Modeling and Diagnostics Studies of Si Plasma Etch and Etch By-Products

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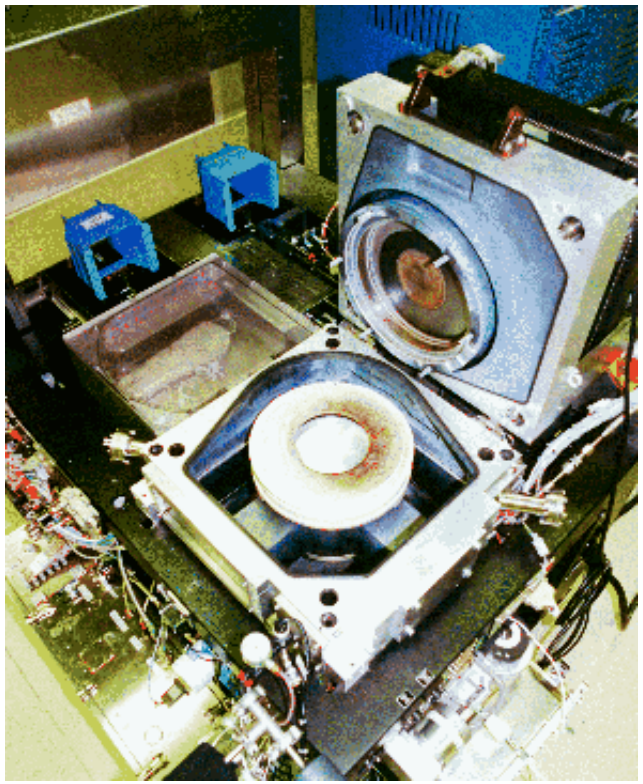
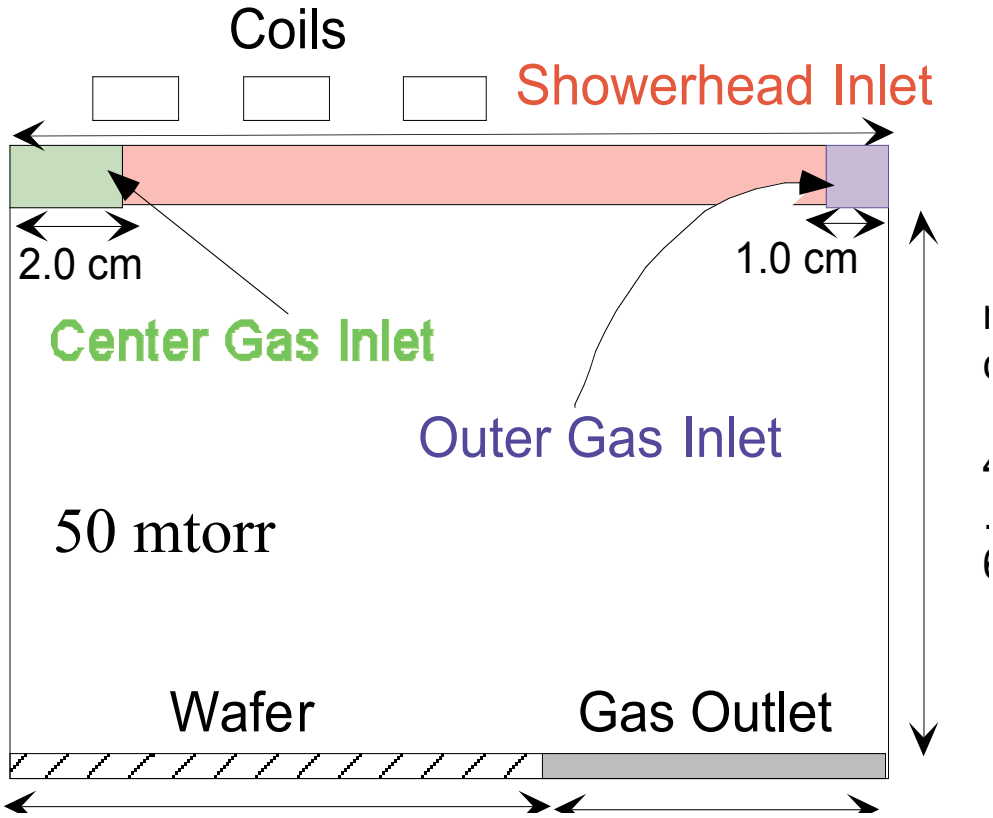
Role of Gas Flow in Plasma Etch By-Product Transport

- Gas flow through plasma etch (or PECVD) tool can play important role in tool effectiveness
- Especially apparent for conductor (e.g. Si) etch: etch by-products often dominate tool CD control and CD uniformity
- Gas *temperature*, gas *pressure* and gas *composition* are coupled and must be treated self-consistently in models
- Inflow and outflow locations important in tool design
- Dielectric etch: flow of deposition and etch precursors, wall interactions and other issues influenced by transport as well

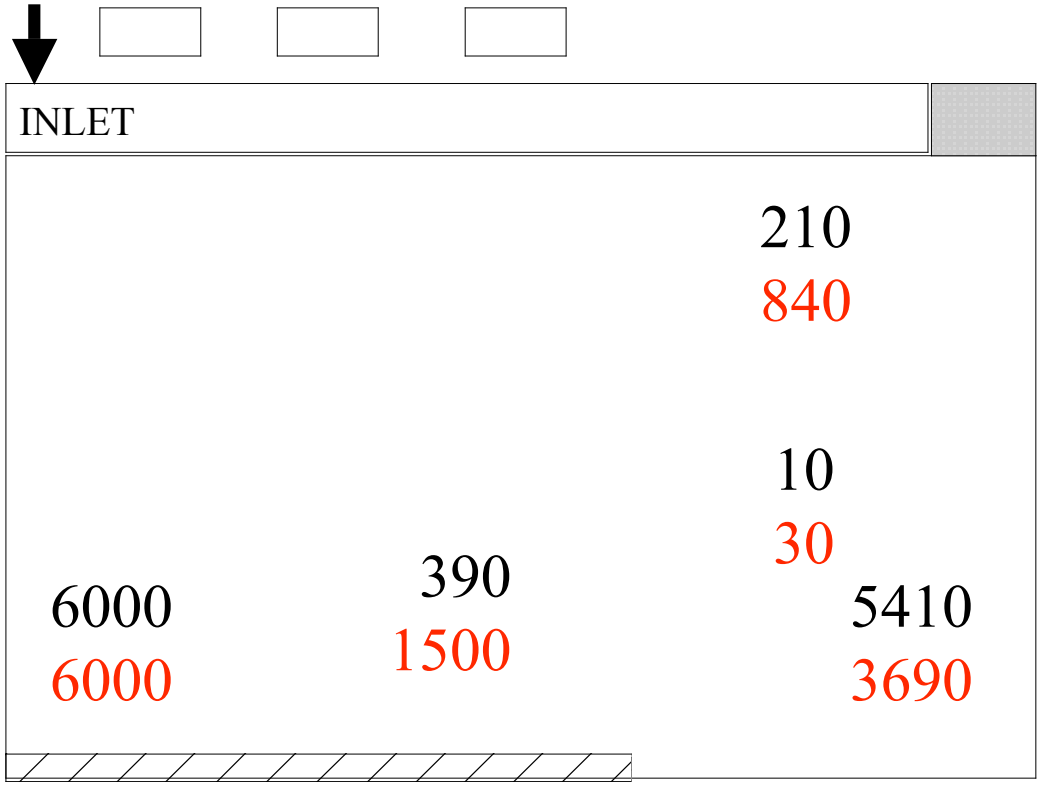
Etch Product Transport: Model Formulation





- Site balance model on walls and wafer (Si_site & Si_Cl).
- Fix absolute (gross) etch rate as 6000 Å/minute.
- Redeposition (and net etch rate), wafer coverage, gas phase chemistry calculated self-consistently: **plasma + neutral model**
- Examine effect of inlet position and flow rate.

From Model Calculations:Silicon Etch Products



1) $SiCl_x$ is etched from wafer.
2) $SiCl_x$ is:
   - ionized/dissociated to depositing species
   - pumped out
3) Depositing species:
   - go to walls
   - redeposit on wafer
   - are pumped out
4) $SiCl_x$ is etched from walls.

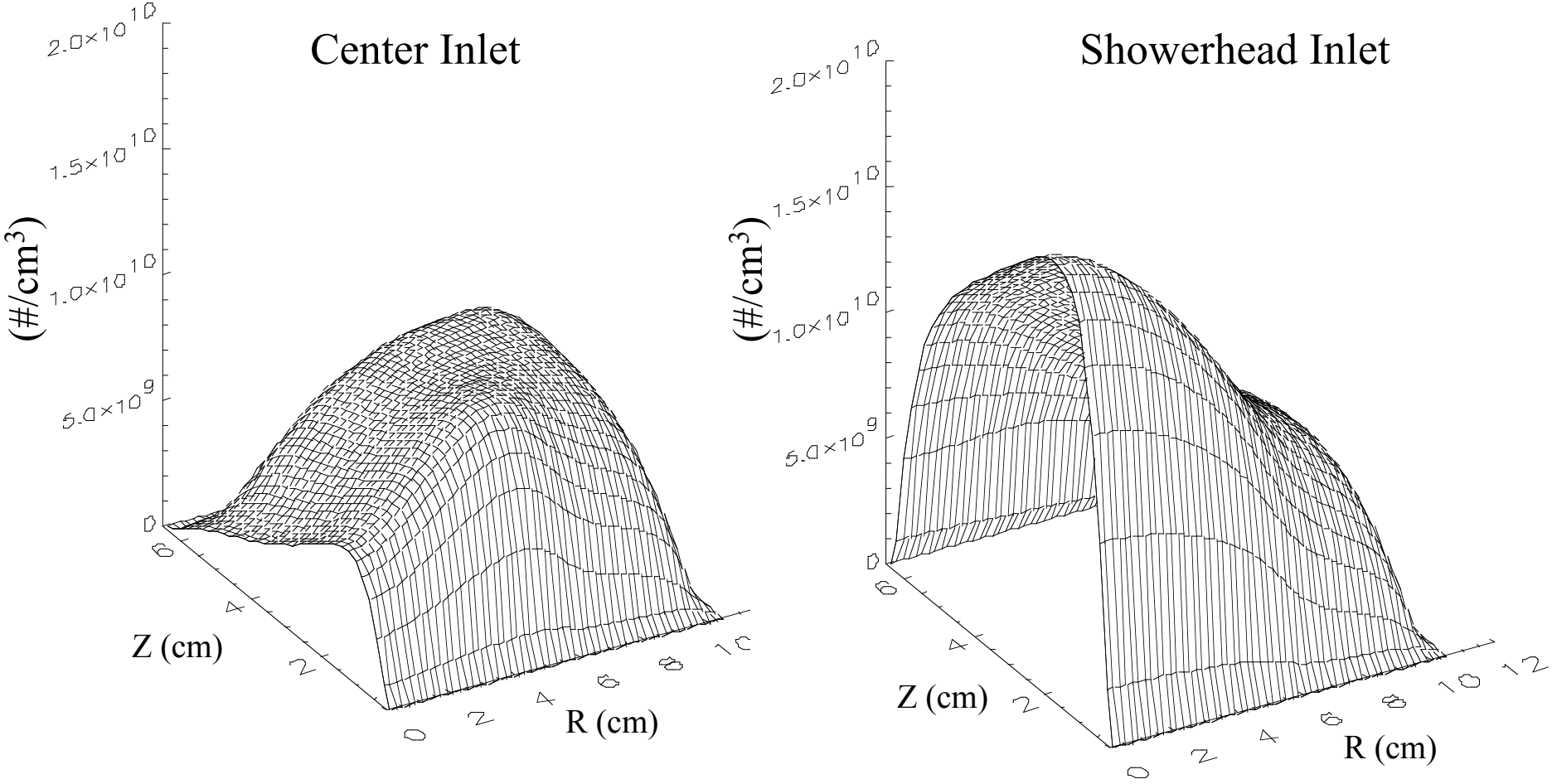
500 sccm
45 sccm

References

1. Role of Etch Products in Polysilicon Etching in a High Density Chlorine Discharge, (with C. Lee, and M.A. Lieberman), Plasma Chemistry Plasma Processing, 16, 99, 1996.

2. The Effect of Neutral Transport on the Etch Product Lifecycle during Plasma Etching of Silicon in Chlorine Gas, (with M.W. Kiehlbaugh), JVST, in print, 2003.

$SiCl^+$ Density: Example of Plasma Profiles vs. Flow Inlet Location

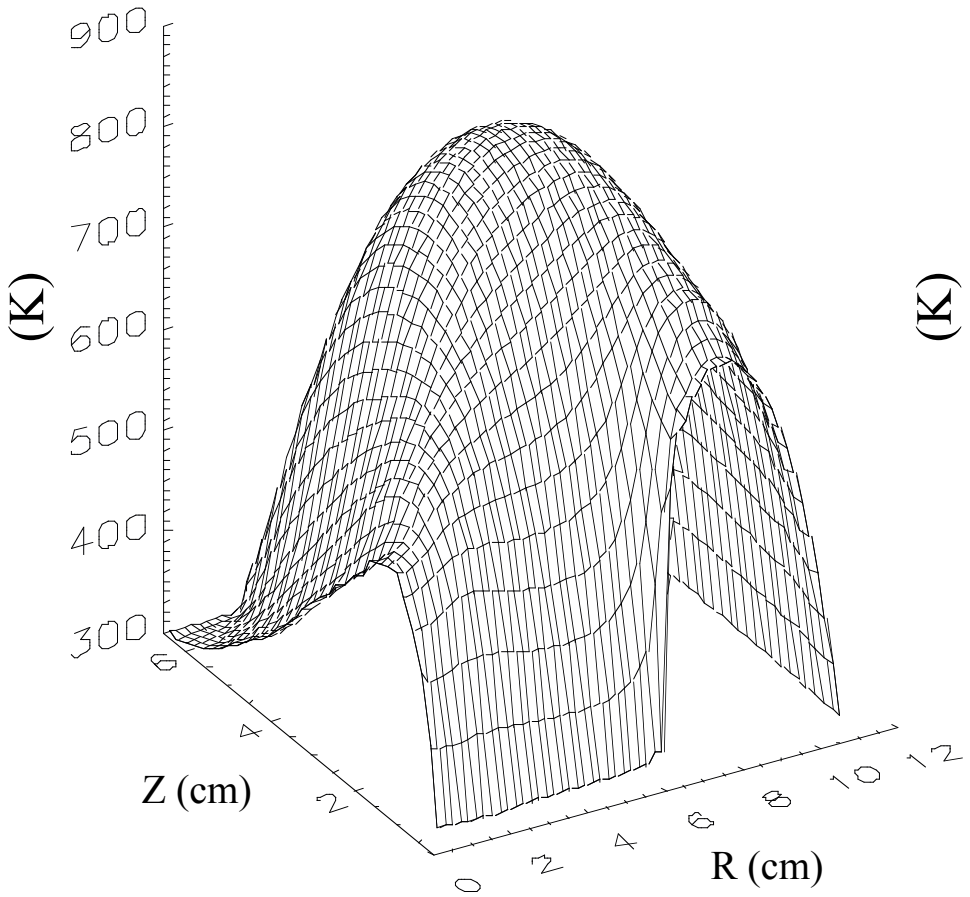


Ion profiles are perturbed by neutral pressure/density & by neutral composition

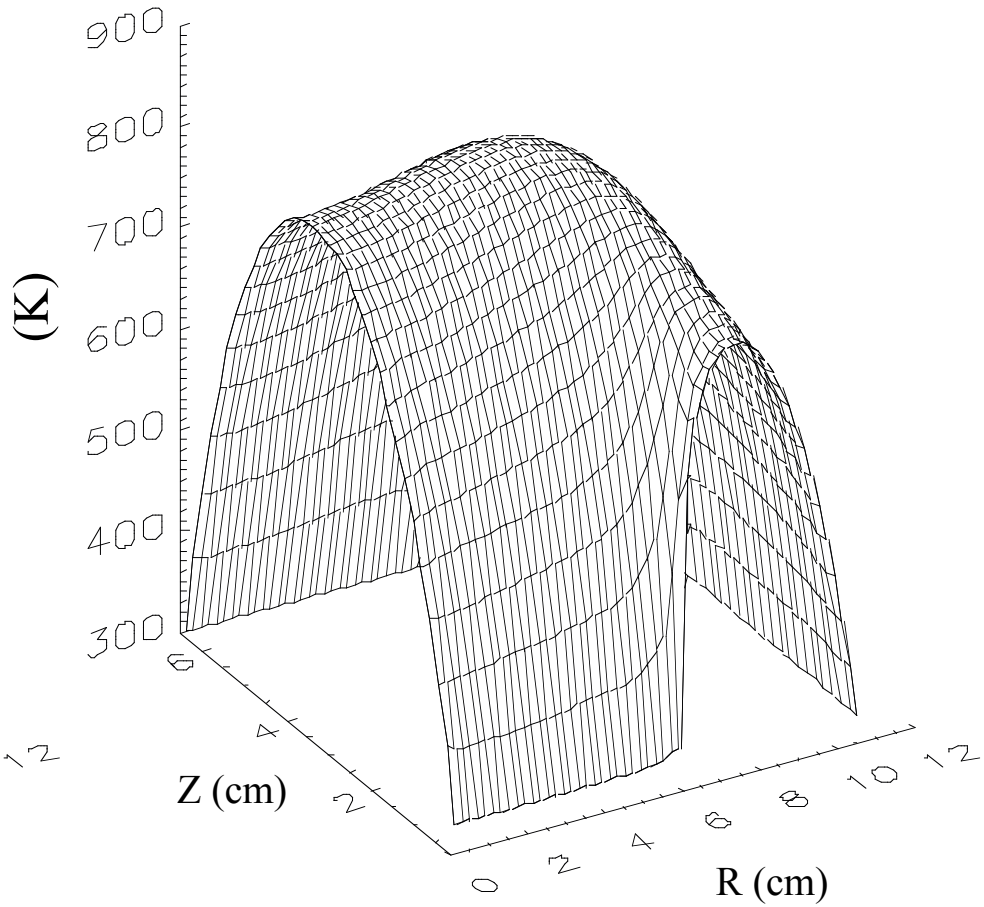
500 sccm

Neutral Temperature

Center Inlet



Showerhead Inlet

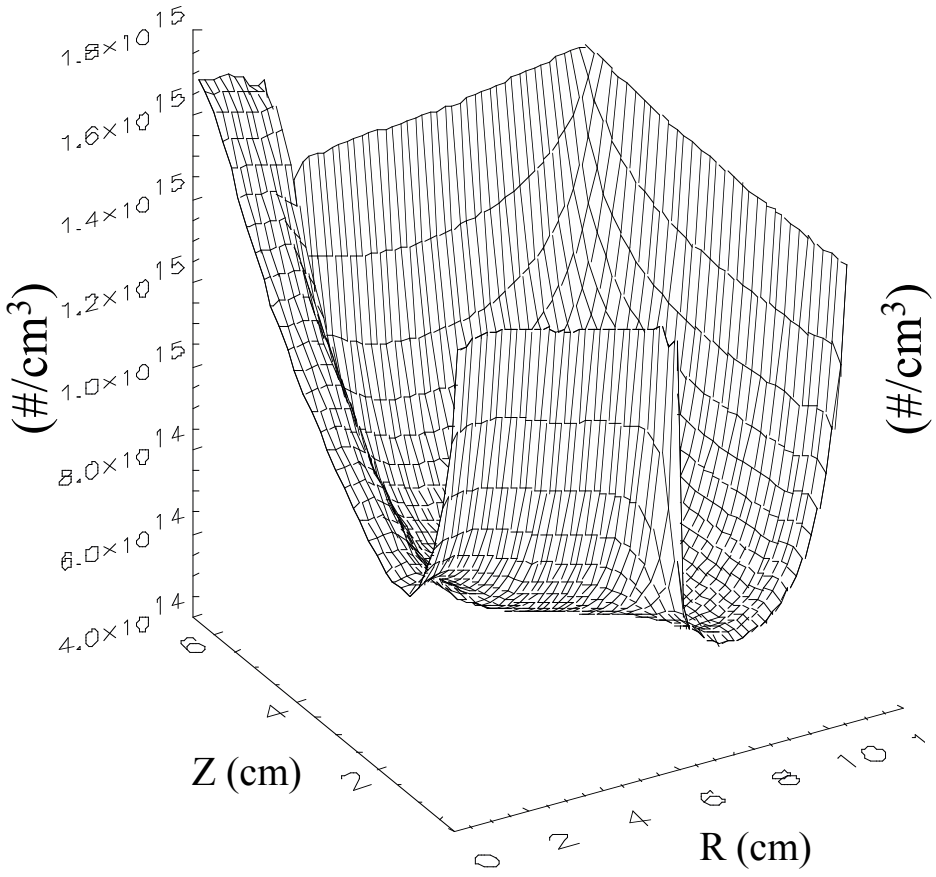


Neutral heating primarily from ion/neutral collisions & Franck-Condon energy upon Cl_2 dissociation.

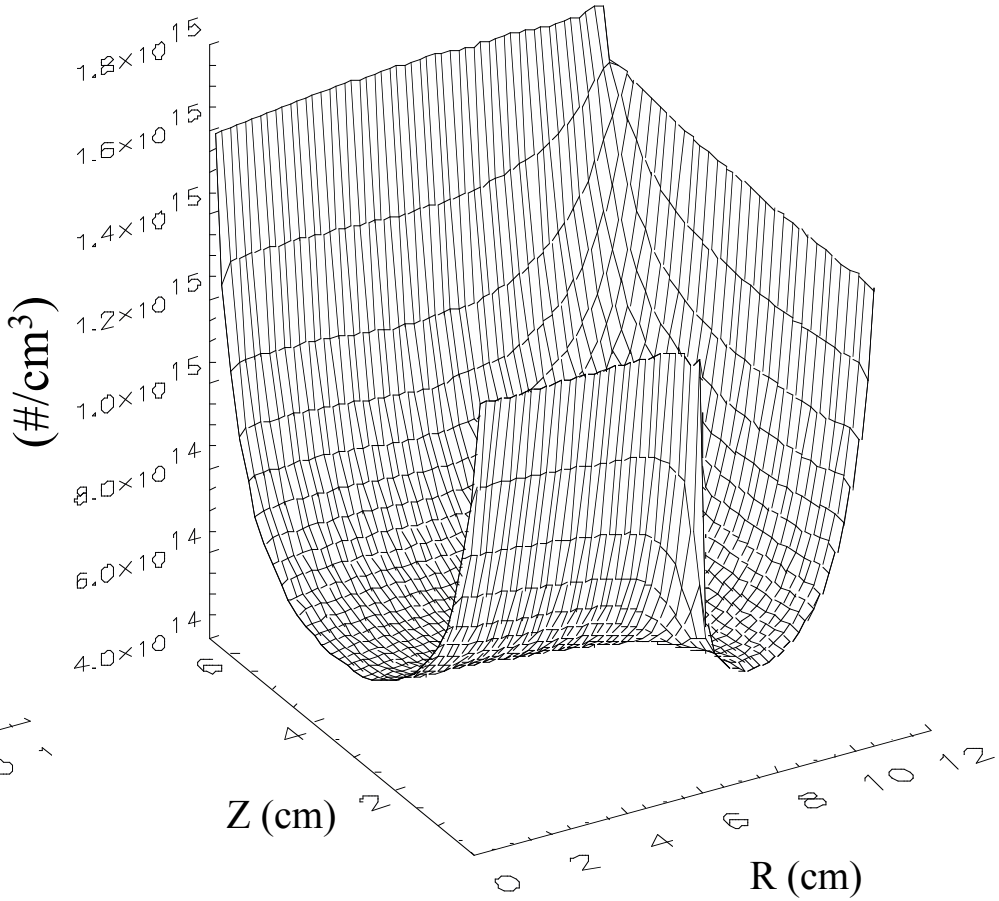
500 sccm

Neutral Density

Center Inlet



Showerhead Inlet

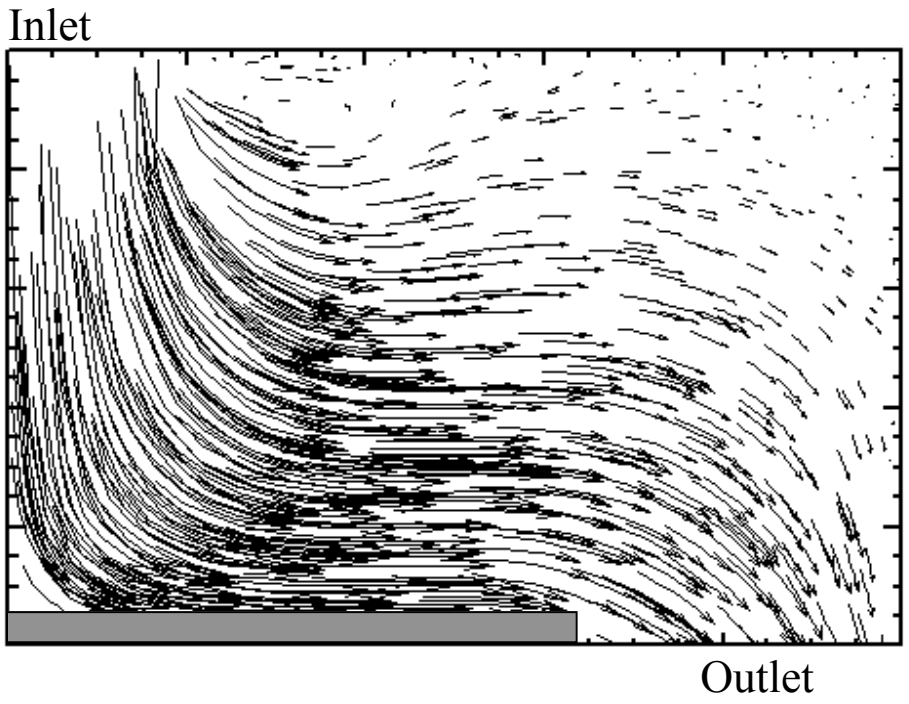


Neutral density profile primarily driven by temperature with some pressure effects near the inlet.

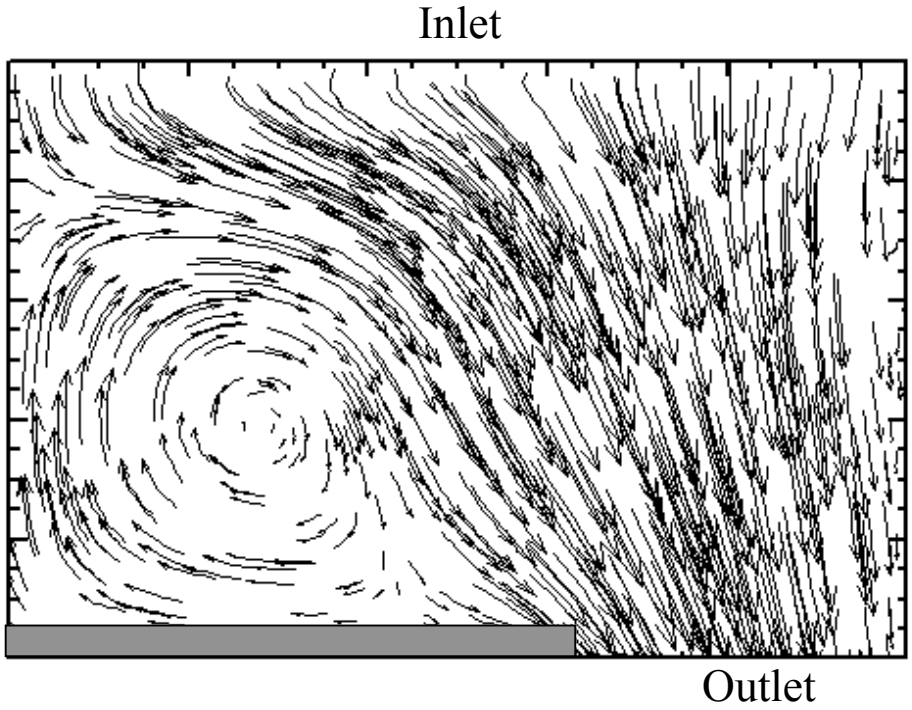
500 sccm

Convective Neutral Transport

Center Inlet Overall Neutral Flux



Showerhead Inlet Overall Neutral Flux

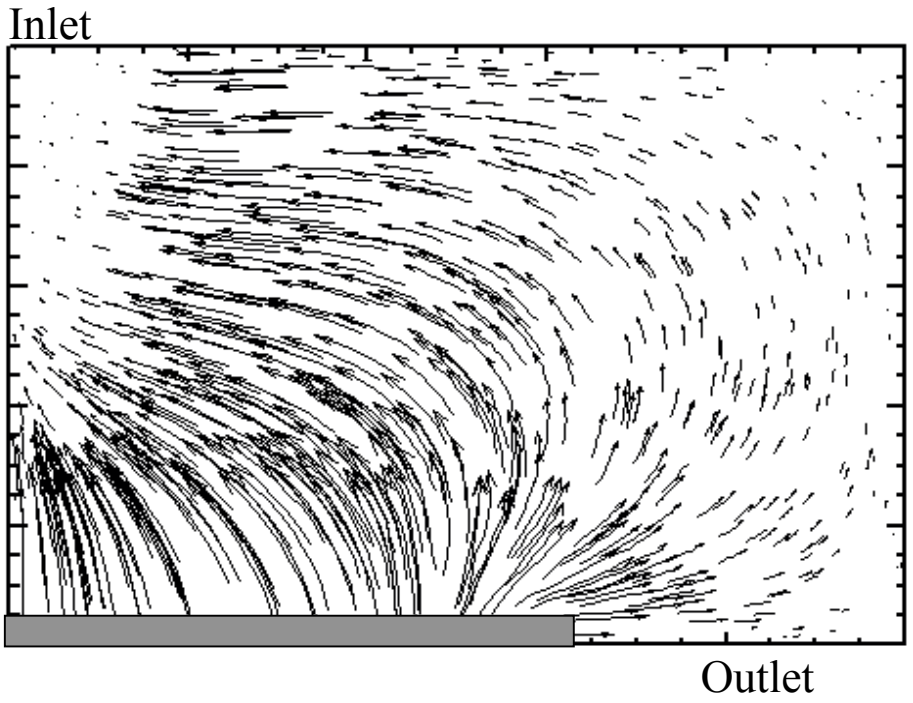


Overall flow driven by □P = f(inlet/outlet position, reactor aspect ratio) and coupling with plasma.

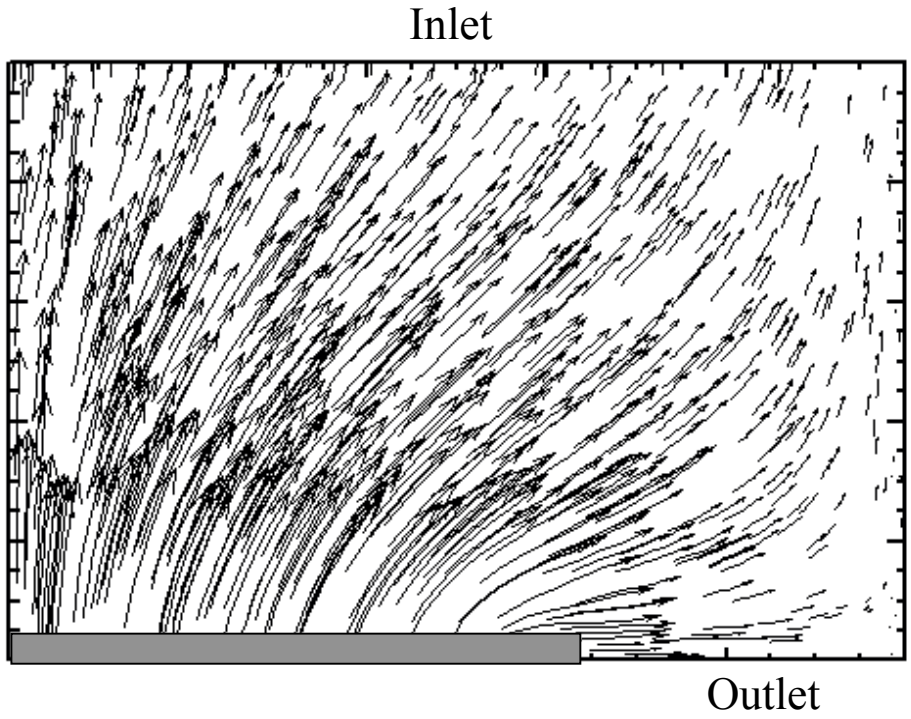
500 sccm

$SiCl_2$ Diffusive Transport

Center Inlet $SiCl_2$ Diffusive Flux



Showerhead Inlet $SiCl_2$ Diffusive Flux



$$N_{spec} * V_{dif,spec} \approx -N_{tot} * D_{spec,eff} * \nabla Y_{spec}$$

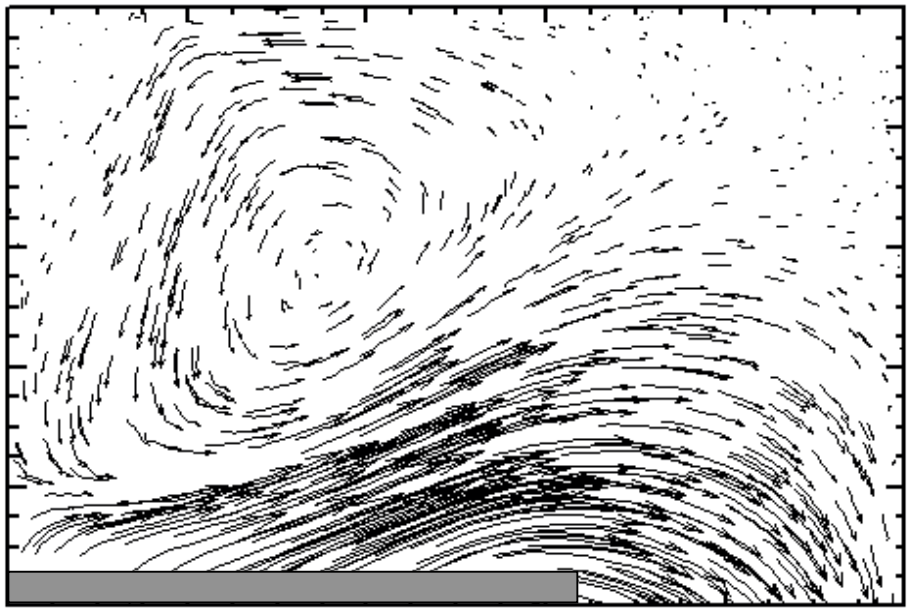
$SiCl_2$ diffuses towards inlet and plasma (sinks) and away from wafer and walls (sources).

500 sccm

$SiCl_2$ Transport & Inlet Position

Center Inlet $SiCl_2$ Flux

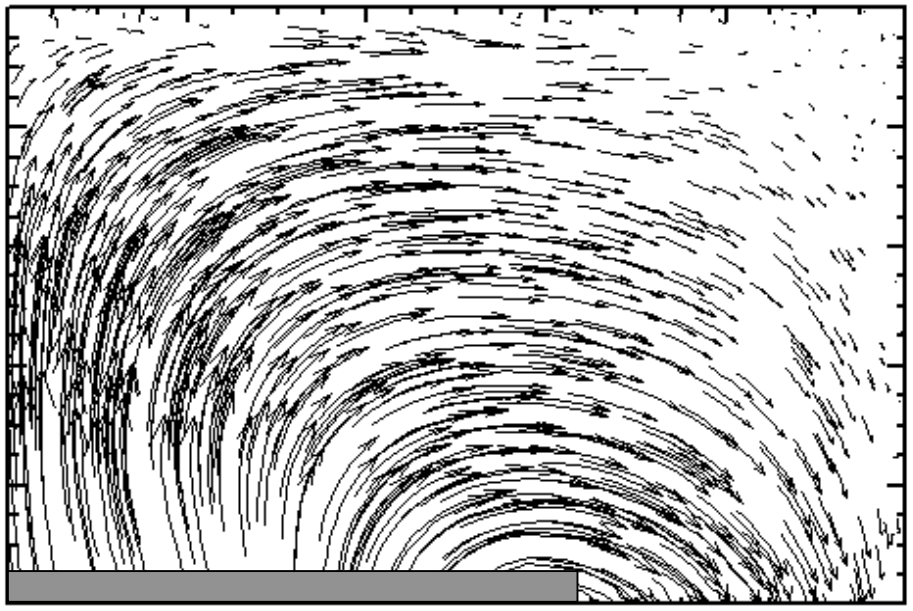
Inlet



Outlet

Showerhead Inlet $SiCl_2$ Flux

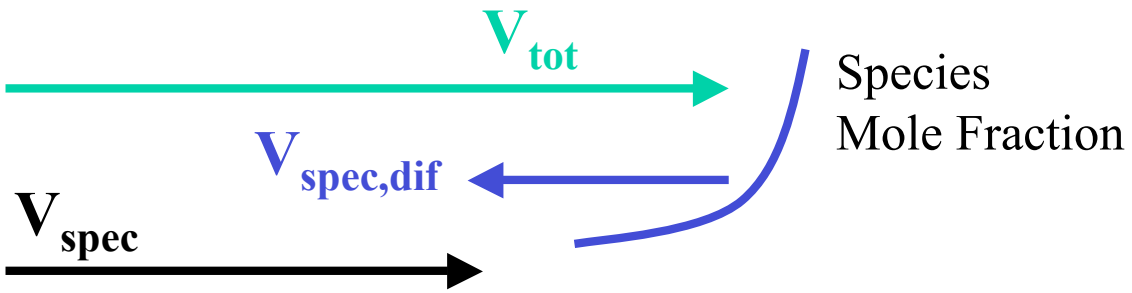
Inlet



Outlet

$$\text{Species Number Flux} = V_{spec} * N_{spec} [=] \frac{\#}{cm^2 * s} \qquad \mathbf{V_{spec}} = \mathbf{V_{tot}} + \mathbf{V_{spec,dif}}$$

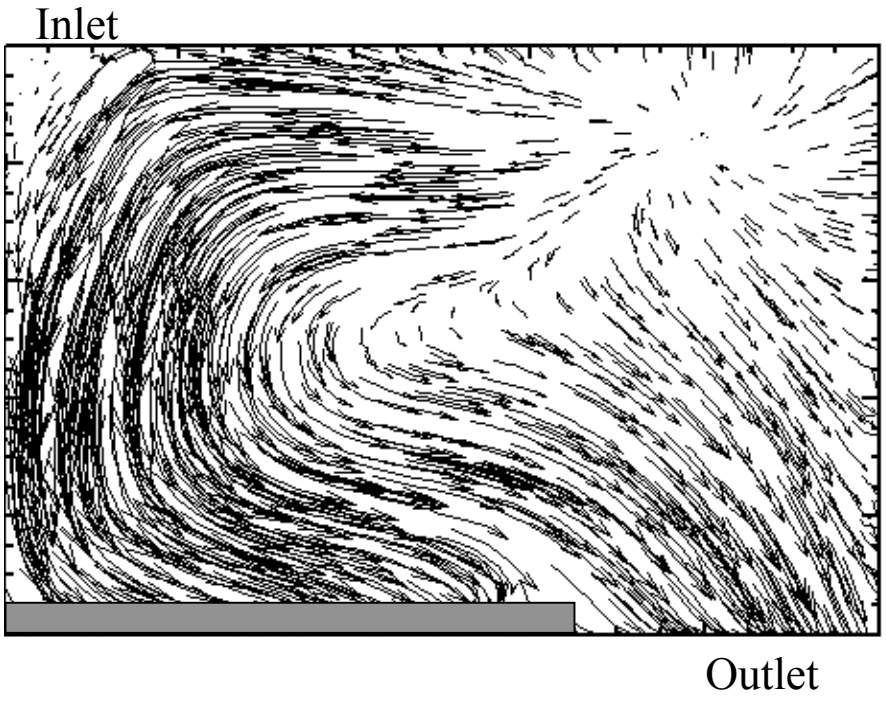
* Outer inlet is similar to showerhead



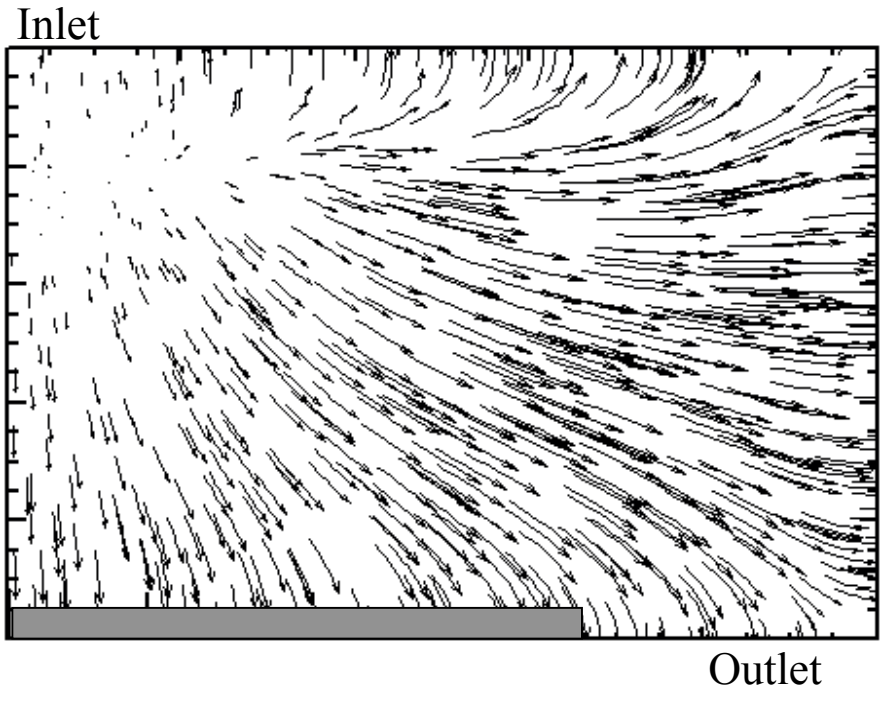
500 sccm

Wafer Redeposition: Si and $SiCl^+$

Neutral Si Flux for Center Inlet



$SiCl^+$ Flux for Center Inlet



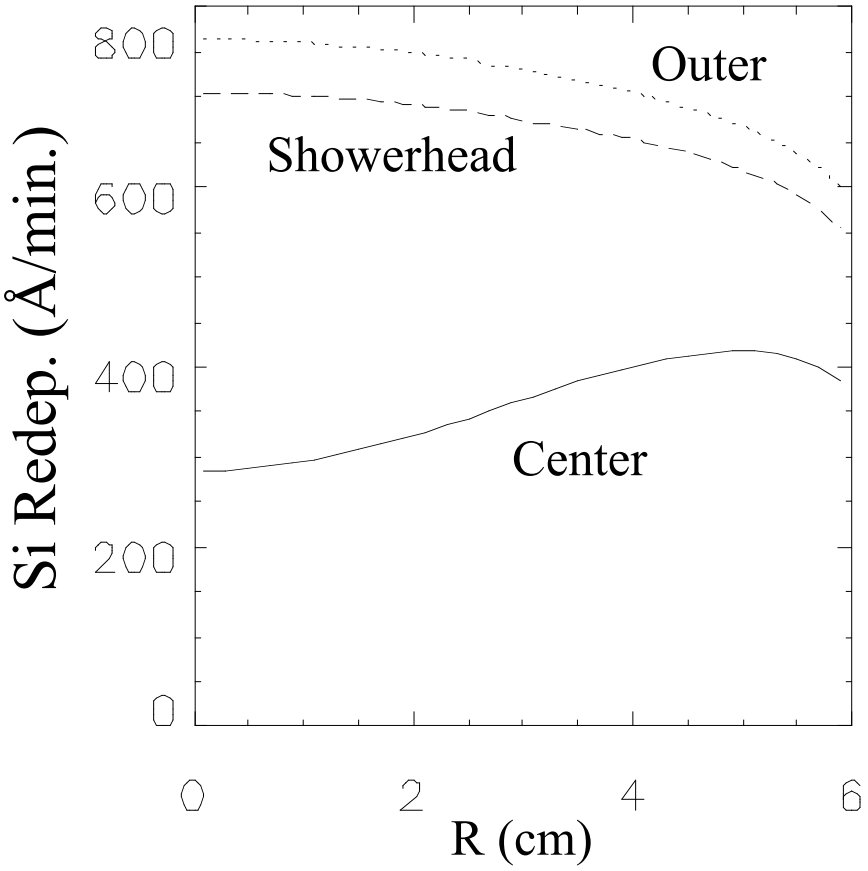
Si is created by fragmentation of etch products and deposits on the walls and wafer with high probability.

500 sccm

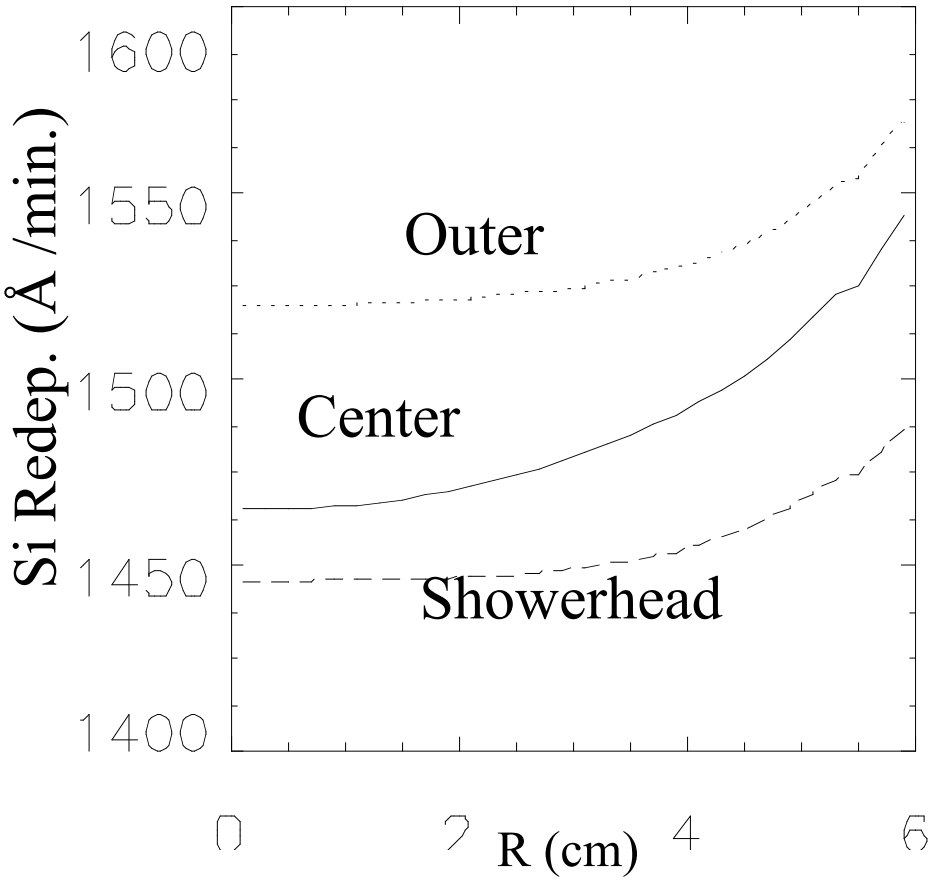
Ion flux is driven by the potential field. Ions can return directly to wafer or recirculate via the walls. $SiCl_x$ breaks up and ionizes easily.

Wafer Redeposition Rate

500 sccm



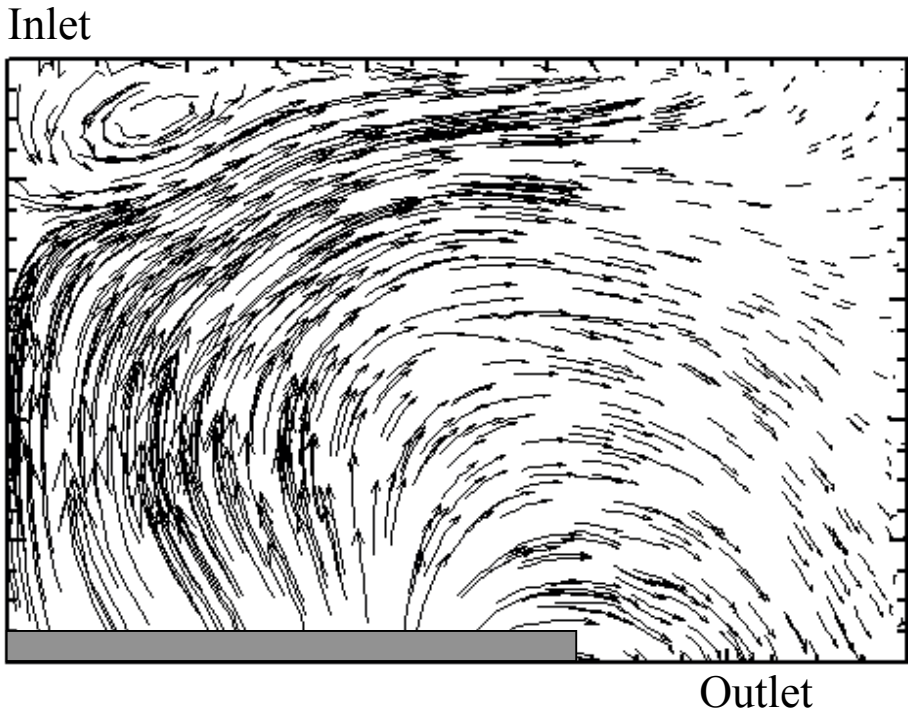
45 sccm



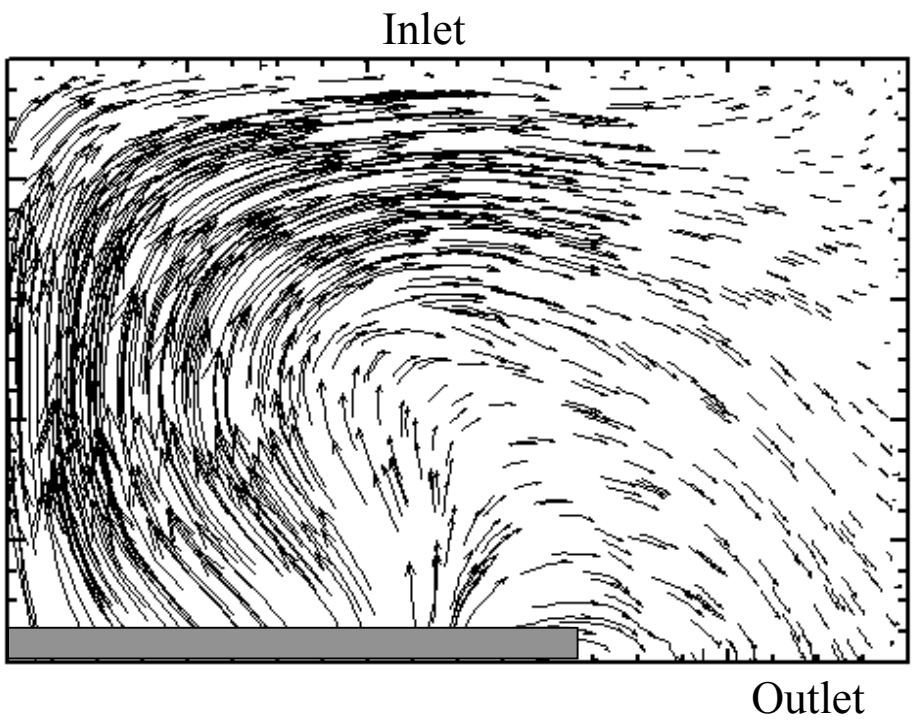
- Redeposition is greater at 45 sccm: Note scales
- Inlet position has less effect on magnitude and profile at 45 sccm.

$SiCl_2$ Transport & Inlet Position

Center Inlet $SiCl_2$ Flux



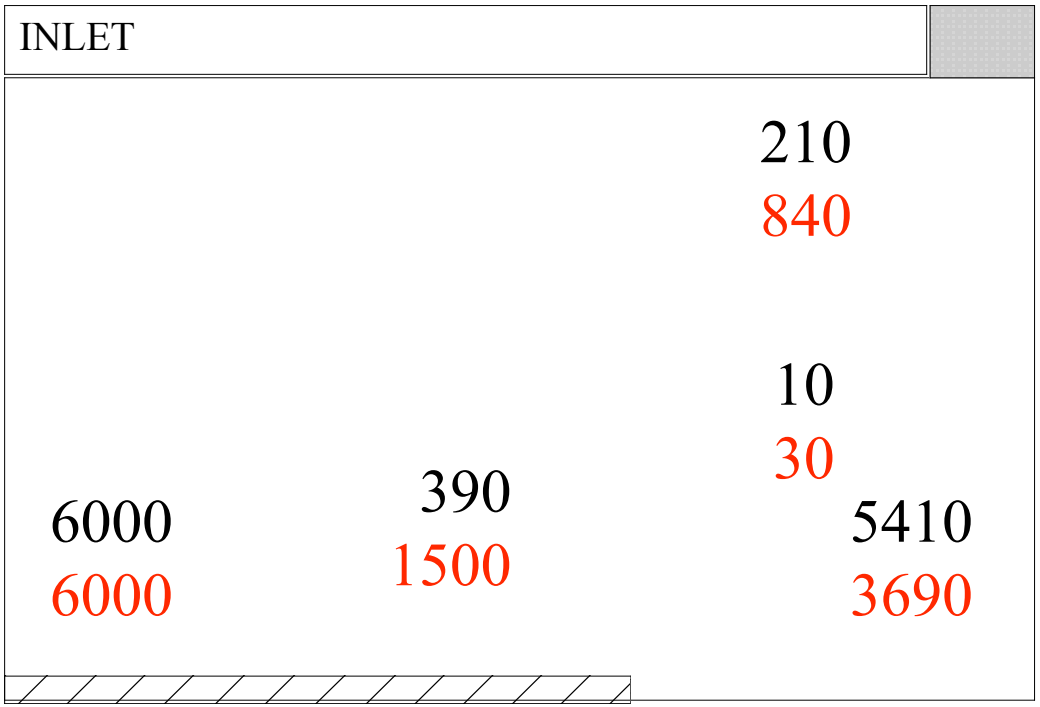
Showerhead Inlet $SiCl_2$ Flux



At lower flowrate, etch product transport is not sensitive to flow inlet location.

45 sccm

The Silicon Lifecycle During Etching



1) $SiCl_x$ is etched from wafer.
2) $SiCl_x$ is:
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   - pumped out
3) Depositing species:
   - go to walls
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4) $SiCl_x$ is etched from walls.

500 sccm
45 sccm

Note: model overpredicts wall deposition in Cl_2 etch w/o O_2 addition

Experimental Study: Etch Products

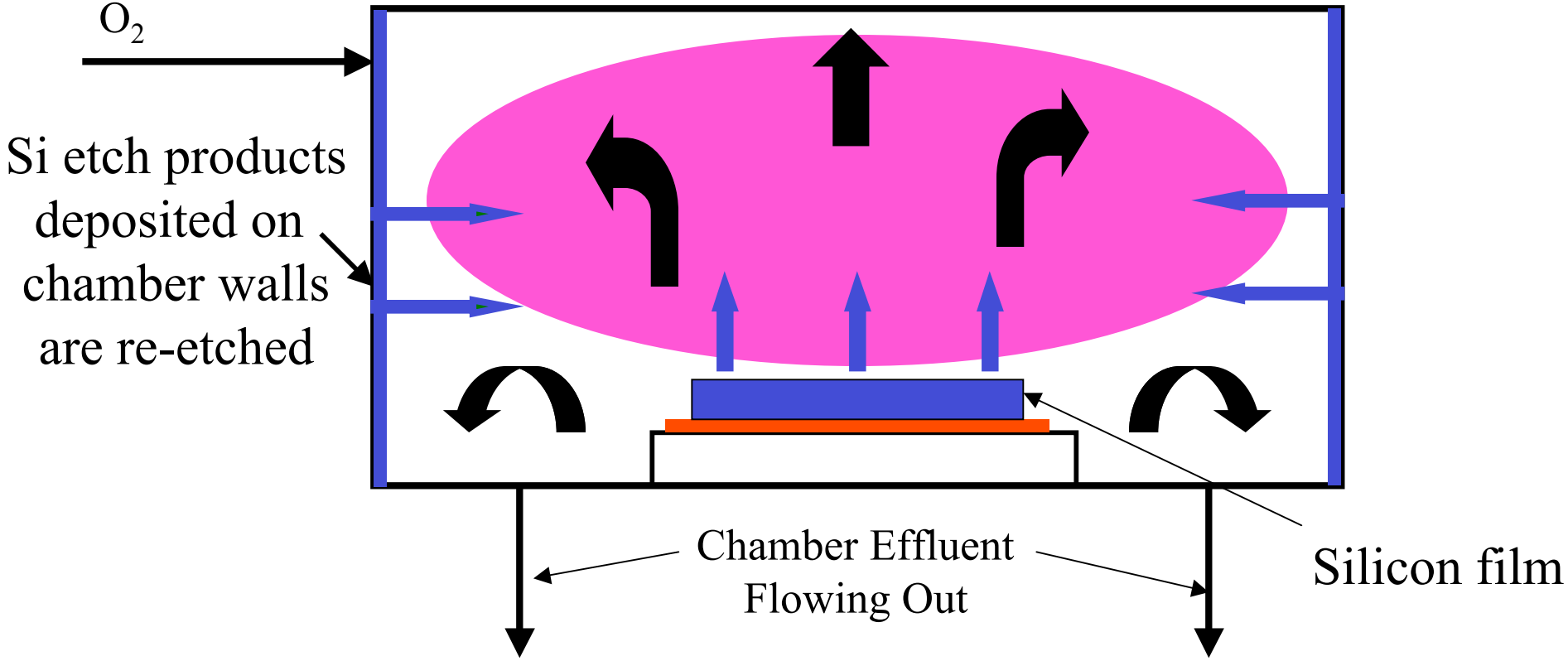
What species are responsible for etch product deposition on walls & wafer?

Etch Gases

Cl_2

O_2

Wall/wafer measurements: deposits SiOCl stoichiometry

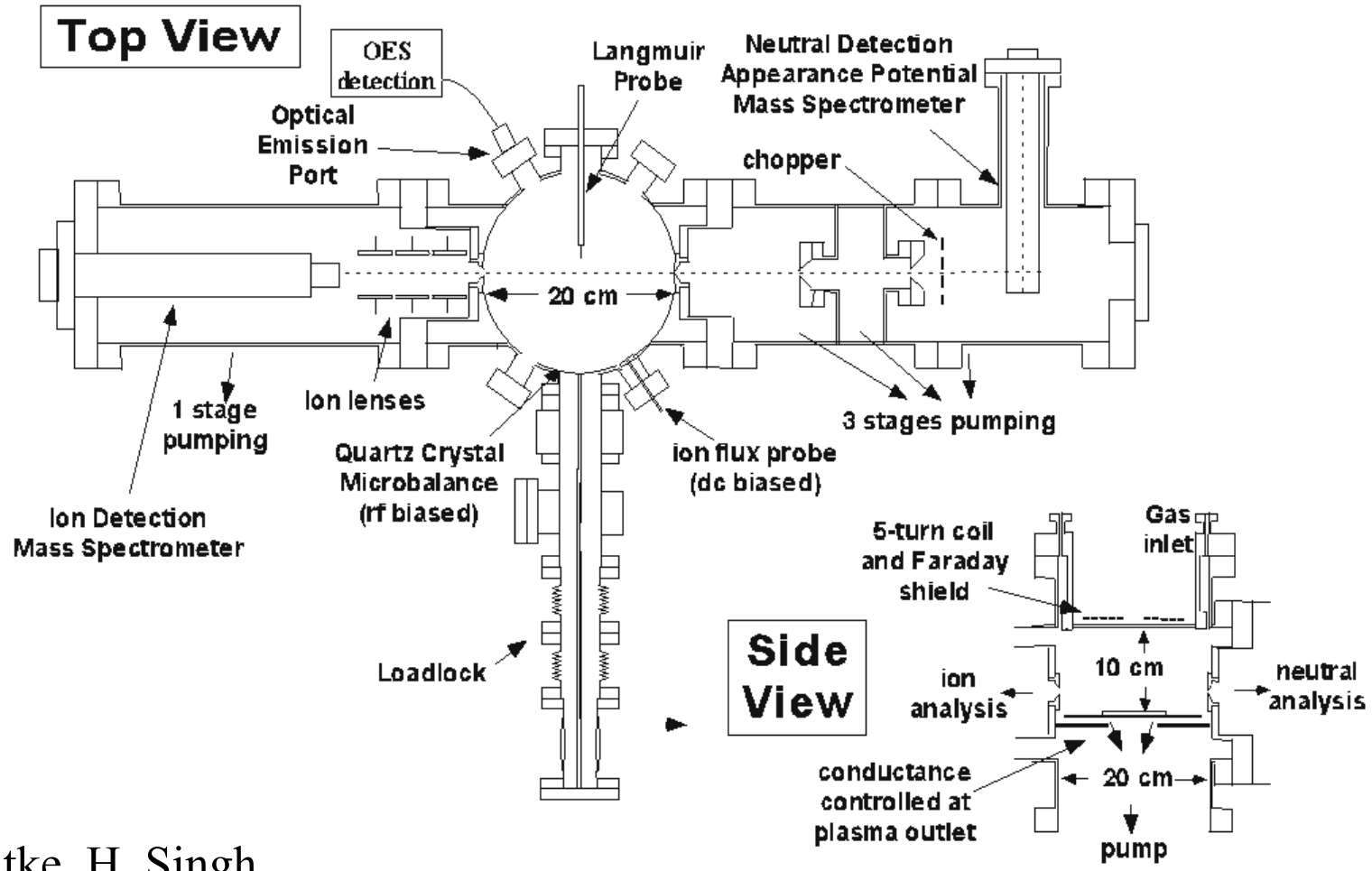


Outstanding Questions

- What are deposition species?
  - what role oxygen?
  - neutral radicals $SiCl_x$?
  - Si-containing ions?
  - SiOCl neutrals or ions?
- Previous beam studies (not shown) indicate that O ions (O^+ or O_2^+) much more effective than O neutrals in affecting poly-Si etch rates*

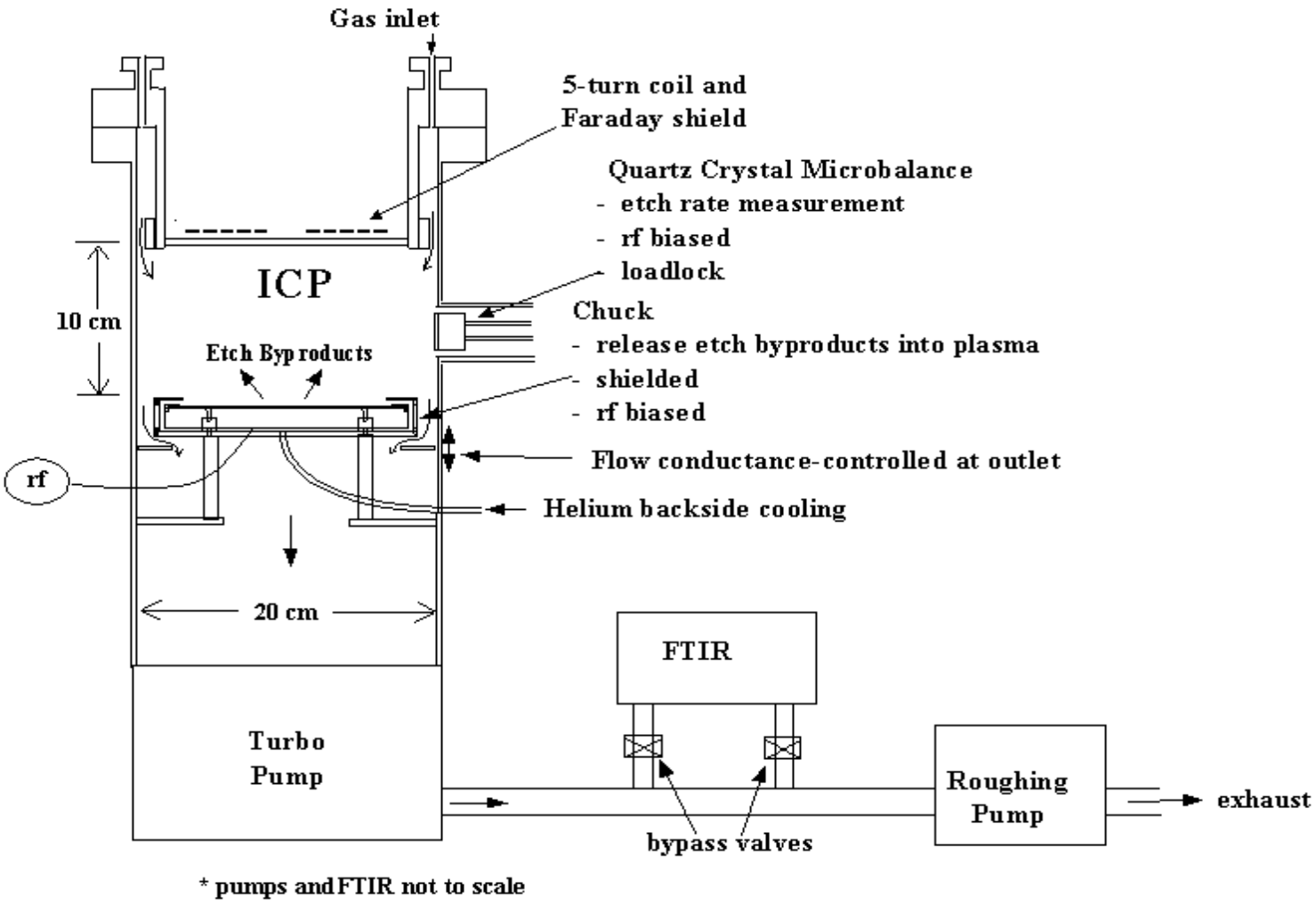
*Role of Oxygen in Ion-Enhanced Etching of Poly-Si and WSix with Chlorine, (with G.P. Kota and J.W. Coburn), J.Vac. Sci. Tech. A, 16(4), 2215 1998.

Experimental Apparatus*



*M. Radtke, H. Singh

Etch Chamber (side view)



Experimental Goals for $Si/O_2/Cl_2$ Study

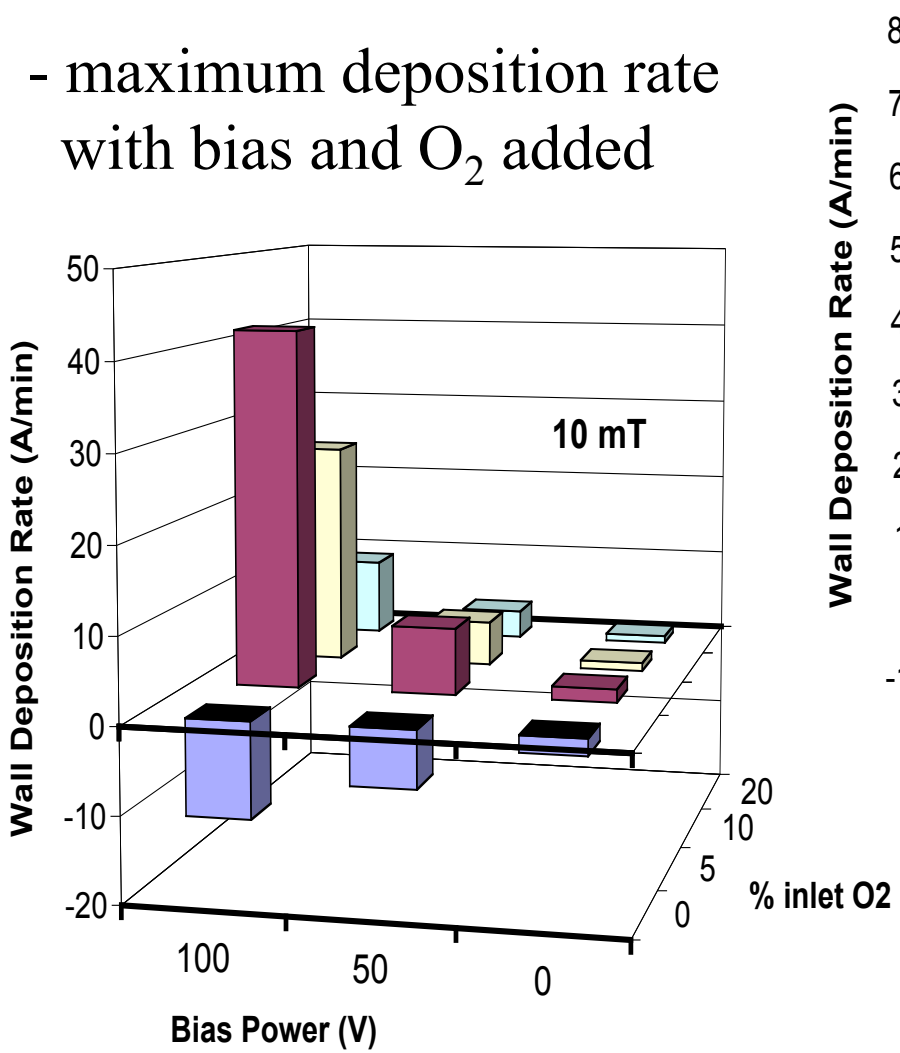
Measure wall deposition rates and corresponding ionic and neutral radical species fluxes to develop kinetics for surface deposition model.

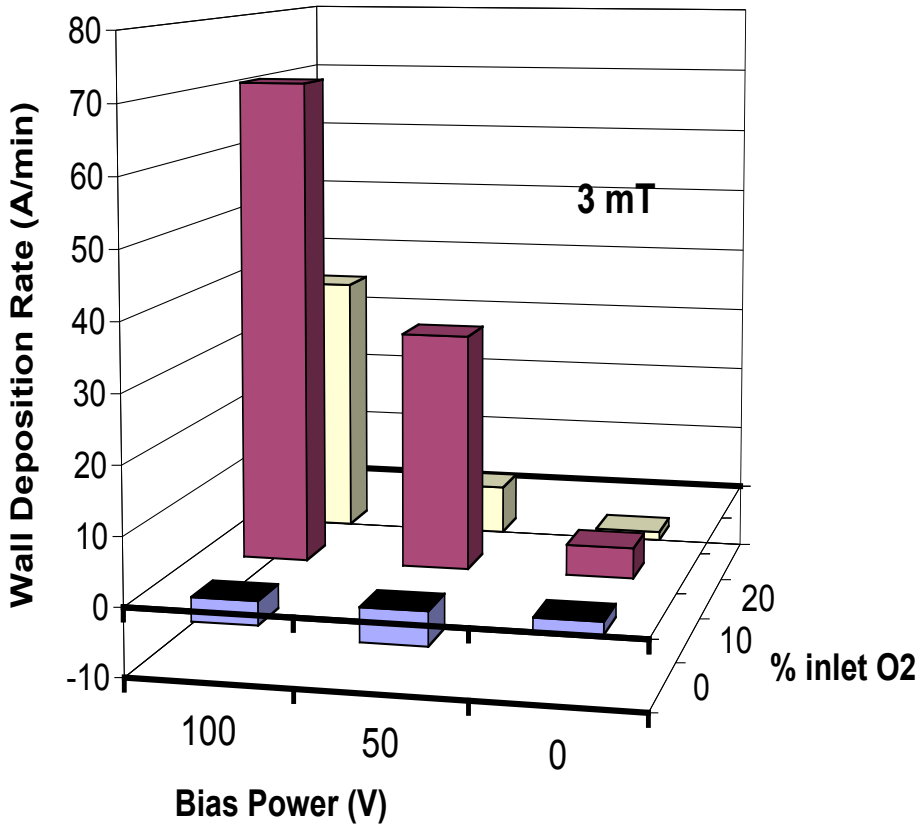
Experimental Conditions

Pressure: 3 and 10 mtorr
Substrate self-bias to alter etch rate: 0, -50, -100V
ICP power (deposited): constant 150 W
Inlet gas composition (Cl_2/O_2) 0, 5, 10, 20% O_2
(3 mtorr ~ 8 sccm; 10 mtorr ~ 20 sccm)
and 1-2 sccm of He backside wafer cooling

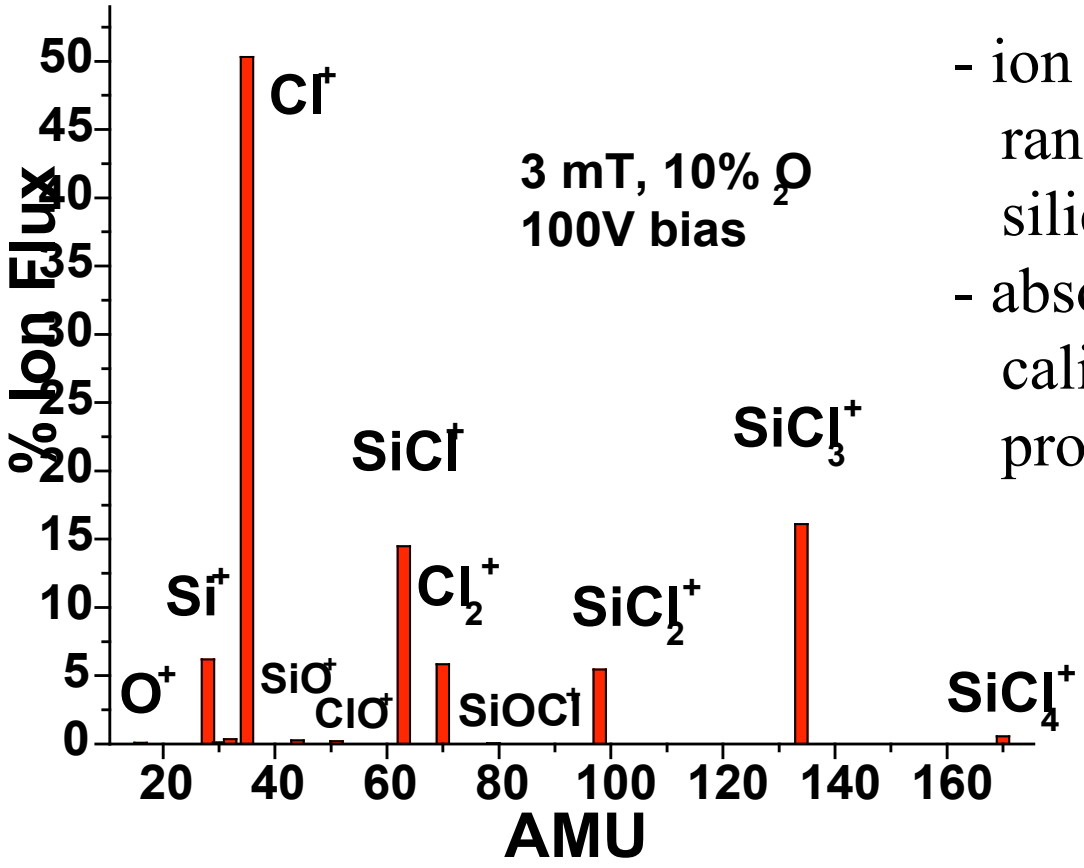
Wall Deposition Rates vs. V_{Bias} and Inlet O_2 Concentration

- maximum deposition rate with bias and O_2 added



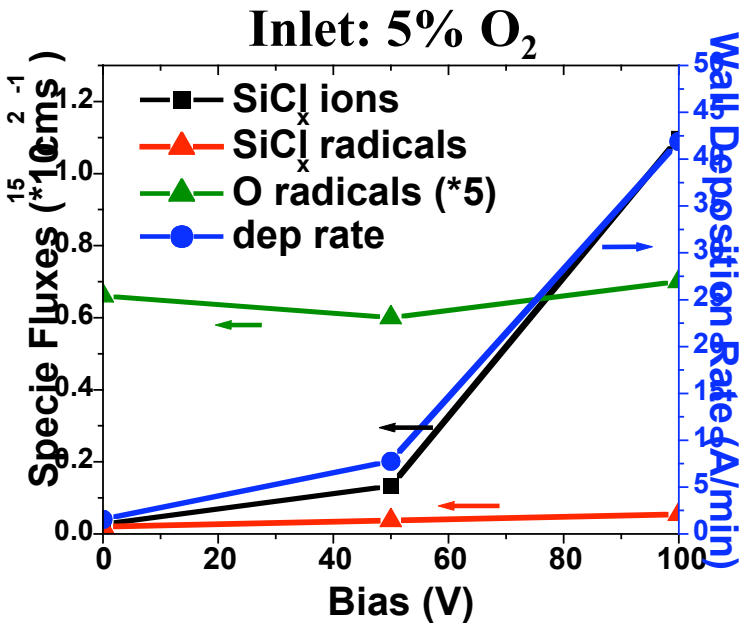


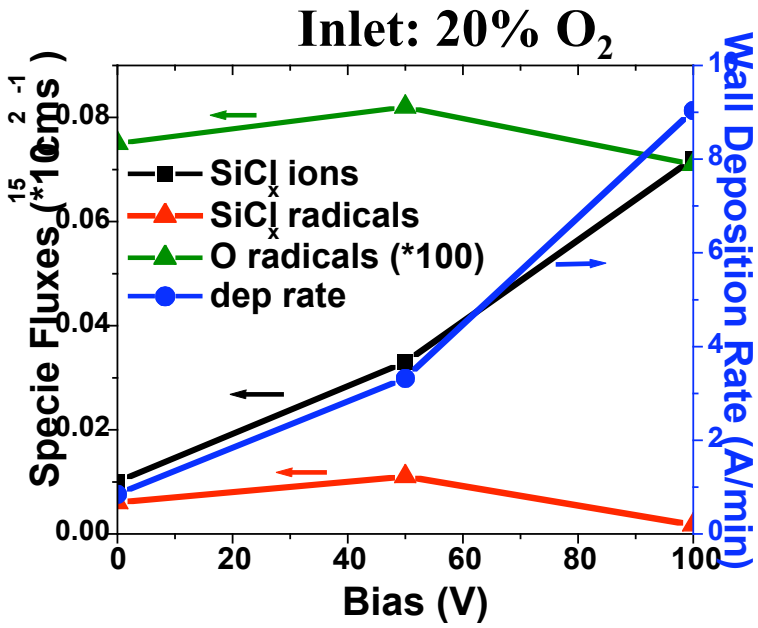
Ion Flux Measurements at Wall

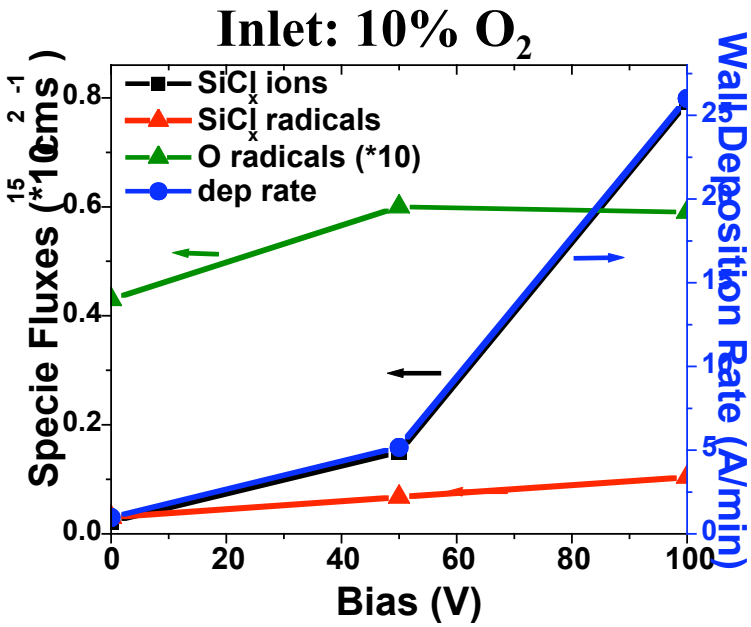


- ion composition ranged from 0-63% silicon-containing
- absolute ion fluxes calibrated from ion probe

Deposition Rate vs. Incident Flux (10 mTorr)

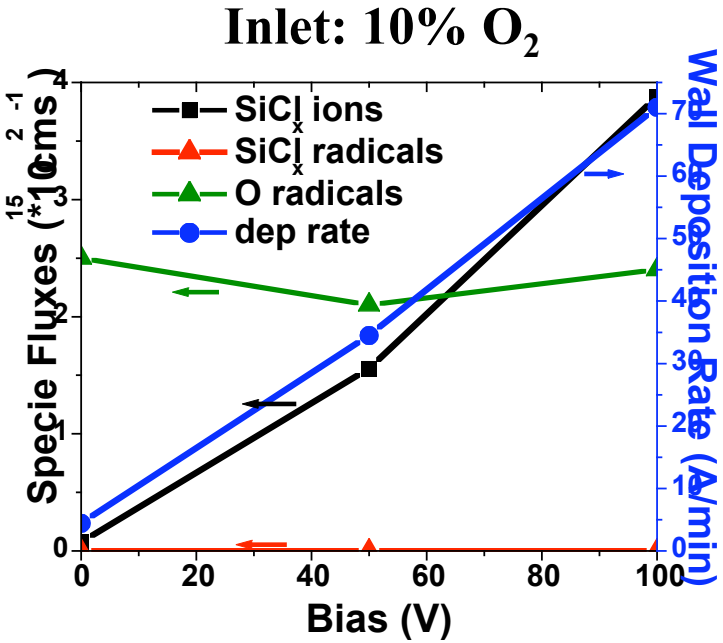


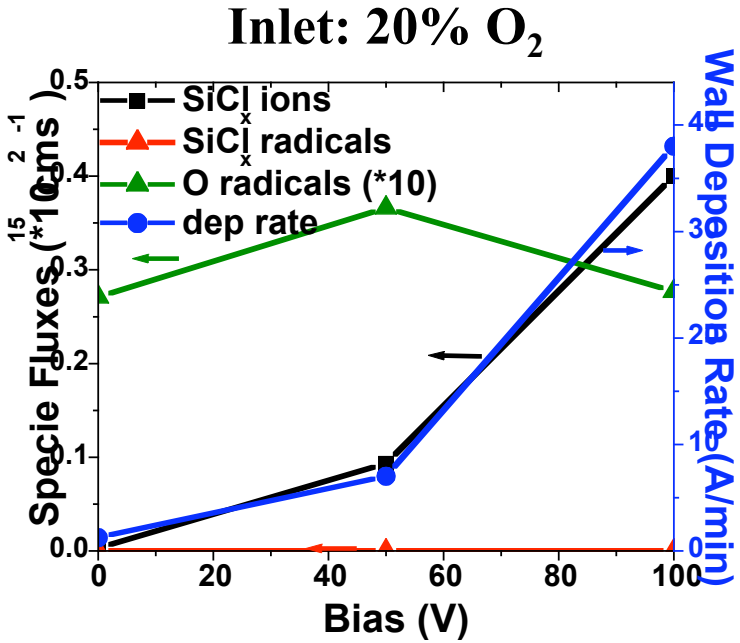




Absolute $SiCl_x$ fluxes
from ionization cross section
estimates in mass spectrometer

Deposition Rate vs. Incident Flux (3 mTorr)





At both pressures:

1. Measured wall film deposition rates proportional to silicon-containing ion fluxes.
2. Ion fluxes to walls can account for deposition rates; neutral $SiCl_x$ radicals appear to be less important or possibly unimportant.
3. O atom flux present in excess.

Conclusions: Etch By-Products

1. Neutral gas flow, temperature, and pressure profiles can strongly affect etch product transport in etch tools.
2. Evidence suggests that etch product wall deposition for $Si/Cl_2/O_2$ is due primarily to positive ions containing etch products.
3. Transport of etch products within chambers, via neutral flow, diffusion, ionization, re-deposition, re-etching, etc., appears to be both scientifically interesting and technologically important.
4. Similar issues exist for deposition/etch precursors in dielectric etch tools and will be the subject of future studies.

Conclusions: Etch By-Products, con't

5. Etch by-products for new materials could represent ESH problems (e.g. RuO_4 formation from metal gate material Ru/RuO_2 etch)
6. Plasma and neutral flow pulsing offer additional degrees of freedom for etch tool operation; etch and deposition precursor transport and kinetics will play central role for these species as well.

Acknowledgements

- Mark Kiehlbaugh (currently at Lam Research)
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