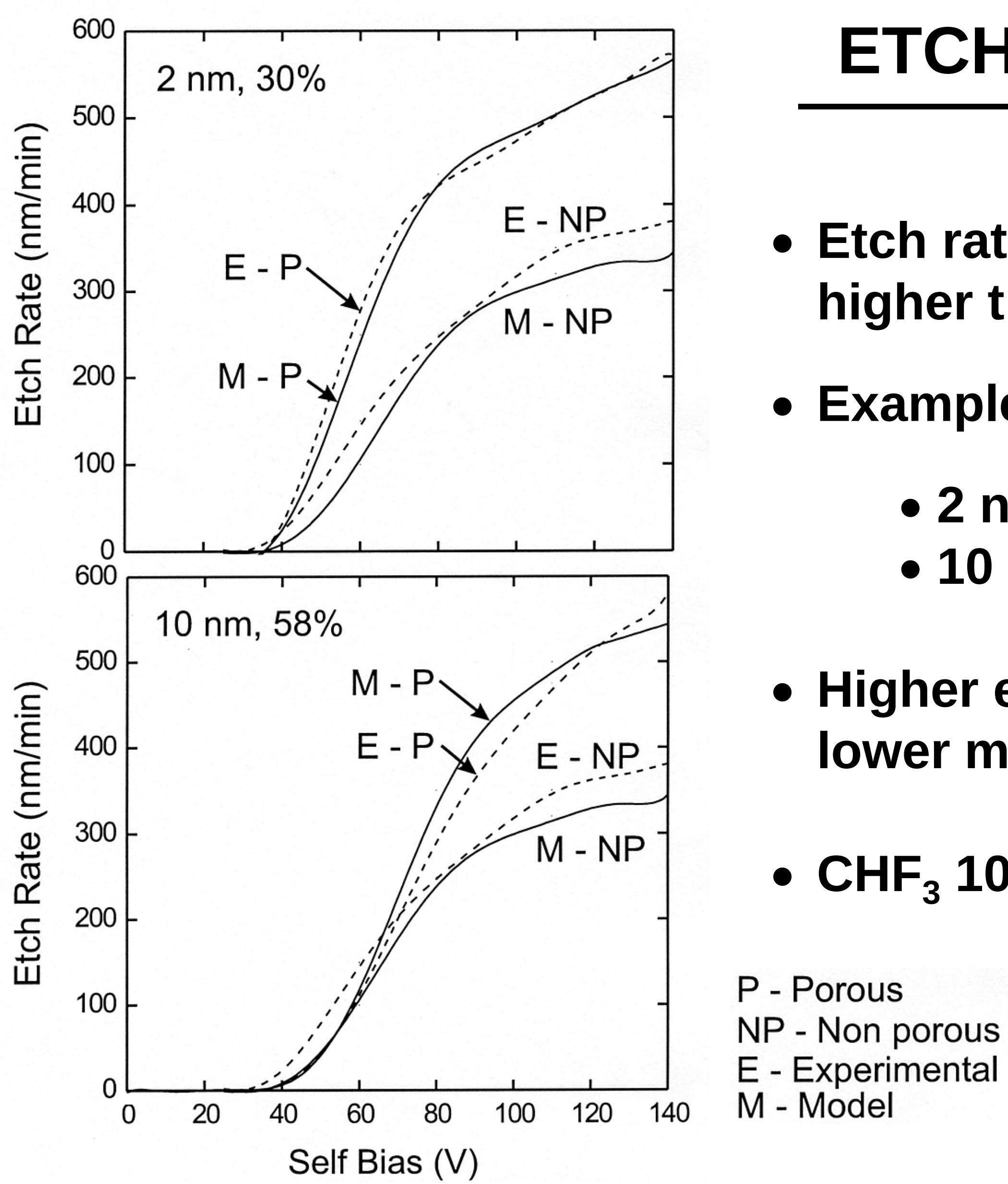
ETCHING OF POROUS SiO_2



- **Etch rates of P-SiO_2 are generally higher than for non-porous (NP).**
- **Examples:**
  - **2 nm pore, 30% porosity**
  - **10 nm pore, 58% porosity**
- **Higher etch rates are attributed to lower mass density of P-SiO_2.**
- **CHF_3 10 mTorr, 1400 W**

Exp: Oehrlein et al. Vac. Sci.Technol. A **18**, 2742 (2000)

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PORE-DEPENDENT ETCHING

- **To isolate the effect of pores on etch rate, corrected etch rate is defined as**

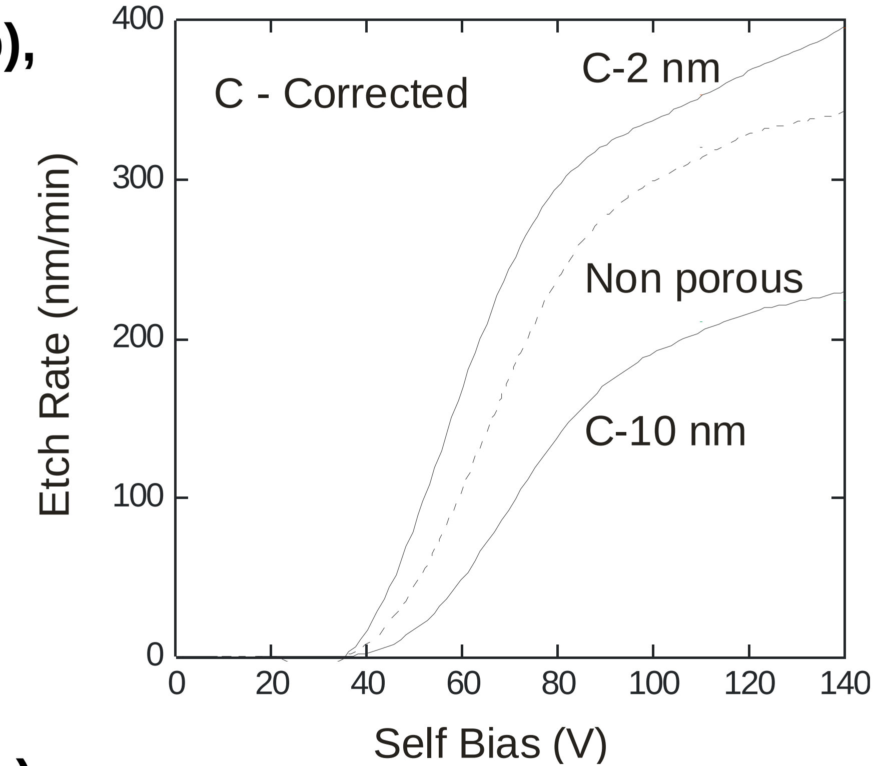
$$\textbf{Etch Rate (ER)}_{\text{corrected}} = \textbf{ER}_{\text{regular}} \times (1 - p),$$

$$p = \text{porosity}$$

- **If etching depended only on mass density, corrected etch rates would equal that of NP- SiO_2.**

- **2 nm pores L/a $\geq$1 : C-ER > ER(SiO_2). Favorable yields due to non-normal incidence may increase rate.**

- **10 nm pores L/a $\leq$ 1 : C-ER < ER(SiO_2). Filling of pores with polymer decrease rates.**



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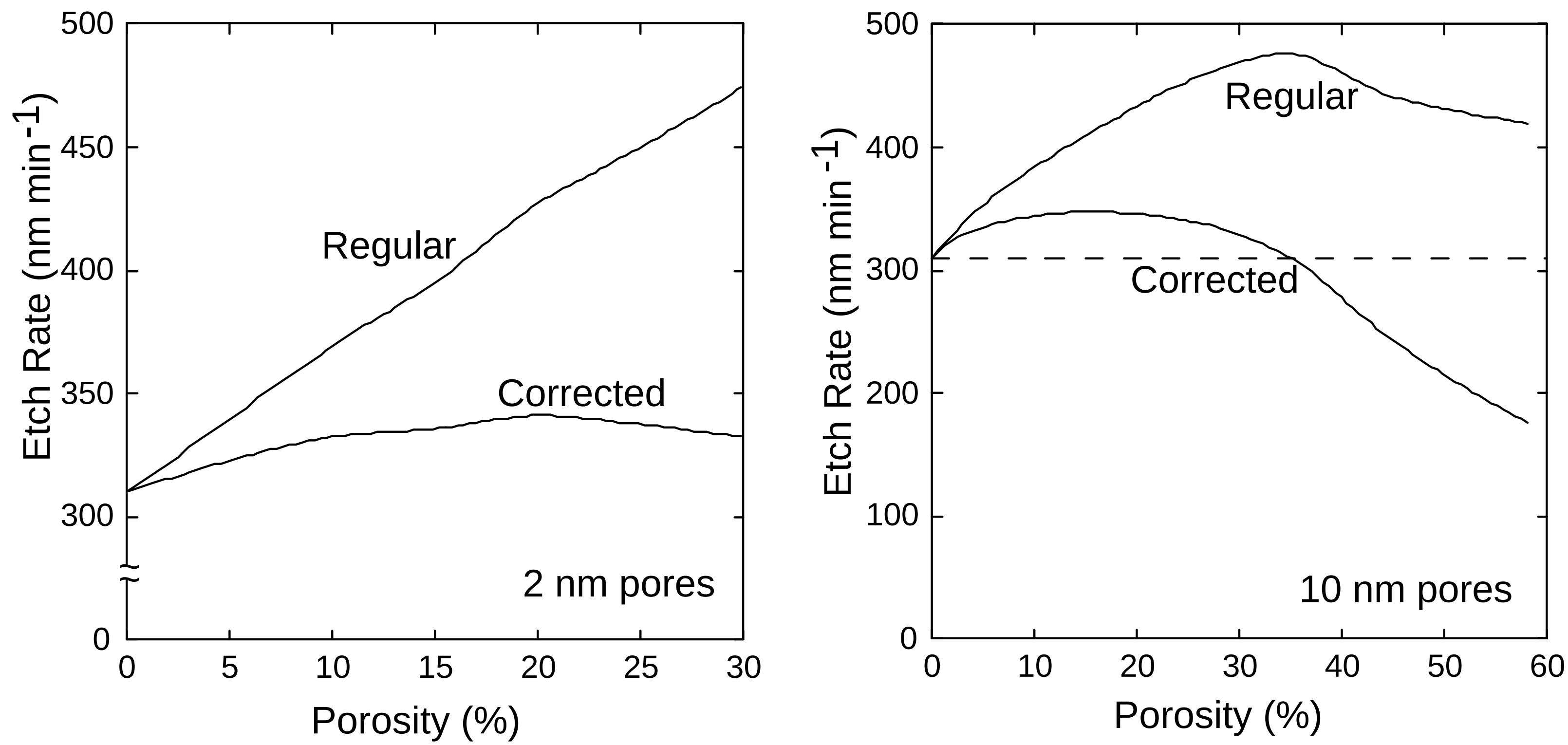
EFFECT OF POROSITY ON BLANKET ETCH RATES



- **2 nm pores: Etch rate increases with porosity.**
- **10 nm pores: Polymer filling of pores reduces etch rate at large porosities.**

OXYGEN PLASMA CLEANING OF POLYMER

- After etching, the polymer must be removed from the feature.

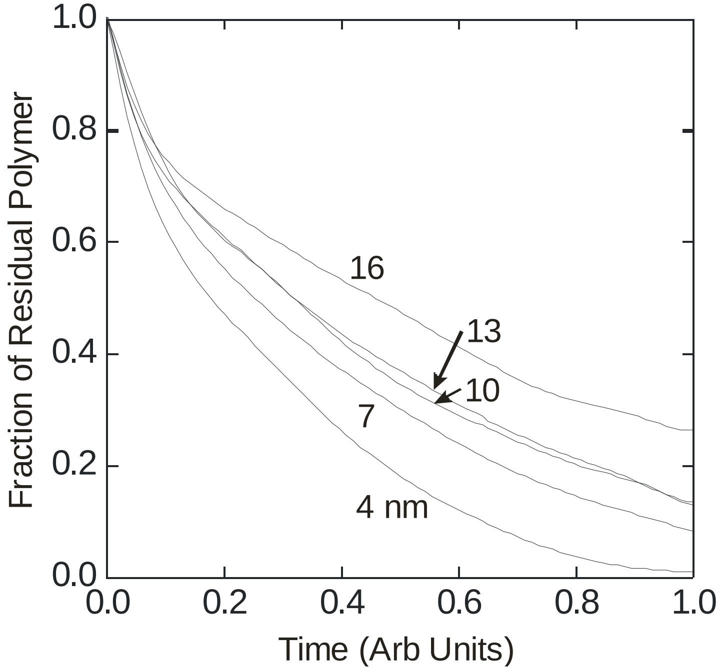
- O_2 plasmas are typically used for polymer stripping, usually during photoresist mask removal.

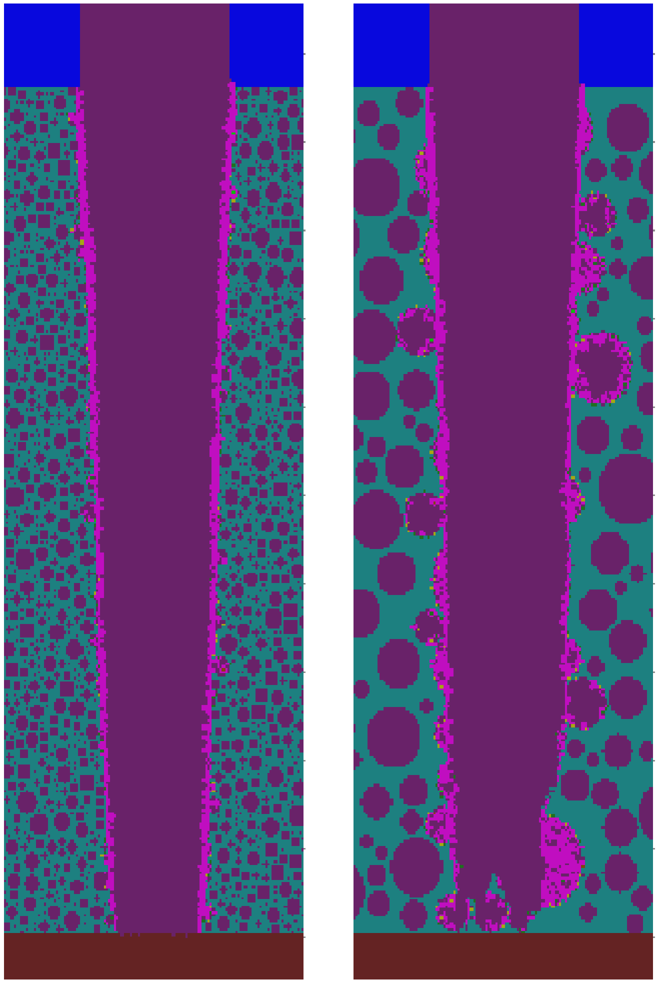
- Unlike hydrocarbon polymers which spontaneously react with O, fluorocarbon polymers require ion activation for etching.

    - Polymer + Energetic Ion $\rightarrow$ Activated Polymer Site (P*)
    - P* + O $\rightarrow$ Volatile Products

- Removal of polymer from porous materials is difficult due to shadowing of ion fluxes caused by the pore morphology.

EFFECT OF PORE RADIUS ON CLEANING





4 nm 16 nm

- **Larger pores are more difficult to clean due small view angle of ion fluxes.**
- **Lower fluxes of less energetic ions reduce activation and lengthen cleaning time.**

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•*TOWARDS INTEGRATED PROCESS MODELING*
(The last step…metal deposition.)

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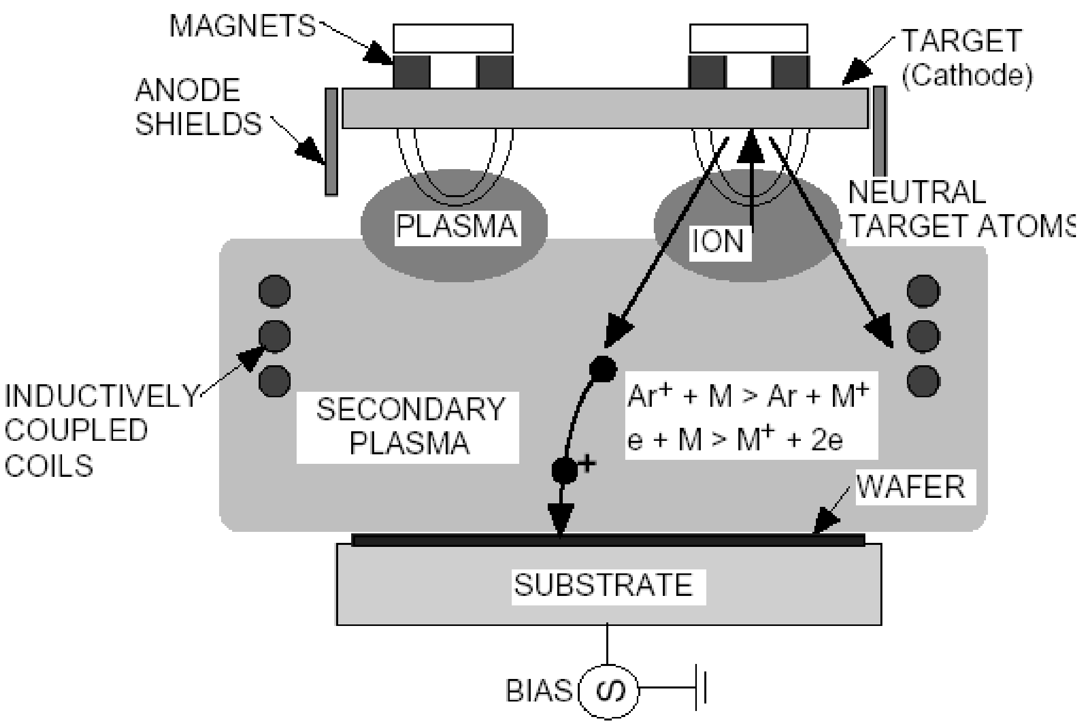
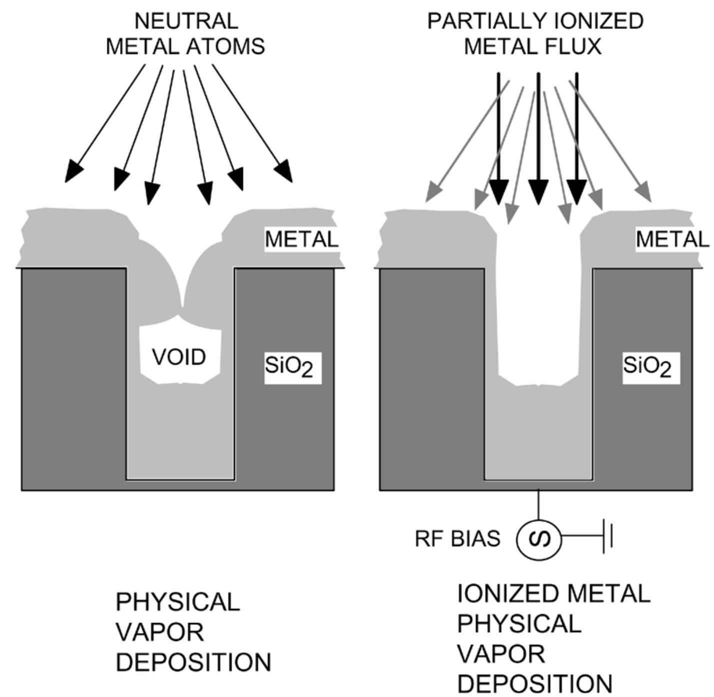
IONIZED METAL PHYSICAL VAPOR DEPOSITION (IMVPD)

- **IMPVD is a technique to deposit seed layers and barrier coatings, and fill trenches.**
- **A flux of both neutral and metal atoms more uniformly produce depositions without formation of voids.**





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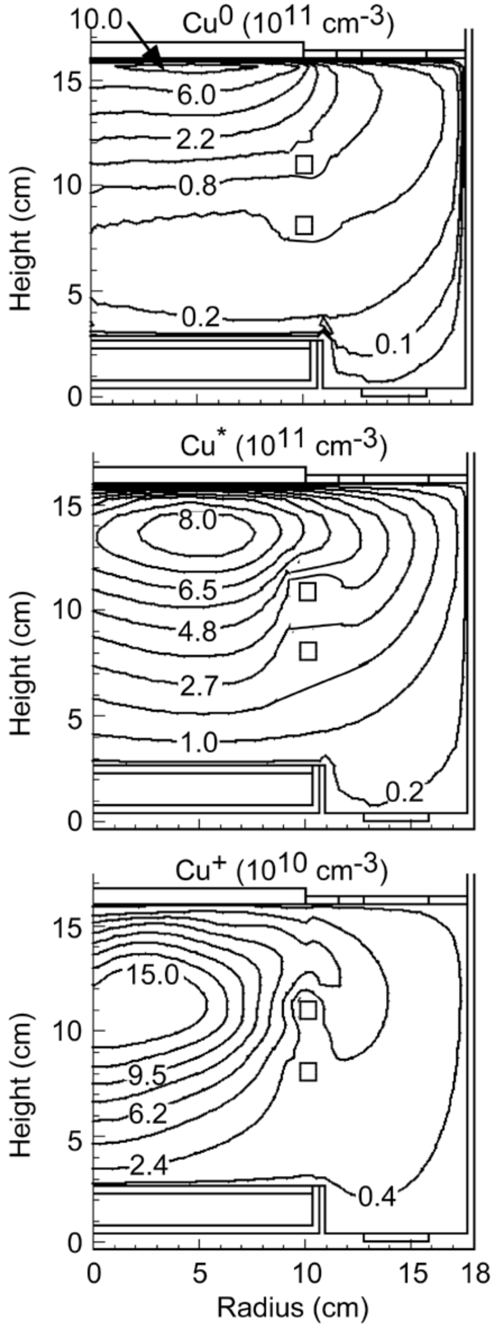
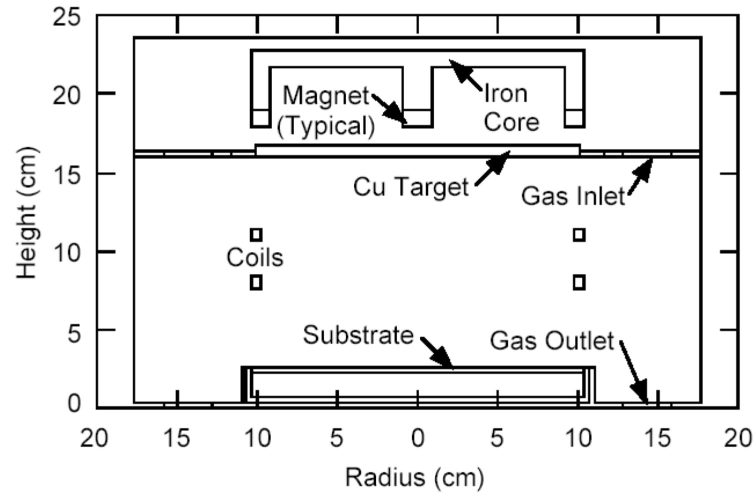
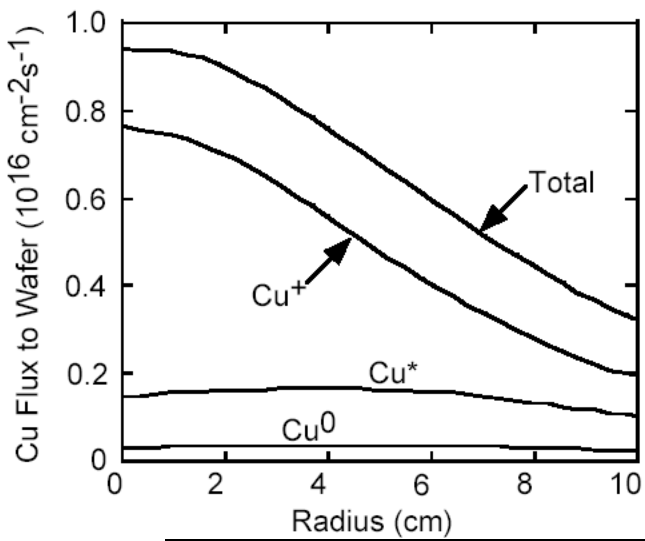
Cu IMVPD: REACTOR SCALE MODELING







- 40 mTorr Ar
- 1 kW ICP
- 0.3 kW Magnetron
- -25 V bias

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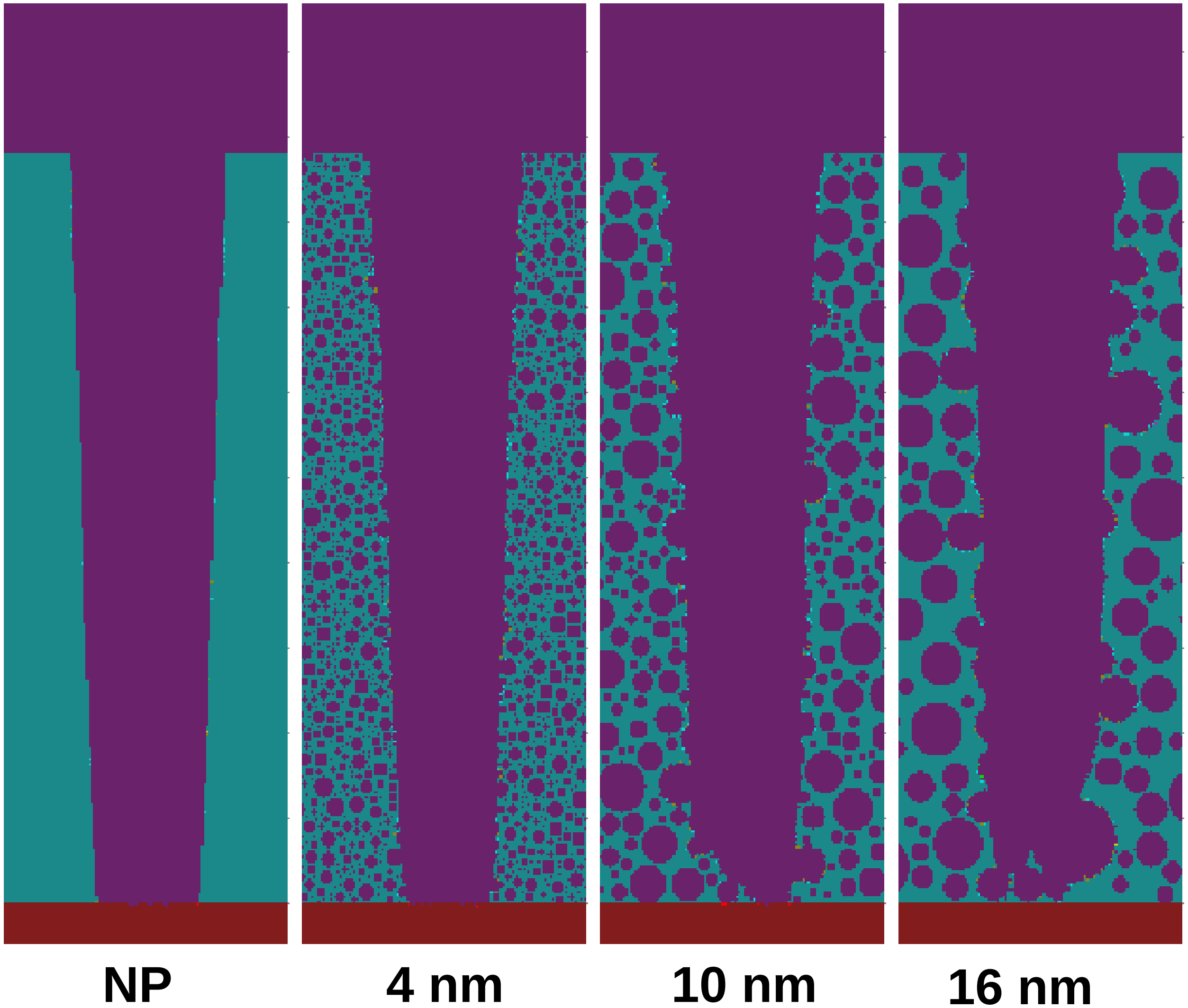
EFFECT OF PORE RADIUS ON Cu DEPOSITION



- Surrogate study for seed layer deposition and barrier coating.
- Voids are created at the pore surface or initiated due to the presence of pores.
- Presence of voids are pronounced for bigger pores.

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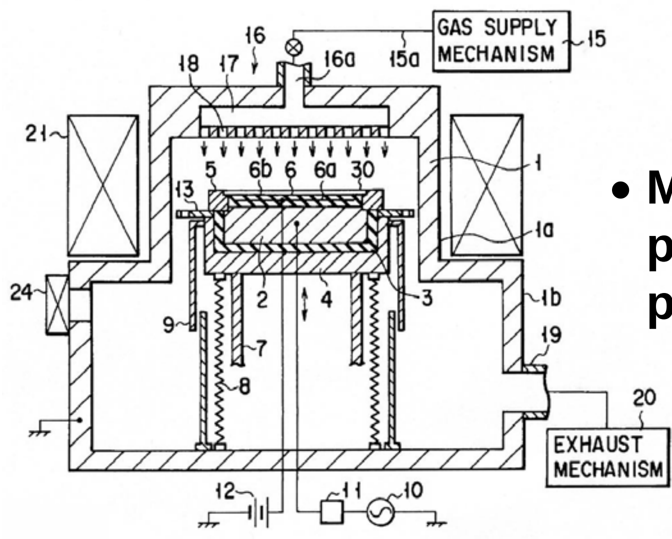
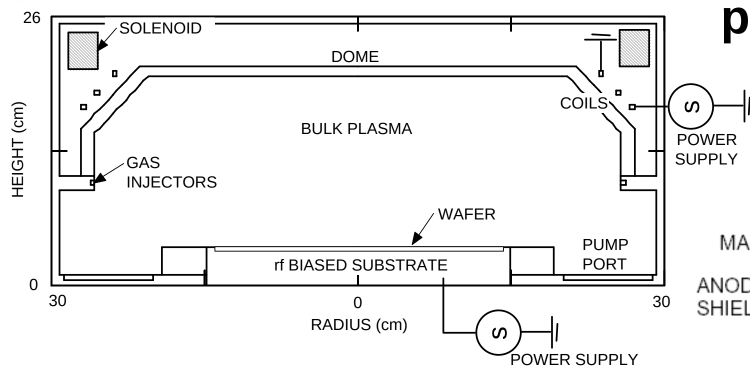
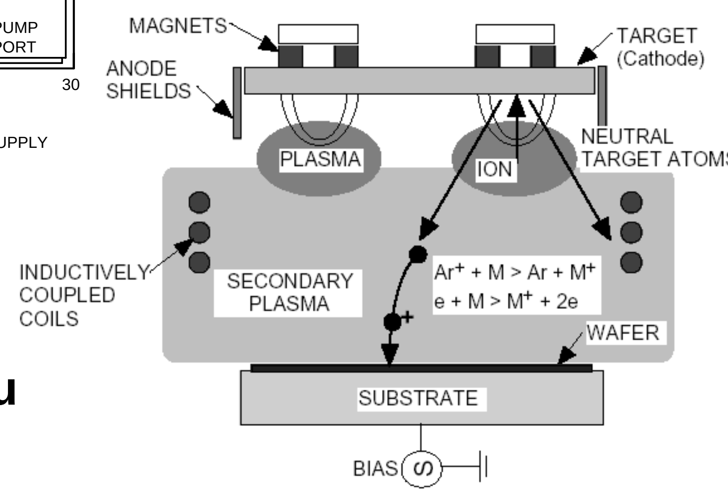


- **MERIE Fluorocarbon plasma etching of porous SiO_2**

- **ICP O_2 plasma cleaning of PR and polymer.**



- **IMPVD of Cu seed layer**



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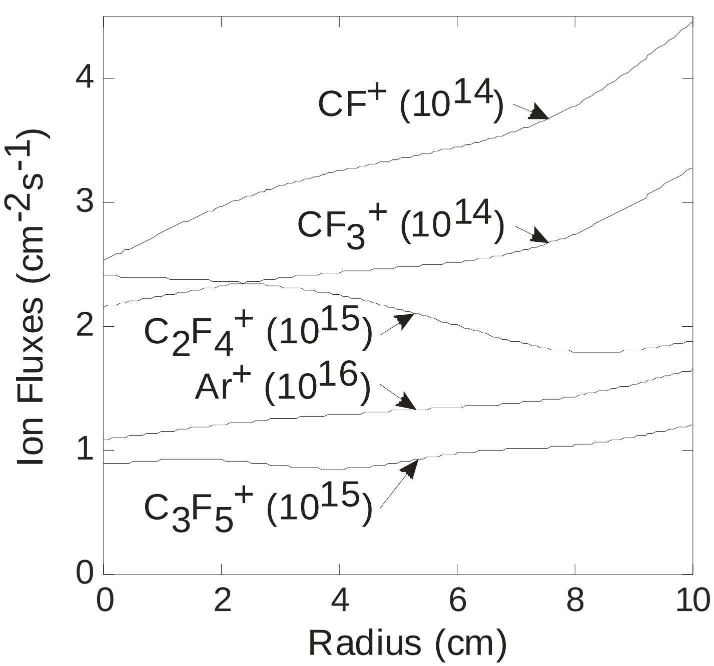
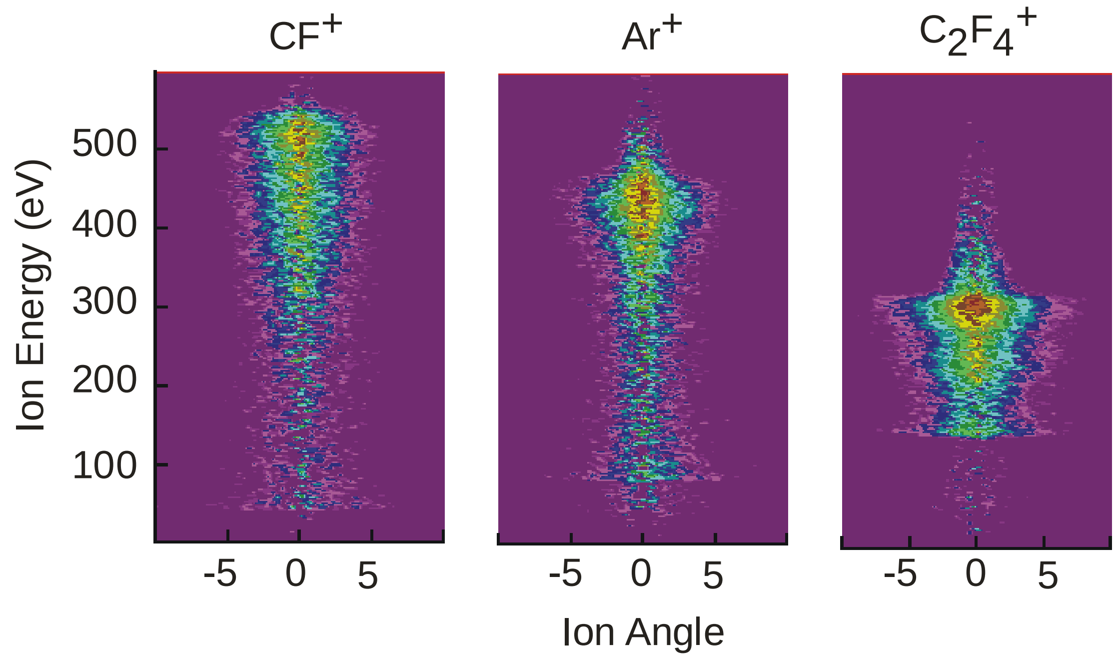
MERIE: ION FLUXES AND ENERGIES





- $Ar/O_2/\ C_4F_8$ = 200/5/10 sccm
- 2000 W
- 40 mTorr

- Due to high dilution and low fractional dissociation, dominant ions are Ar^+, $C_2F_4^+$

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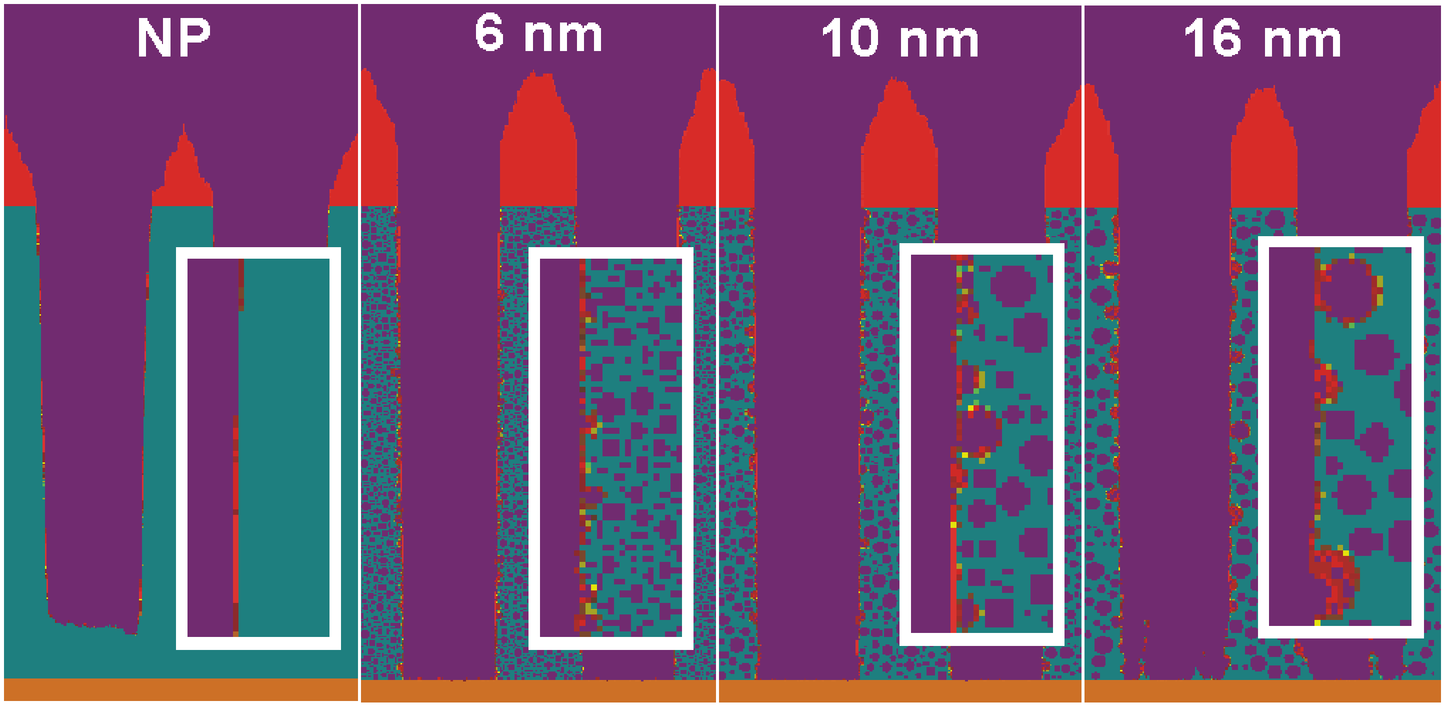
MERIE: POROUS SiO_2 ETCH



- More rapid etching with porous SiO_2 results in less mask erosion and better profile control, but more polymer filling of pores.

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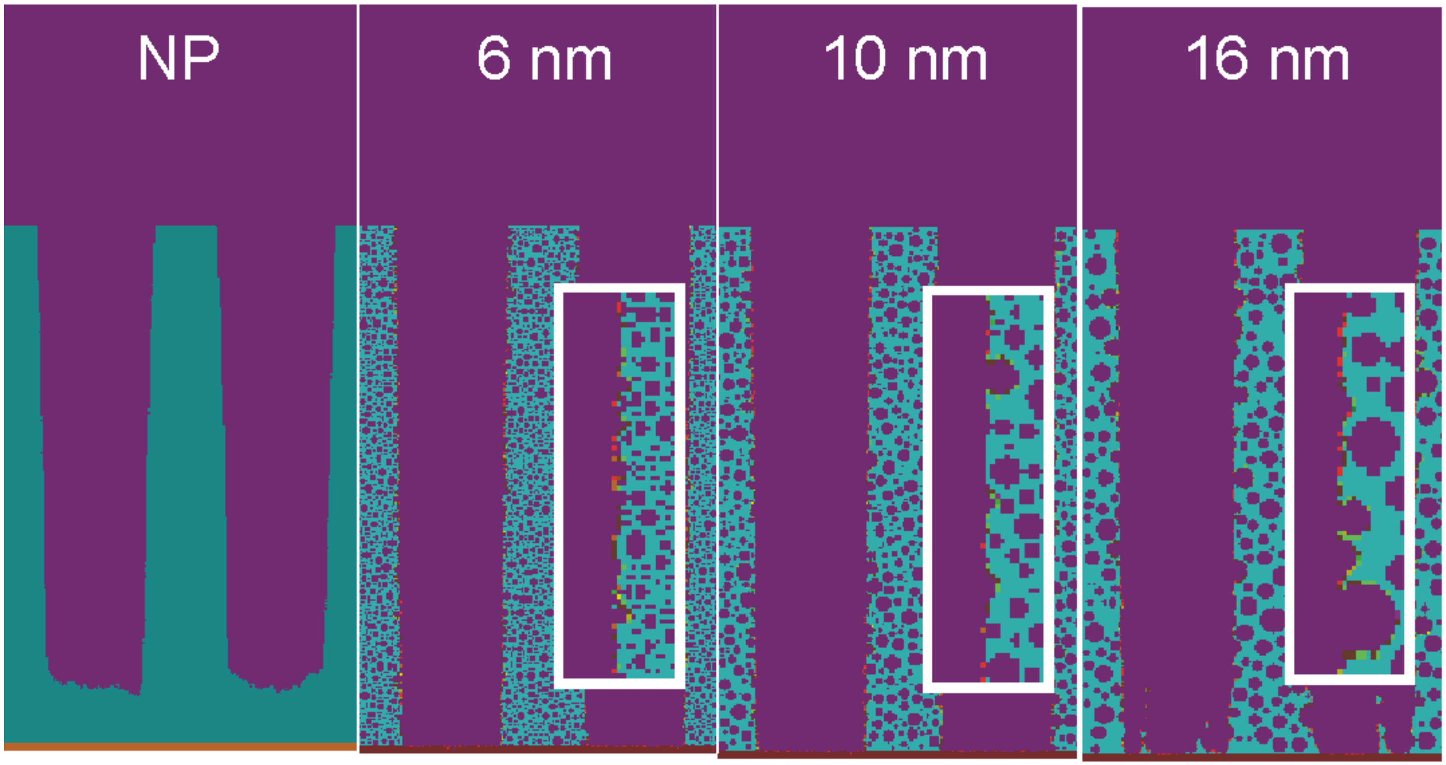
ICP: POROUS SiO_2 AND PHOTORESIST CLEAN



- **Longer cleaning times are required with more porous materials to remove polymer which is shaded from ion flux.**

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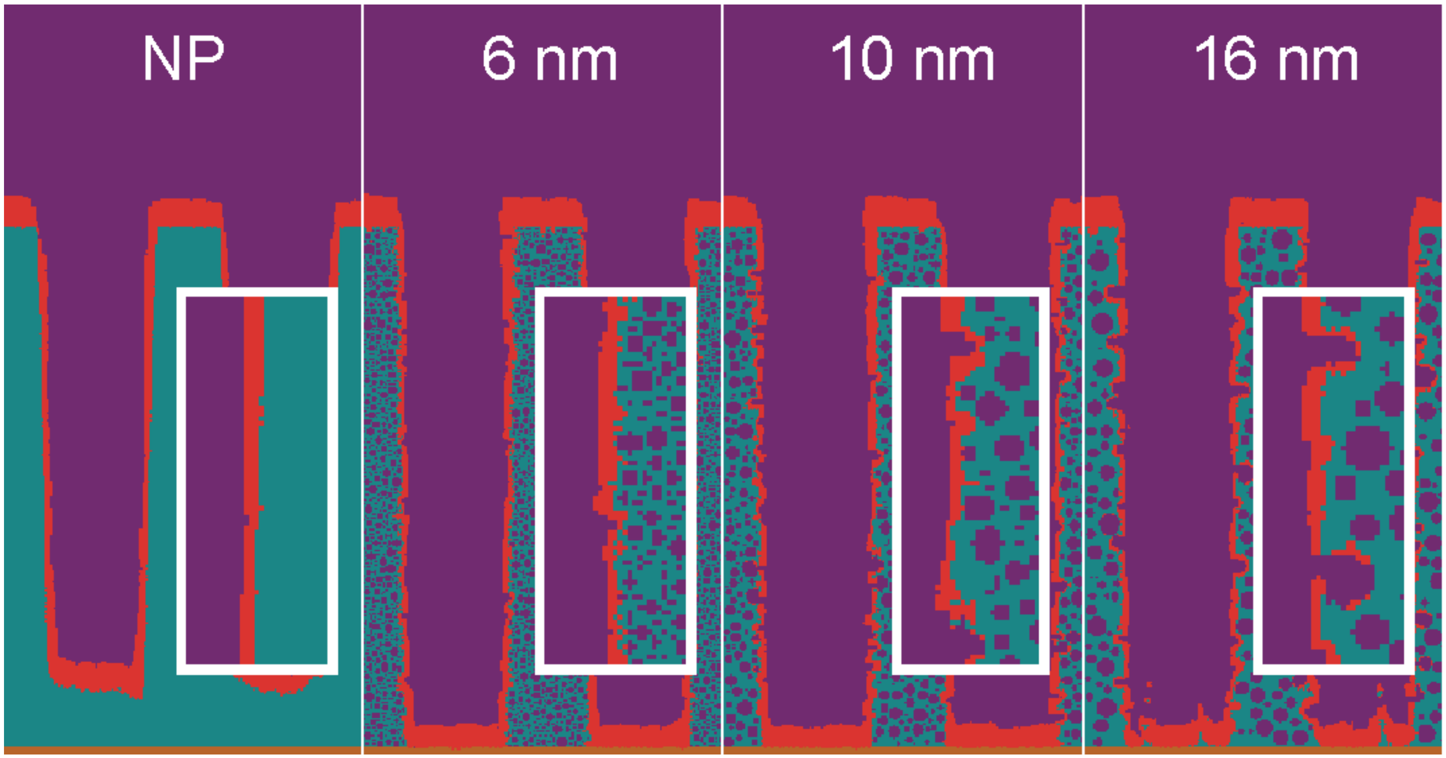
IMPVD: Cu SEED LAYER DEPOSITION



- **Thicker seed layers are required with large pores to cover over (or fill) gaps resulting from open structures.**

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CONCLUDING REMARKS

- Integrated plasma process modeling requires addressing a wide range of physical phenomena.

- The large variety of gas mixtures, reactor geometries, plasma sources and materials motivates development of generalized modeling platforms with few a priori assumptions.

- The fundamental modeling challenges are no different than in experimental integration:

    - If a single module (process) is validated (optimized) in isolation, will it still be valid (optimum) when integrated with other steps?

ACKNOWLEDGEMENTS

- Dr. Alex V. Vasenkov
- Dr. Gottlieb Oherlein
- Mr. Arvind Sankaran
- Mr. Pramod Subramonium

- Funding Agencies:

  - 3M Corporation
  - Semiconductor Research Corporation
  - National Science Foundation
  - SEMATECH
  - CFDRC Inc.