MODELING OF FINITE 3D FEATURES IN HIGH DENSITY PLASMA ETCHING TOOLS*

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* Work supported by Semiconductor Research Corp. and National Science Foundation.

AGENDA

- Background

- Hybrid Plasma Equipment Model Overview

- Monte Carlo - Feature Profile Model
  - Model Description
  - Chlorine Etch of Polysilicon
  - Specular Reflection and Microtrenching

- 3D Profile Modeling
  - Finite Length Trenches
  - Dual Damascene

- Conclusions

PLASMA CHEMISTRY MONTE CARLO MODE

HPEM

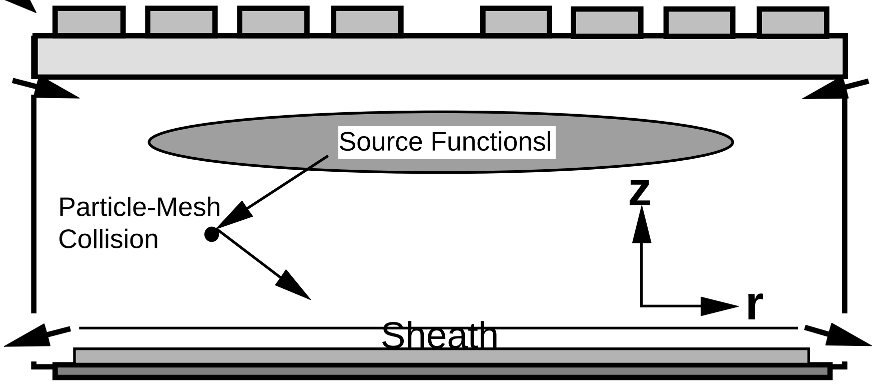
Momentum(r,z)

Sources(r,z)

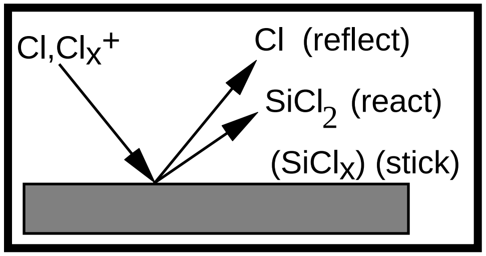
E(r,z,t)

Sheath(r,t)

- The PCMC model uses data from the HPEM along with heavy body reaction rates and surface reactions.



Energy Dependent Surface Reactions

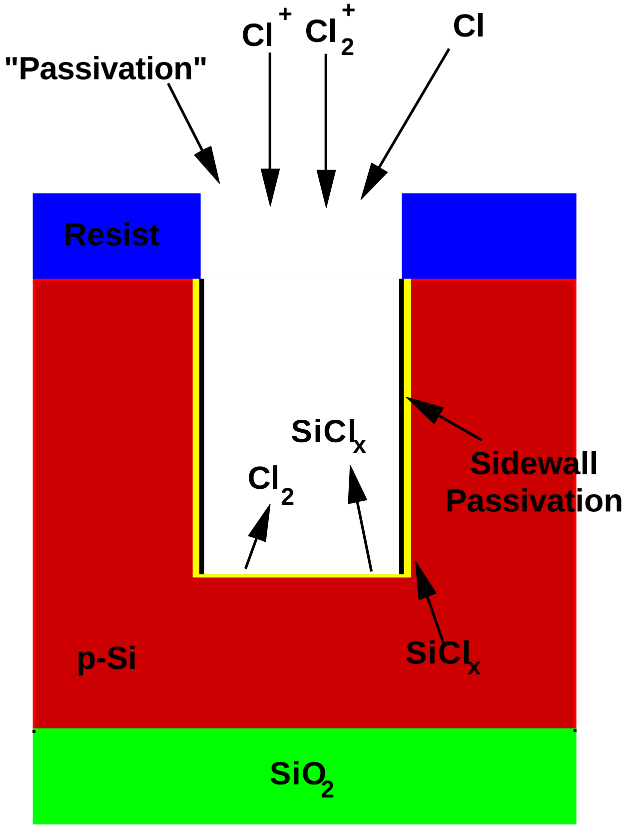


- Flux distributions are produced which can be used by the Monte Carlo Feature Profile Model (MCFPM) to determine the time evolution of etch profiles.

Ion and Neutral Surface Flux Distributions

- Location
- Magnitude
- Energy
- Angle

MONTE CARLO FEATURE PROFILE MODEL (MCF



- The MCFP model determines the time dependent etch profiles across the substrate using ion and neutral angular energy distributions from the PCMC model.

- Surface processes are implemented using a chemical reaction scheme:

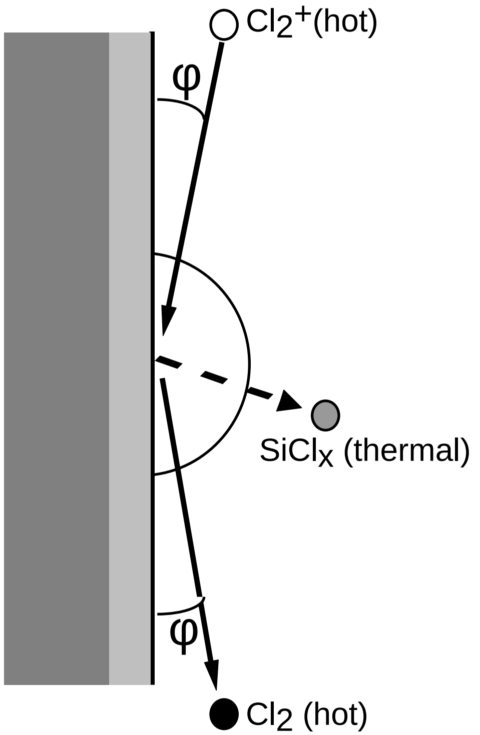
  e.g., Cl_2^+ + $SiCl_3$(s) --> $SiCl_3$(g) + Cl_2

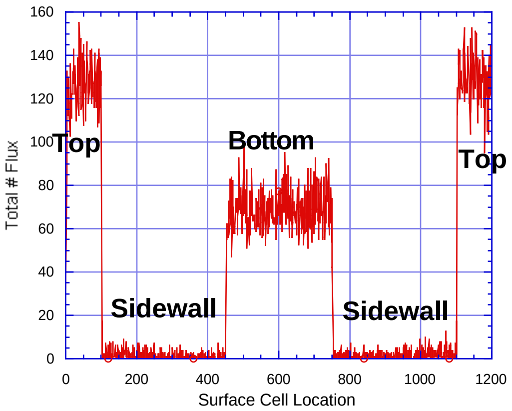
- Many different processes can be included: thermal etching, ion assisted etching, sputtering, redeposition, passivation, etc.

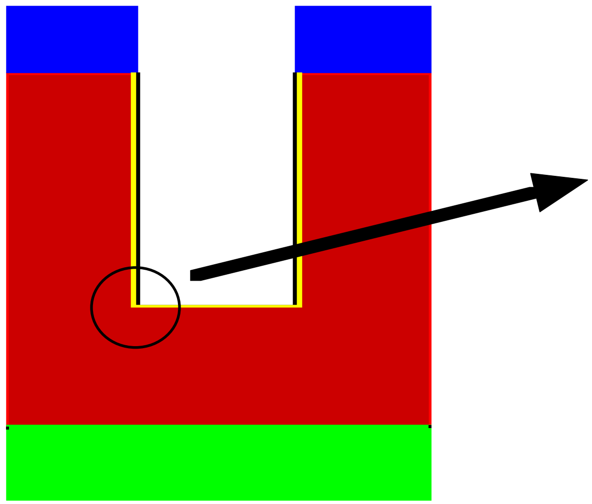
- Parametric forms for reaction coefficients:
  - energy dependence
  - angular dependence

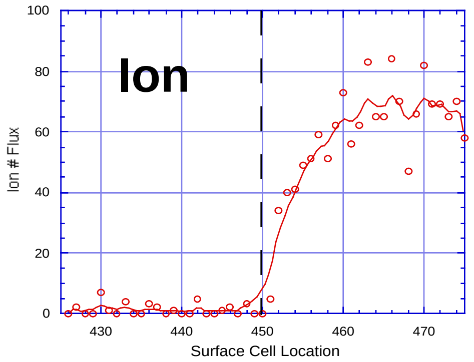
- Many different chemistries and feature shapes can be examined by modifying the reaction scheme and material mesh.

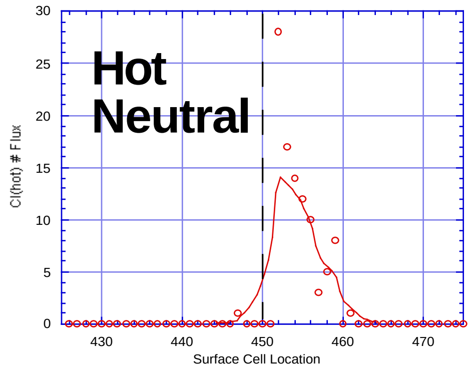
SPECULAR SIDEWALL REFLECTION

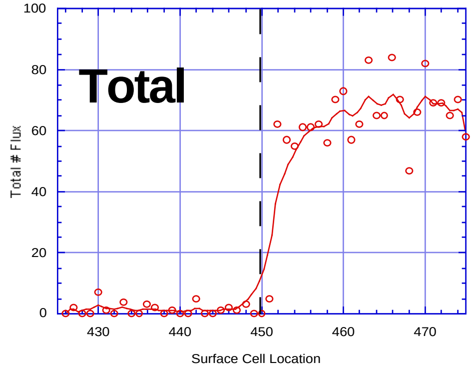






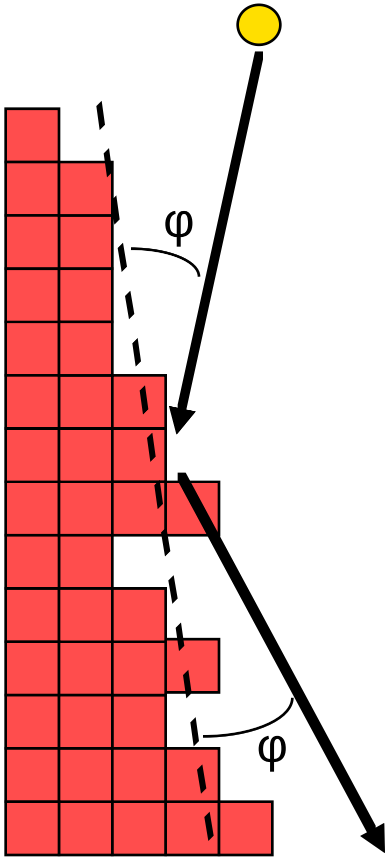






- **High energy particles which impact at a small angle to the surface tangent can retain >90% of their energy and reflect specularly.**
- **This effect leads to enhanced etching of the trench bottom due to “focusing” of the high energy flux near the sidewalls.**

SPECULAR REFLECTION IMPLEMENTATION



1. Particle impact with filled mesh cell.
2. Surface angle determined using a least squares fit for *n* neighboring surface cells. (*n* =9)
3. Ion enhanced reactions calculated as:

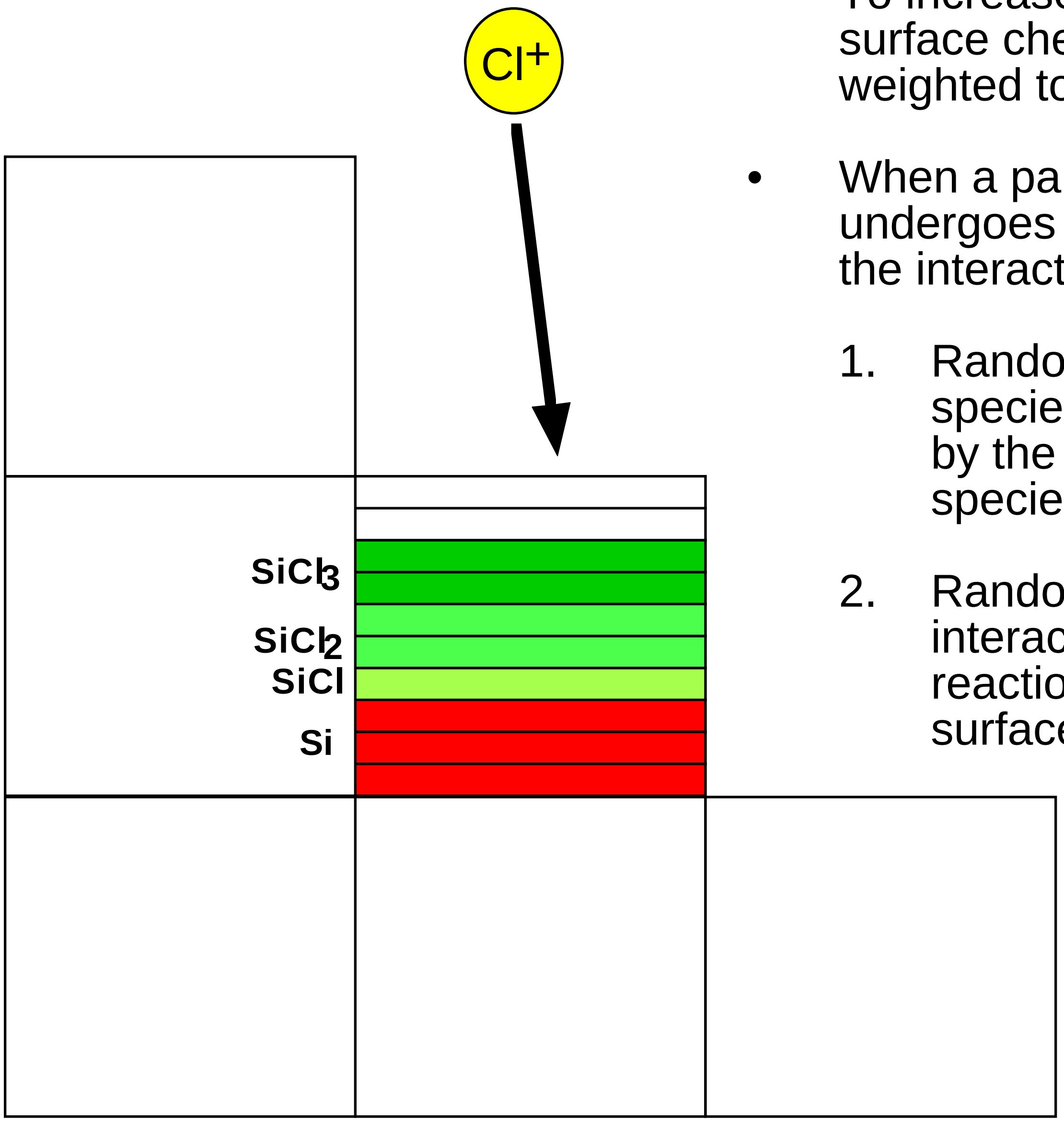
$$Y=\alpha(E^{1/2}-E_{th}^{1/2}) \text{ x } F_{adey}(\varphi)$$

4. Specular energy of outgoing particle is calculated as:

$$E/E_0=\min[1,E/E_{th}] \text{ x } \max[0,(\varphi-\varphi_{th})/(90^o-\varphi_{th})]$$

5. Particle is moved out along outgoing path until clear of filled cells.

MULTIPARTICLE MESH CELLS



- To increase the statistical significance of the surface chemistry, mesh cells can be weighted to be larger than gas particles.

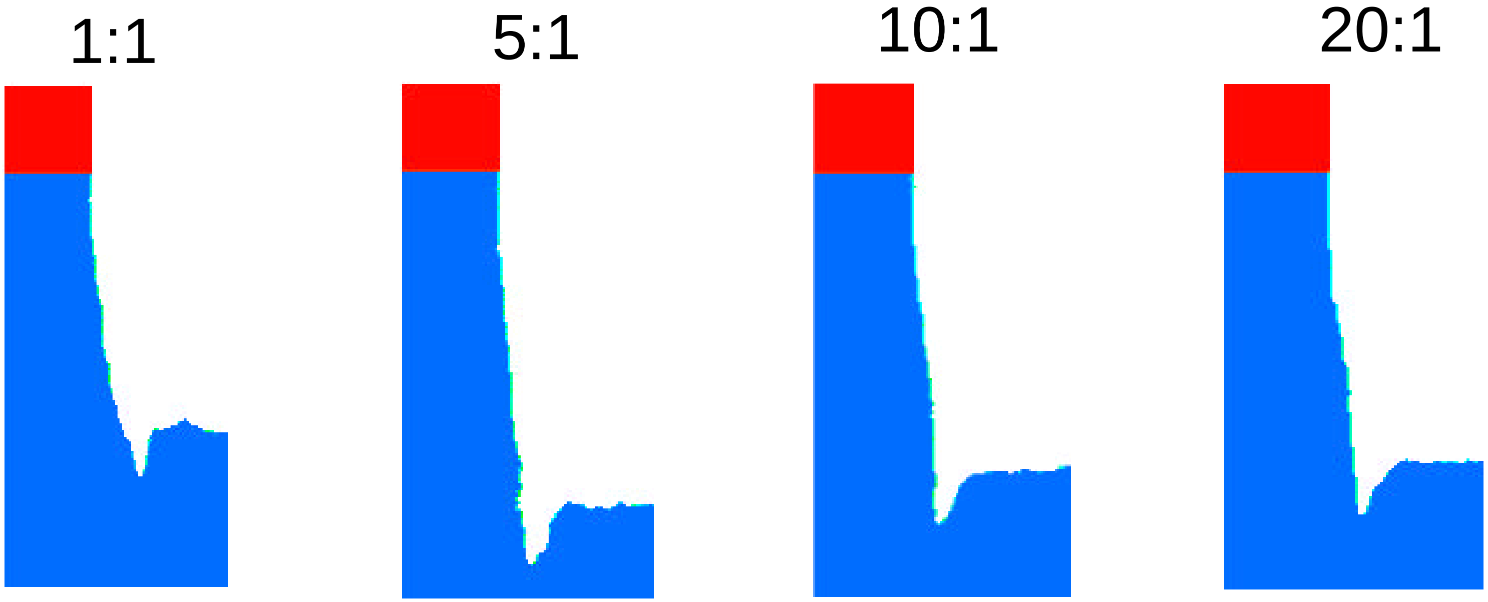
- When a particle impacts a mesh cell, it undergoes a two step algorithm to determine the interaction.

  1. Randomly determine which surface species with which to interact weighted by the fraction of the cell filled by that species.

  2. Randomly determine the chemical interaction weighted by the relative reaction probabilities given in the input surface chemistry.

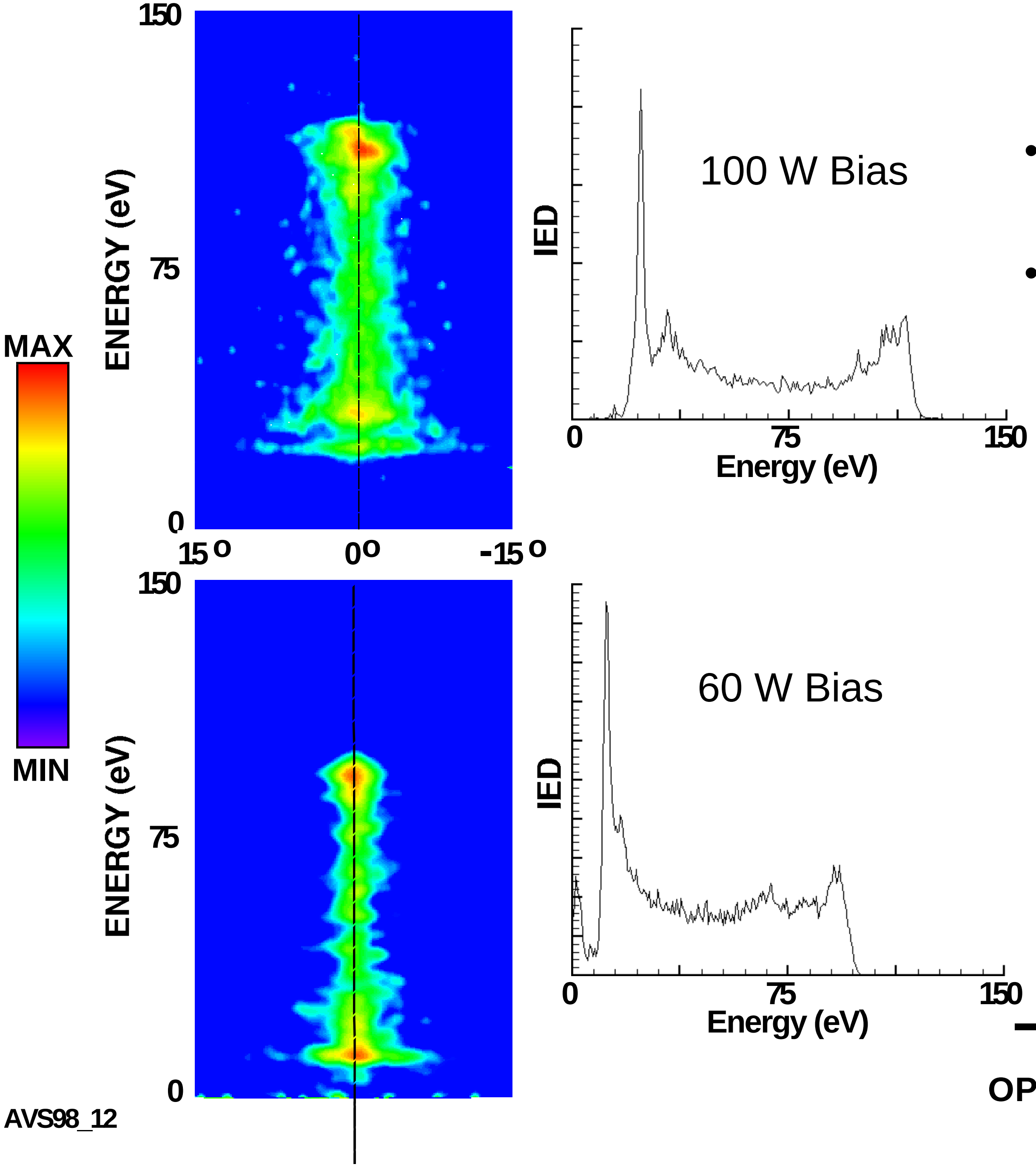
     - Start: 50%
     - Redist.: >80%
     - Empty: <20%

Mesh:Particle Weight Ratio



- As the ratio is increased the surface statistics increase.
- The surface becomes less “noisy”.
- The overall trench etch rate stabilizes.
- Above 10:1, the profile changes become less significant

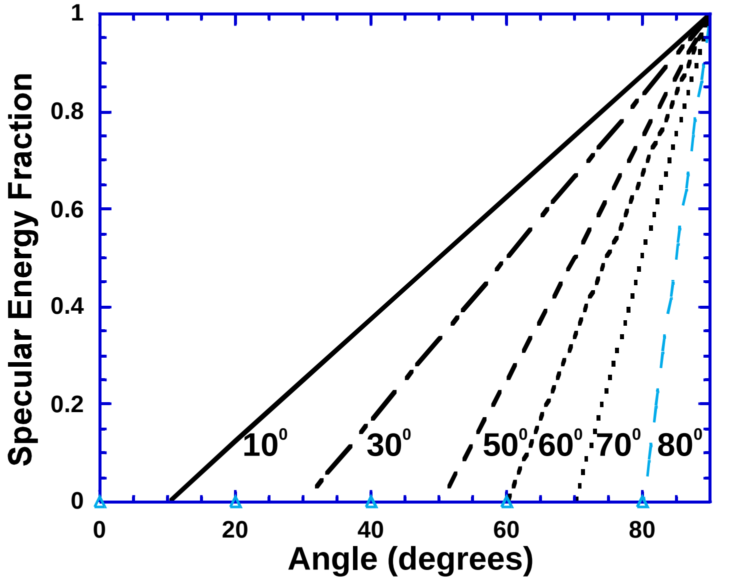
ION ENERGY ANGULAR DISTRIBUTIONS

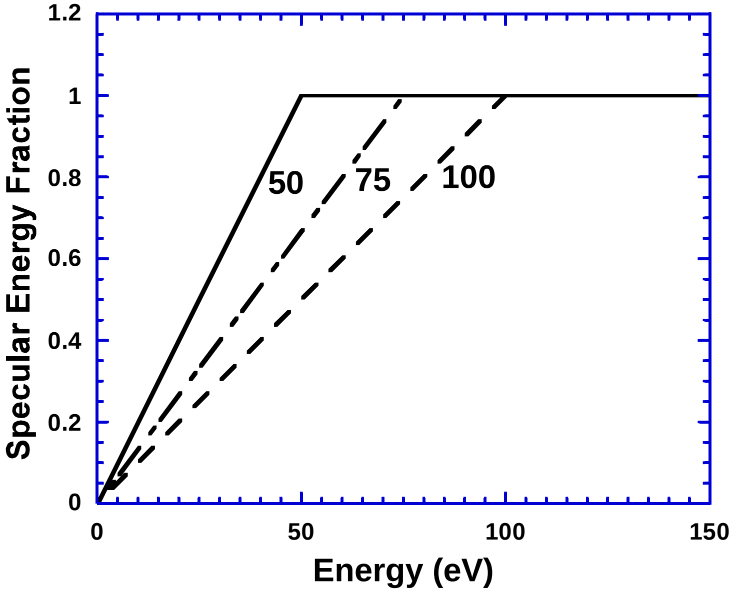


- The higher bias leads to a more capacative IED
- For both cases the average incoming ion angle 2°

- 10 mTorr Cl_2 (60 sccm)
  600 W ICP
  LAM 9400SE Reactor

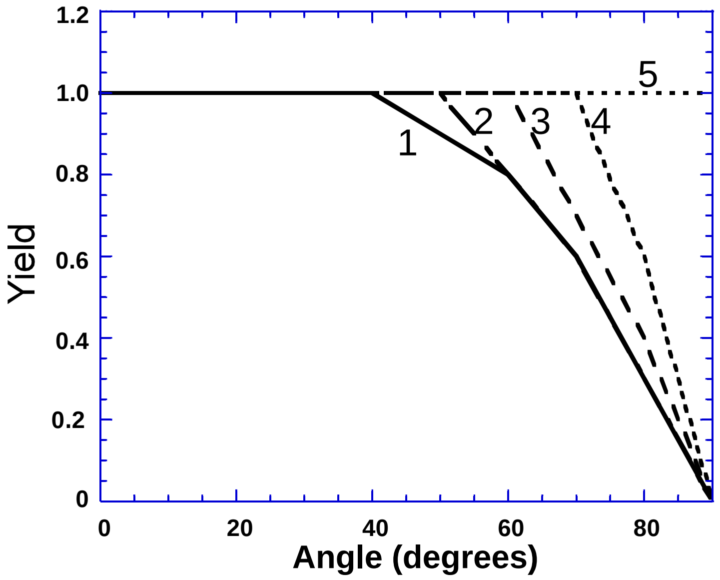
Specular Reflection

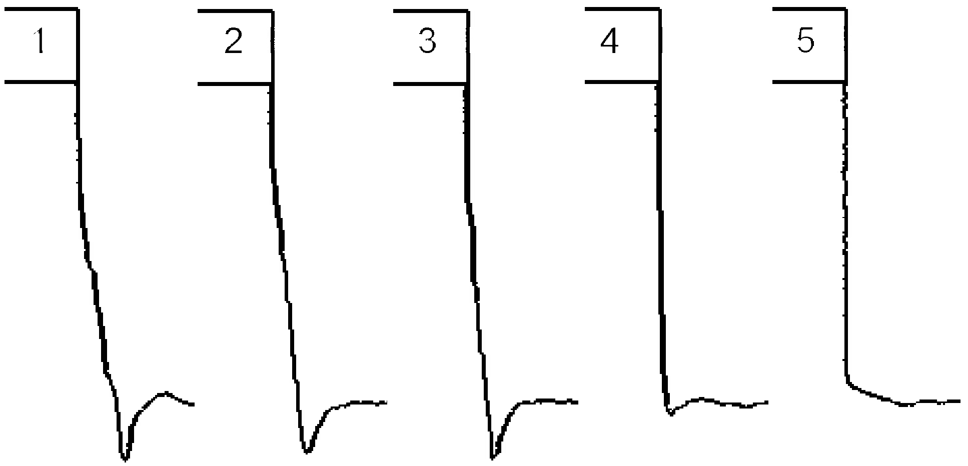




- Currently, there is no experimental results for specular reflection measurements.
- Helmer and Graves demonstrated specular reflection for a molecular dynamics model.
- Necessary to determine the energy and angular dependence of specular reflection.
- An attempt has been made to determine the possible cutoff energies and angles for the system.

Angular Dependent Etch Yield



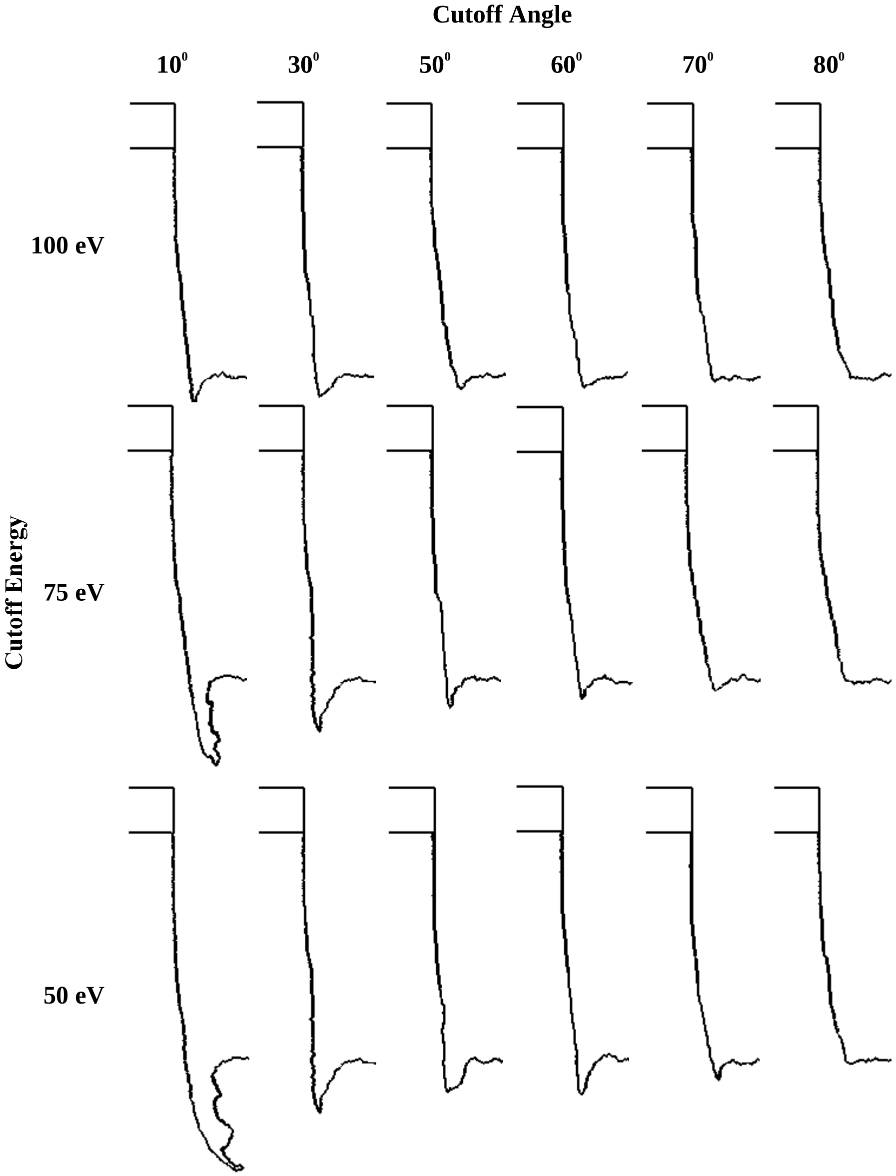


- The Angular Dependent Etch Yield (ADEY) of the ion flux affects both the microtrench development and the sidewall slope.

- Experimental result by Chang and Sawin (Case 1).

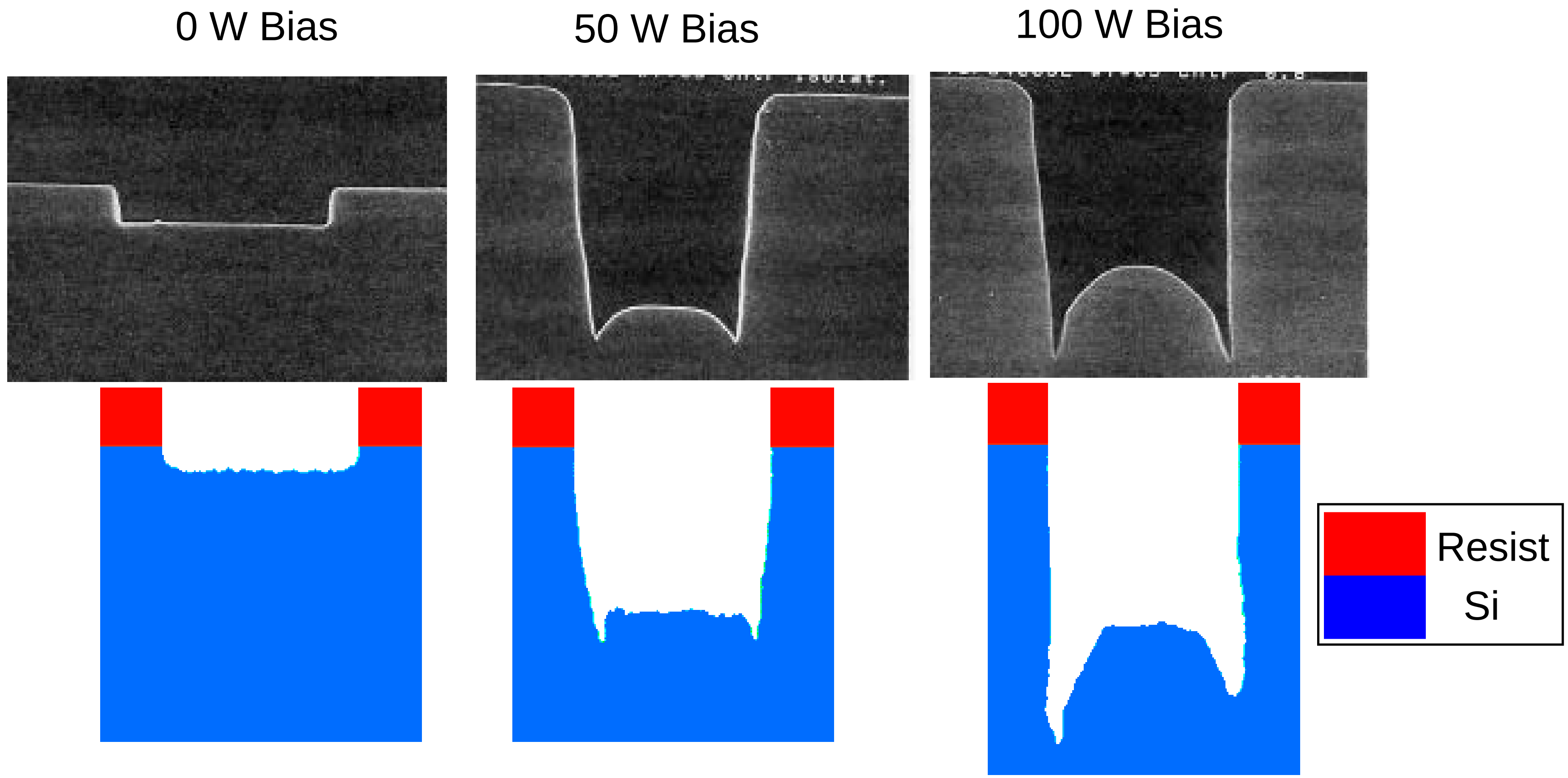
- As the slope of the ADEY increases the sidewalls become more vertical and the microtrenching decreases due to lack of “focusing” of the ions by the sidewalls

Specular Reflection



- For large cutoff angles and energies, there is little microtrenching.
- As the cutoff angle is decreased, the microtrenching dramatically increases and the sidewall becomes more vertical.
- Above 30^0, the trenching becomes reentrant.
- Since microtrenching is seen for 50 W rf bias cases, the cutoff energy is expected to be below 75 eV.
- The best range for microtrench formation is near 50 eV and between 30^0 and 60^0.

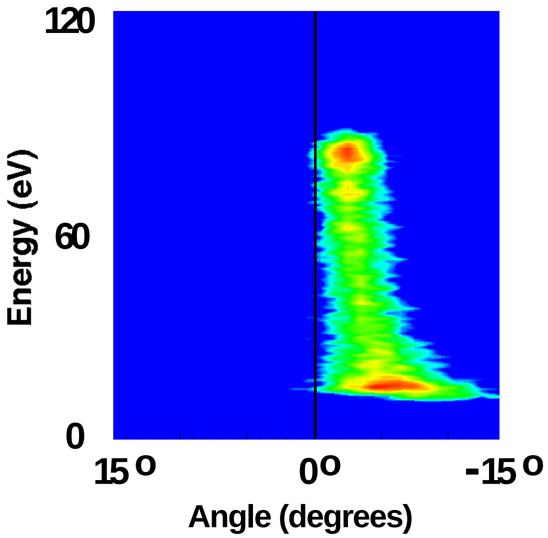
EXPERIMENTAL COMPARISON

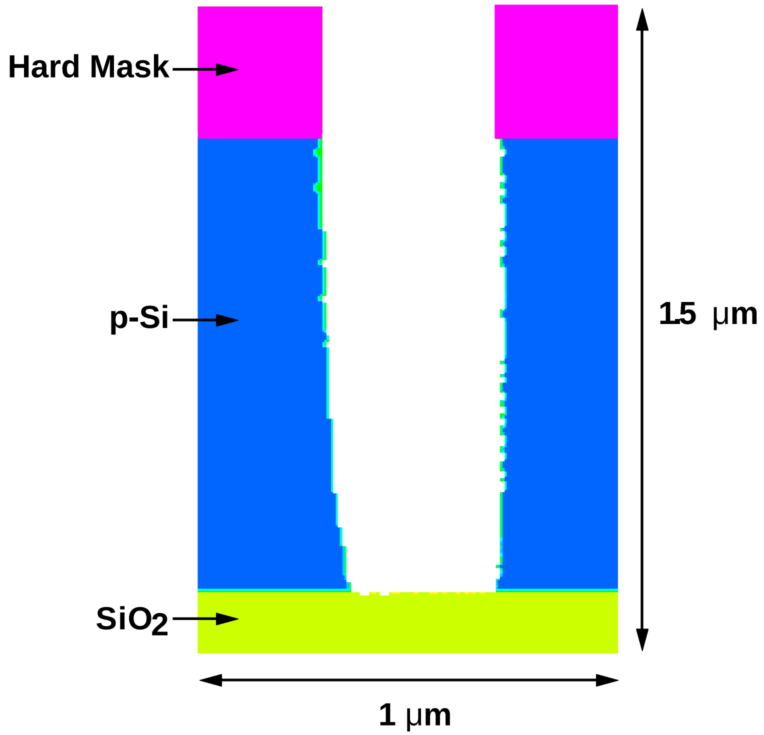


- Comparison to experiment shows reasonable agreement if sloped resist sidewalls are used.
- At high bias powers, simulation shows asymmetric microtrenching due to slight asymmetry of the IEAD and numerical sensitivity of the model.

- **9400SE LAM TCP Reactor**
  10 mTorr Cl_2 (60 sccm)
  600 W Bias
  LSI Logic Corporation

3-d FINITE TRENCH EFFECTS



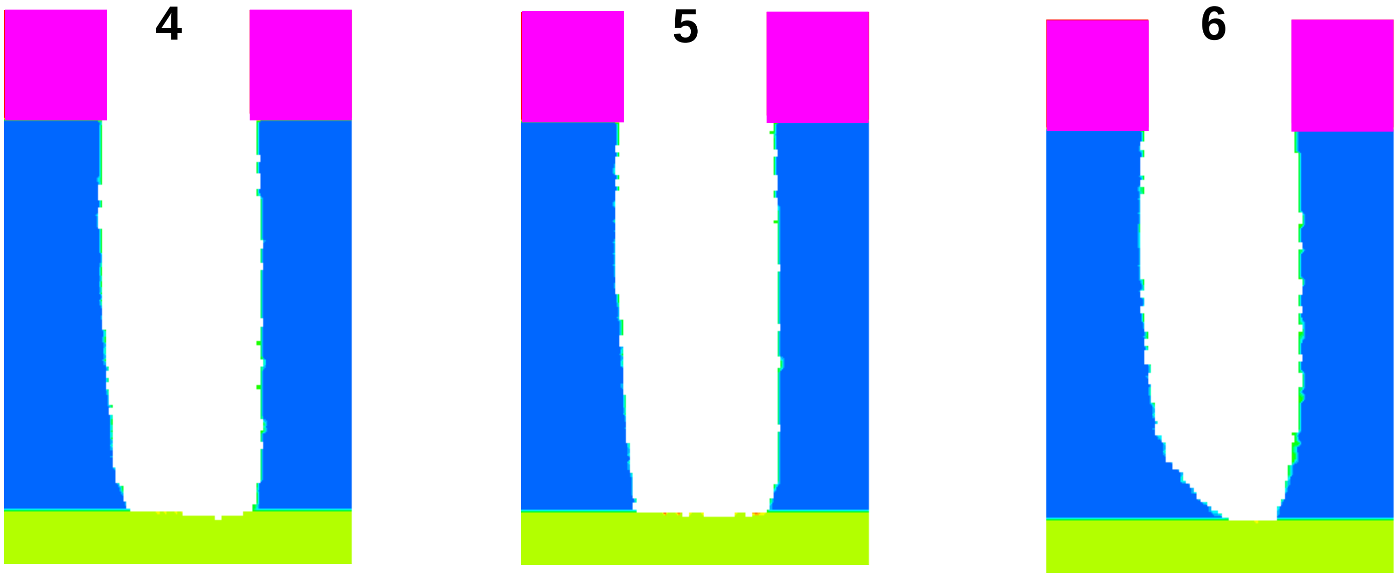


- The asymmetric IEAD from over the subwafer dielectric was used.
- The 2D model result is indicative of a infinite trench and shows limited skew due to the IEAD.

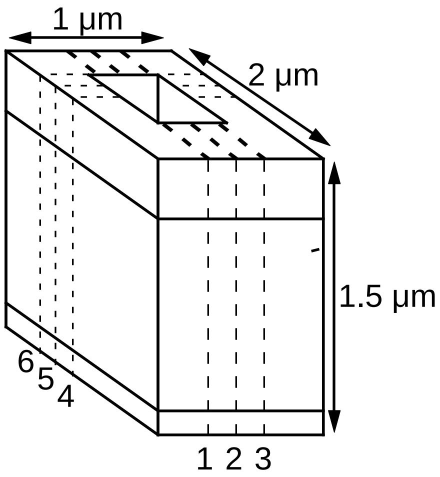
🟪 Resist
🟦 Si
🟩 SiO_2

- **LAM TCP 9400SE Reactor**
  10 mTorr Cl_2 (60 sccm)
  100 W RF Bias

3-d FINITE TRENCH EFFECTS



- In the center of the trench, the profile is similar to the 2D simulation.
- Near the endwall (0.05 μm) the asymmetry and underetch is strongly evident.
- This will require > 30% overetch to clear the endwall corners.



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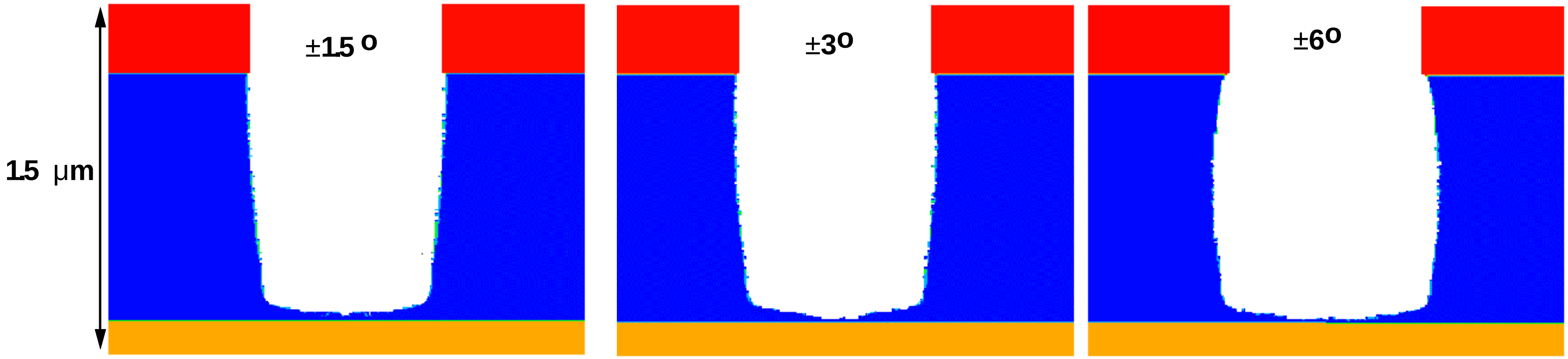
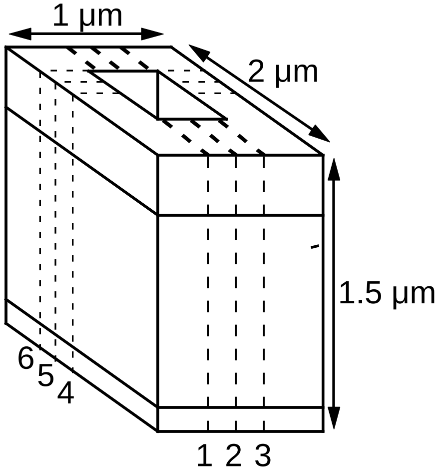
3D Finite Trench (IAD)



- The angular distribution of the standard case is 3o
- For narrower angular distributions, the endwalls taper strongly inward leading to differential etch rates near them.
- For broader angular distributions, the endwalls taper outward producing undercutting but also uniform bottom etch rates.



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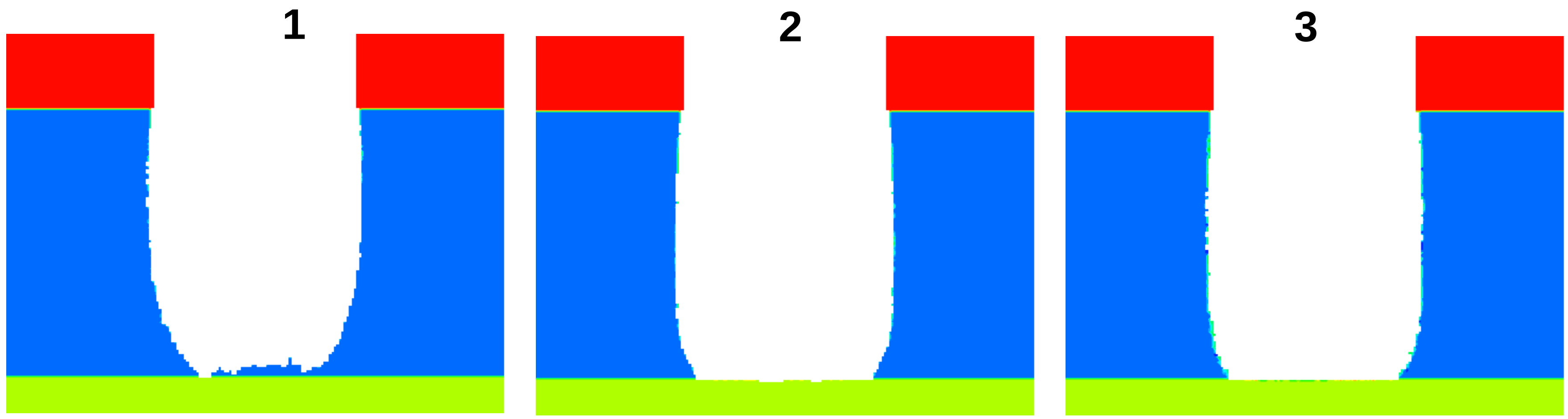
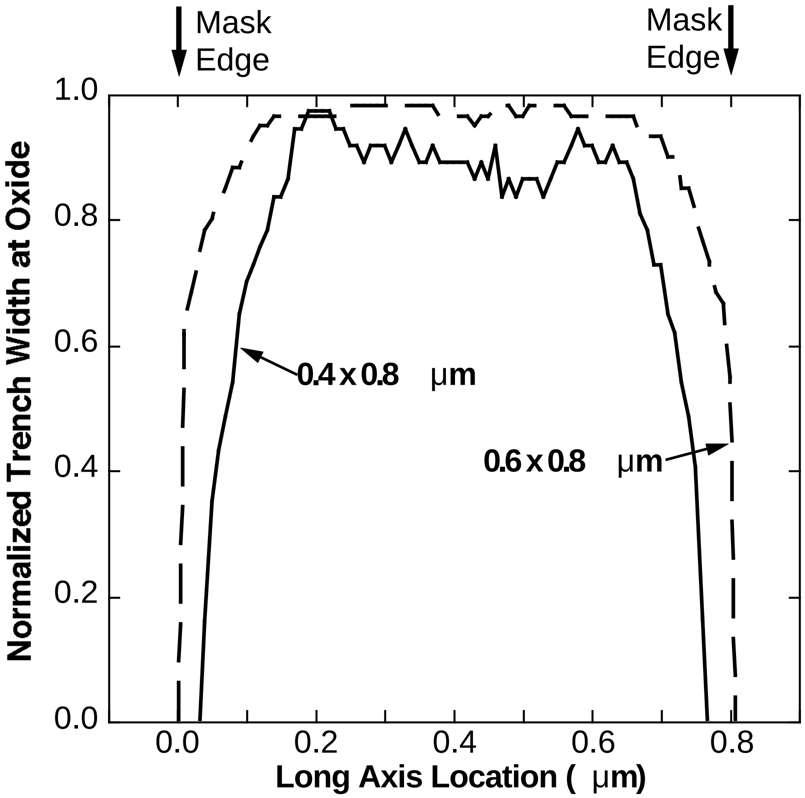
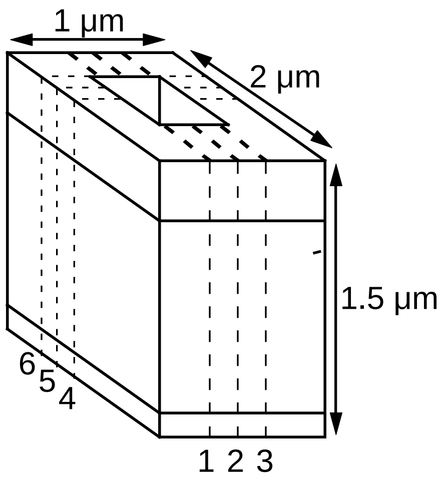
3-d FINITE TRENCH EFFECTS



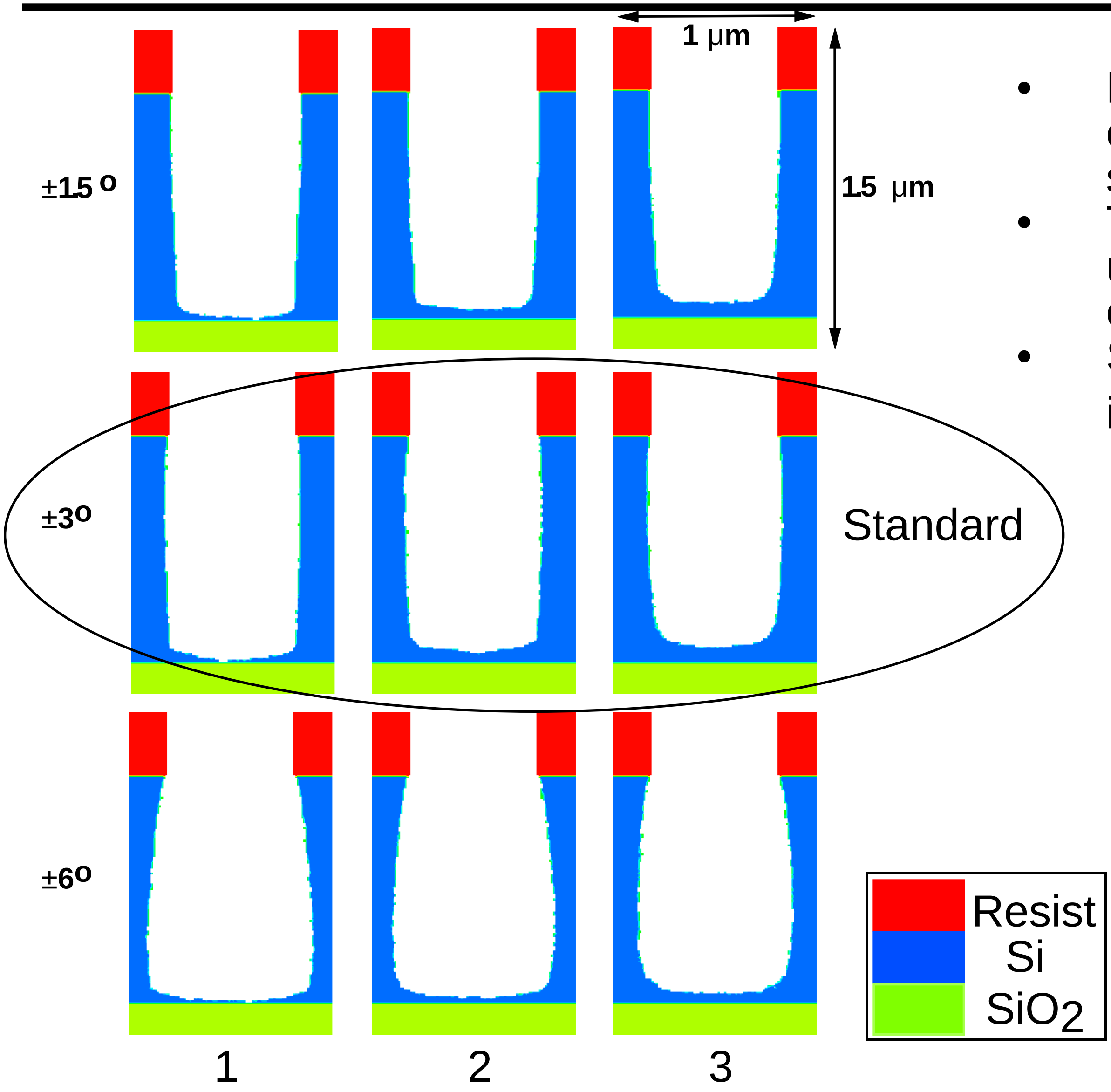


- Near the shadowed edge the profile is strongly underetched.
- Due to the narrow width the endwalls show greater curvature.
- For the wider trench, the shadowing of the endwalls is decreased.

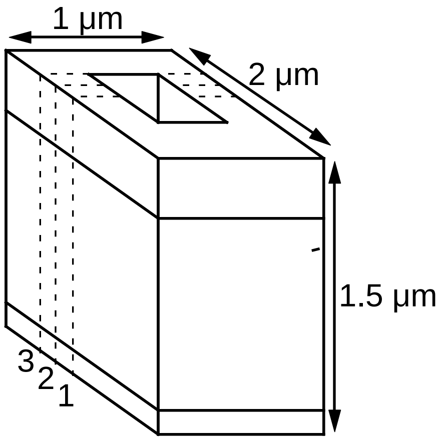


- **LAM TCP 9400SE Reactor**
  10 mTorr Cl_2 (60 sccm)
  100 W RF Bias

3-d FINITE TRENCH EFFECTS



- Narrowing the angular spread of the IEAD produces a sloped sidewall.
- The broad IEAD produces undercutting the greatest corner rounding
- Sticking coefficient of $SiCl_x$ is 10%



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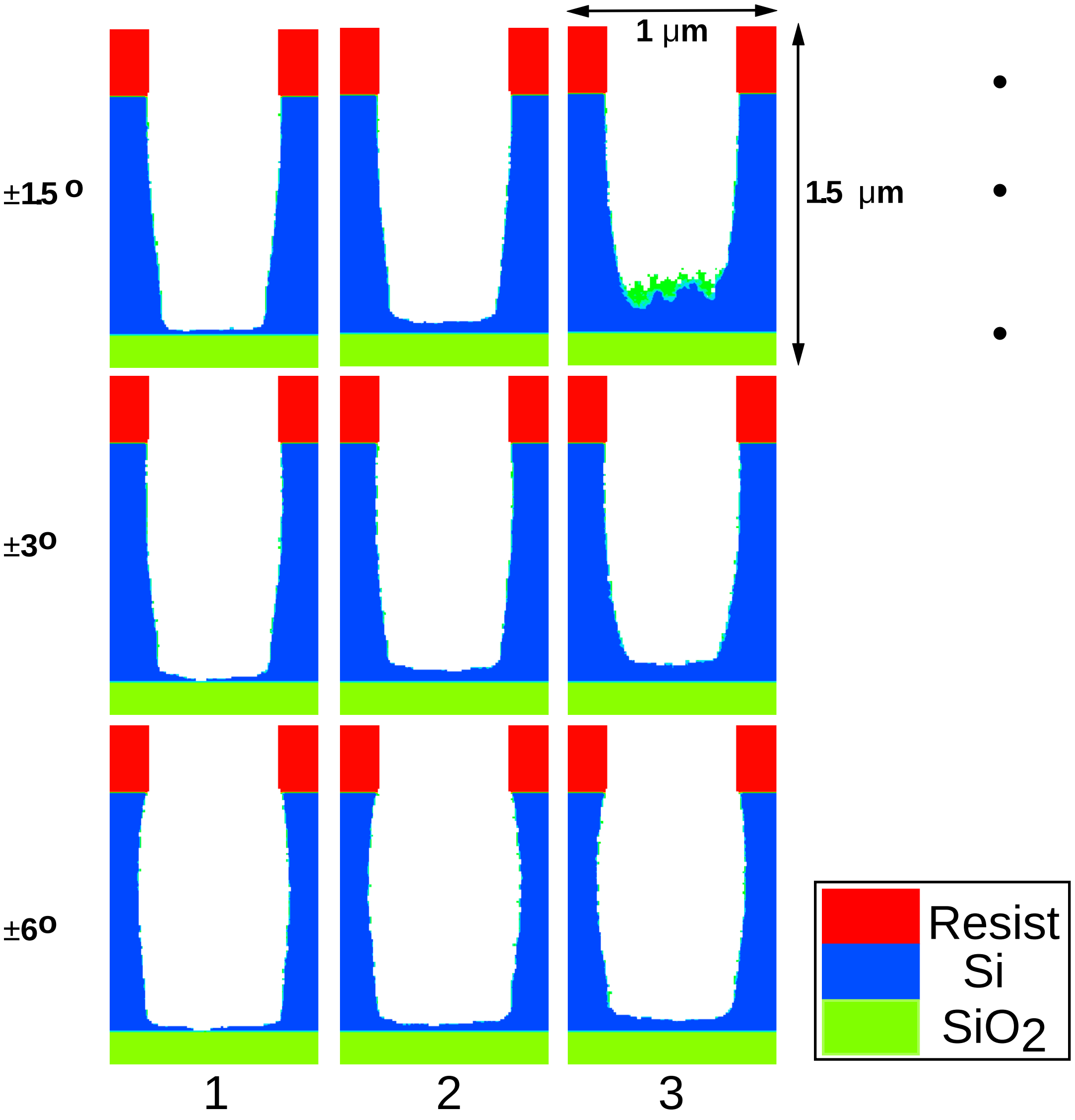
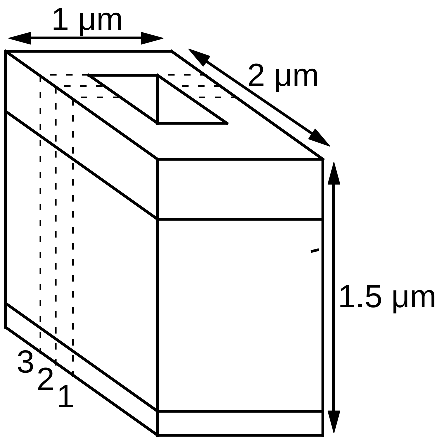
3-d FINITE TRENCH EFFECTS



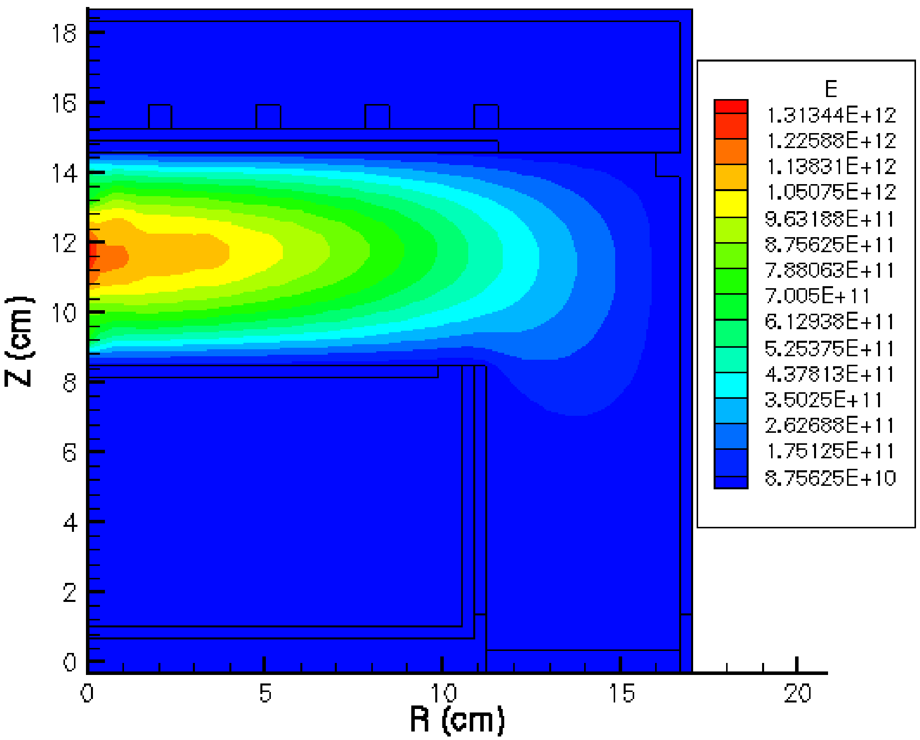
- Sticking coefficient of $SiCl_x$ is 30%.
- As the redeposition rate increases, the sidewalls taper inward.
- For the narrow IEAD, the endwall encroaches on the trench leading to a dramatic underetch.

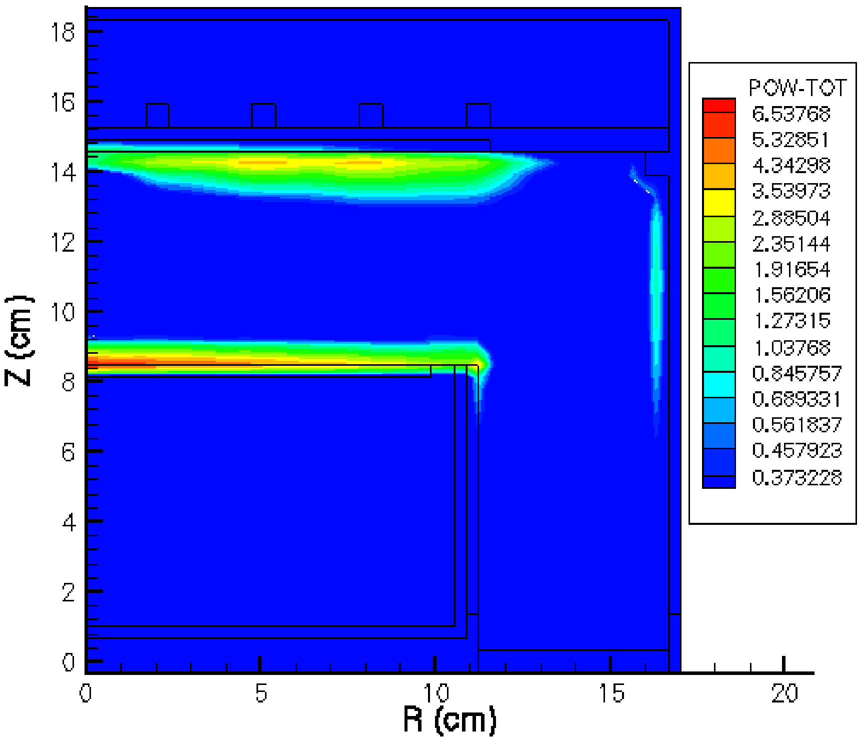


- **LAM TCP 9400SE Reactor**
  10 mTorr Cl_2 (60 sccm)
  100 W RF Bias

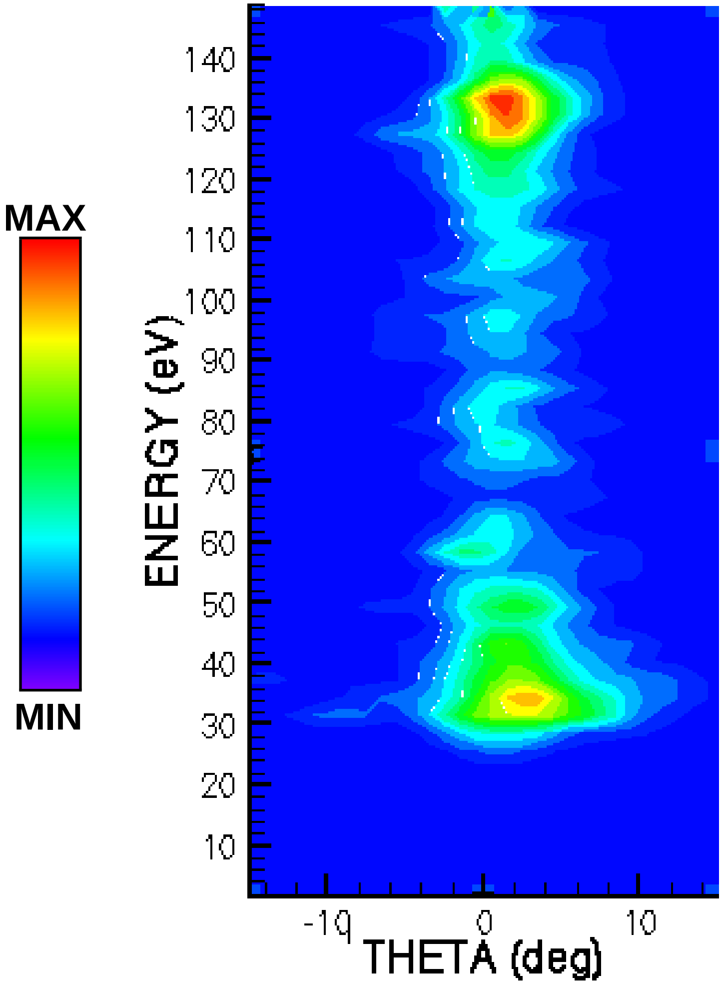
SIMULATED REACTOR PROPERTIE

- LAM TCP Type Reactor
- 10 mTorr
- 1 kW ICP (13.56 MHz)
- 300W Substrate Bias (13.56 MHz)
- Ar/CF_4 60/40 (200 sccm)


e^- Density

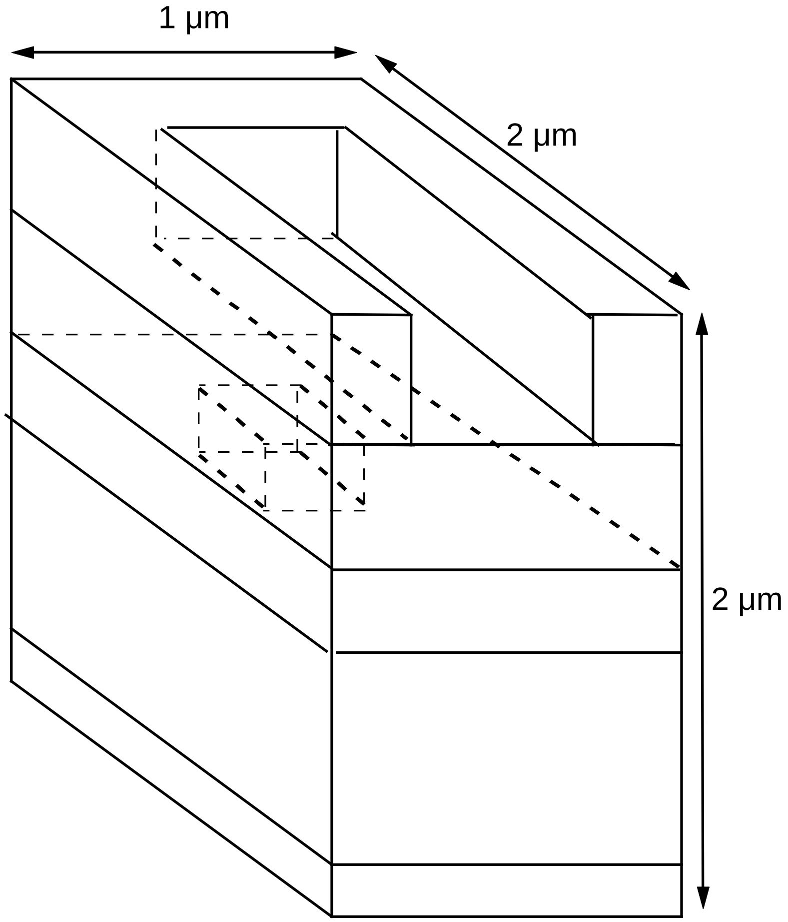

Power Deposition

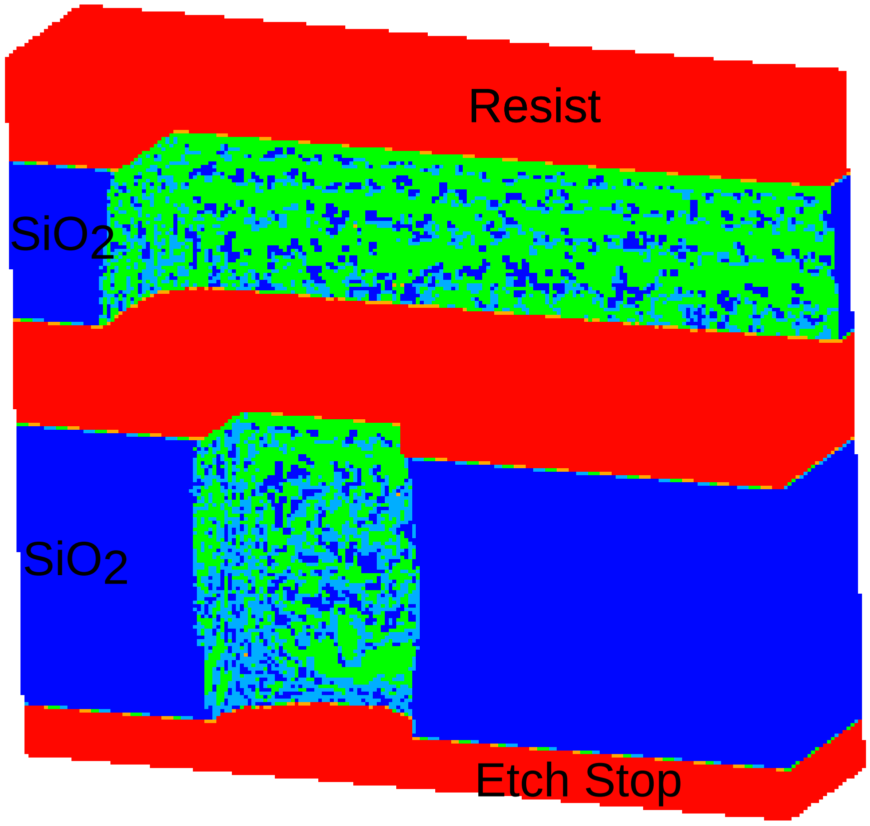
ION ENERGY ANGULAR DISTRIBUTION



- The combined IEAD for Ar$^+$ and CF_3^+
- The IAD ranges to 10^o
- The IED ranges from 30 to 140 eV

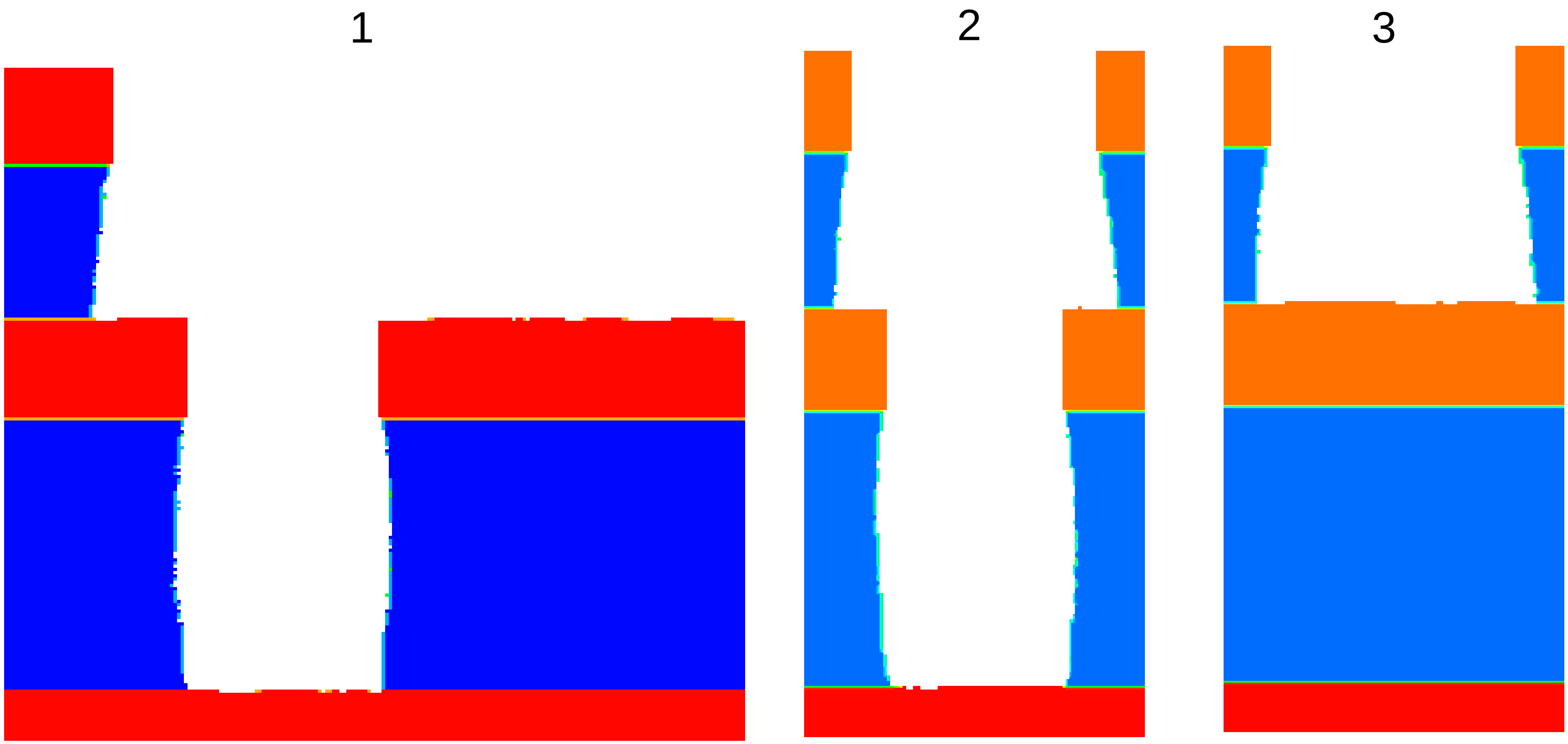
3-d FINITE TRENCH EFFECTS





- 10 mTorr Ar/CF$_4$ (200 sccm)
  1 kW ICP
  300 W RF Bias

3-d DUAL DAMASCENE ETCH



- The single etch step in dual damascene processing requires highly anisotropic etching due to the extend etch through the vias.
- Undercutting becomes more pronounced for the upper trench region.

- **10 mTorr Ar/CF$_4$ (200 sccm)**
  1 kW ICP
  300 W RF Bias

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CONCLUSIONS

- The Monte Carlo-Feature Profile Model (MCFPM) has been extended to 3 dimensions.

- Comparison of otherwise identical 2-d infinite trench and 3-d finite length trench trenches show that:

    - Proximity to 3-plane corners produces significant side-wall curvature.
    - 2-d models underpredict etch rate and required over-etch to clear corners.

- Redeposition of etch product on end-walls of finite length trenches can produce significant curvature. As a consequence, IEADs having finite angular breadth produce the most aniostropic etches.

- Specular reflection has been examined and it’s role in microtrenching and sidewall slope. Comparison to experiments indicates that the angular-dependent -etch yield in large part determines energy dependence of microtrenching.

- Dual damascene structures were examined demonstrated different degrees of undercutting on the upper and lower levels.