PLASMA MODELING FOR DESIGN OF EQUIPMENT, PROCESSES AND REAL-TIME-CONTROL STRATEGIES*

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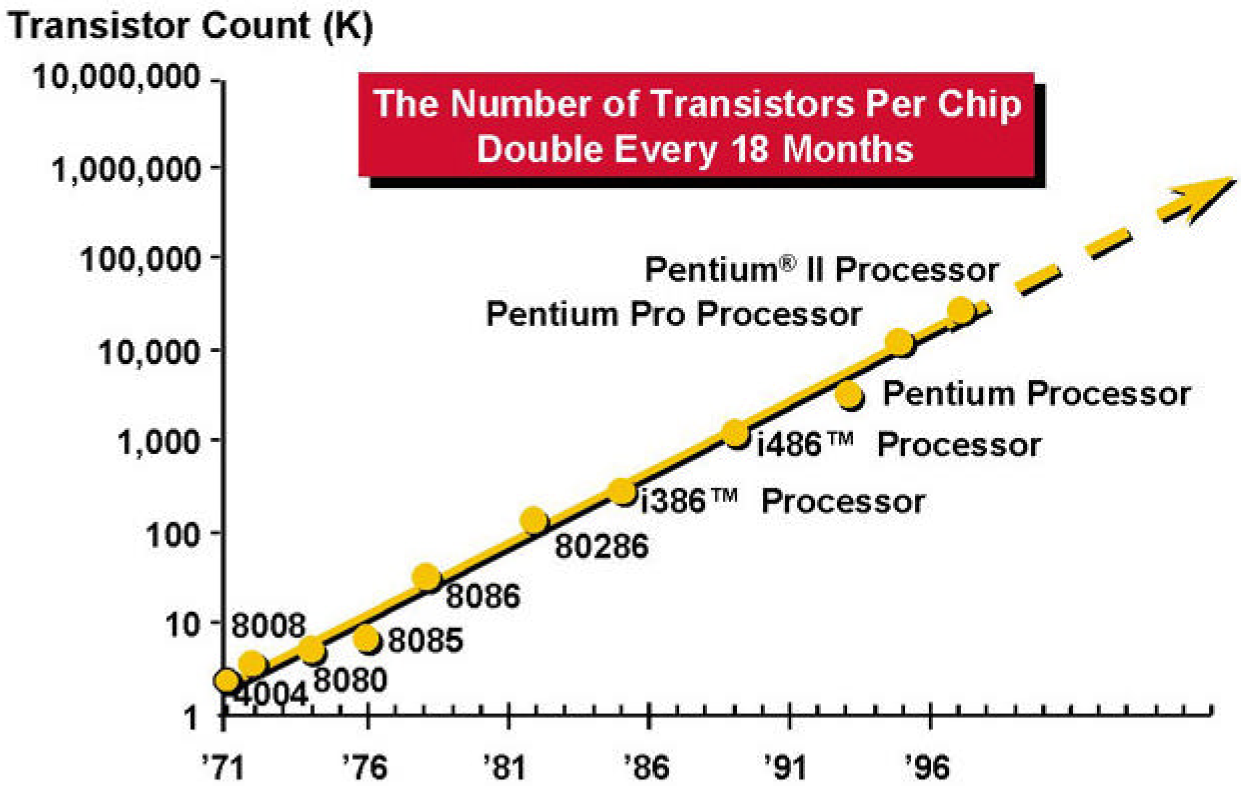
AGENDA

- Introduction to plasma processes of microelectronics.
- Needs and requirements for plasma equipment modeling.
- Description of the Hybrid Plasma Equipment Model.
- Example of Equipment Design: Ionized Metal PVD
- Virtual Plasma Equipment Model: Real Time Control Strategies
- Concluding Remarks

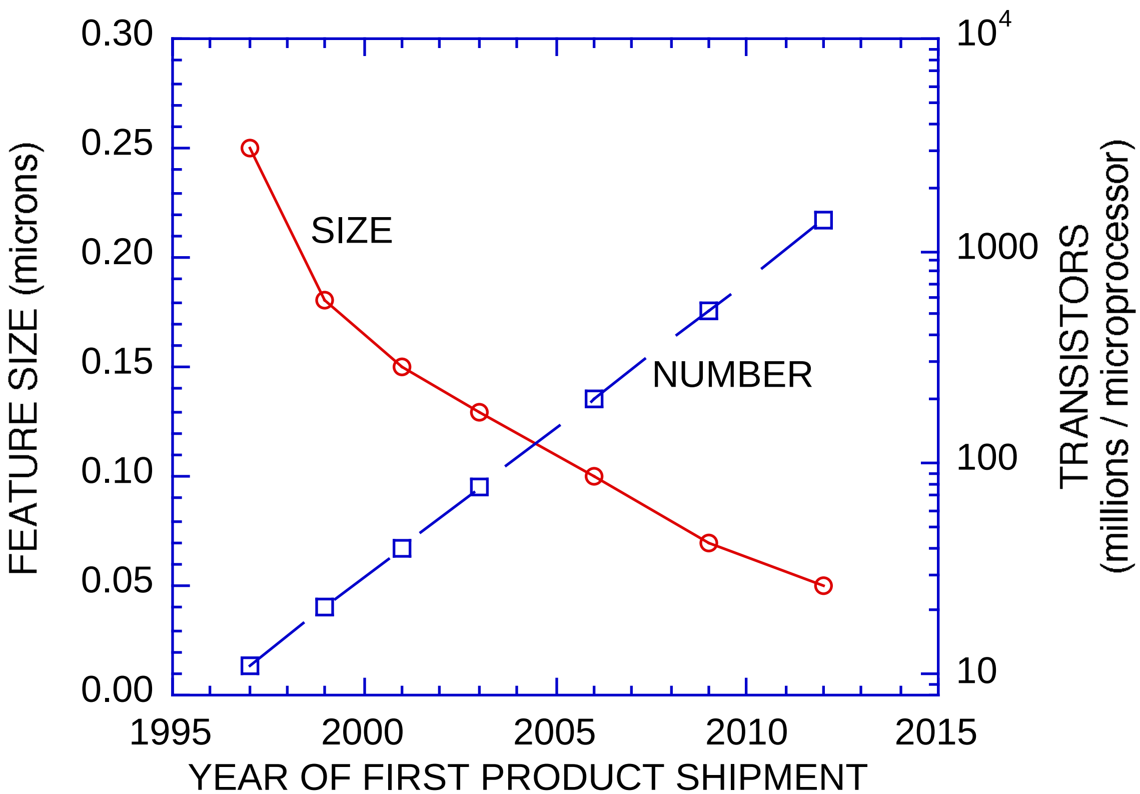
MOORE'S LAW IN MICROELECTRONICS FABRICATION



- **In the early 1980s Gordon Moore (Intel) observed that the complexity and performance of micrelectronics chips doubles every 18 months.**
- **The industry has obeyed "Moore's Law" through > 12 generations of devices.**

NATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS

- The NTRS sets goals for the microelectronics fabrication industry for future generation of devices.



- Feature sizes will continue to shrink with more transistors per chip while....

- Ref: "National Technology Roadmap for Semiconductors", SIA, 1997.

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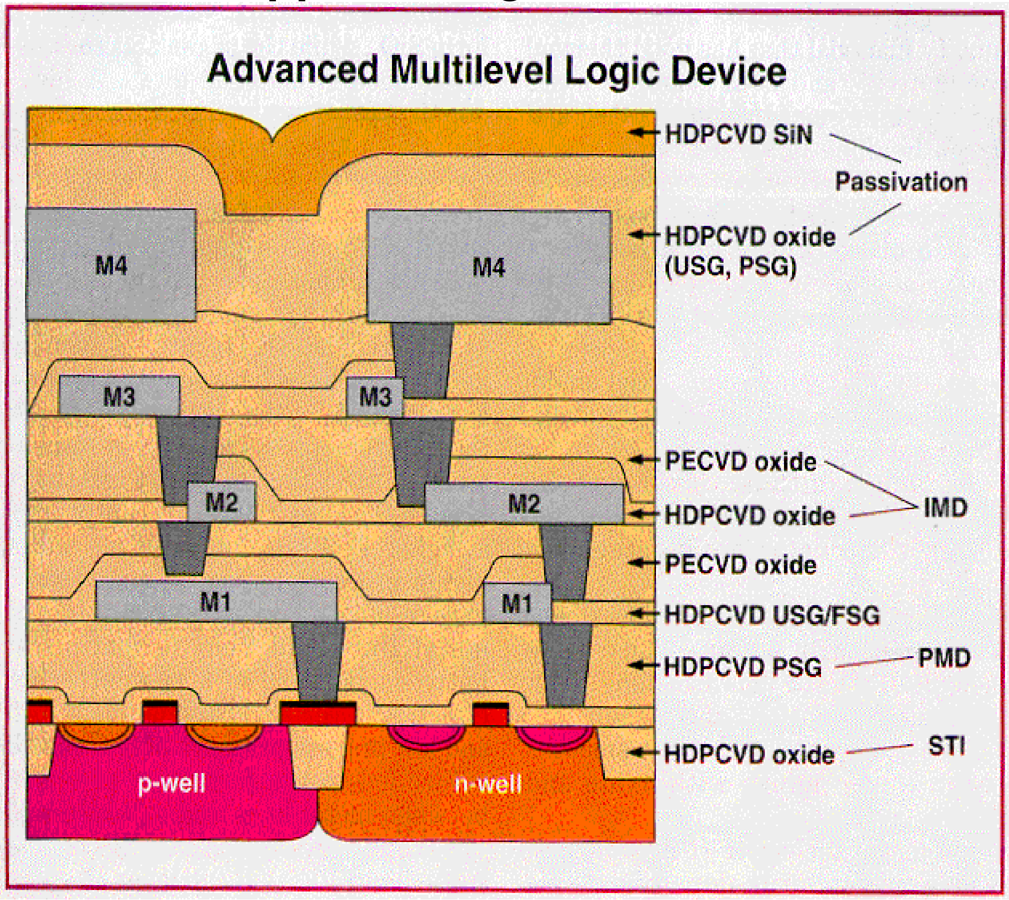
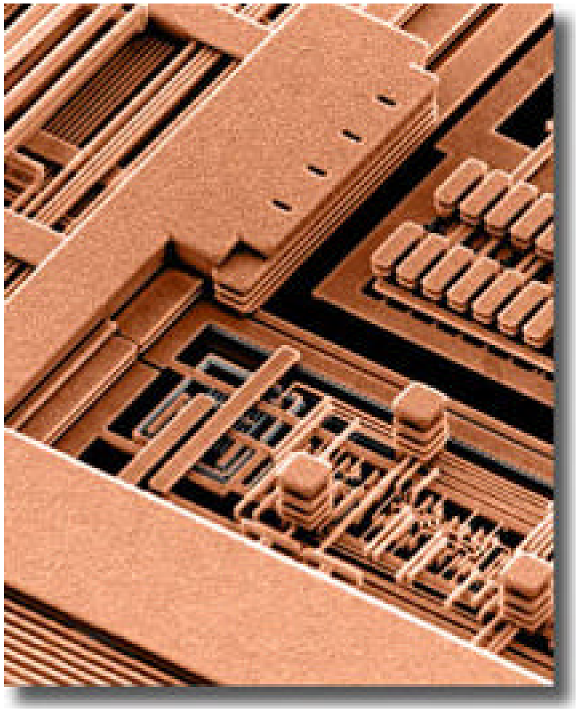
INCREASED COMPLEXITY REQUIRES NEW SOLUTIONS: INTERCONNECT WIRING

- The levels of interconnect wiring will increase to 8-9 over the next decade producing unacceptable signal propogation delays. Innovative solutions such as copper wiring and low-k dielectrics are being implemented.

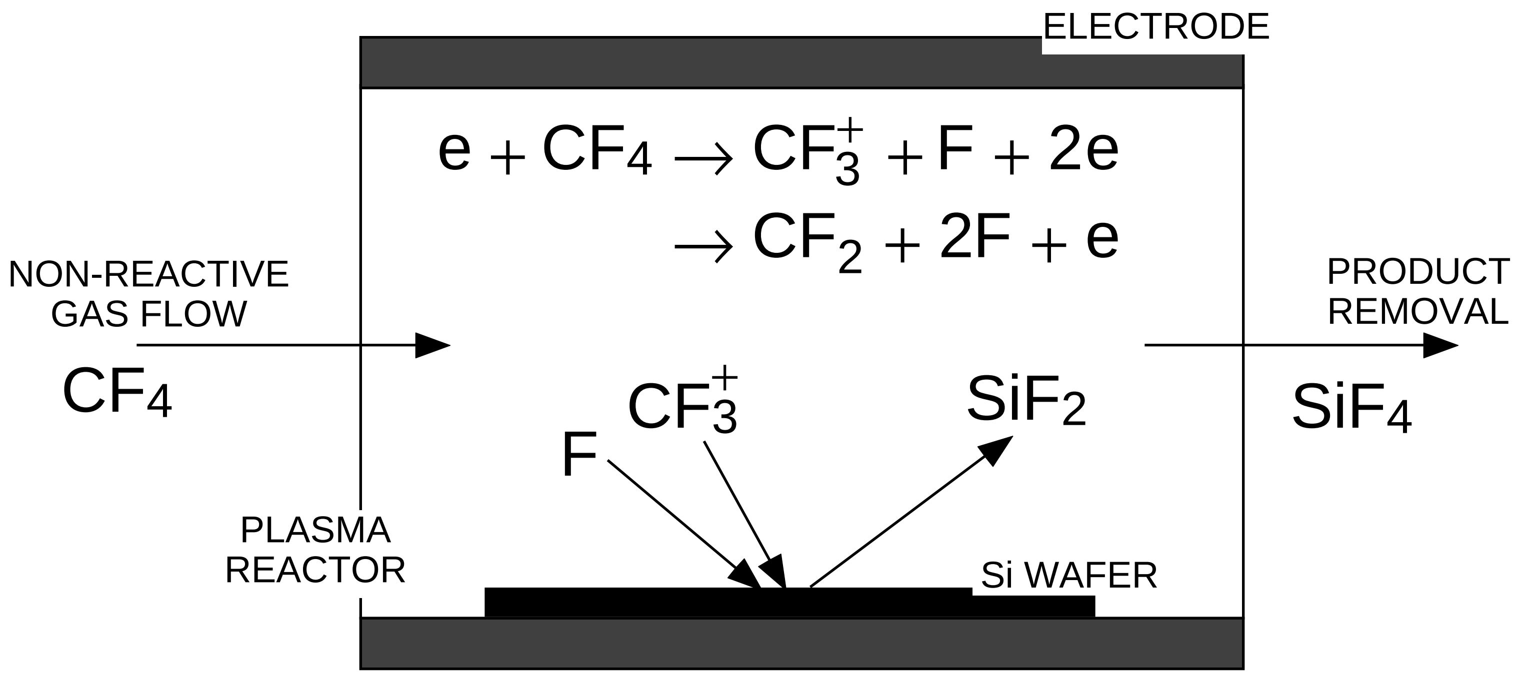




Ref: IBM Microelectronics

PLASMA PROCESSING FOR MICROELECTRONICS

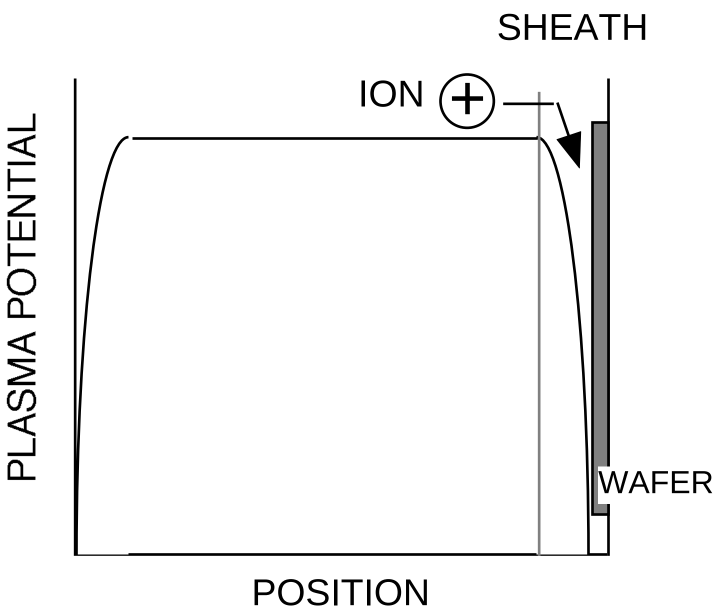
- In plasma processing of semiconductors, electron impact on feedstock gases produces neutral radicals and ions which drift or diffuse to the wafer where they remove or deposit materials.

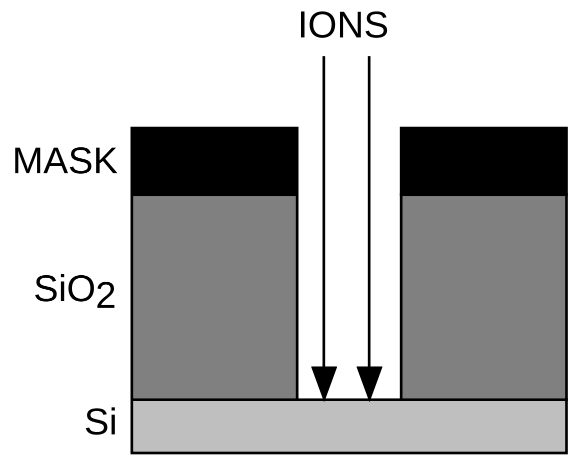


- This process is often called “cold combustion” since the feedstock gases are cool compared to the electrons.

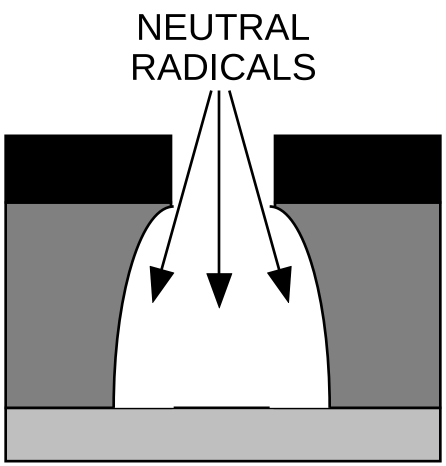
PLASMAS ARE ESSENTIAL FOR ECONOMICALLY FABRICATING FINE FEATURES IN MICROELECTRONICS

- In plasma processing, ions are accelerated nearly vertically into the wafer, thereby activating etch processes which produce straight walled, anisotropic features





- Ion Assisted Etching



- Neutral Dominated Etching

CECAM98M21

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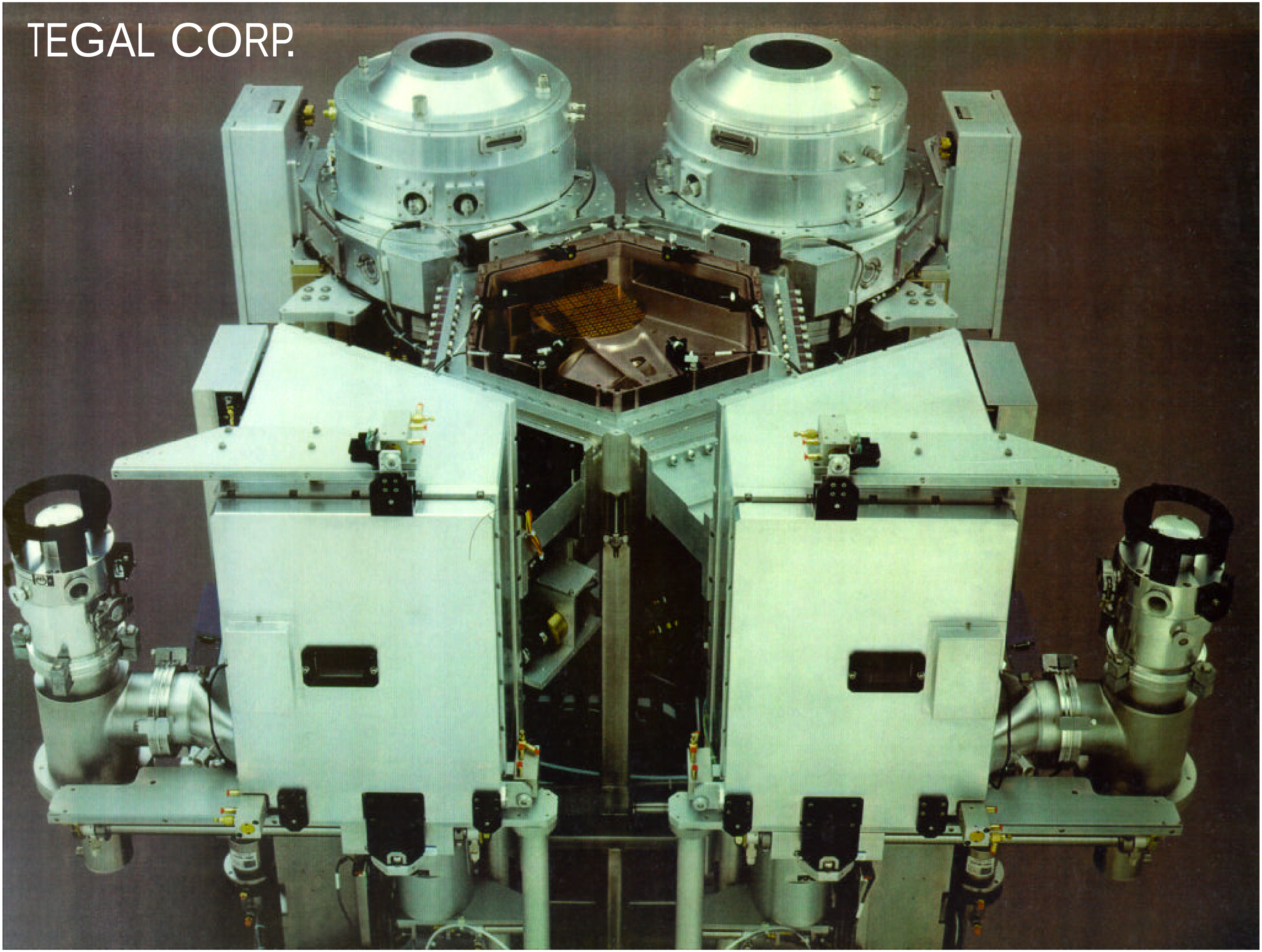
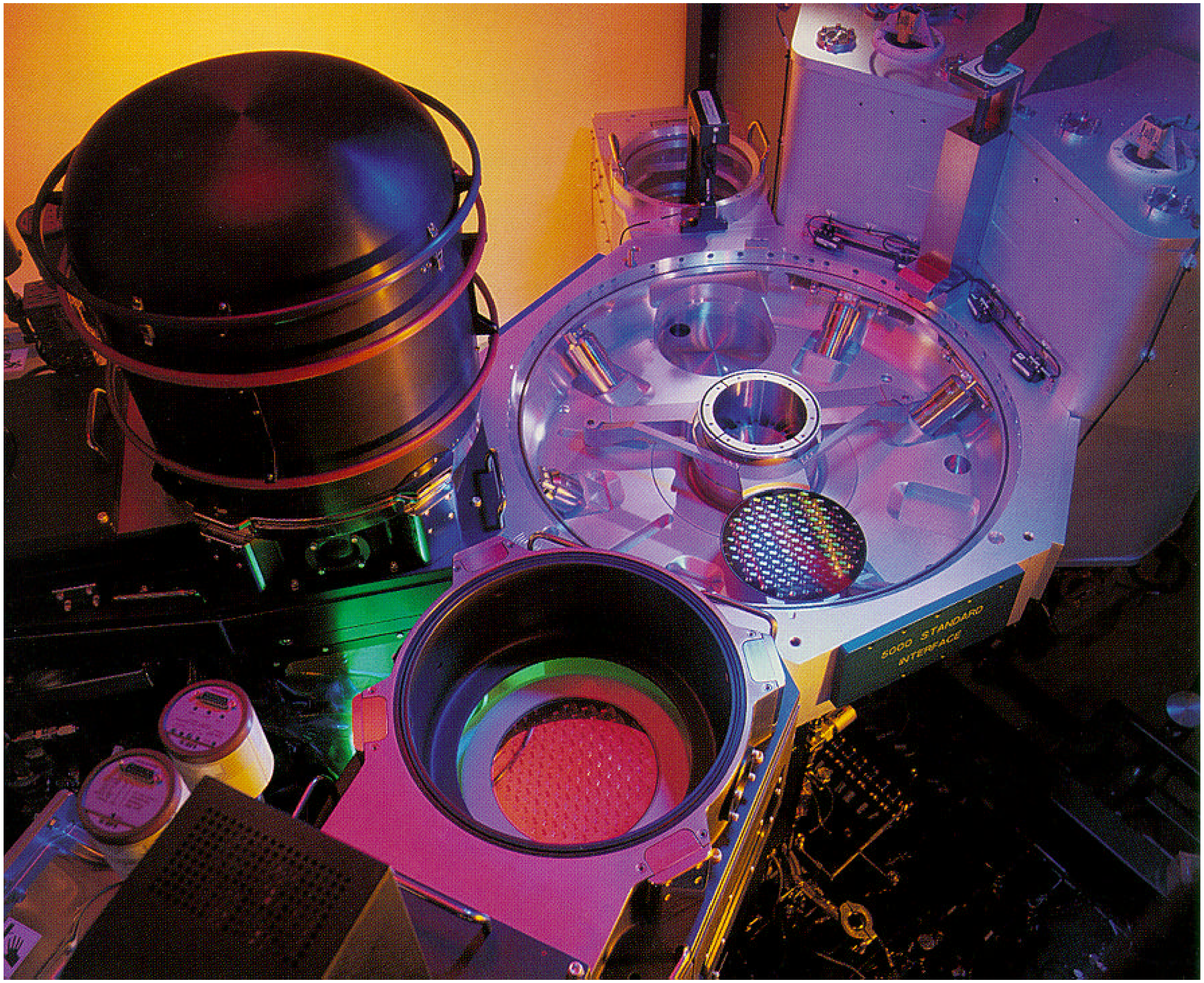

TEGAL CORP.

APPLIED MATERIALS DECOUPLED PLASMA SOURCE (DPS)



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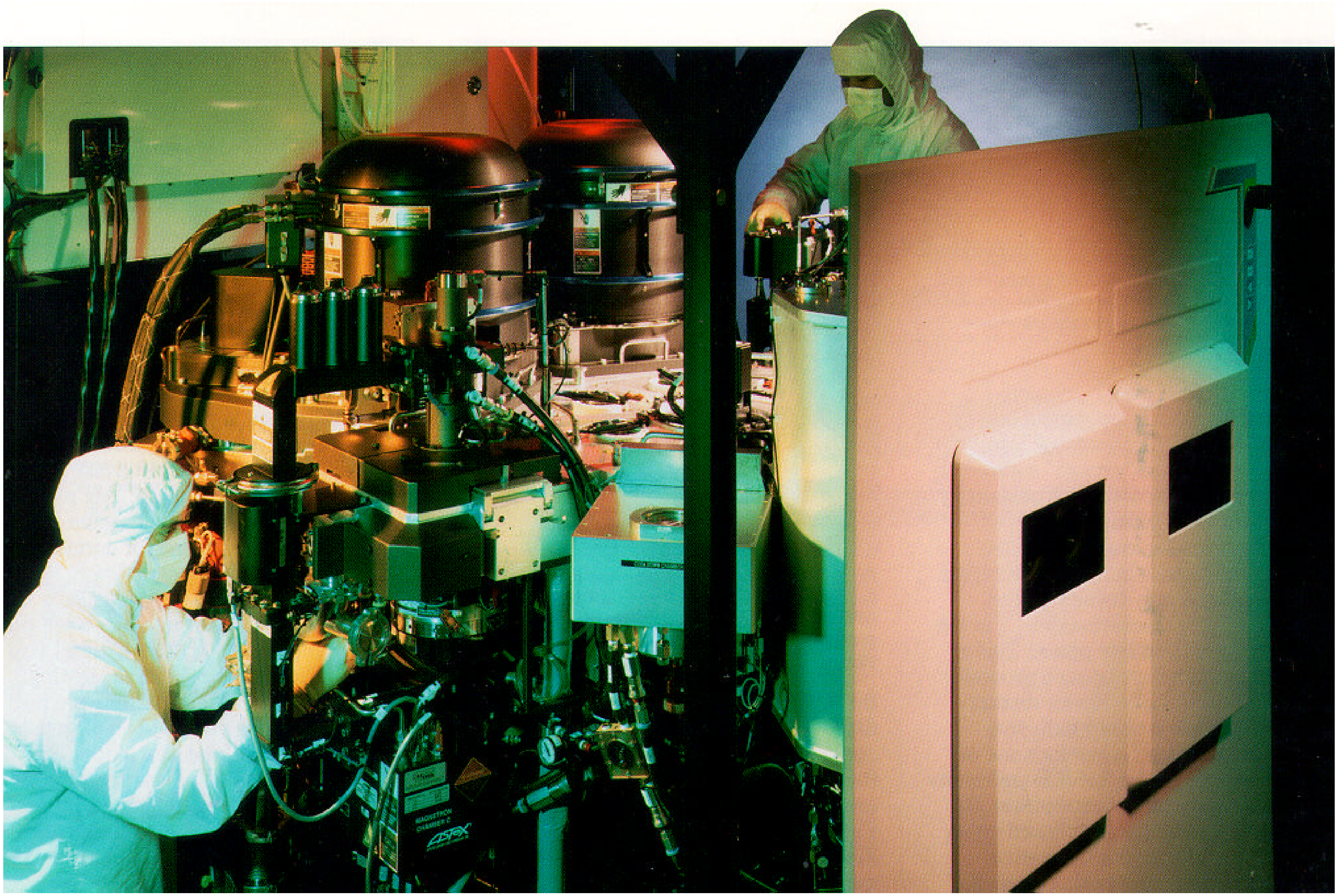
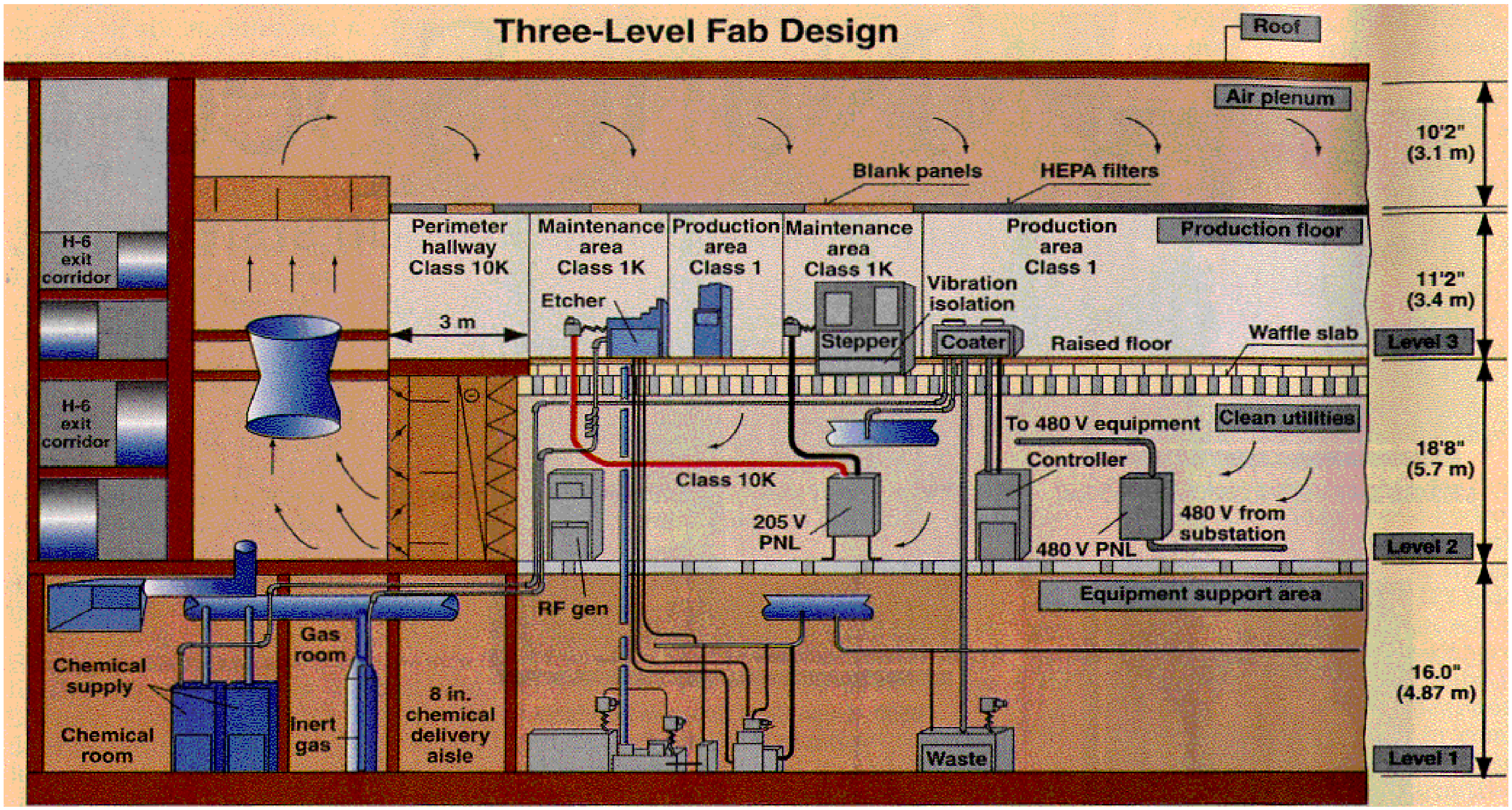
APPLIED MATERIALS DECOUPLED PLASMA SOURCE (DPS)



MICROELECTRONICS FABRICATION FACILITIES

- **Modern microelectronics fabrication facilities are designed as "compact", modular and non-redundant as possible to minimize the area of expensive clean room space.**



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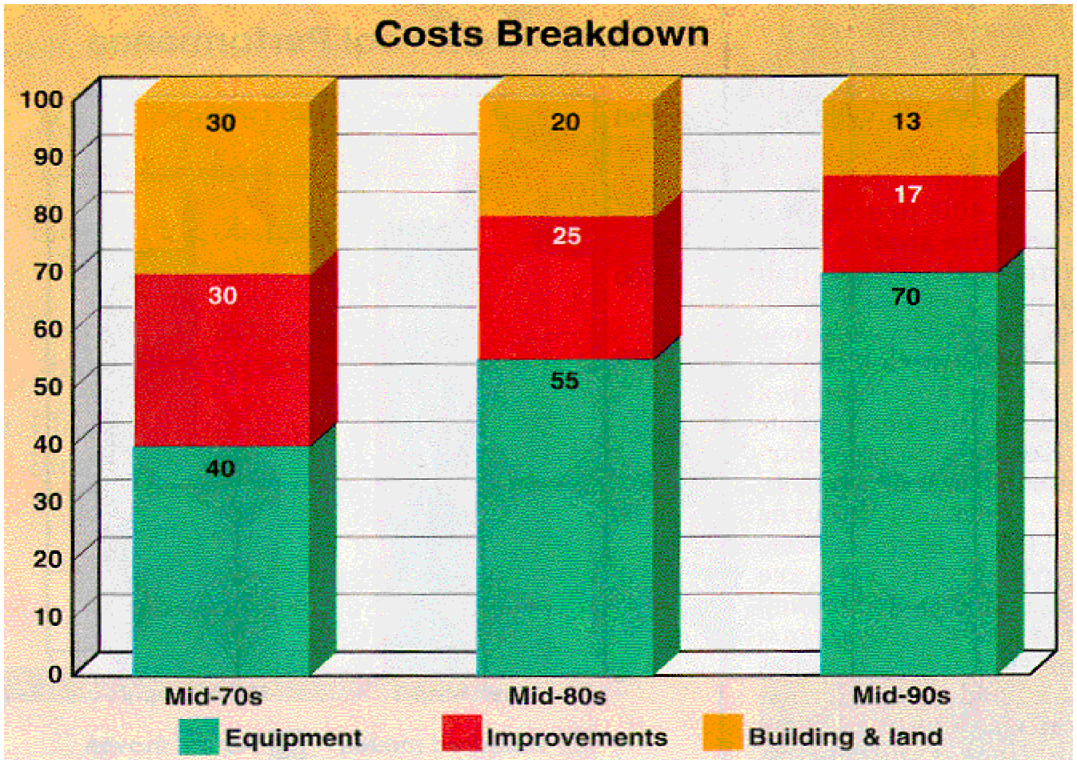
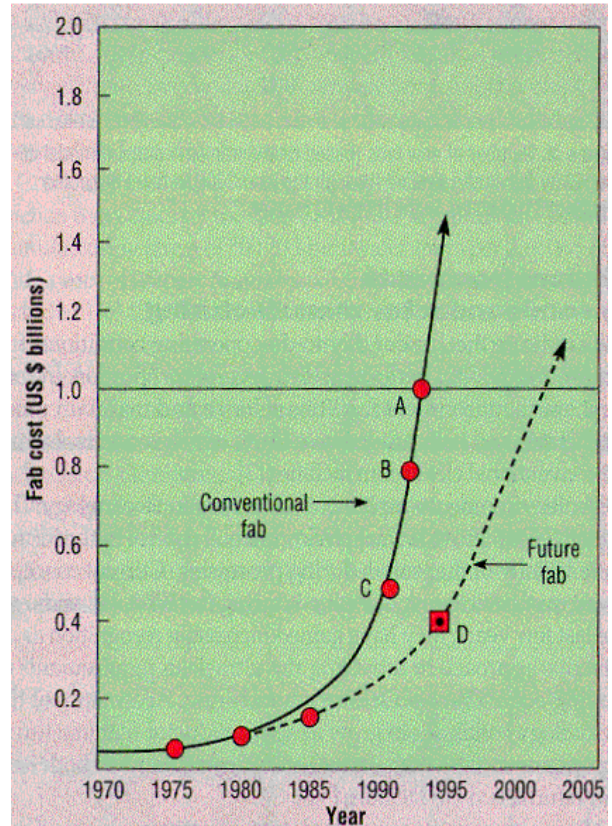
COST OF FABRICATION FACILITIES

- The cost of a major (> 20,000 wafers/month) fabrication facility exceeds $1 Billion with an increasing fraction of the cost being the processingequipment.



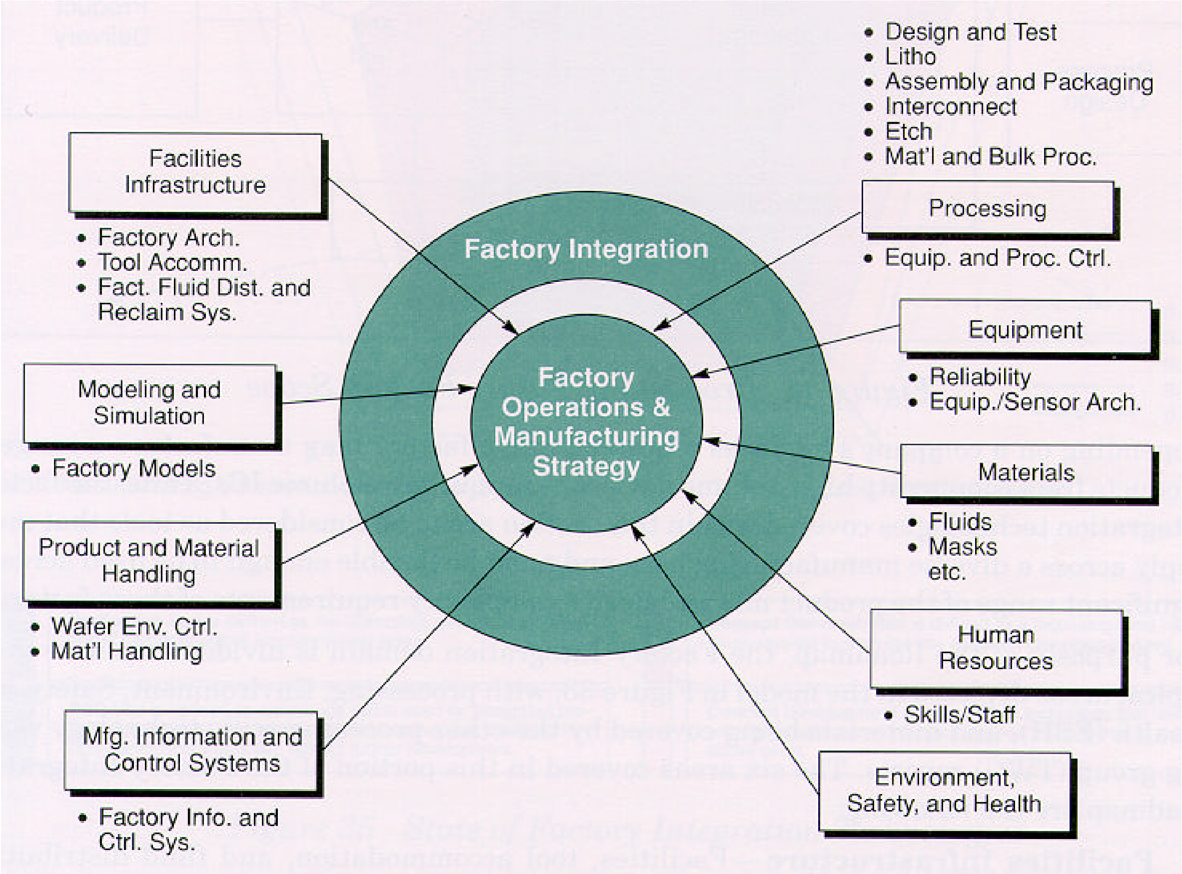


Point	DRAM (Mbit)	Wafer diam. (mm)	Throughput (wafers/mo.)	CD (µm)
A	64	200	25,000	0.35
B	16	200	20,000	0.50
C	1	150	20,000	0.80
D*	Logic (four-level metal)	200	15,000	0.35

* Paradigm shift: single wafer, cluster tooling, minienvironment.

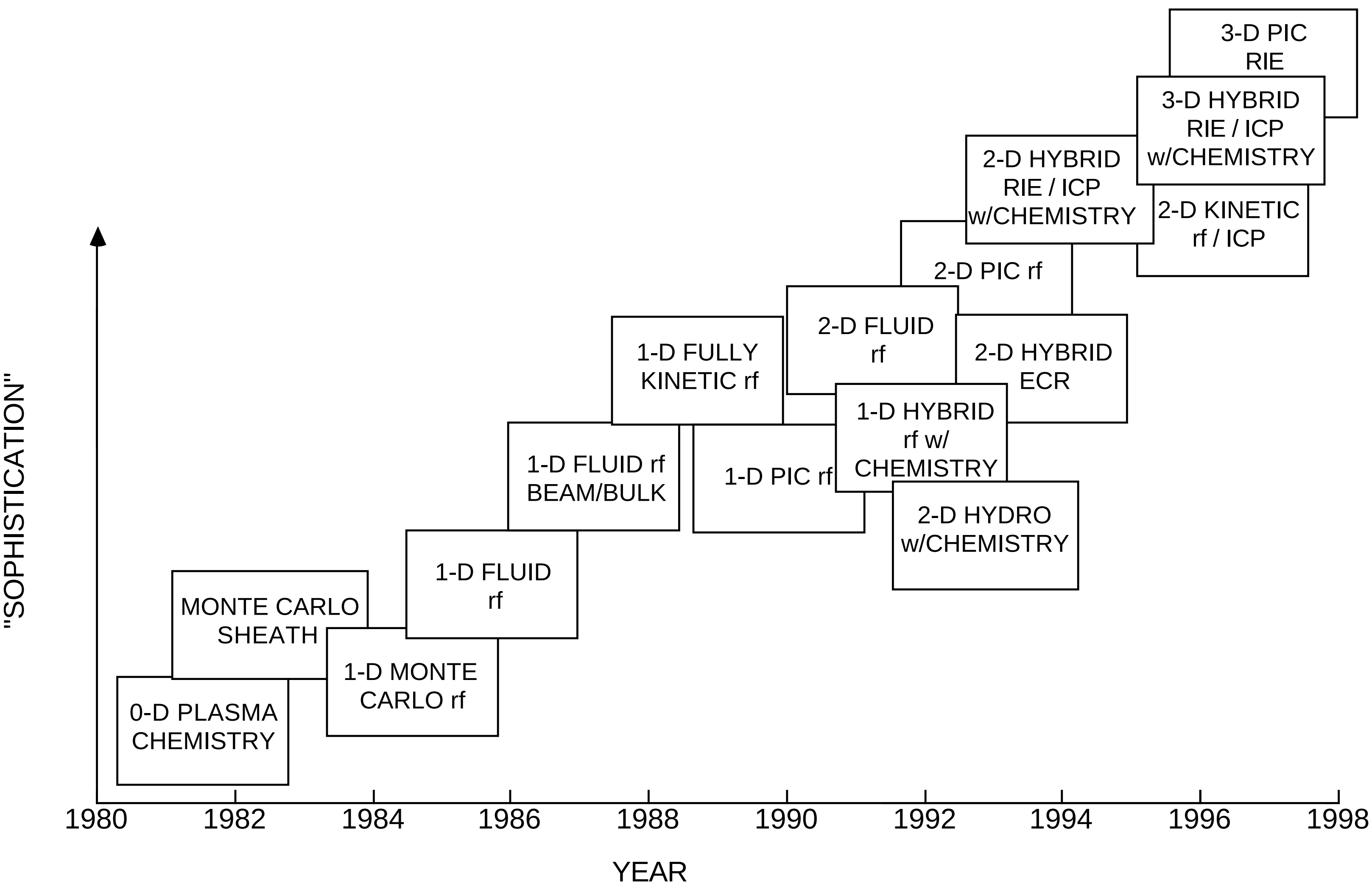
THE VIRTUAL FACTORY: A DESIGN PARADIGM

- **The "virtual factory" is a computer representation of a fabrication facility, modeled either heuristically or from basic principles.**



- **Ref: SIA Semiconductor Industry Association Roadmap, 1994.**

HISTORICAL PERSPECTIVE OF DEVELOPMENT OF PLASMA ETCHING MODELS



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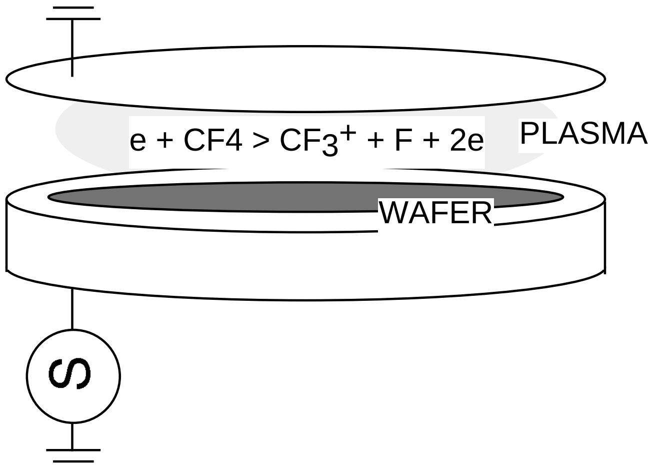
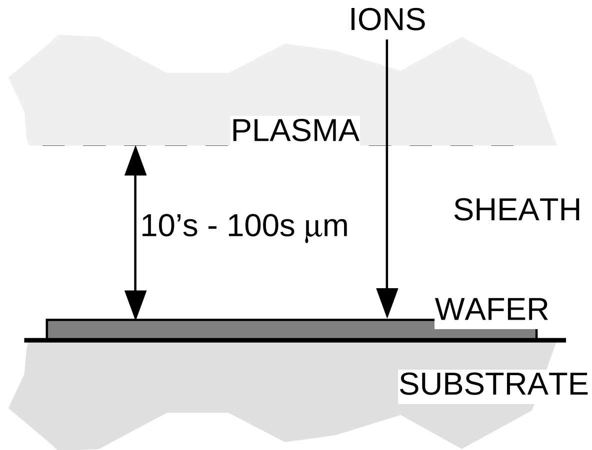
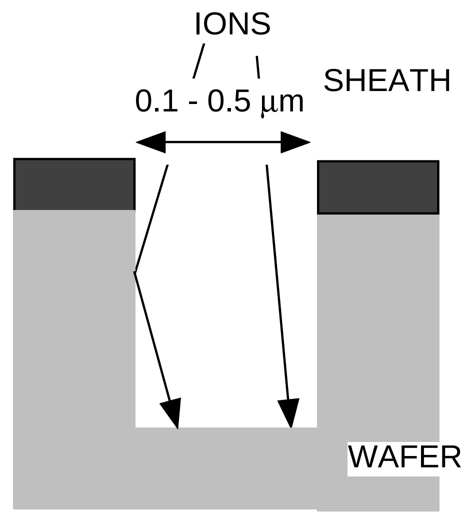
SPATIAL SCALES IN PLASMA PROCESSING SPAN MANY ORDERS OF MAGNITUDE



- EQUIPMENT SCALE (cm - 10s cm)
  - Gas Flow
  - Heat Transfer
  - Plasma Transport
  - Chemical Kinetics



- “TRANSITION SCALE” (10s -100s µm)
  - Electron and Ion Transport
  - Sparse Collsions
  - Electrodynamics



- FEATURE SCALE” (10s nm - µm)
  - Electron, Ion, Radical Transport
  - Plasma Surface Interaction
  - Surface chemistry

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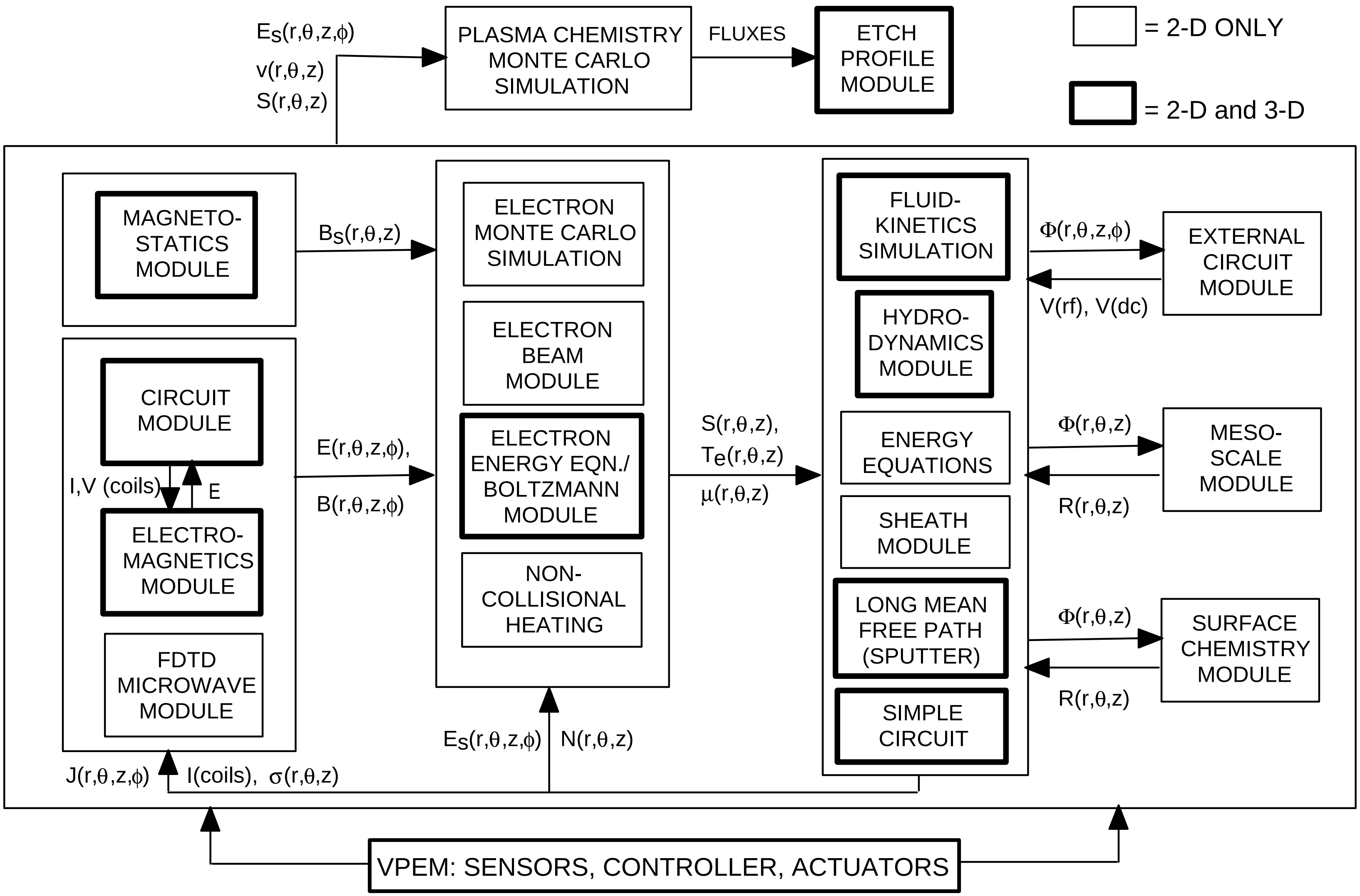
SCHEMATIC OF THE HYBRID PLASMA EQUIPMENT MODEL



ELECTROMAGNETICS-CIRCUIT MODULES

- **In the Electromagnetics-Module, the wave equation is solved in the frequency domain**

$$\nabla \cdot \frac{1}{m}\nabla\vec{E} = \frac{\P^2\left(e\vec{E}\right)}{\P t^2} + \frac{\P\left(s\vec{E}+\vec{J}_o\right)}{\P t}, \qquad s = \sum_j \frac{q^2 n_j}{m_j n_j\left(1-\frac{iw}{n_j}\right)}$$

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

- **With static applied magnetic fields, conductivities are tensor quantities:**

$$\ddot{s} = s_o \frac{mn_m}{qa} \frac{1}{\left(a^2+\left|\vec{B}\right|^2\right)} \begin{pmatrix} a^2 + B_r^2 & aB_z + B_r B_q & -aB_q + B_r B_z \\ -aB_z + B_r B_q & a^2 + B_q^2 & aB_r + B_q B_z \\ -aB_q + B_r B_z & -aB_r + B_q B_z & a^2 + B_z^2 \end{pmatrix}$$

$$\vec{j} = \ddot{s} \cdot \vec{E} \qquad a = \frac{(iw + n_m)}{q/m}, \quad s_o = \frac{q^2 n_e}{mn_m}$$

ELECTROMAGNETICS-CIRCUIT MODULES

- **Coil currents J_o are obtained from an equivalent circuit model for the antenna. Each discrete element of the transmission line has impedance:**

$$Z_i = -iwL_i + i/wC_i + R_c + Z_{Ti}$$

L_i	=	**Physical inductance**
C_i	=	**Capacitive coupling**
R_c	=	**Ohmic resistance of coil**
Z_{Ti}	=	**Transformed impedance of the plasma**

- **The driving voltage from the generator is obtained by specifying a total power deposition by the electric field.**

- **Match conditions are obtained by varying the matchbox circuit elements to minimize the reflected power.**

- **The complex amplitudes of the components of the wave are obtained using either successive-over-relaxation or conjugate-gradient-sparse matrix techniques.**

ELECTRON ENERGY TRANSPORT

- Electron transport coefficients and electron impact source functions are obtained by solving the electron energy equation.

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

where	$S(T_e)$	=	Power deposition (from EEM and FKS)
	$L(T_e)$	=	Electron power loss due to collisions
	Φ	=	Electron flux (obtained from FKS)
	$\kappa(T_e)$	=	Electron thermal conductivity
	S_{EB}	=	Electron source from beam electrons (MCS)

- Transport coefficients are obtained as a function of average energy (ε = (2/3) T_e) from solution of Boltzmann' Equation for the electron energy distribution.
- The energy equation is implicity solved using Successive-over-Relaxation.
- Secondary electron emitted from surfaces are addressed using a Monte Carlo simulation.

PLASMA CHEMISTRY KINETICS SIMULATION

- **In the plasma chemistry module we solve separate continuity, momentum and energy equations for ions and neturals, and the electron continuity equation.**

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

$$\frac{\partial (N_i \vec{v}_i)}{\partial t} = \frac{1}{m_i}\nabla(kN_iT_i) - \nabla \cdot (N_i \vec{v}_i \vec{v}_i) + \frac{q_i N_i}{m_i}\left(\vec{E} + \vec{v}_i \times \vec{B}\right) - \nabla \cdot \bar{\mu}_i$$

$$- \sum_j \frac{m_j}{m_i + m_j} N_i N_j \left(\vec{v}_i - \vec{v}_j\right)\nu_{ij}$$

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

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

PLASMA CHEMISTRY KINETICS SIMULATION

- **Slip boundary conditions are used for neutral transport for momentum and energy to address temperature jump conditions.**

- **Gas flow (input nozzle, pumping) is included by specifying influx/outflux boundary conditions. Pressure is specified and the pump-speed is throttled to maintain constant pressure and mass flux.**

- **Important aspects of this formulation are:**
  - **Including "reflux" of species from surfaces**
  - **Momentum trransfer between species leading to ion drag, jetting of input gases and entrainment.**

- **All equations are discretized using flux-conservative finite-volume techniques.**

- **Tensor transport coeffiecients are used with static magnetic fields.**

- **PDEs are integrated in time using Runge-Kutta techniqes.**

PLASMA CHEMISTRY KINETICS SIMULATION

- **Poisson's equation is solved using a semi-implicit formulation which includes a prediction of densities for the time at which the fields will be used. Surface charges are included here.**

$$\nabla \cdot e \nabla \Phi(t + \Delta t) = -\left(r_s + \sum_i q_i N_i - \Delta t \cdot \sum_i \left(q_i \nabla \cdot \vec{f}_i \right) \right)$$

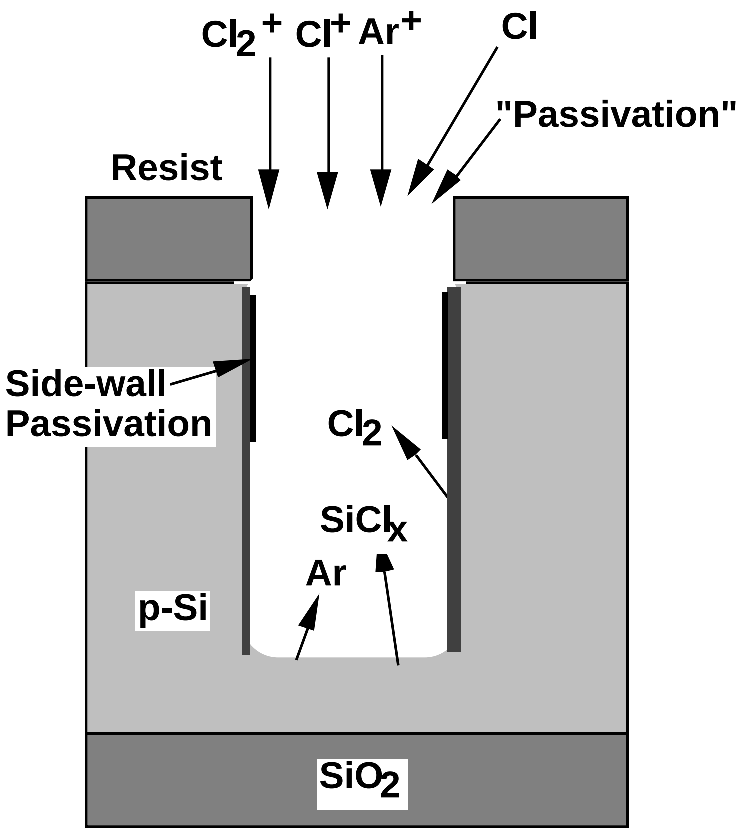
where

$$\vec{f}_e = -q_e m_e \nabla \Phi - D_e \nabla n_e$$

$$\vec{f}_{ION} = (\text{from momentum equations})$$

- **Boundary conditions are obtained from a circuit model of the reactor and driving electronics which specify voltage harmonics (amplitude and phase) on metal surfaces.**

MONTE CARLO FEATURE PROFILE MODEL (MCFP)



- The MCFP model predicts time and spatially dependent etch profiles using neutral and ion fluxes from the PCMCS.

- Any chemical mechanism may be implemented in the MCFP using a "plasma chemistry" input hierarchy.

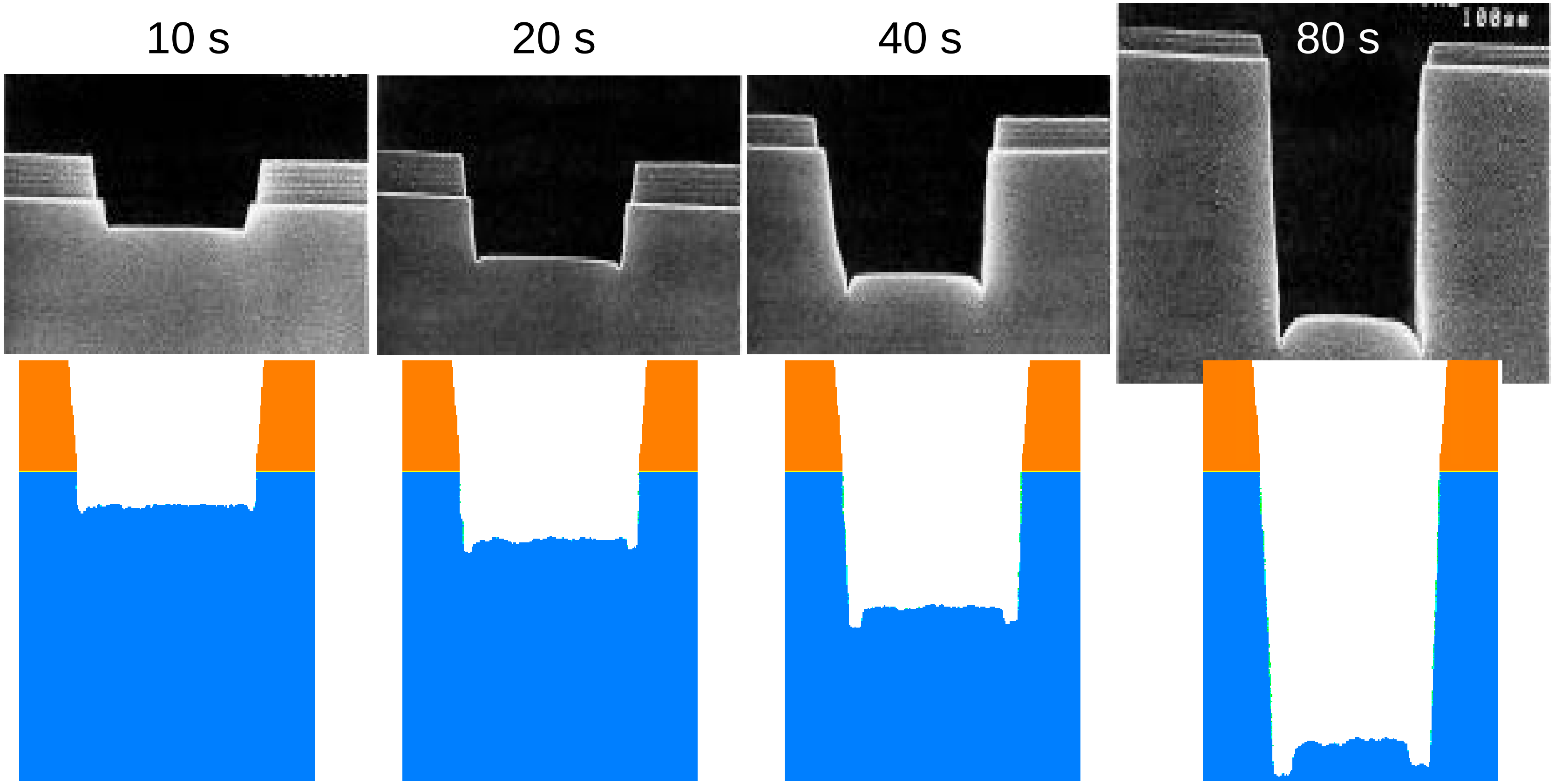
e.g., $Cl^+ + SiCl_2(s) > SiCl_2(g)$

- All pertinent processes can be included: thermal etch, ion assisted etch, sputter, redeposition, passivation.

- Energy dependent etch processes may be implemented using parametric forms.

- The MCFP may utilize ALL flux statistics from the PCMCS
  - Ion energy and angular distributions
  - Neutral energy and angular distributions
  - Position dependent fluxes

ETCH PROFILE EVOLUTION



• The time evolution of the trench etch is well matched by the simulation.

• The microtrenching develops more slowly for the experimental results possibly due to differences in slope of the resist sidewalls.

• 9400SE LAM TCP Reactor
10 mTorr Cl_2 (60 sccm) 600 W , 100 W bias
LSI Logic Corporation

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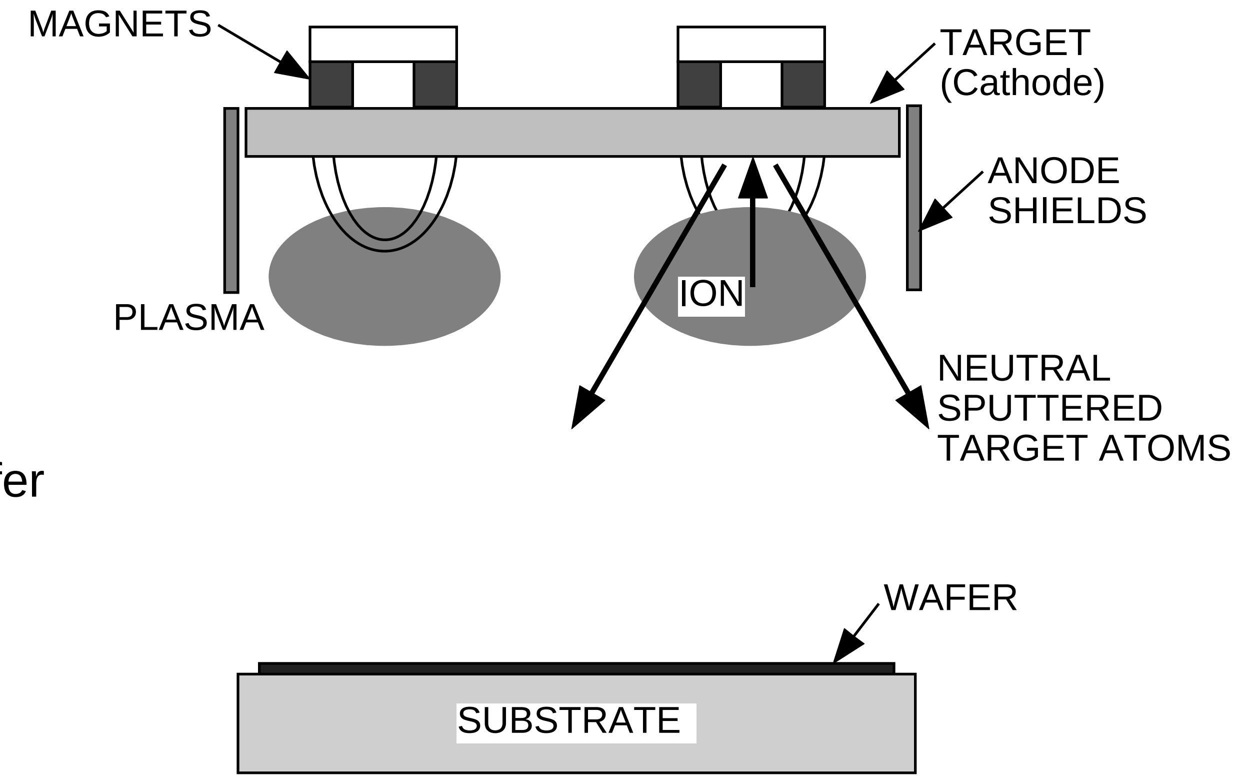
PHYSICAL VAPOR DEPOSITION OF METALS

- Physical-vapor-deposition (PVD) is a sputtering process in which metal (and other) layers are deposited for barrier coatings and interconnect wiring.



- Typical Conditions:
  - < few mTorr Ar buffer
  - 100s V bias
  - 100s W - a few kW

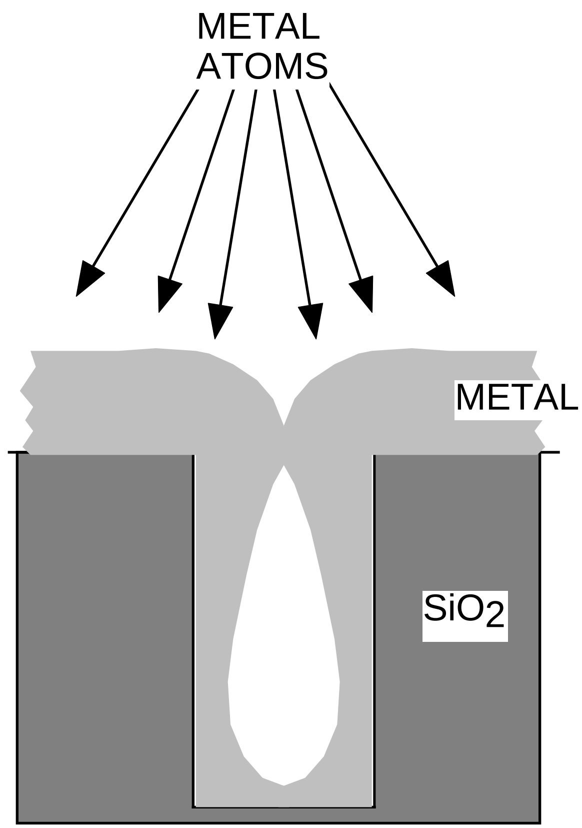
PVD DEPOSITION PROFILES

- In PVD, the atoms arriving at the substrate are mostly neutral with broad angular distributions.

- The corners of the trench see a larger solid angle of the metal atom flux, and so have a higher deposition rate.

- The end result is a nonuniform deposition and void formation.

- Columnators are often used to filter out large angle flux; at the cost of deposition rate and particle formation.



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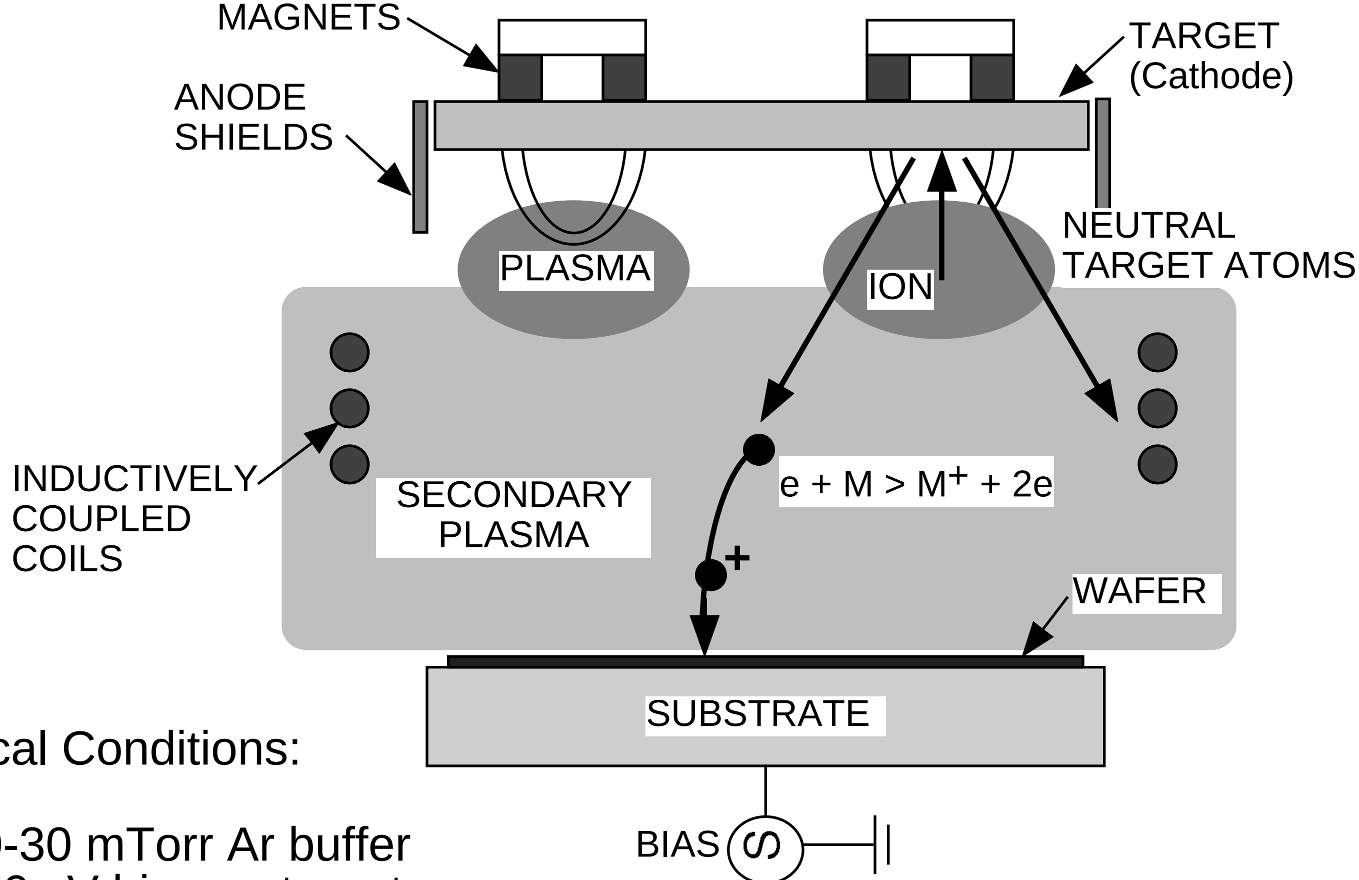
IONIZED METAL PHYSICAL VAPOR DEPOSITION (IMPVD)

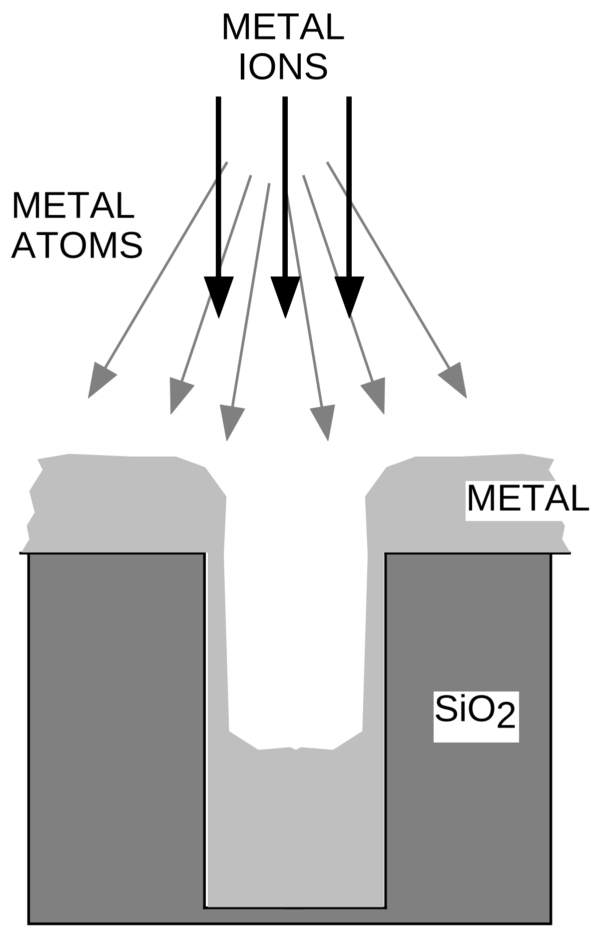
- In IMPVD, a second plasma source is used to ionize a large fraction of the the sputtered metal atoms prior to reaching the substrate.



- Typical Conditions:
  - 10-30 mTorr Ar buffer
  - 100s V bias on target
  - 100s W - a few kW ICP
  - 10s V bias on substrate

IMPVD DEPOSITION PROFILES

- In IMPVD, a large fraction of the atoms arriving at the substrate are ionized.
- Applying a bias to the substrate narrows the angular distribution of the metal ions.
- The anisotropic deposition flux enables deep vias and trenches to be uniformly filled.



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DESCRIPTION OF SPUTTERING MODEL

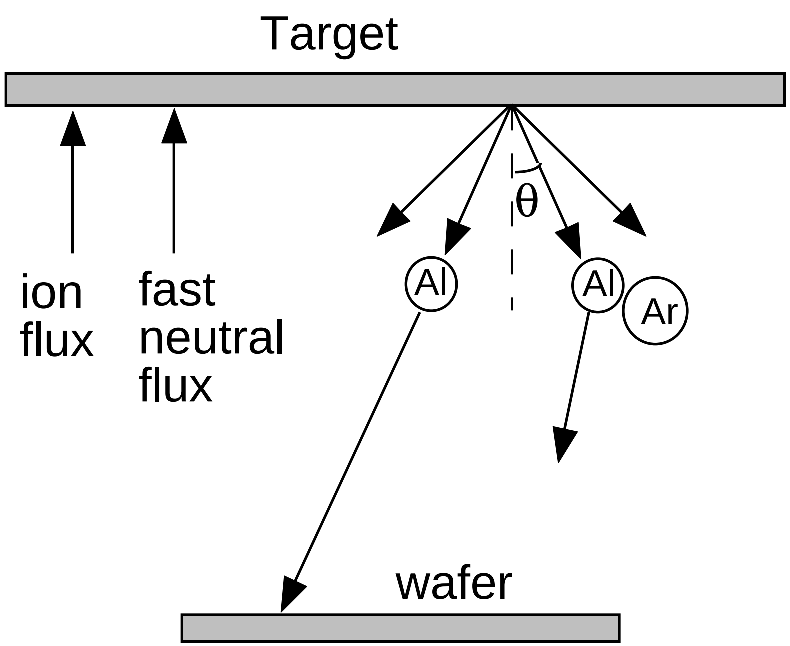
- Energy of the emitted atoms (E) obeys the cascade distribution, an approximation to Thompson's law for $E_i \approx$ 100's eV:

$$F(E) = \begin{cases} 2\left(1+\dfrac{E_b}{\Lambda E_i}\right)^2 \dfrac{E_b E}{(E_b+E)^3}, & E \le \Lambda E_i \\ 0, & E > \Lambda E_i \end{cases}$$

where

$$\Lambda = 4 m_i m_T / (m_i + m_T)^2$$

subscripts: b ~ binding, i ~ ion, T ~ target.

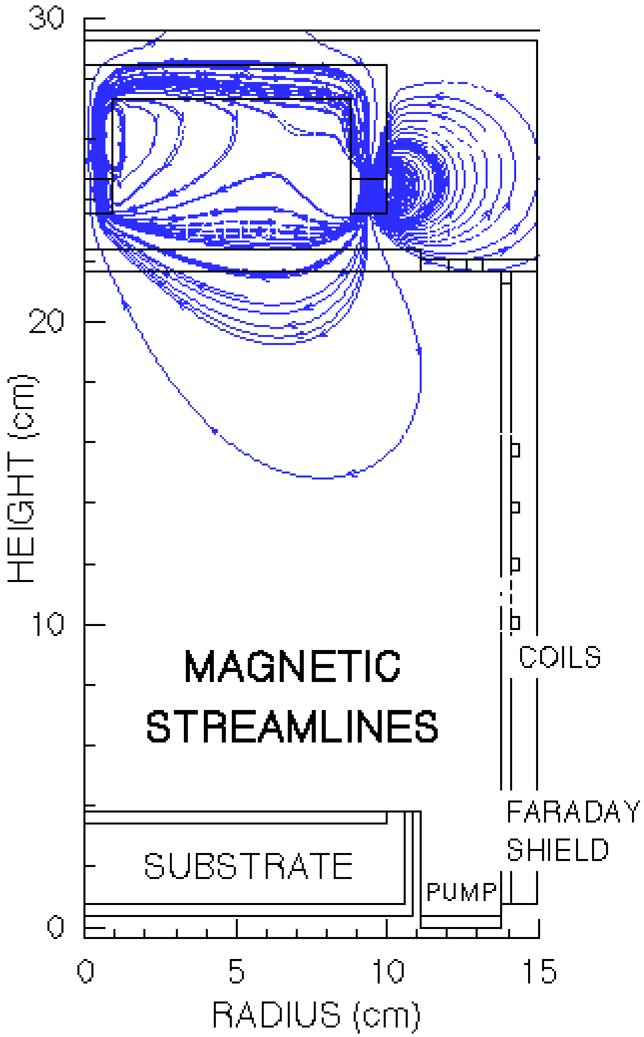


- The sampling of sputtered atom energy E from the cascade distribution gives

$$E = \frac{E_b \Lambda E_i \sqrt{RN}}{E_b + \Lambda E_i\left(1-\sqrt{RN}\right)}$$

where RN is a random number in interval [0,1].

PVD/IMPVD OF Cu: REACTOR LAYOUT



- **PVD/IMPVD reactor with Cu Target**
  - **3.5- 20 mTorr Ar (constant pressure), 150 sccm**
  - **Annular magnetic field (200 G below target**
  - **Target: -200 V dc (2.4 kW)**
  - **Substate: 40 V, 10 MHz, 350 W**
  - **Coils: 2 MHz, 1250 W with Faraday shield**

- **Physics included:**
  - **Gas heating by sputtered target atoms**
  - **Ion energy dependent sputter yield**
  - **Neutral and ion momentum and energy**
  - **Bulk electron energy equation**
  - **Monte Carlo secondary electrons**
  - **Cross field Lorentz forces**

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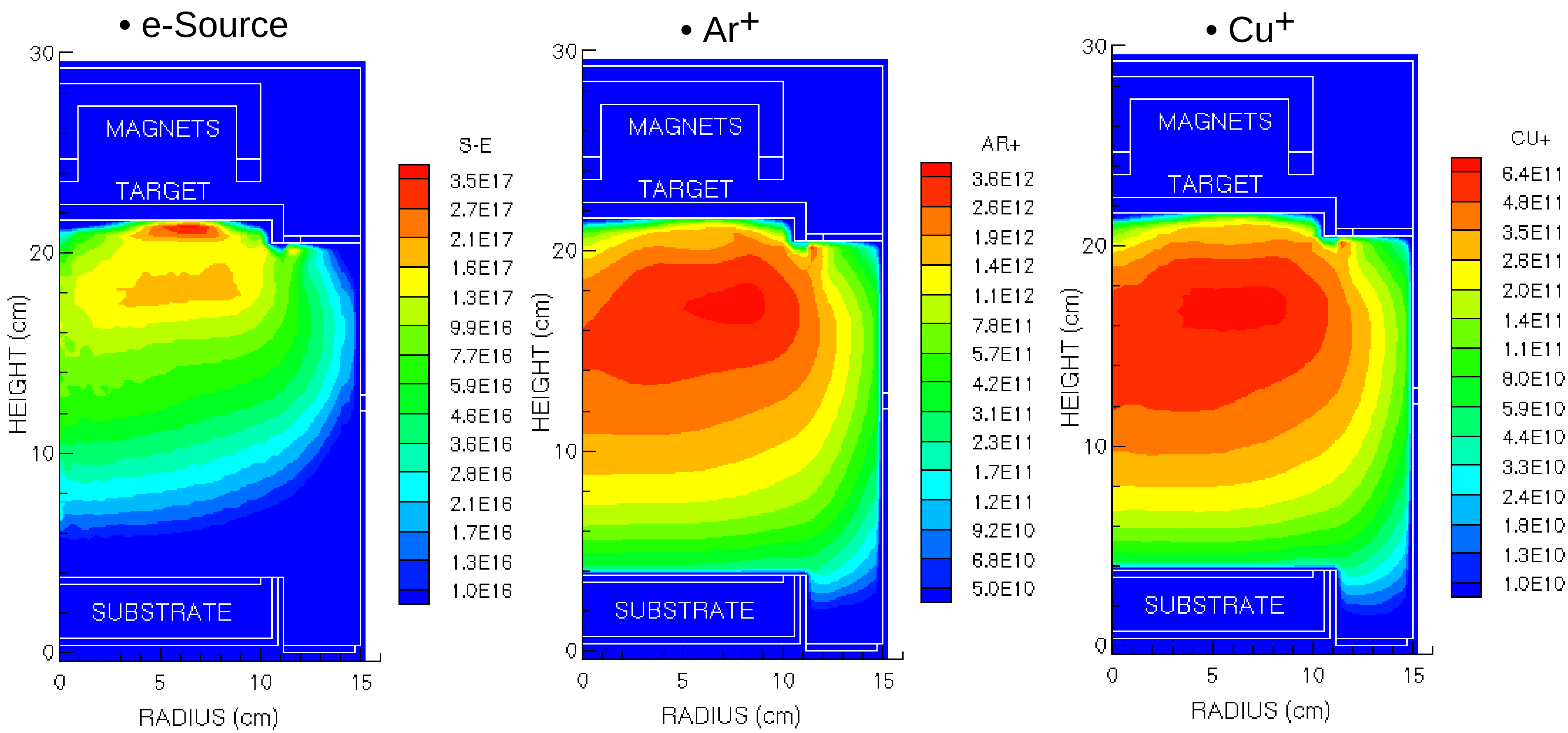
MAGNETRON SPUTTER TOOL: Ar/Cu

- Secondary electron emission from the target, and electron heating in the sheath, produces a torroidal electron source.

- Peak ion densities are mid-10^{12} cm^{-3}.



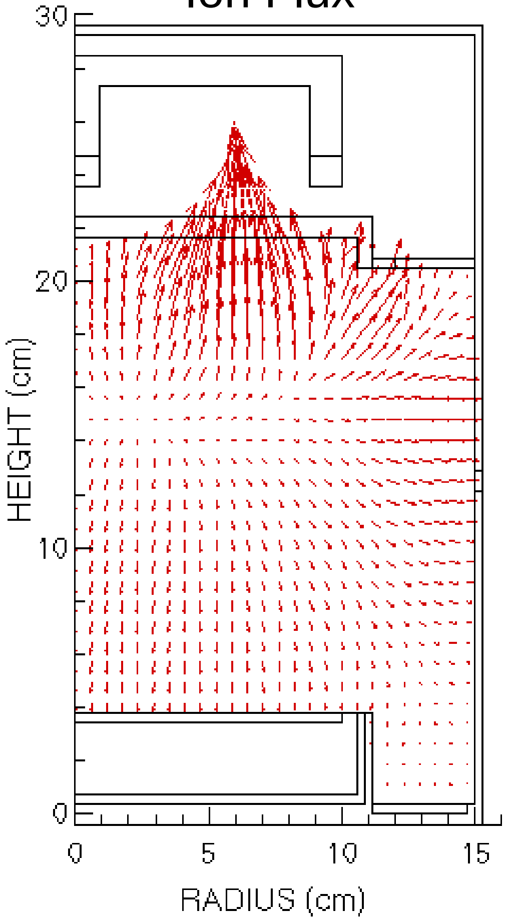
- Ar, 3.5 mTorr
- -200 V Target, 200 G

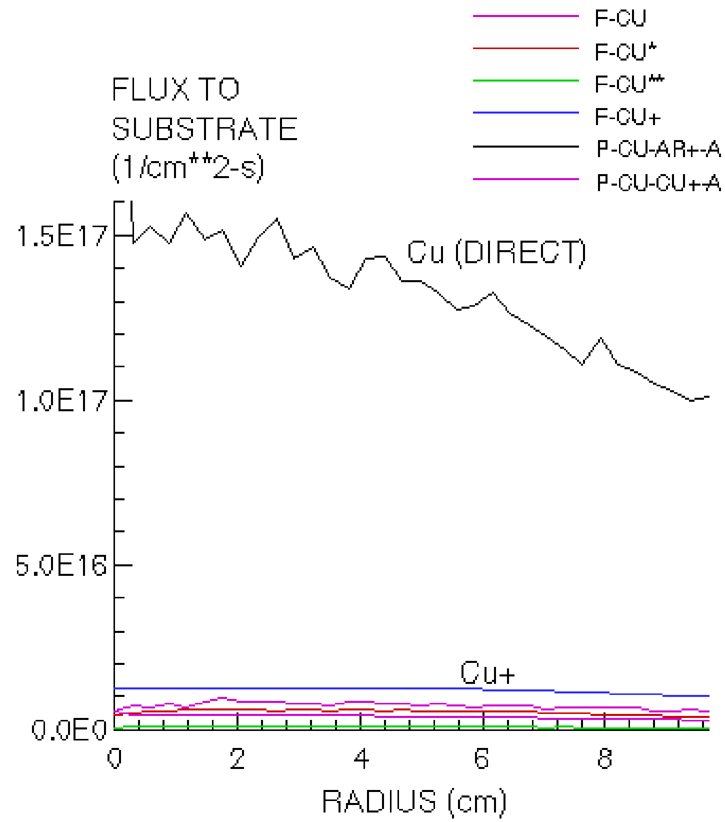
FLUXES IN THE Ar/Cu PVD TOOL

- Ion sputtering of the target produces a neutral Cu flux into the plasma.

- The low gas pressure and long mean free math of Cu atoms results in the flux to the substrate being "direct" neutrals.

- Ion Flux





- Ar, 3.5 mTorr
- -200 V Target, 200 G

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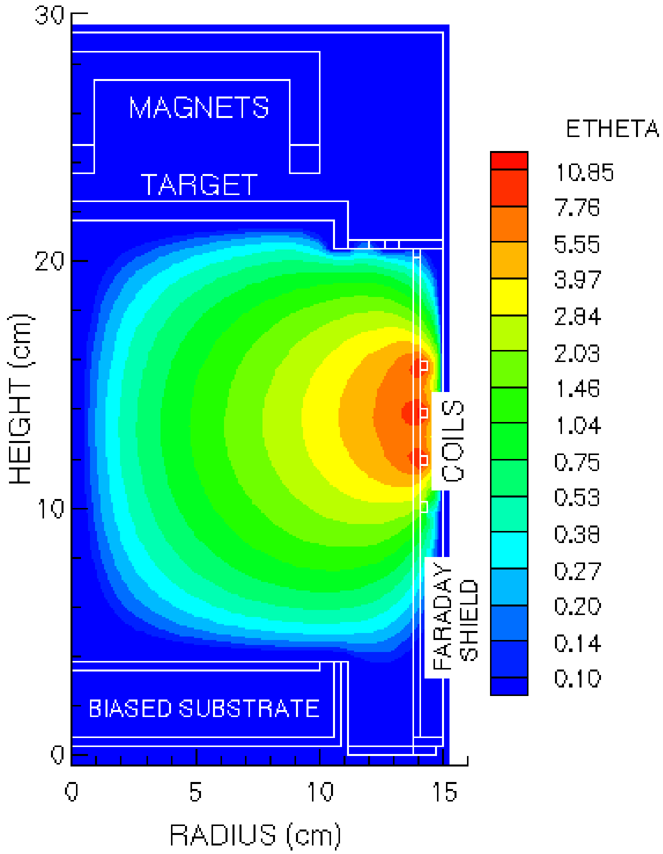
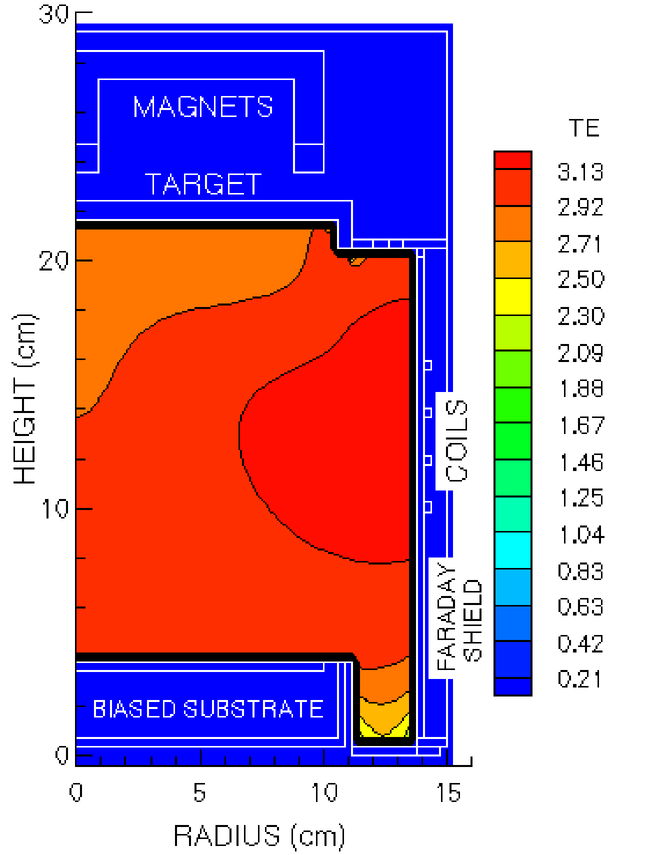
IMPVD TOOL: FIELDS AND TEMPERATURES

- The added inductively coupled electric field from the rf coils heats electrons in the bulk plasma producing a peak in temperature away from the target.

- Electric field



- Electron Temperature

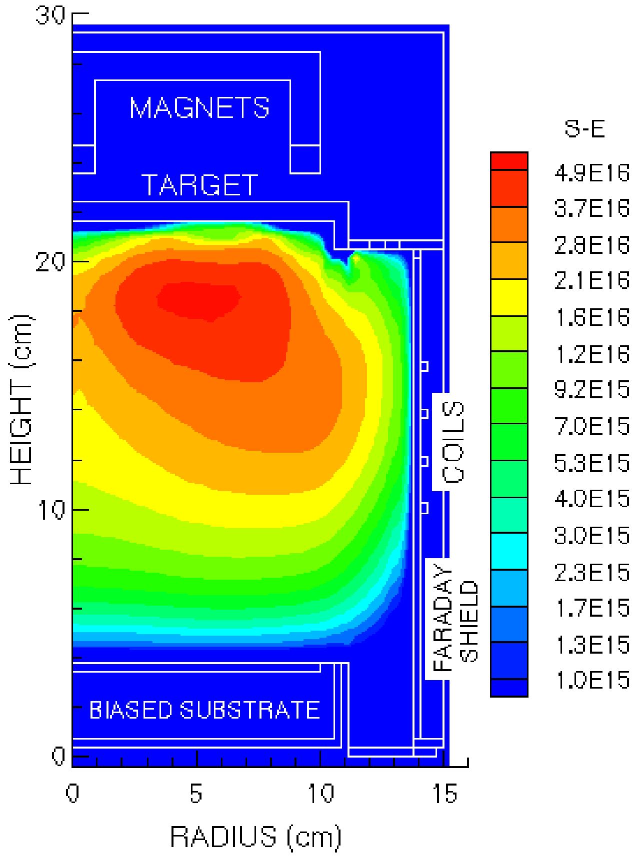


- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz

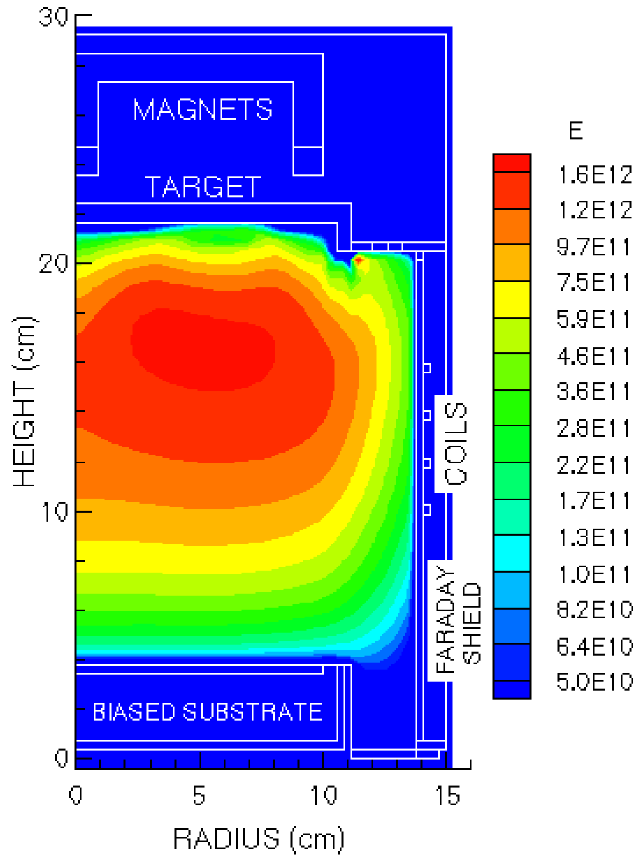
IMPVD TOOL: ELECTRON SOURCE AND DENSITY

- The combination of the magnetron fields and heating from the rf coils produces a more extended electron source and electron density. The ion density is 75% argon.

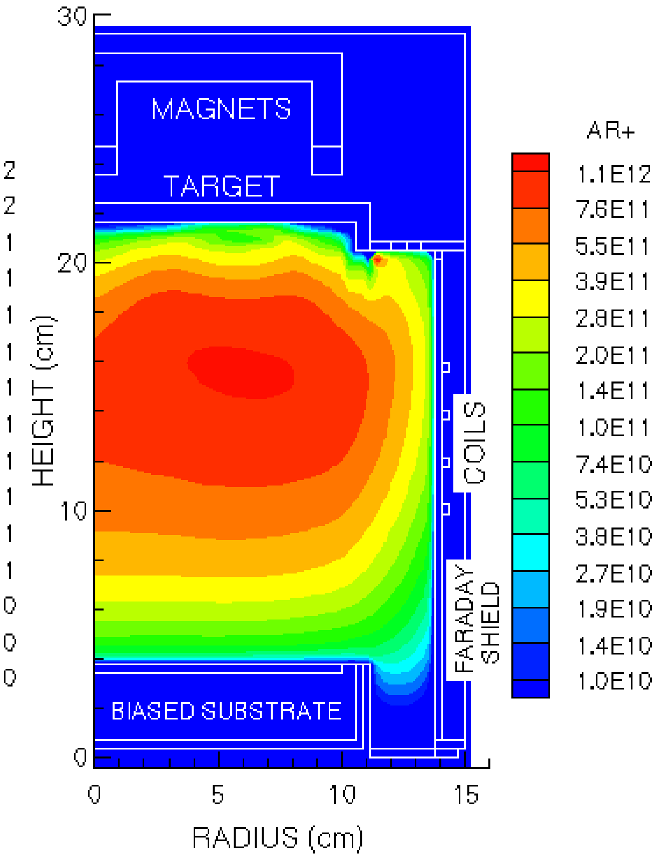
- Electron Source



- Electron Density



- Ar^+



- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz

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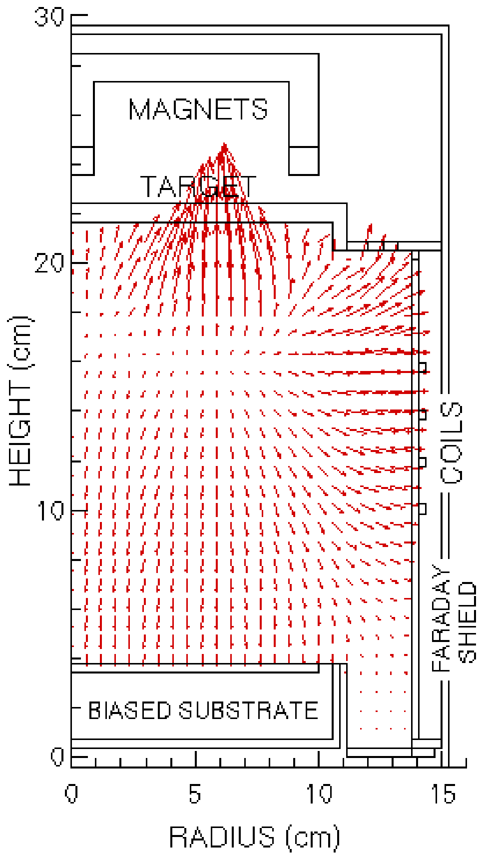
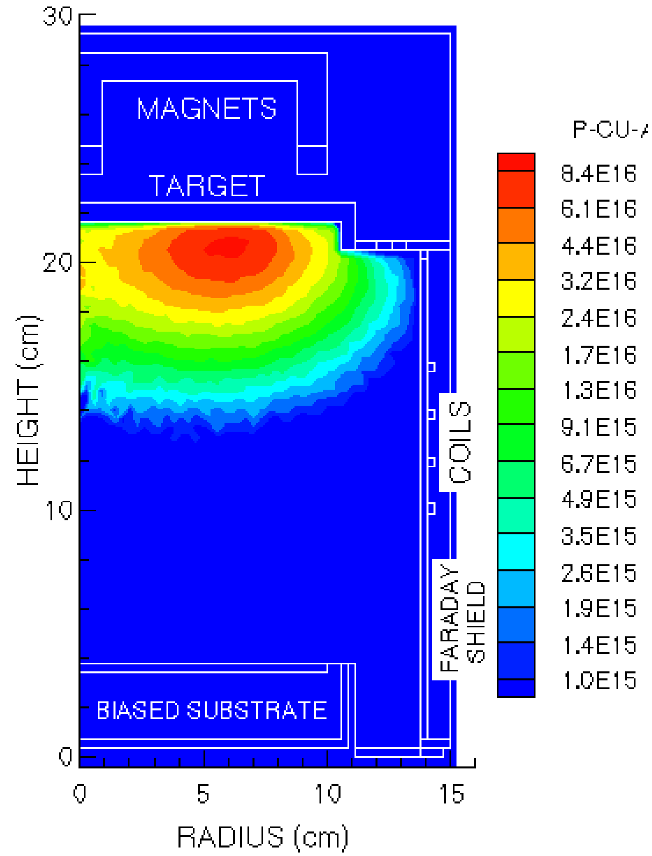
IMPVD TOOL: ION FLUX AND SPUTTER SOURCE

- The magnetron focus the ion flux to the target, producing a sputter source of Cu atoms.

- Due to the high gas pressure, the Cu atoms are thermalized in the vicinity of the target.

- Ion Flux





- Cu Source

- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz

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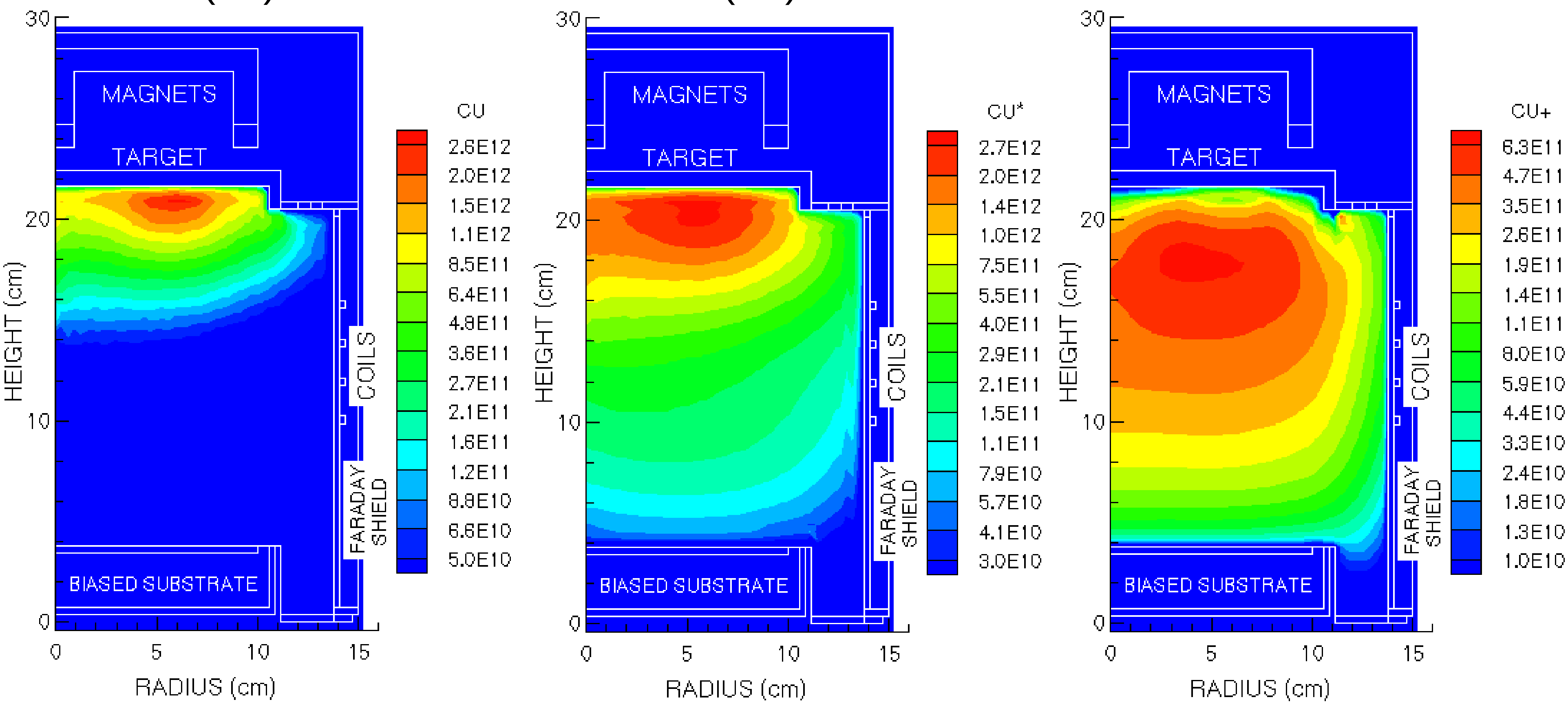
IMPVD TOOL: Cu DENSITIES

- Due to the longer residence time of Cu in the chamber and the higher electron temperature produced by the rf heating, the Cu inventory is largely converted to ions and metastables [Cu(^{2}D)].

• Cu(^{2}S) • Cu(^{2}D) • Cu$^+$



- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz

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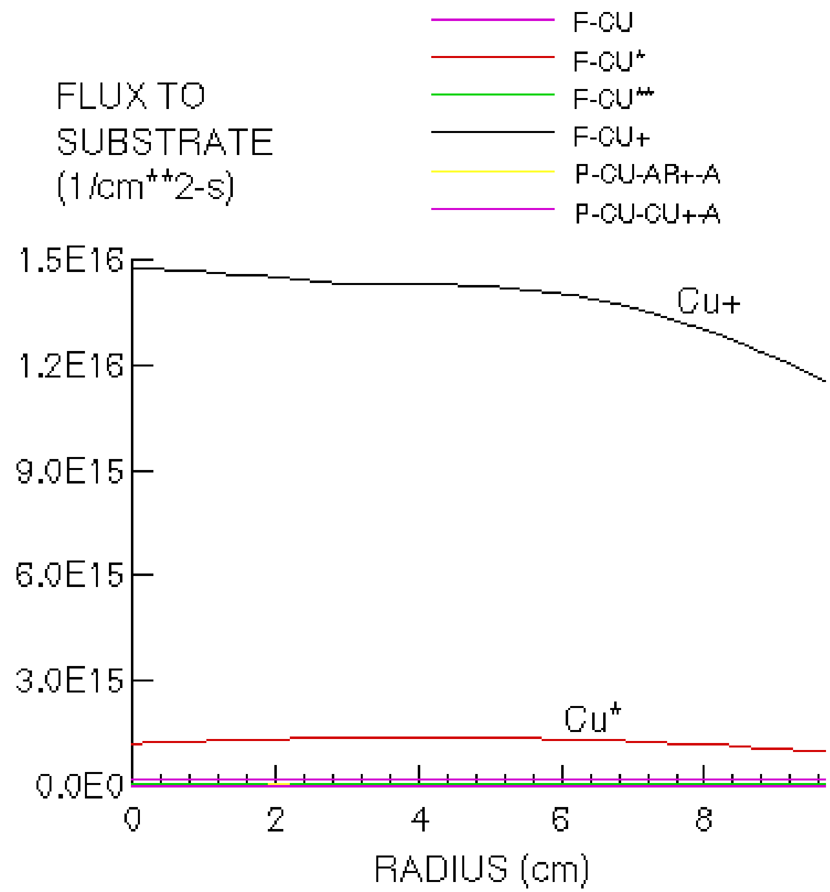
IMPVD TOOL: Cu FLUXES TO SUBSTRATE

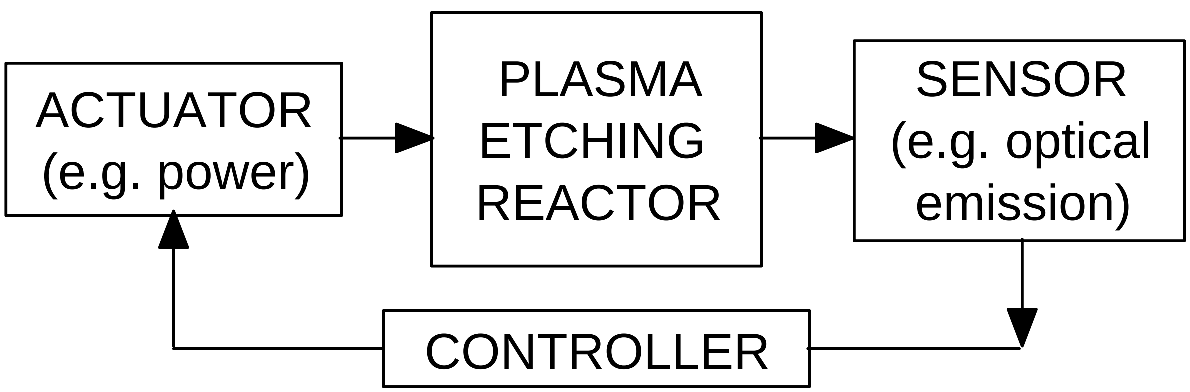
- The flux of Cu to the substrate is 85-90% ionized.
- The neutral flux is largely metastable Cu(^{2}D).



- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz

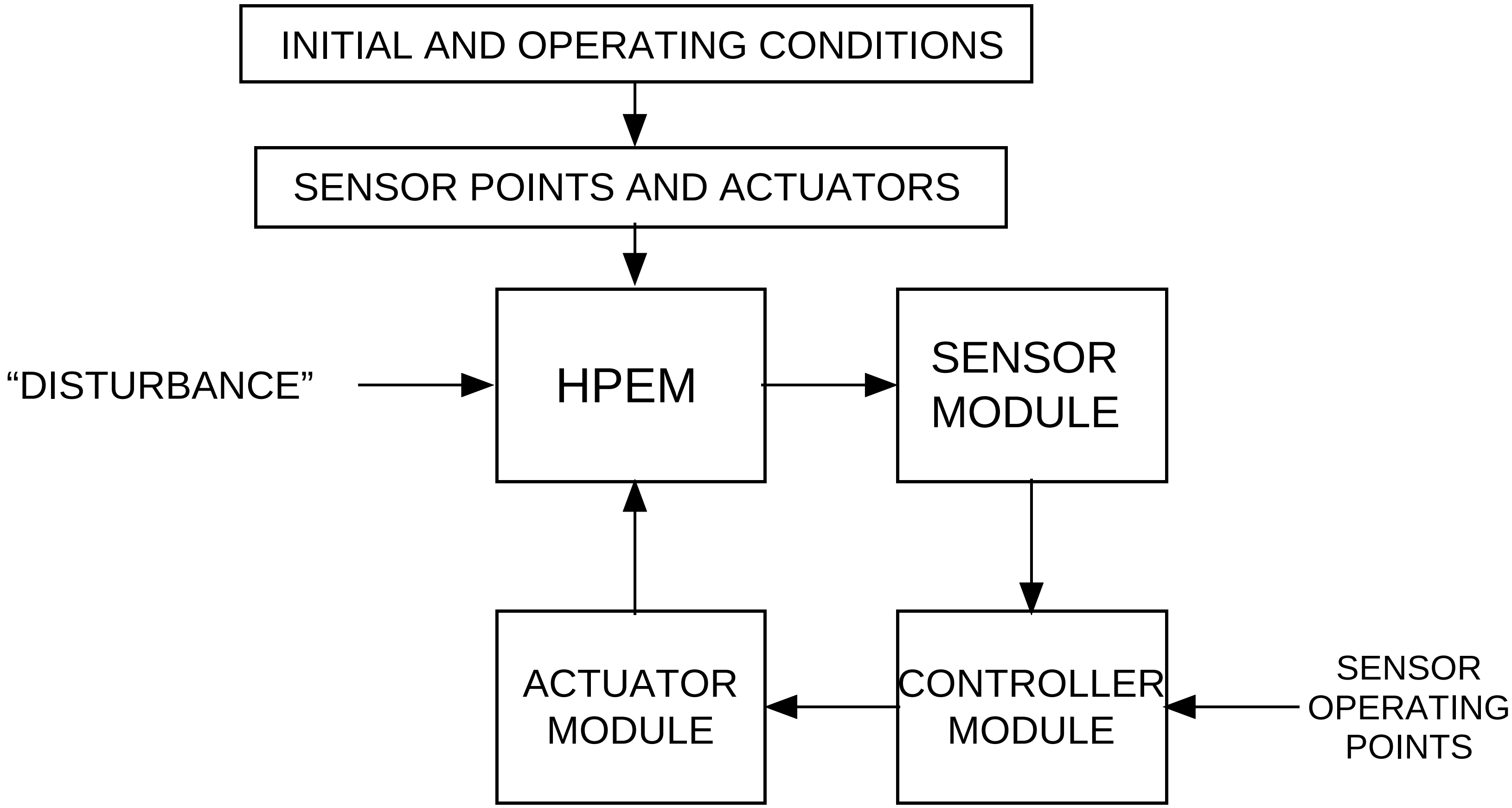
REAL TIME CONTROL

- The "street" value of a processed 300 mm silicon wafer containing state-of-the-art microprocessors is about $300,000.
- There are 300-400 manufacturing steps over about 1 month.
- A single manufacturing step which goes "sour", particularly at the back-of-the-line, and which kills a die or reduces performance of the microprocessors has an extreme "opportunity" cost.
- Real-time-control (RTC) strategies are being developed to maintain manufacturing processes within desired ranges of operating conditions, and so minimize loss of wafers (and consumables).



VIRTUAL PLASMA EQUIPMENT MODEL (VPEM)

- The Virtual Plasma Equipment Model (VPEM) is a “shell” which supplies sensors, controllers and actuators to the HPEM.



SENSORS AND ACTUATORS IN THE VPEM

- **The VPEM has been equipped with a variety of sensors and actuators.**
- **Sensors:**
  - **Spatially averaged densities**
  - **Densities at points**
  - **Optical emission through ports**
  - **Electrical sensors (I-V)***
  - **Optical Interferometer***
  - **Mass spectroscopy**
  - **Fluxes to surfaces**
  - **Bias power**
  - **Langmuir probe***
  - **Pressure**
- **Actuators:**
  - **Pressure**
  - **Inductive power**
  - **Coil currents**
  - **Power supply frequency**
  - **Flow rate/mole fractions**
  - **Bias power**
  - **Electrode voltage**
  - **Match box settings***

*** Under development**

RESPONSE SURFACE BASED CONTROL ALGORITHM

- **Response-surface based controllers are typically used in the VPEM.**
- **The response surface is developed by performing a "S-DOE" (statistical design of experiments) using the commercial software package "E-CHIP".**
- **The response surface is constructed in the following manner:**
  - **Sensors, actuators and parameter are specified.**
  - **Using E-CHIP, a statistical model is specified, a set of "experimental" points are selected; and simulations run for those parameters.**
  - **A response surface is constructed from the simulation results, and least mean square (LMS) polynomial coefficients are computed. In the case of a 2 sensor-2 actuator control scheme**

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} x^{1}_{2} \\ x^{2}_{2} \end{bmatrix} + \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} x_1 x_2$$

- **We assume that small perturbations do not significantly alter the response surface, and linearize the system.**

RESPONSE SURFACE BASED CONTROL ALGORITHM

- **The changes in sensor outputs resulting from small changes in actuator settings are**

$$\begin{bmatrix} dy_1 \\ dy_2 \end{bmatrix} = \begin{bmatrix} b_{11} + 2c_{11}x_1 + d_1x_2 & b_{12} + 2c_{12}x_2 + d_1x_1 \\ b_{21} + 2c_{21}x_1 + d_2x_2 & b_{22} + 2c_{22}x_2 + d_2x_1 \end{bmatrix} \begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = A \begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix}.$$

- **Taking the inverse,**

$$\begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = A^{-1} \begin{bmatrix} dy_1 \\ dy_2 \end{bmatrix}.$$

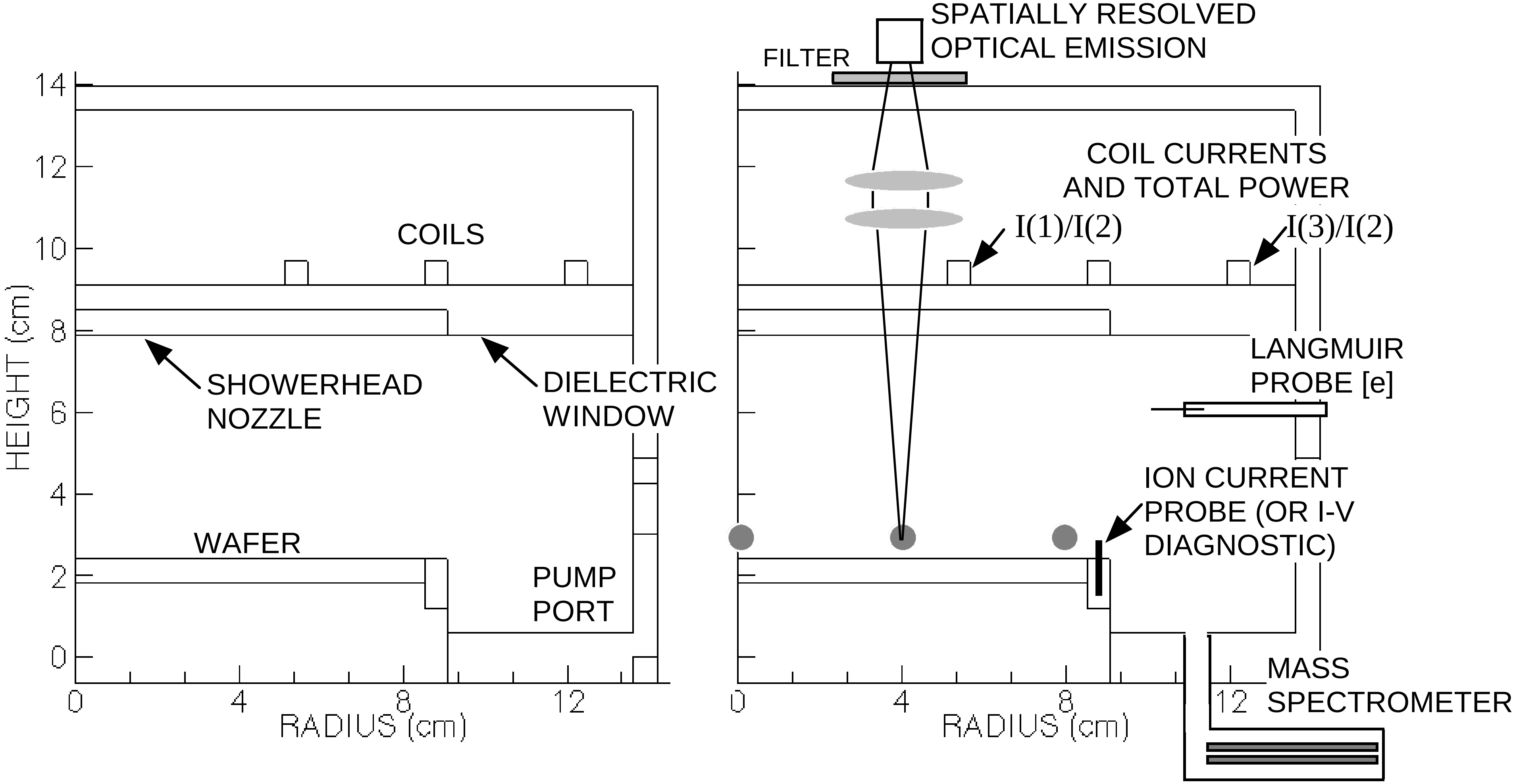
- **To restore the system from a perturbed condition (y_1',y_2') to desired a desired condition (y_1,y_2) the actuators are changed by**

$$\begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = gA^{-1} \begin{bmatrix} \left(y_1 - y_1'\right) \\ \left(y_2 - y_2'\right) \end{bmatrix}$$

where g is a specified gain.

ICP PLASMA TOOL: GEOMETRY, SENSORS, ACTUATORS

- An Inductively Coupled Plasma (ICP) reactor will be used to demonstrate control strategies during transients and recipe changes.
- Sensors: Optical emission, mass spectroscopy, ion current, electron density
  Actuators: Coils currents, power deposition, pressure



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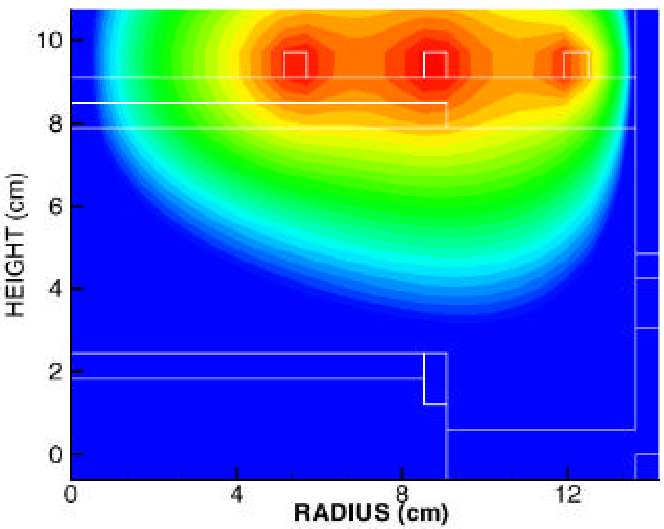
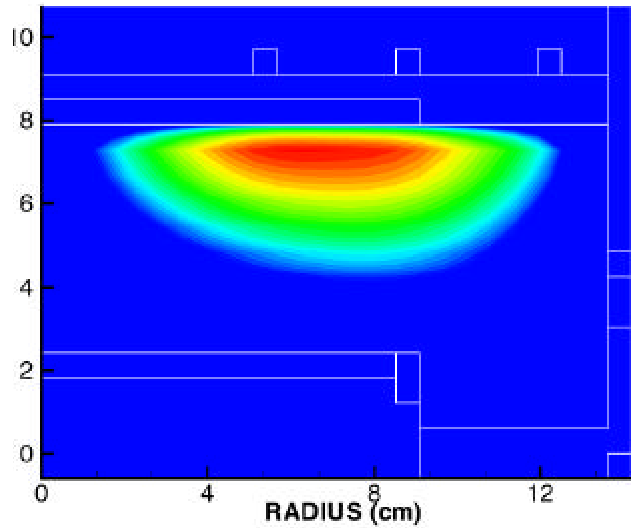
TYPICAL ICP DENSITIES

• Electric Field (8.8 V/cm)

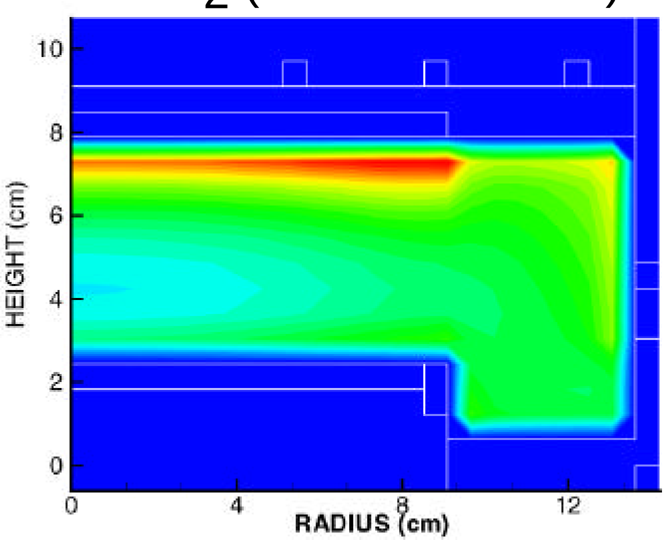


• Power (0.5 W/cm^3)

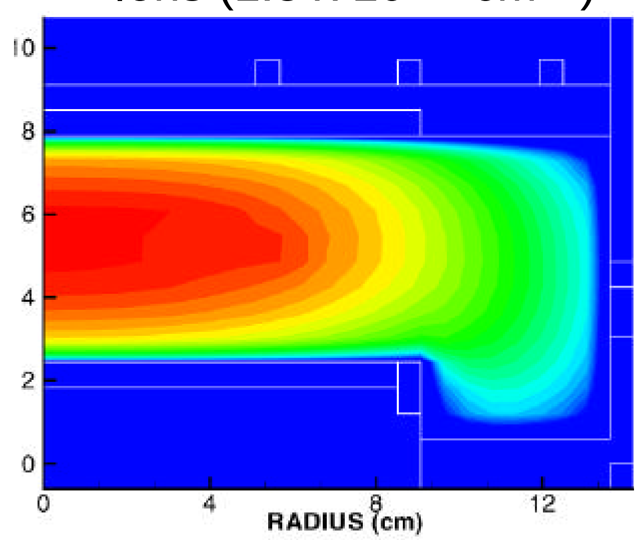


• Ar/Cl_2 = 98/2, 10 mTorr, 200 W, 250 sccm

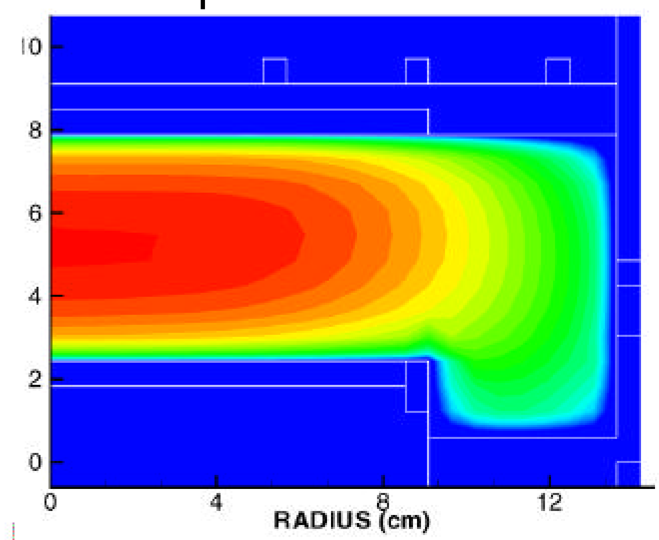
• Cl_2 (6.9 x 10^{11} cm^{-3})



• Ions (1.8 x 10^{11} cm^{-3})



• Optical Emission



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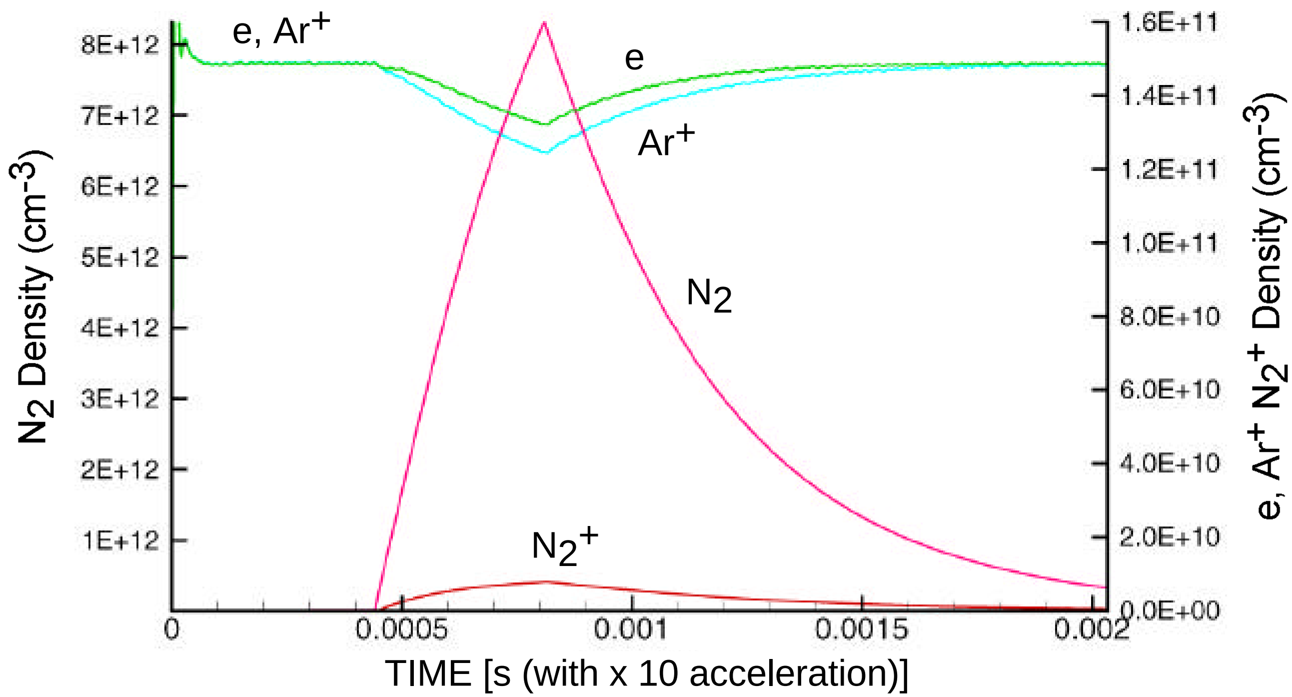
ICP Ar PLASMA TOOL WITH N_2 INJECTION

- The Mass Flow Controller (MFC) in an ICP plasma tool (Ar, 10 mTorr) malfunctions and injects a pulse of N_2 (25 sccm)

- Due to the large inelastic electron impact cross sections of N_2, the electron and ion densities decrease.



- Ar, 10 mTorr, 250 sccm, 200 W

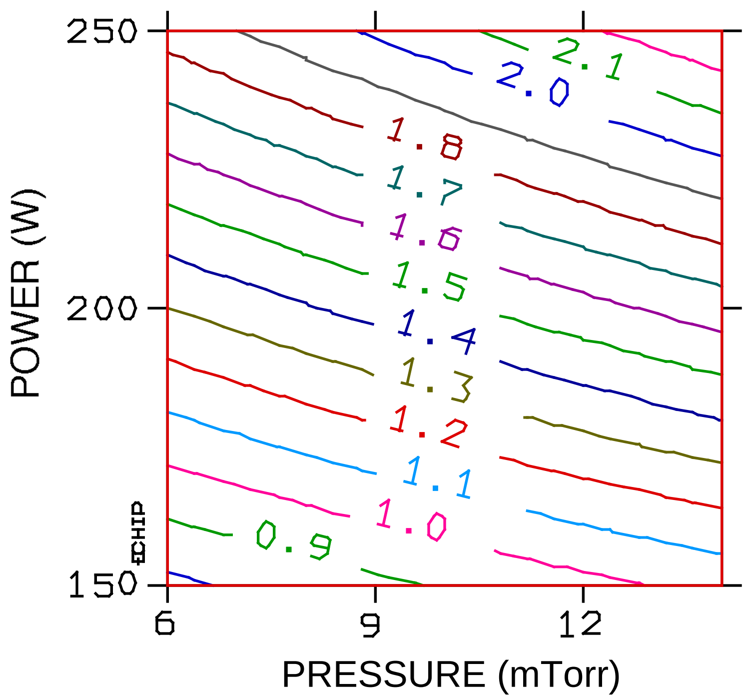
SENSORS-ACTUATORS FOR CONTROL OF GAS INJECTION

- Since etch rate depends on the total rate of radical production and ion bombardment on the wafer, choose electron density and ion flux as sensors.

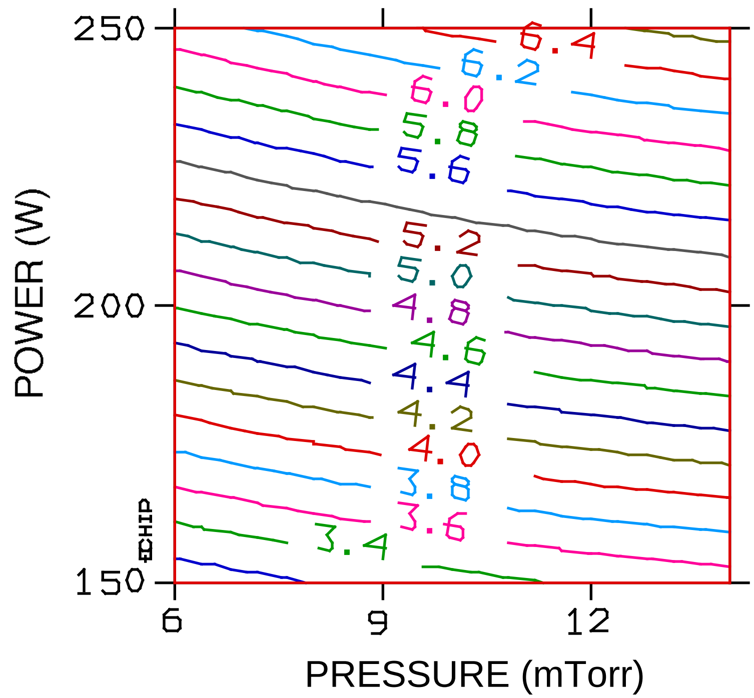
- Since radical production scales with electron density and ion flux with pressure, choose power and pressure as actuators.

- Response surfaces obtained from DOE. Note weaker dependence on pressure implying need for lower gain.

ELECTRON DENSITY (10^{11}cm^{-3})



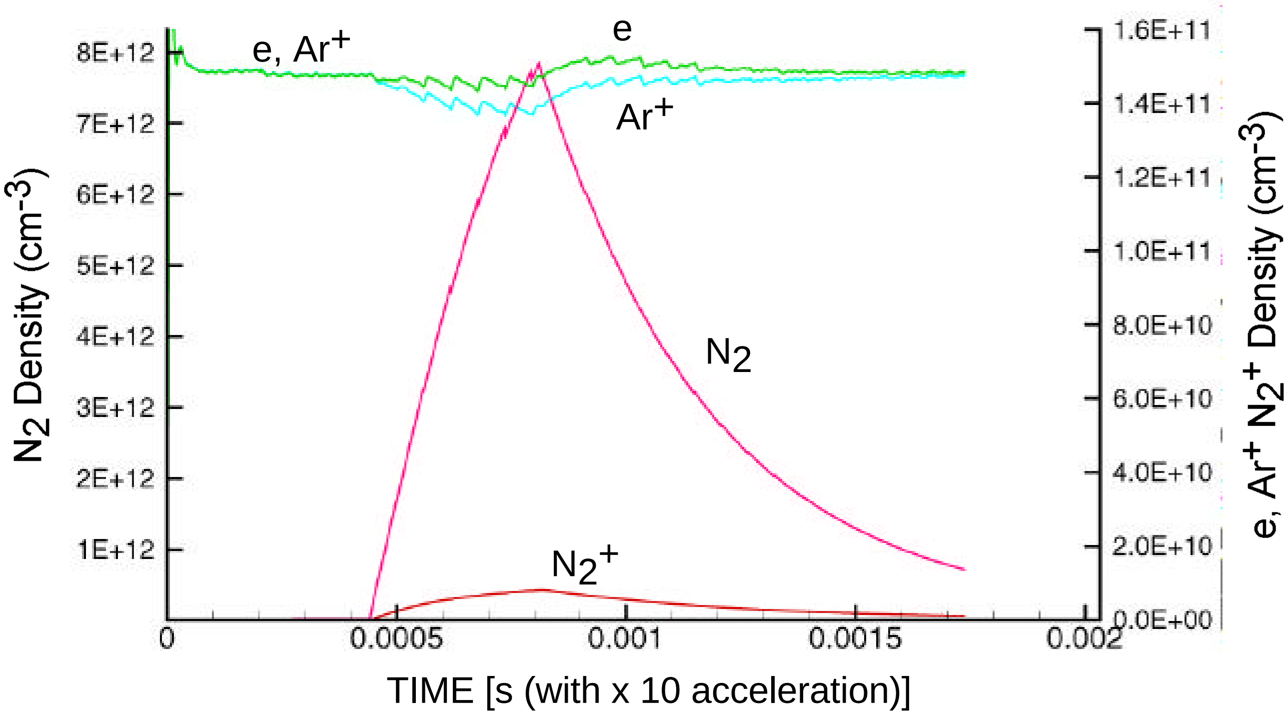
ION FLUX TO WAFER (10^{18} s^{-1})



- Ar, 10 mTorr, 250 sccm

ICP Ar PLASMA TOOL: N_2 INJECTION w/CONTROL

- The electron (and ion) densities are only moderately well regulated against the perturbation by N_2 injection.
- The response surface was formulated using pure Ar, whereas the characteristics of the perturbed system differ significantly.
- As the N_2 density increases as the "pulse" moves through the reactor, larger actuator adjustments "in the future" are required than the controller suggests.



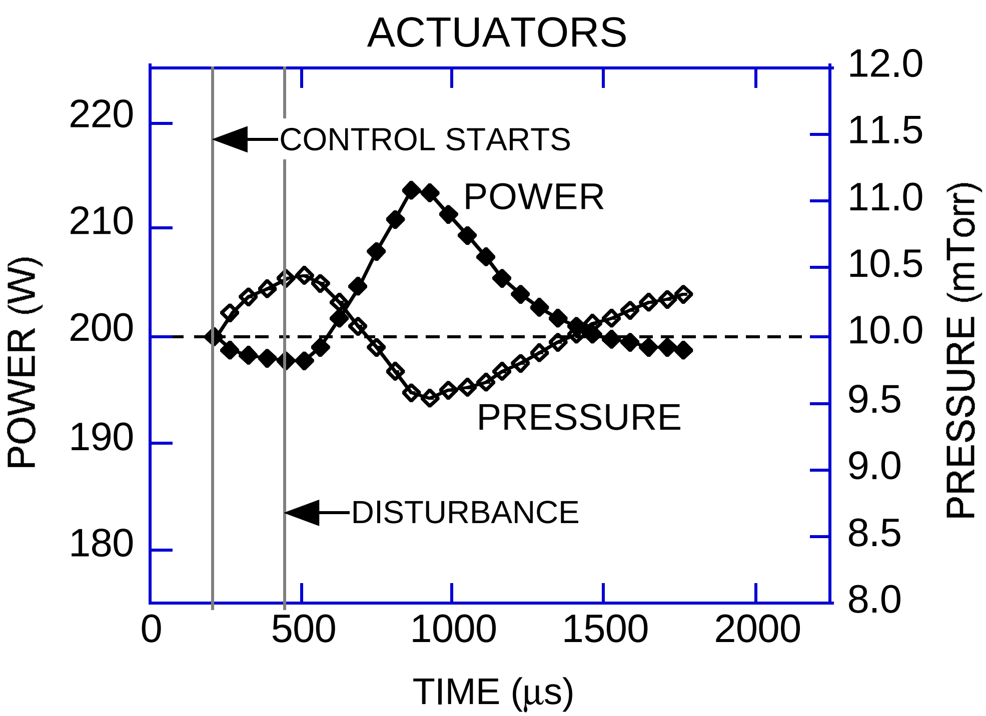
- Ar, 10 mTorr, 250 sccm, 200 W

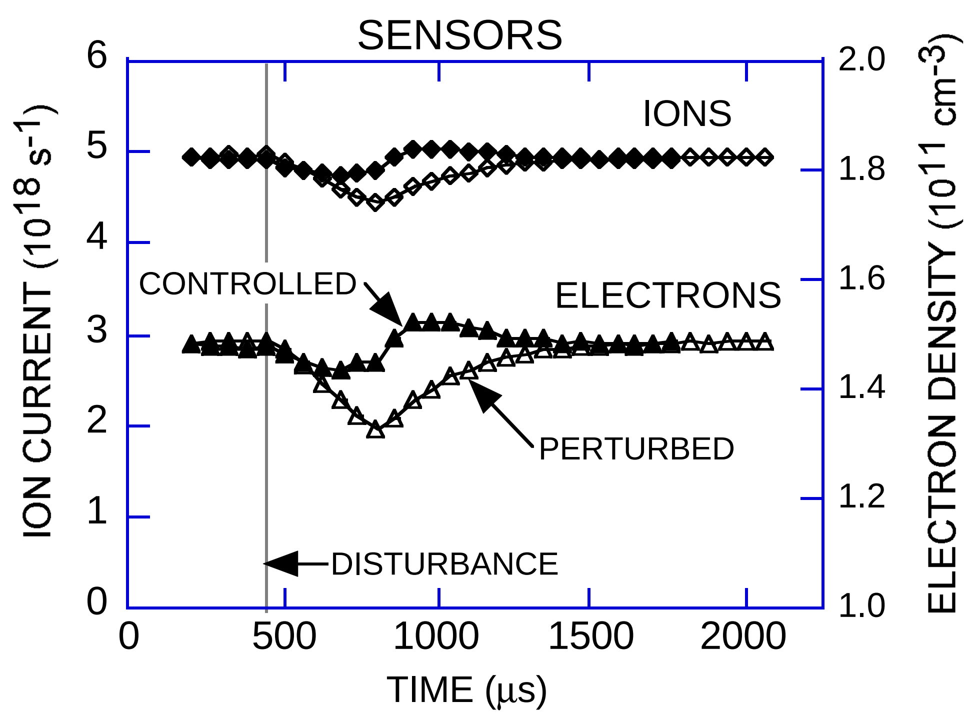
ICP Ar PLASMA TOOL: N_2 INJECTION w/CONTROL (cont.)

- When the N_2 density increases, the controller underpredicts changes in actuator settings since the “future” conditions are always “worse”. When the N_2 density decreases, the controller overpredicts changes since future conditions are “better”.

.

- To address these issues, the controller requires knowledge of the “physics” of the disturbance or must cycle at a high enough frequency to negate poor knowledge of the future.





- Ar, 10 mTorr, 250 sccm, 200 W

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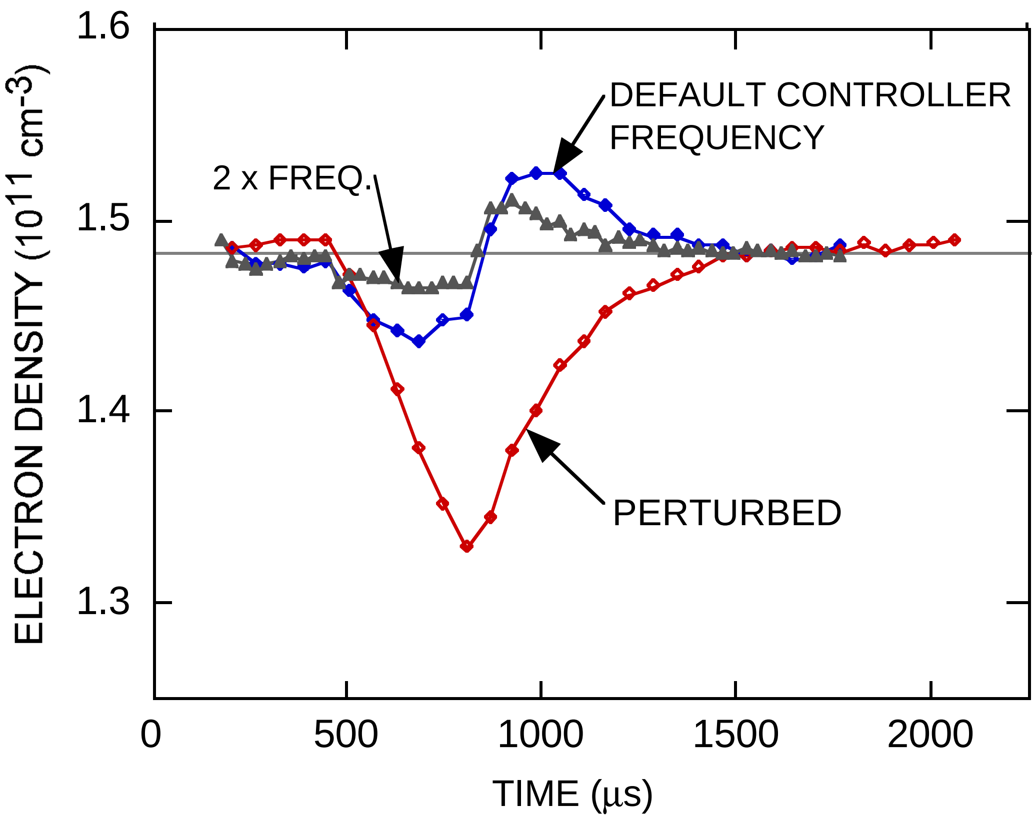
CONTROLLING AGAINST UNKNOWN TRANSIENTS (cont.)

- With no apriori knowledge of the "physics" of the transients, one strategy is to increase the frequency of the controller so that lack of knowledge of future (or present) conditions is less of an issue.

- By doubling the frequency of the controller, a higher degree of control is obtained.



- Ar, 10 mTorr, 250 sccm, 200 W

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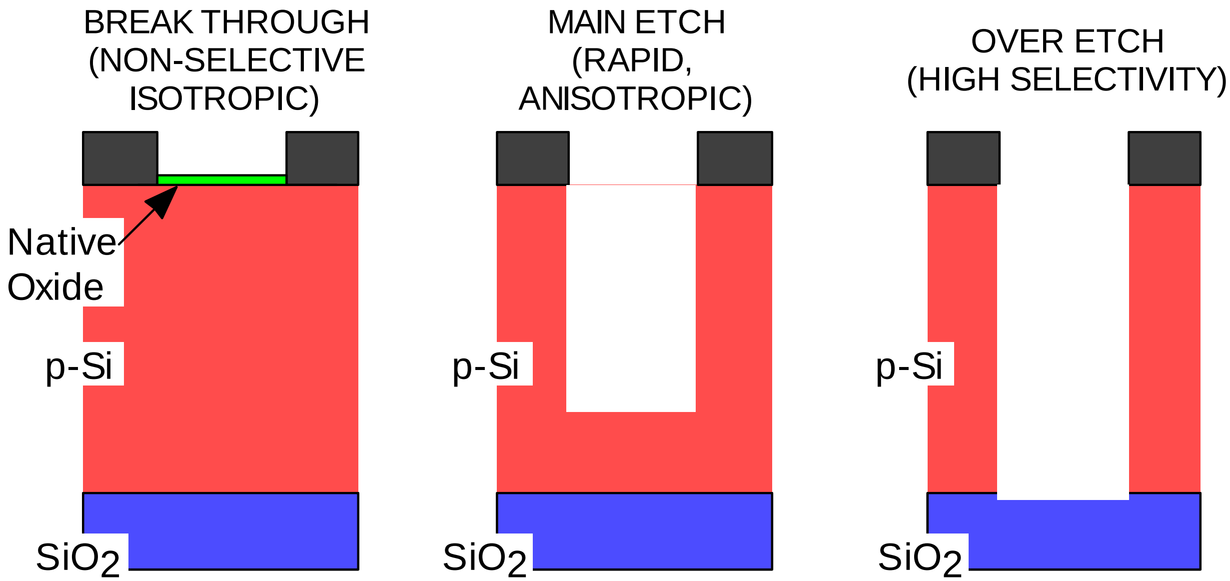
RECIPE CHANGES AND IMPACT ON CONTROL

- During a plasma etching process, it is not unusual for there to be 2-4 "recipe" changes.
- Recipe changes are different values of, for example, power, pressure, flow rate or gas mixture to address beginning, middle and end of the etch.



- Changes in recipes may produce unanticipated changes in plasma parameters such as uniformity or rate which may need to be controlled.

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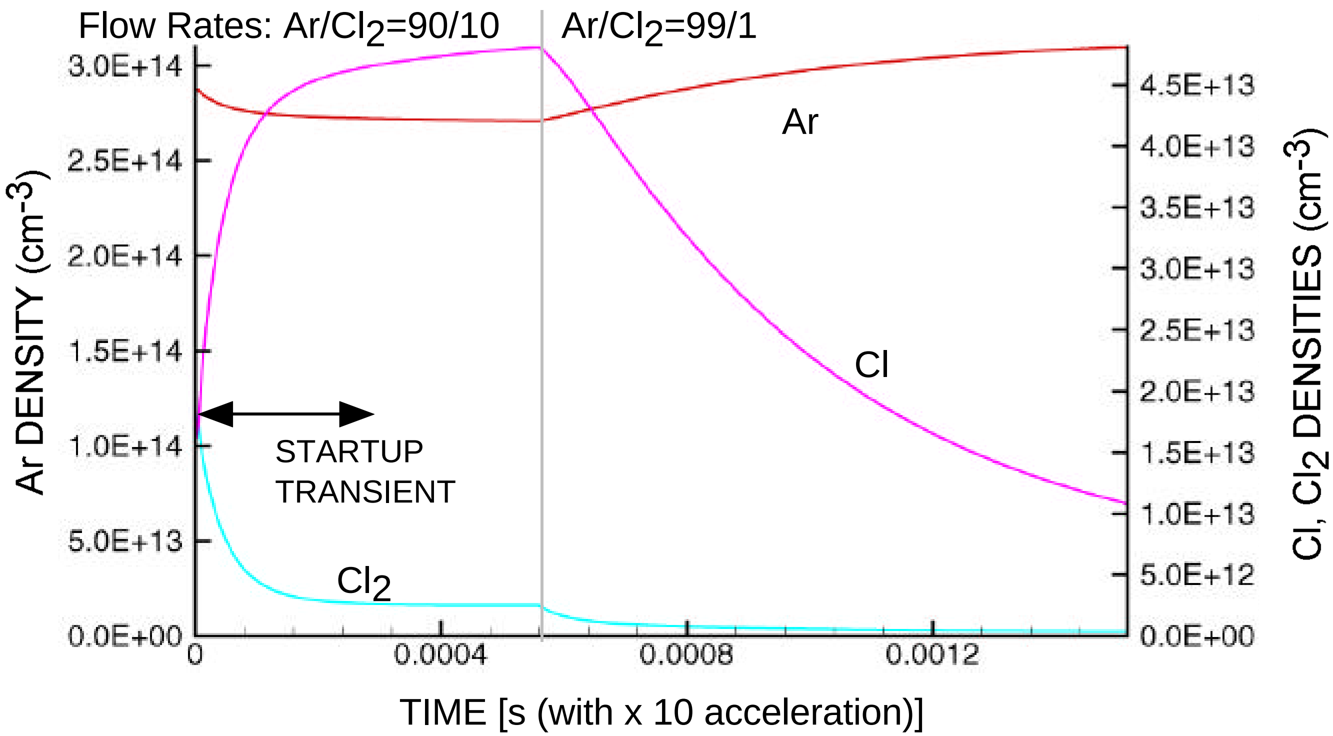
Optical and Discharge Physics

RECIPE CHANGE: Ar/Cl_2 p-Si ETCH TOOL

- An ICP reactor undergoes a recipe change during which the input flow rate changes from Ar/Cl_2 = 90/10 to 99/1. “Clearing” through the reactor produces an intermediate term transient which will be “controlled”.

- Electron impact processes deplete Cl_2, produce radicals, ions and excited states which radiate.



$e + Cl_2 > Cl + Cl$

$e + Cl_2 > Cl_2^+ + 2e$

$e + Cl_2 > Cl^- + Cl$

$e + Cl > Cl^+ + 2e$

$e + Cl > Cl^* + e$

$e + Cl^* > Cl^+ + 2e$

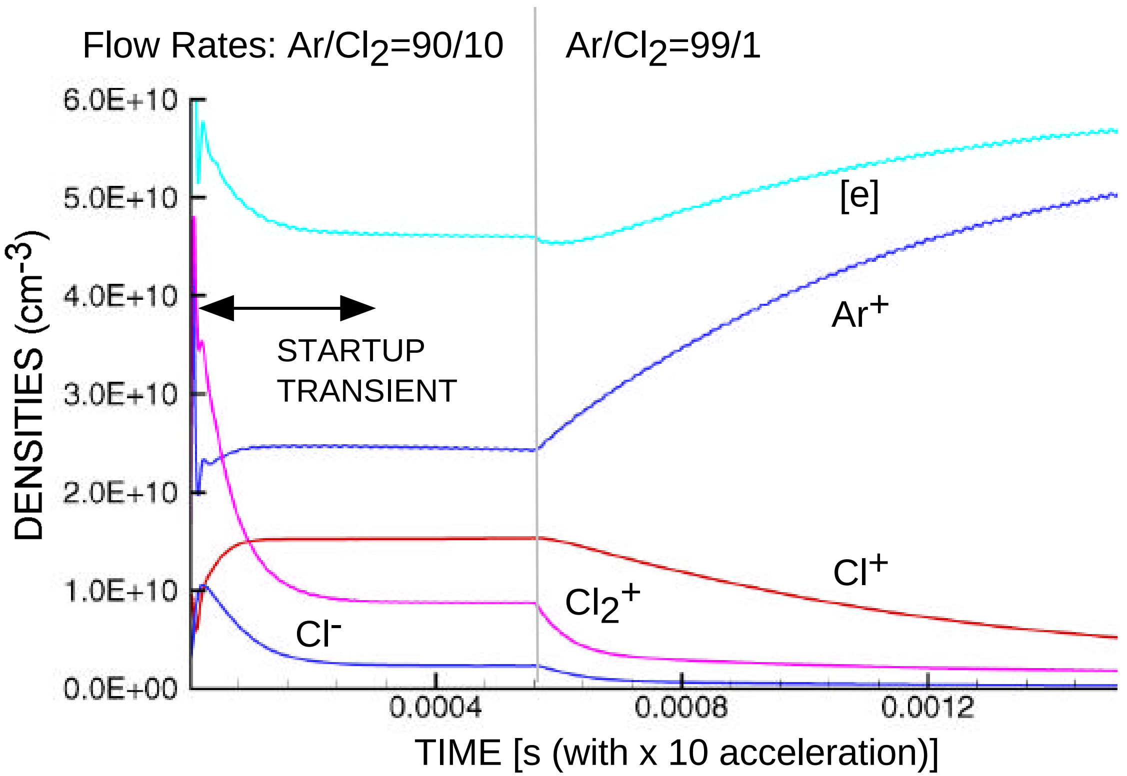
$e + Ar > Ar^+ + 2e$

$e + Ar > Ar^* + e$

- 10 mTorr, 250 sccm, 200 W

RECIPE CHANGE: Ar/Cl p-Si ETCH TOOL (cont.)

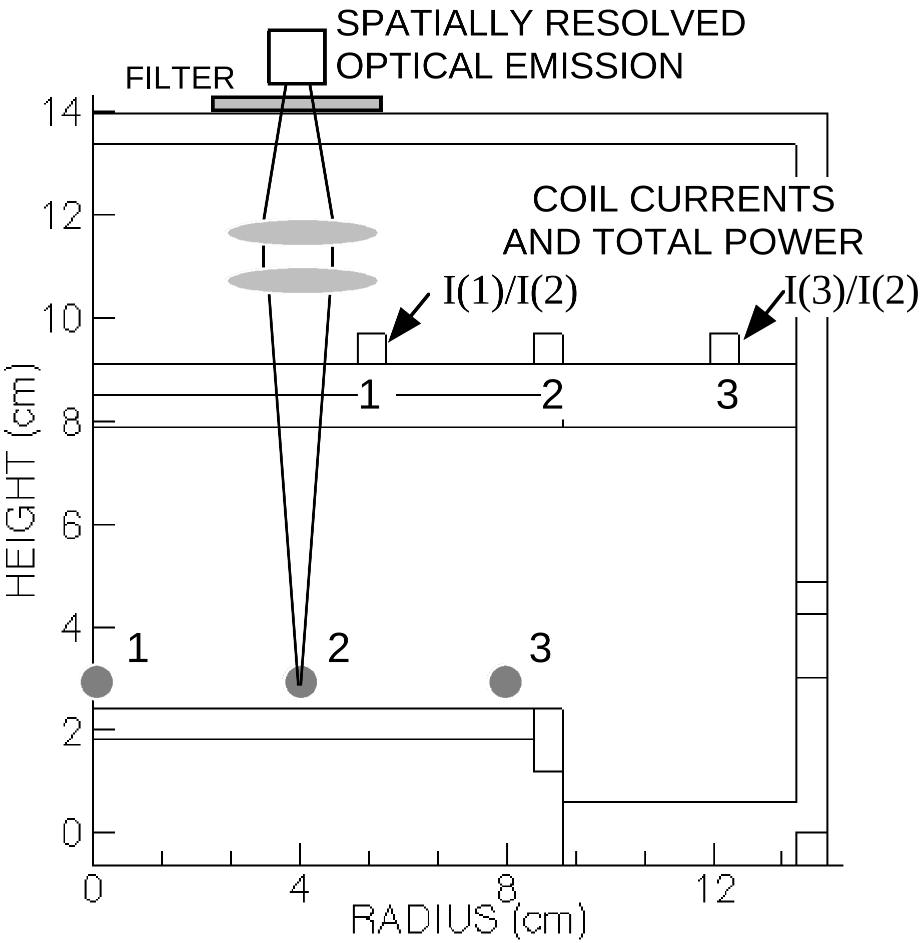
- Although the power deposition remains constant through the recipe change, the decreasing Cl_2 produces a decrease in electron loss rates and power transfer.
- As a consequence, total electron and ion densities increase (which one may want to control...)



- 10 mTorr, 250 sccm, 200 W

RECIPE CHANGE: CONTROL OF UNIFORMITY

- Goal: Control uniformity of etching before and after recipe change. Prior studies have shown a close correlation between Cl* emission and local etch rate.
- Sensors: Optical emission S(1)/S(2), S(3)/S(2)
  Actuators: Coils currents I(1)/I(2), I(3)/I(2)



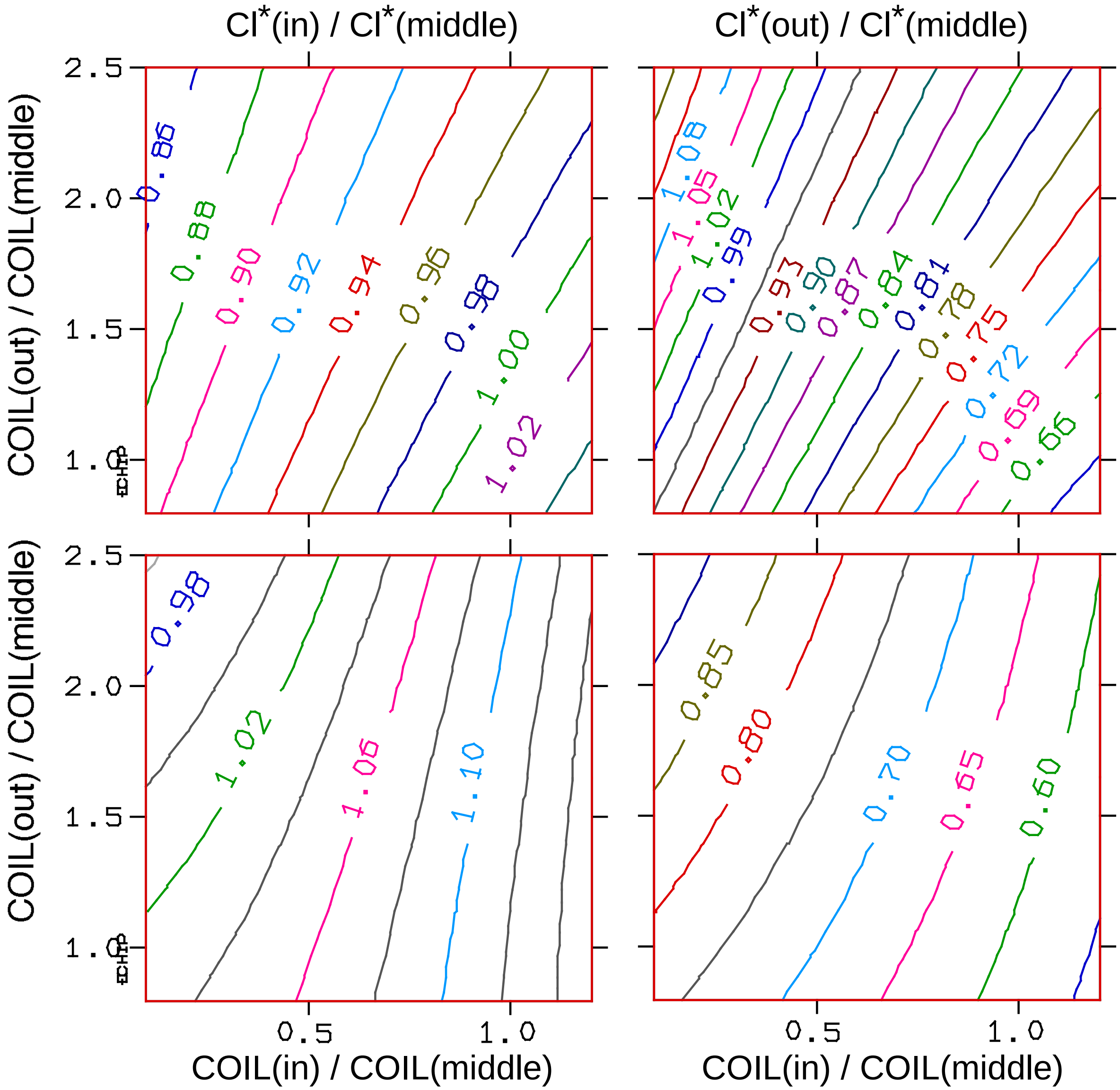
- During the recipe change, the chlorine density changes from 10% to 1%, with there being commensurate changes in plasma properties.
- In the absence of additional information, one must choose a chlorine density at which the response surface is developed and coefficients for the controller are derived.

RESPONSE SURFACES vs Ar/Cl_2 RATIO

- Response surfaces for uniformity of Cl* critically depend on the Ar/Cl_2 ratio.

Ar/Cl_2 = 90/10

Ar/Cl_2 = 99/1



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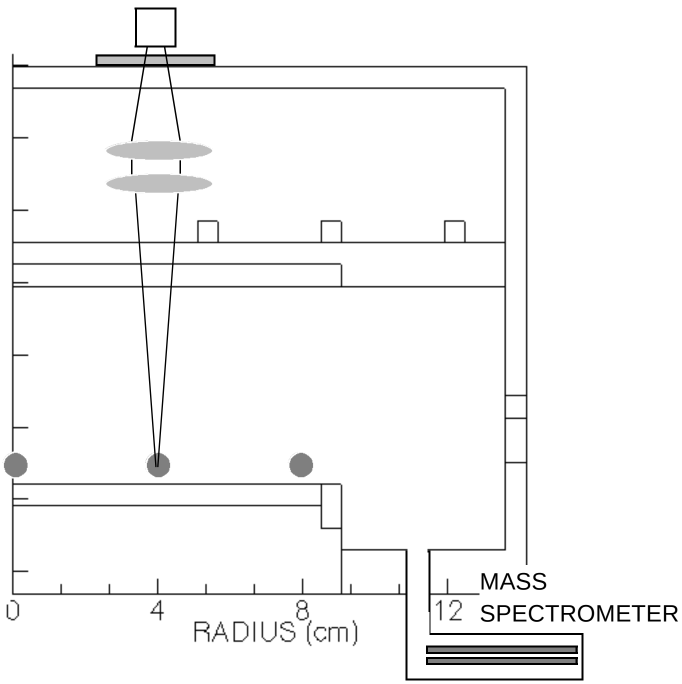
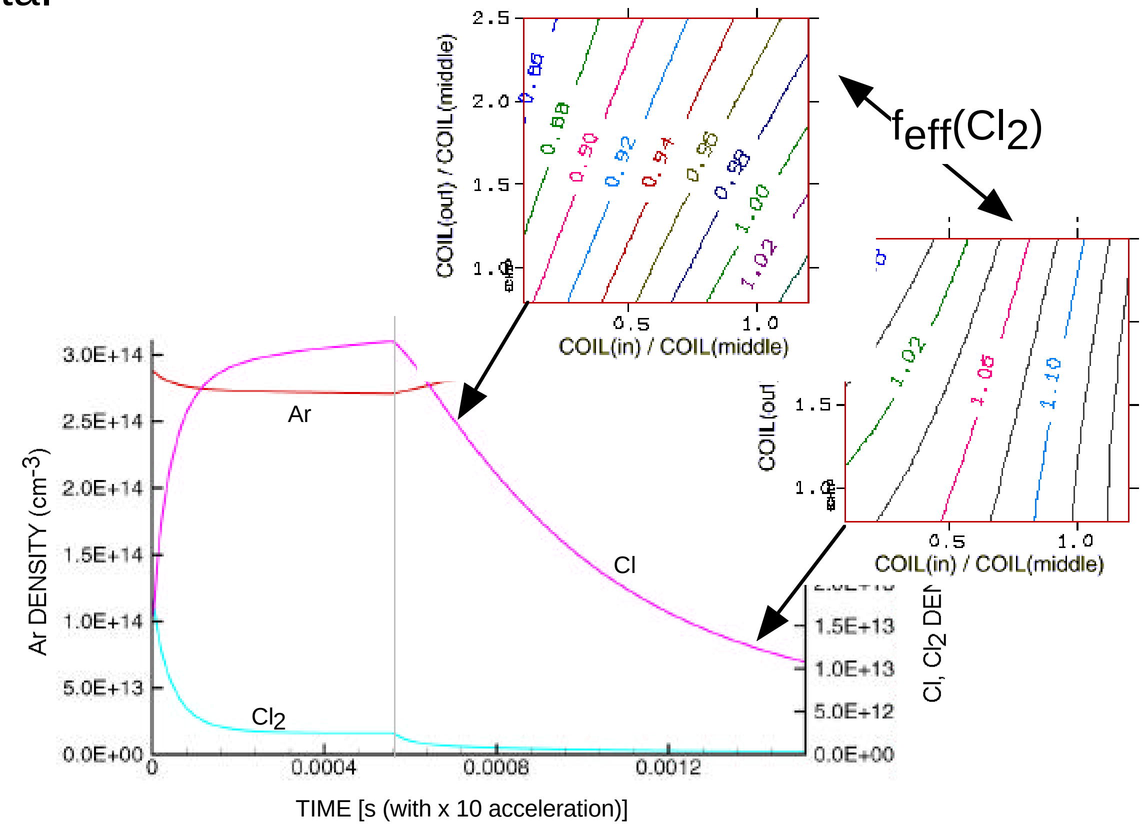
MULTI-PLANE RESPONSE SURFACES

- Although the additional sensor data from the mass spec cannot be used directly by the (2 x 2) controller, it can be used to select *coefficients* for the controller which better represent the current conditions.
- So interpolate *between* response surfaces developed for different Cl_2 flow rates based on mass spectrometer data.





$f_{eff}(Cl_2) = 0.5\, f(Cl) + f(Cl_2)$

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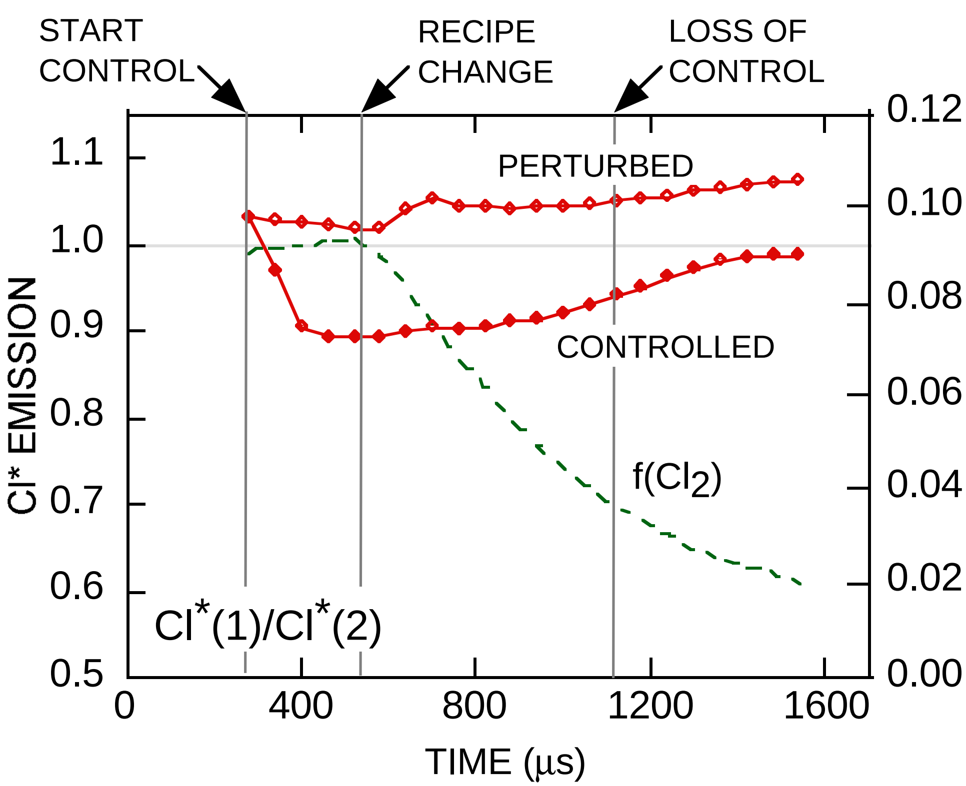
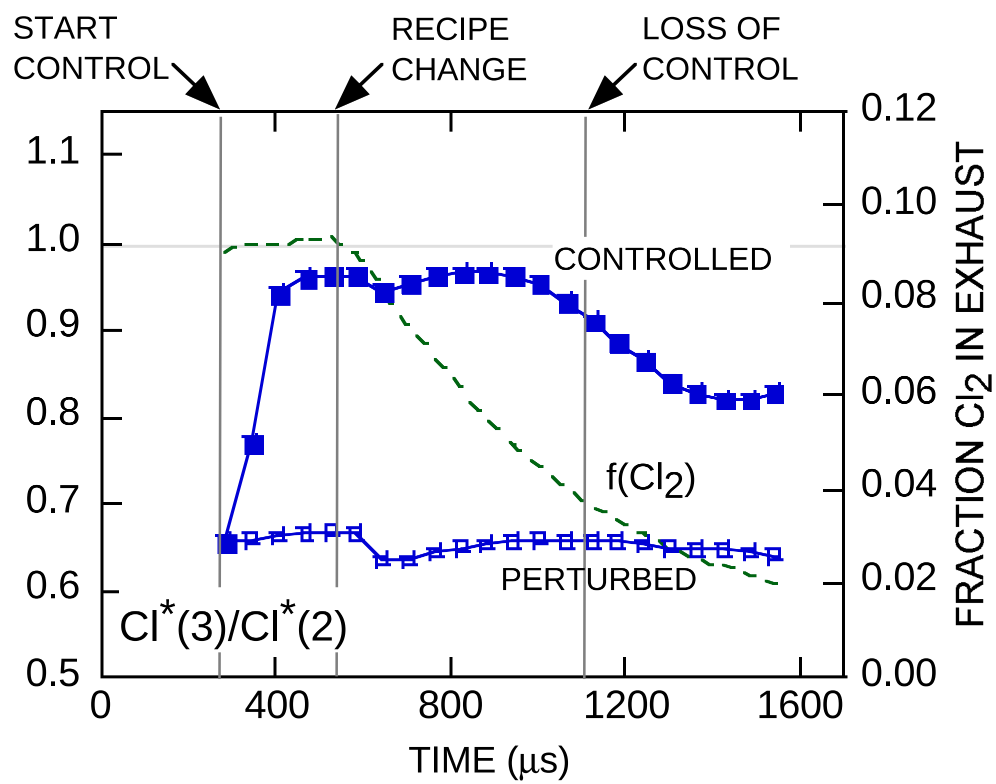
Ar/Cl_2 RECIPE CHANGE: SENSORS WITH 2 PLANE CONTROL

- In the absence of control, Cl* emission is peaked towards the center.
- With 2-plane control (Ar/Cl_2 = 90/10, 99/1), uniformity of emission at large radii is significantly improved, leading to an overall improvement in uniformity.
- Control is lost half way through the transient when the control surfaces do not represent instantaneous reactor conditions.





- Ar/Cl_2, 10 mTorr, 250 sccm, 200 W

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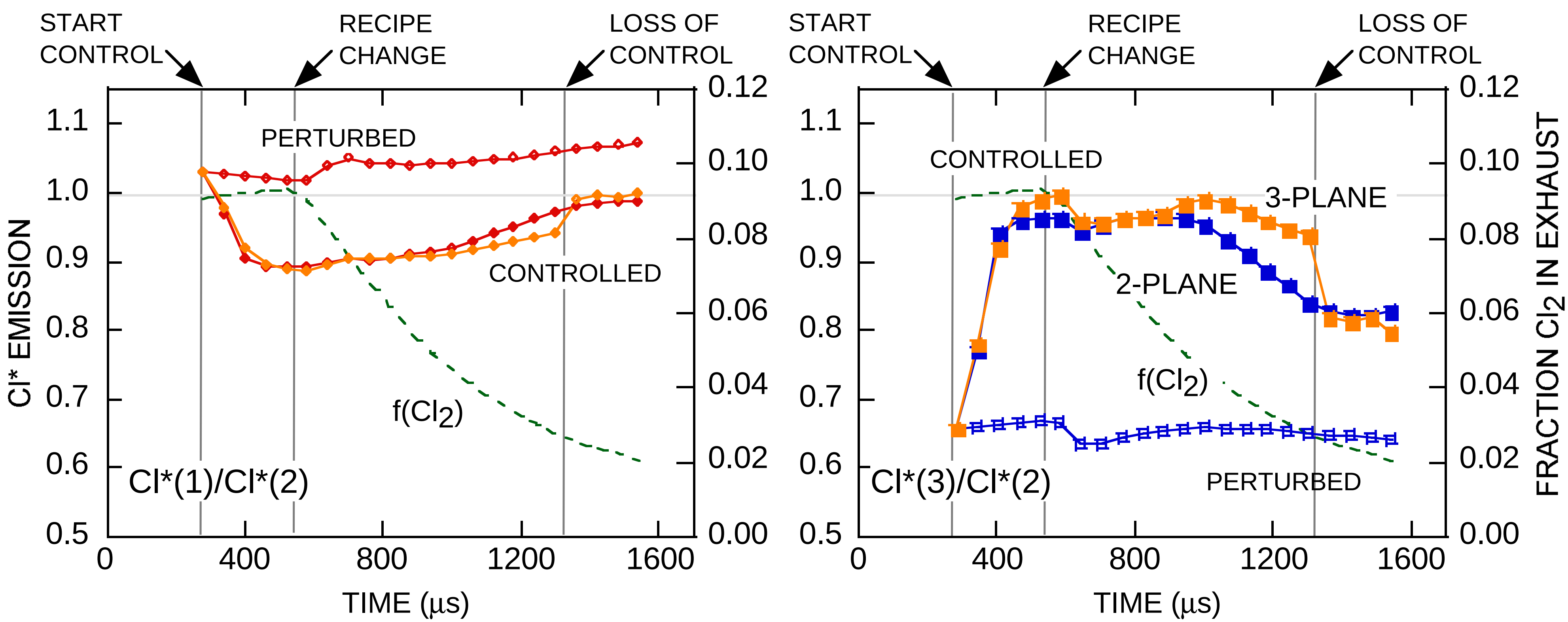
Ar/Cl_2 RECIPE CHANGE: SENSORS WITH 3 PLANE CONTROL

- By adding an additional plane of response surfaces (Ar/Cl_2 = 90/10, 95/5, 99/1), the time of control is extended.
- Control is most difficult to maintain at low mole fractions of Cl_2 where the spatial distribution of the plasma is changing most rapidly.



- Ar/Cl_2, 10 mTorr, 250 sccm, 200 W

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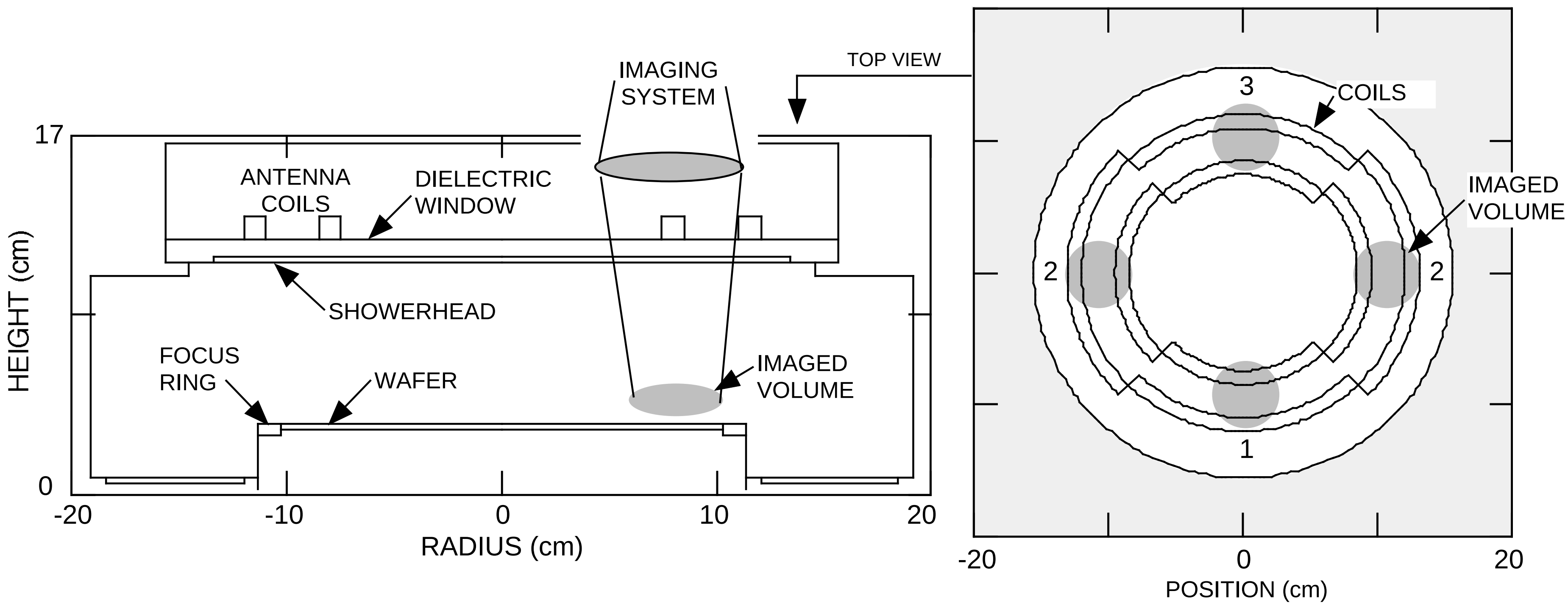
GEOMETRY FOR SEGMENTED ANTENNA CONTROL PROBLEM



- Sensors are optical emission from excited states of Cl atoms.
- Actuators are current through coils segments.
- For a 2 x 2 controller....

Sensor 1: (S(1)-S(3)) / [(S(1)+S(3)) x 0.5] Actuator 1: $I_{coil}(1) / I_{coil}(3)$
Sensor 2: (S(2)-S(3)) / [(S(2)+S(3)) x 0.5] Actuator 2: $I_{coil}(2) / I_{coil}(3)$

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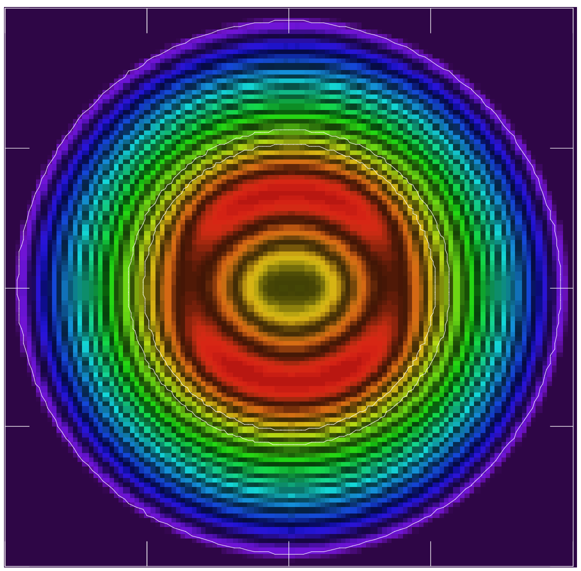
CHOICE OF DIAGNOSTIC

- Chlorine etching of p-Si in inductively coupled plasma reactors is typically in the “ion-starved regime”...That is, the etch rate uniformity weakly depends on Cl atom density (because it is so large) and strongly depends on the ion flux.

$$\text{Etch Rate} \propto \frac{j_{ion}}{j_{ion} + a\phi_{Cl}}$$

- The optical emission from Cl* is closely correlated with ion flux to the substrate, approximates this function well.

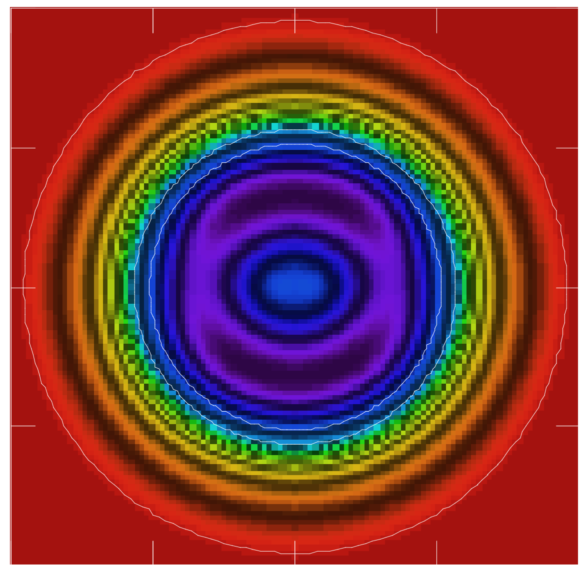
• Cl* EMISSION



-20 0 20

POSITION (cm)

• ION FLUX



-20 0 20

POSITION (cm)

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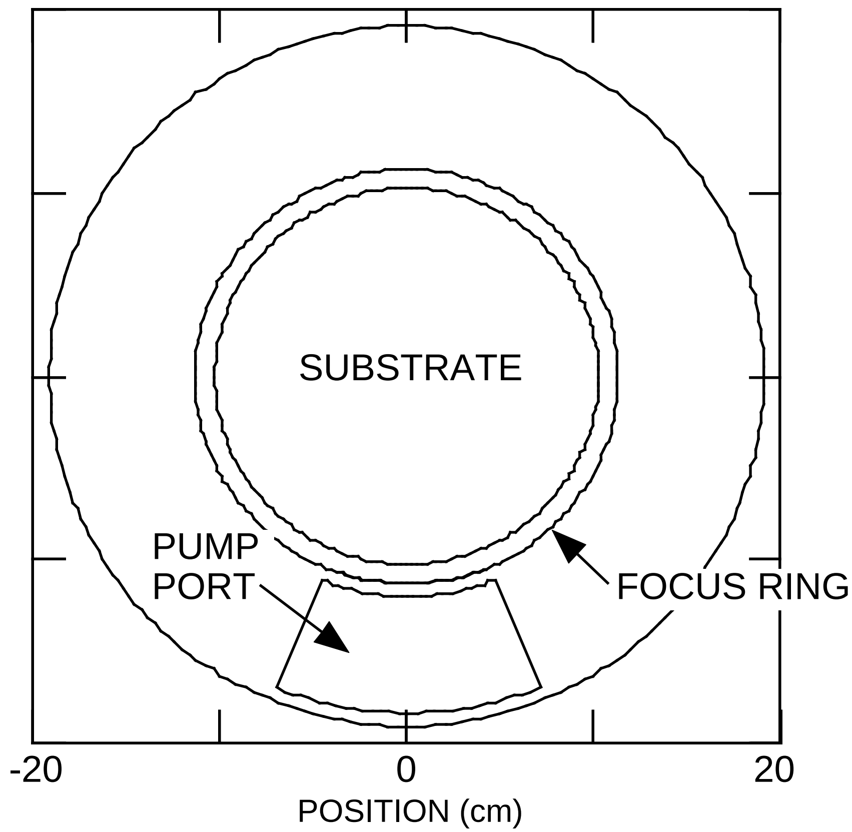
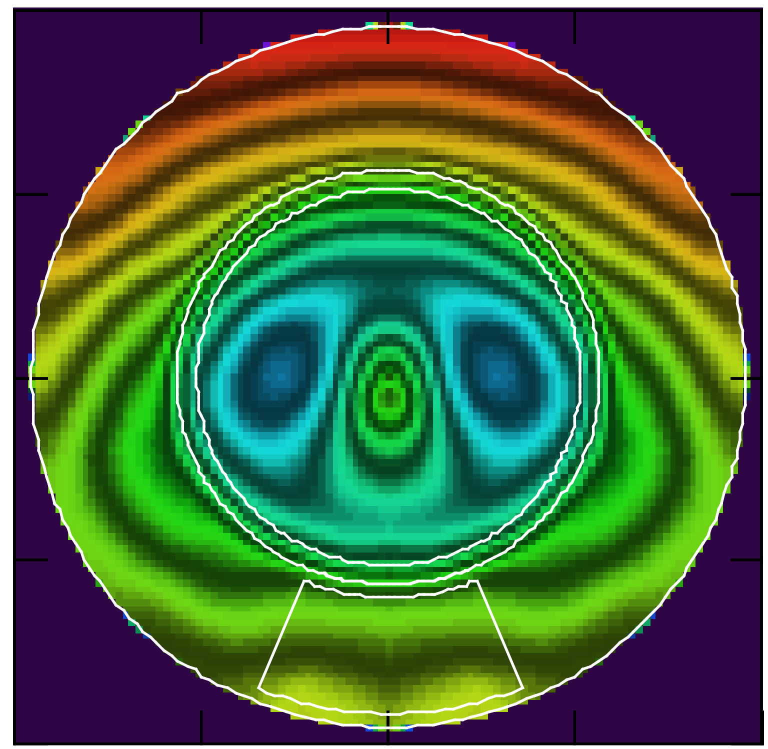
PERTURBATION CAUSED BY SIDE PUMPING

- At low pressures, side pumping can perturb Cl atom densities across the wafer by 5-10%. The segmented antenna controller will be used to restore uniformity in the etching fluxes.





- Cl atom density at wafer (85% - 100%)

- Cl_2, 10 mTorr, 400 W, 150 sccm

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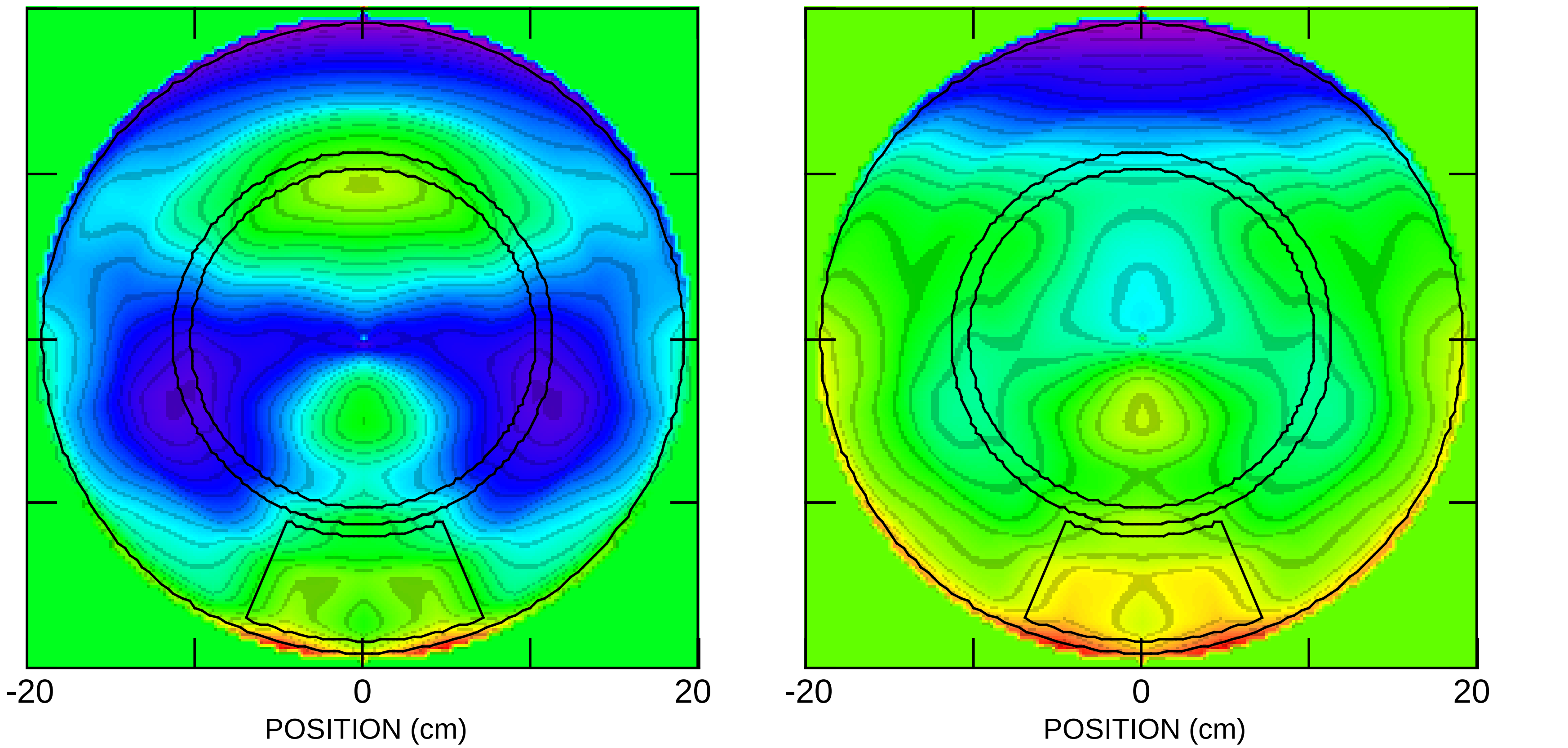
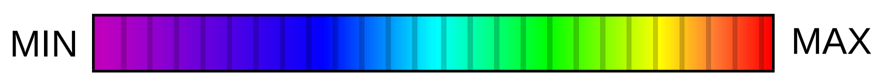
RESTORED Cl* UNIFORMITY WITH SIDE PUMPING

- The RTC algorithm again restores the Cl* uniformity to within the “noise” level. Prior knowledge of the type of nonuniformity would be necessary to select sensors, coils which are better geometrically matched.



- **Perturbed** : Sensor 1,2 = -1.89,-1.47
- **Corrected** : Sensor 1,2 = -0.033,-0.014



- Cl_2, 10 mTorr, 400 W, 150 sccm

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CONCLUDING REMARKS

- Fundamental, first principles computer modeling of complex plasma processing reactors has matured to the point that equipment is now first designed "virtually".

- This modeling capability is now being applied to investigation and design of real time control processes.

- Improvements in algorithms and data structures are required to provide a similar capability to process design (i.e., device performance vs equipment design)
    - Extreme dynamic range in space. (1000 A to 10 cm)
    - Extreme dynamic range in time (ns to 10 s)
    - Database management
    - Expert systems

ACKNOWLEDGMENTS

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June Lu

Ronald Kinder

Da Zhang