Test Structure Experiments and Modeling of Very Deep Dry Etching Processes for MEMS Applications

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OUTLINE

- ❑ Background and Motivation

- ❑ Statistical experiments for characterizing the etch process as a whole (done at TRW NovaSensor Co.):

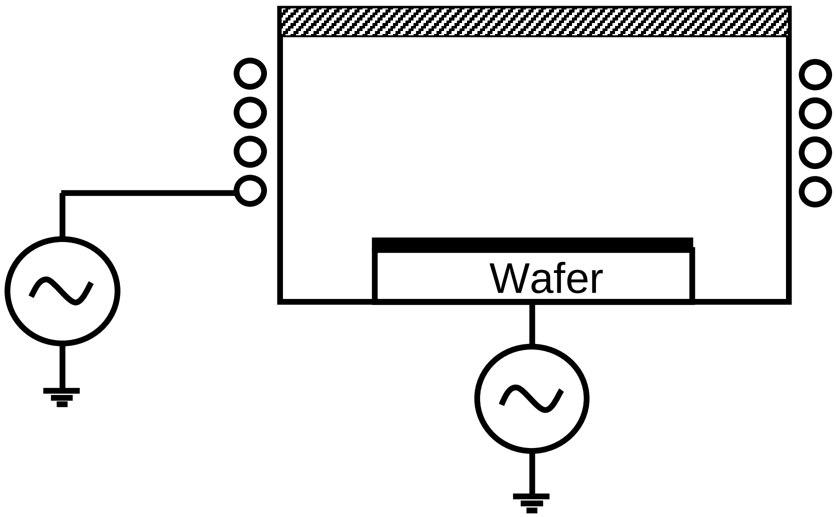
  - Effects of different input parameters on etching characteristics: Silicon etch rate, Photoresist etch rate, Lag, ….

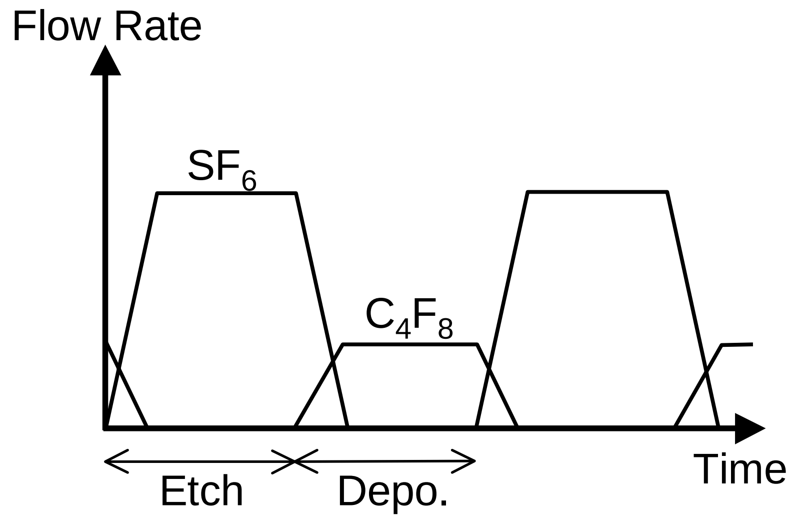
- ❑ Polymer deposition experiments (done at Stanford University):

  - Effects of ions on the deposition process

- ❑ Summary

Motivation: STS Deep Trench Etcher





- Inductively Coupled High Density Plasma (ICP)
- The etching process switches back and forth between etch (using SF_6) and deposition (using C_4F_8) cycles
- The deposition phase protects the sidewalls and makes the etching process anisotropic

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❑ Polymer deposition experiments (done at Stanford University):

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❑ Summary

Design of Etch Experiments (1)

- Goal: Characterization of the STS etcher with respect to the input parameters using statistical methods
- Two masks were designed: one with 7% area usage and the other with 21% area usage
- High density mask was used so that non-uniformity effects could be seen
- Masks consist of trenches with widths between 3µm and 200µm and square vias with sizes between 20µm and 200µm
- Resist thickness: 8µm

Design of Etch Experiments (2)

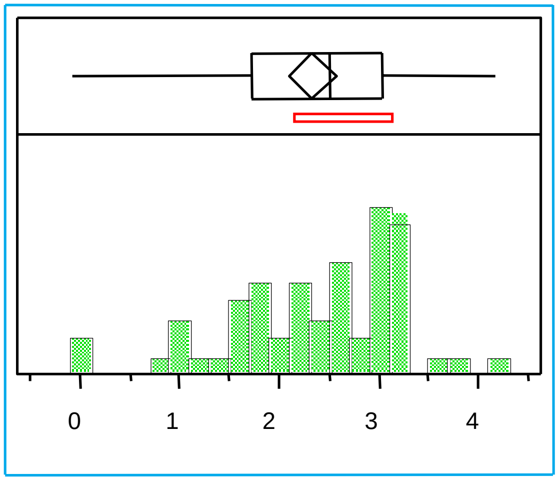
- Too many input parameters: SF_6 flow rate, C_4F_8 flow rate, Etch time, Deposition time, APC, Coil Power and Electrode Power in etching and depositions cycles
- The following parameters were chosen:

Code	*Parameter*	*Equip. Range*
A	SF6 Flow Rate (sccm)	0 , 260
B	Etch Time (s)	5 , 30
C	C4F8 Flow Rate (sccm)	0, 170
D	Deposition Time (s) 5	5 , 30
E	APC (Degrees)	0.1 , 90
F	Top Power (W)	0 , 1000
G	Bottom Power (etch) (W)	0 , 30
H	Bottom Power (Dep.) (W)	0 , 30

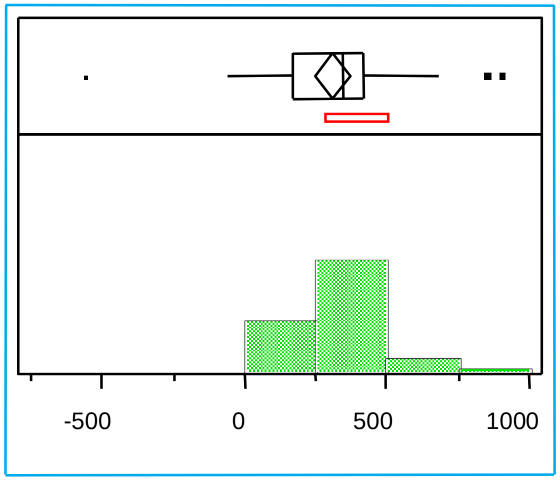
Design of Etch Experiments (3)

- Full Factorial design requires 2^8 = 256 experiments!
- Partial Factorial design was done assuming all third and higher order interactions and also some of the second order interactions to be negligible
- Number of experiments : Initial = $2^{(8-3)}$ + 4 center points = 36
  CCD = 2*8 + 3 center points = 19
- Etch time = 90 min.
- Responses: Etch rate, Lag (ARDE), Non-uniformity, Sidewall Angle and Photoresist Etch rate (Selectivity)

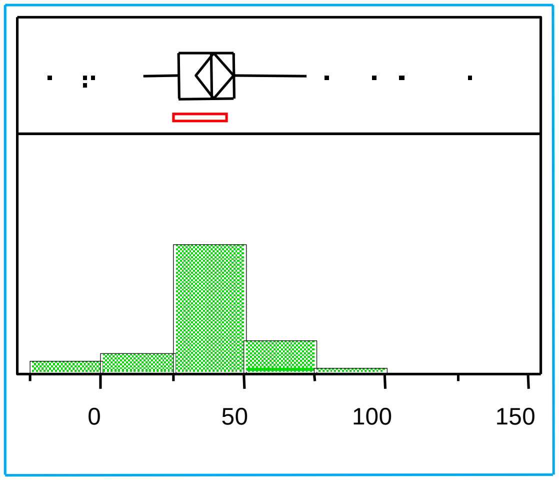
Range of Responses



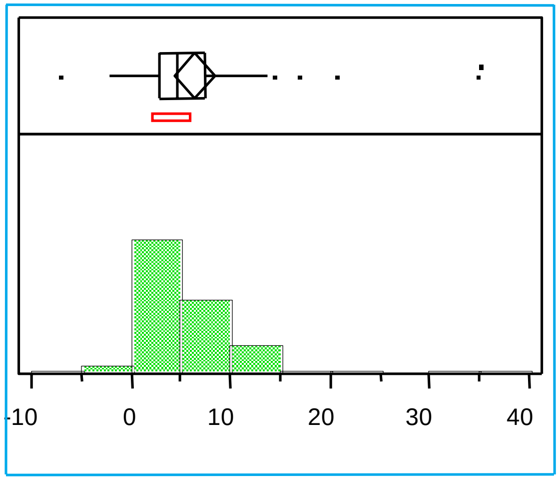
Etch Rate (200 µm, C) (µm/min)



Photoresist Etch Rate (A/min)

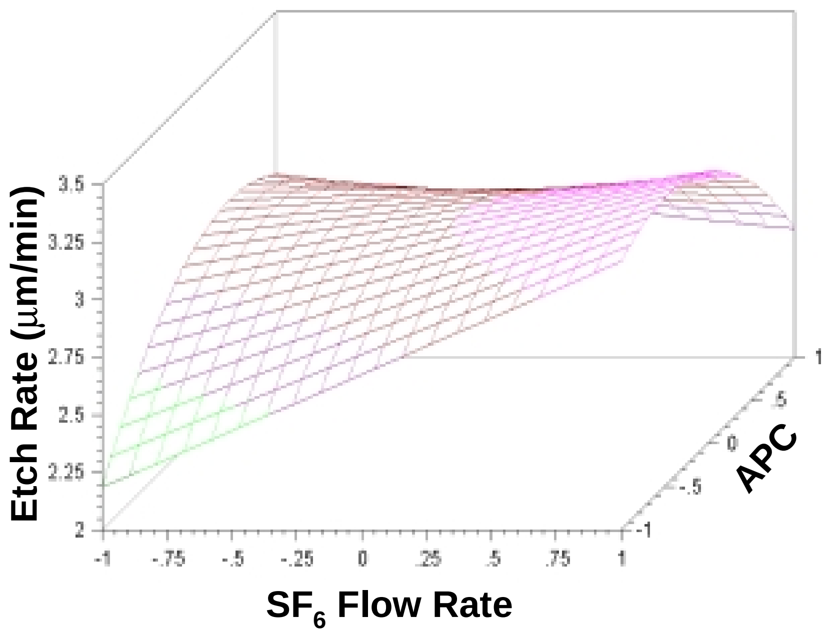


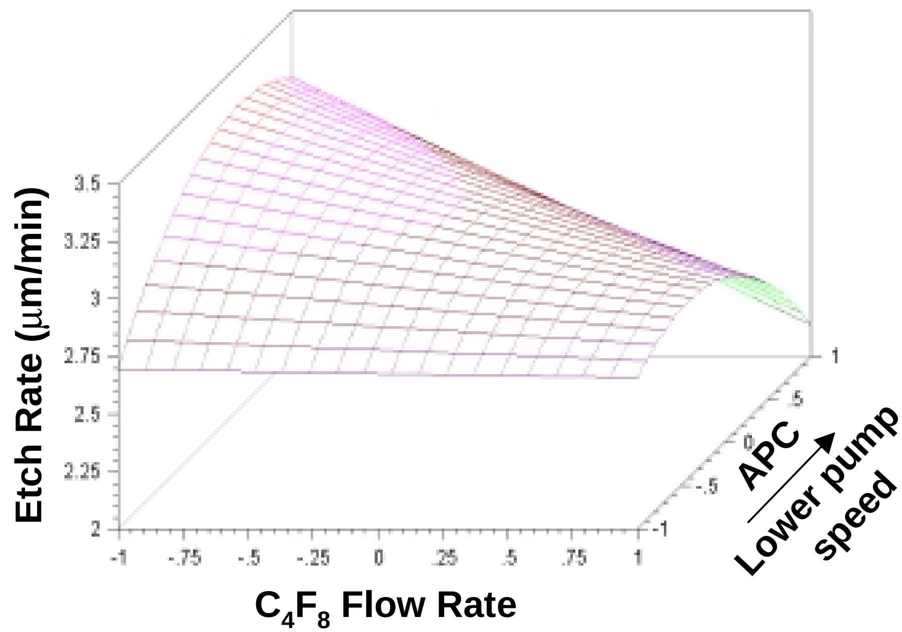
Lag(ER) (%)



Non-uniformity (200 µm) (%)

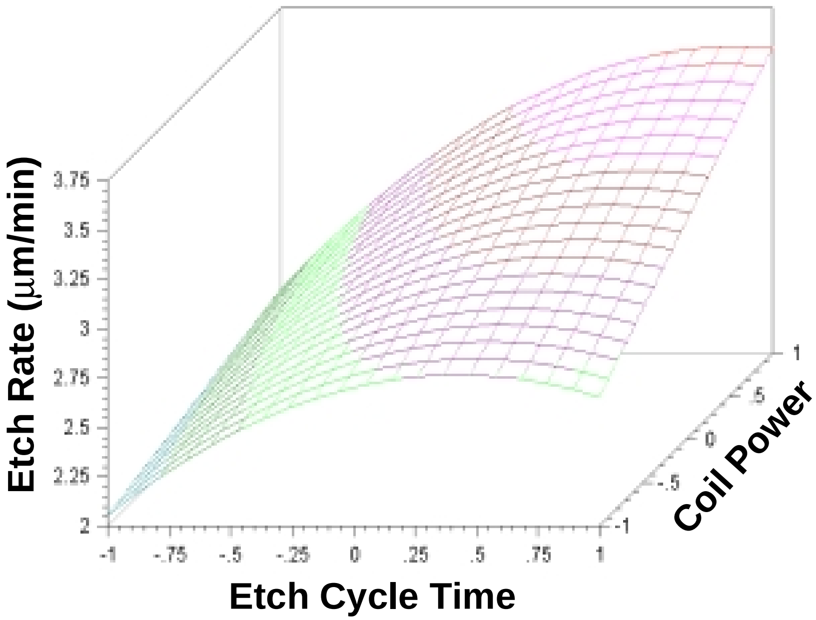
Silicon Etch Rate (1)

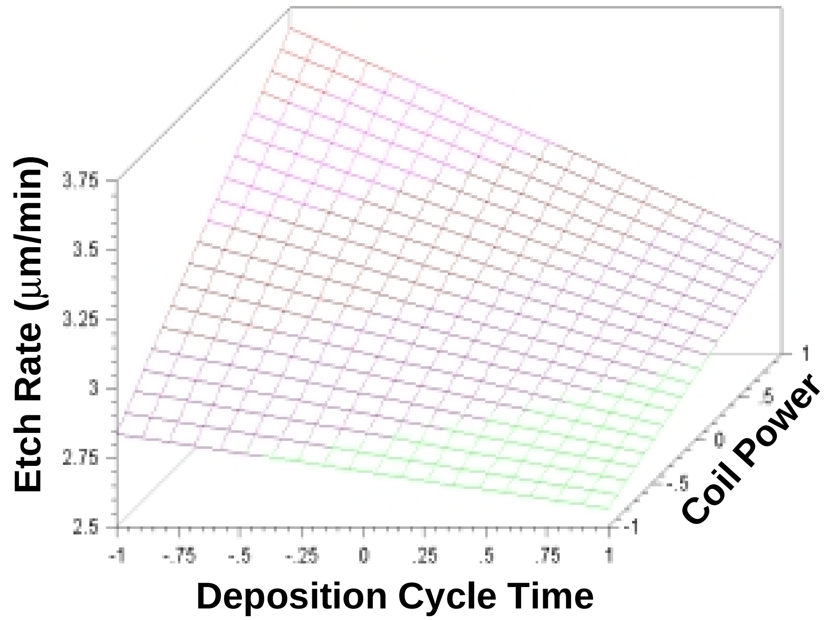




- Etch rate is measured for 200 μm trenches at the center of the wafer
- Increasing pressure decreases the etch rate

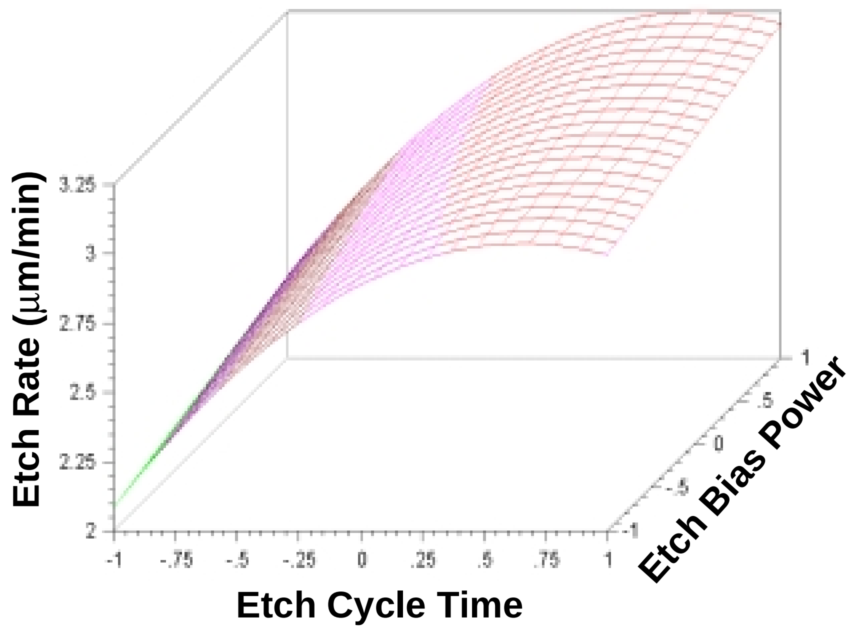
Silicon Etch Rate (2)





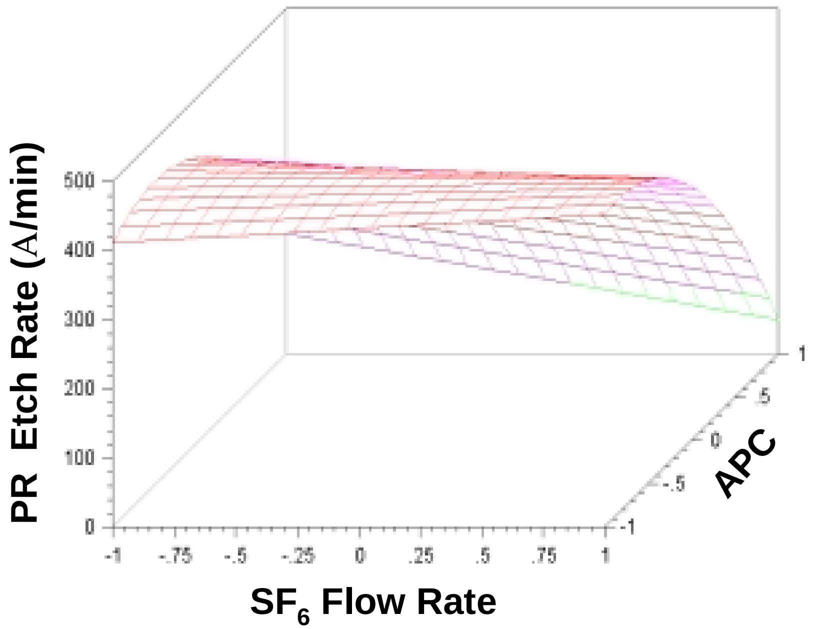
- Effect of Coil power depends on the cycle times

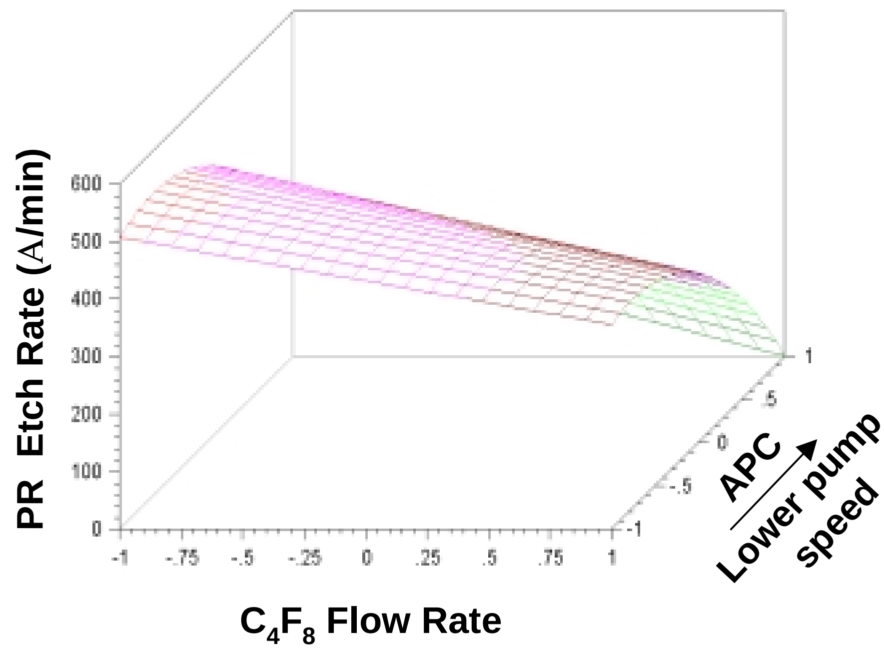
Silicon Etch Rate (3)



- Bias power during deposition cycle has no significant effect
- R^2_{adj}=94% , R^2_{pred}=88%

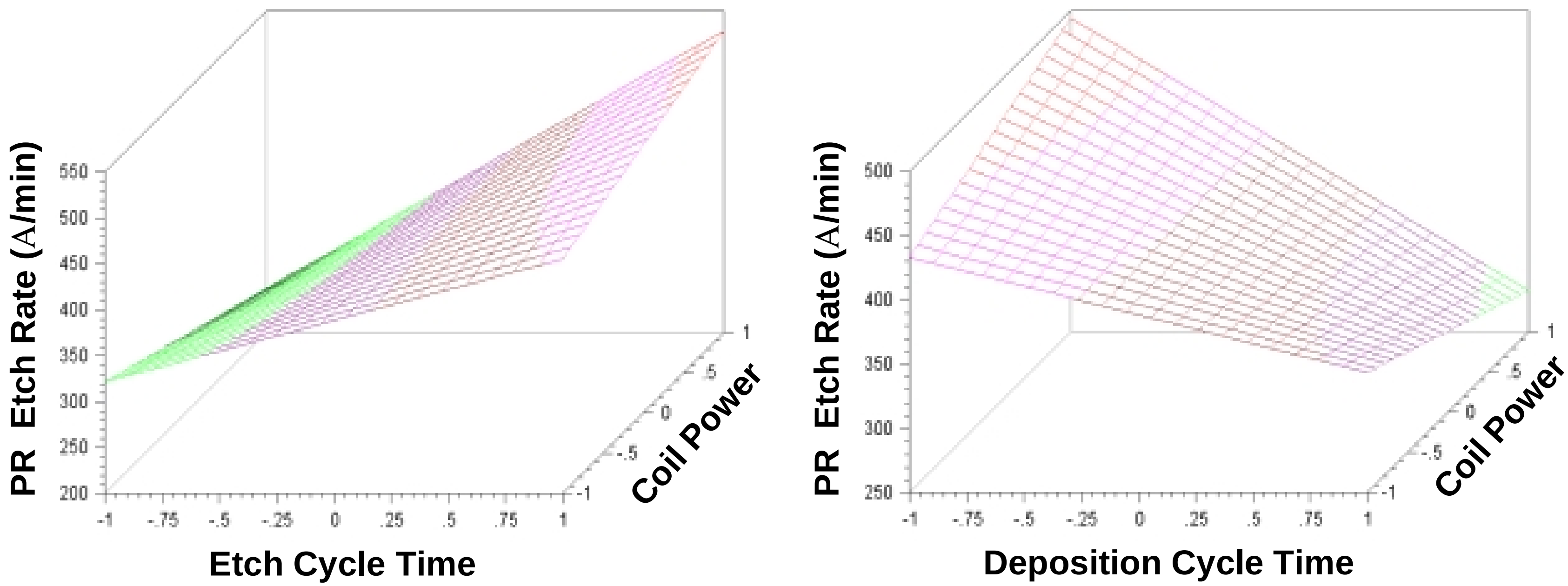
Photoresist Etch Rate (1)





- Etch rate is averaged over 5 points on the wafer
- Increasing pressure and residence time during the etch cycle tend to decrease photoresist etch rate significantly

Photoresist Etch Rate (2)



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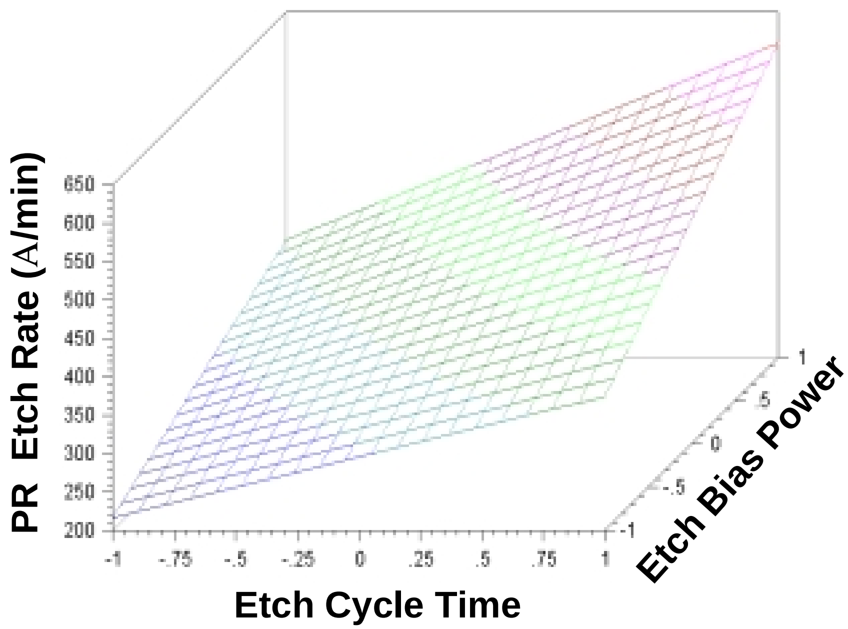
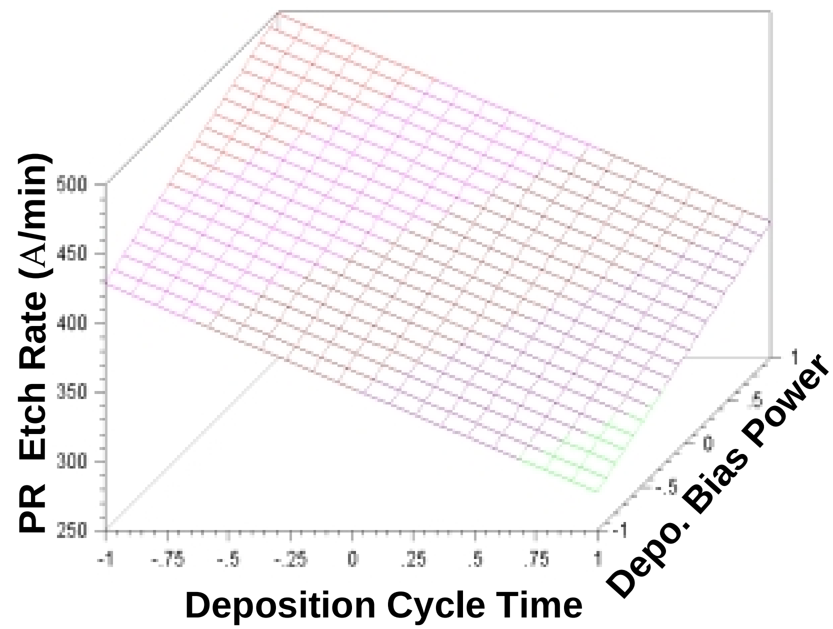
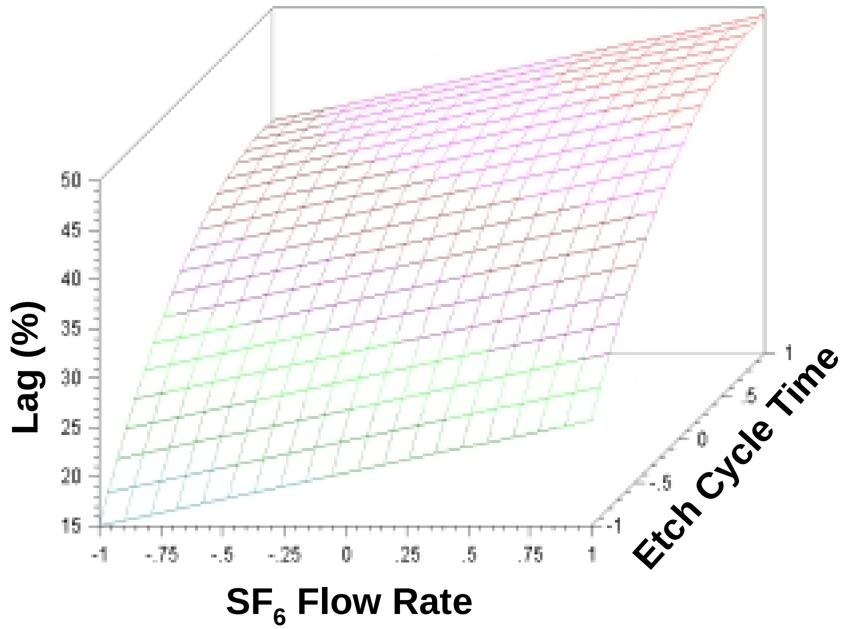
Photoresist Etch Rate (3)

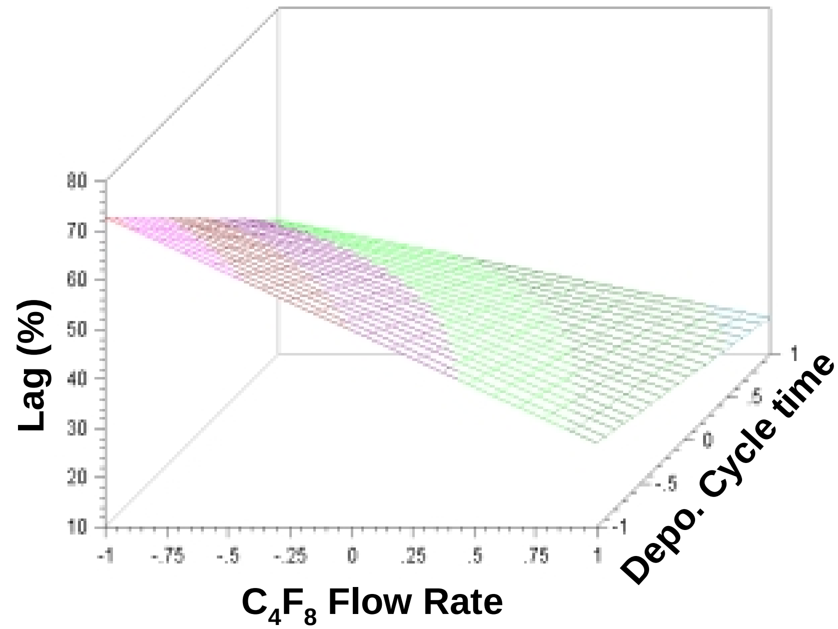




- Increasing Bias power during deposition cycle increases photoresist etch rate
- R^2_{adj} = 96% , R^2_{pred} = 84%

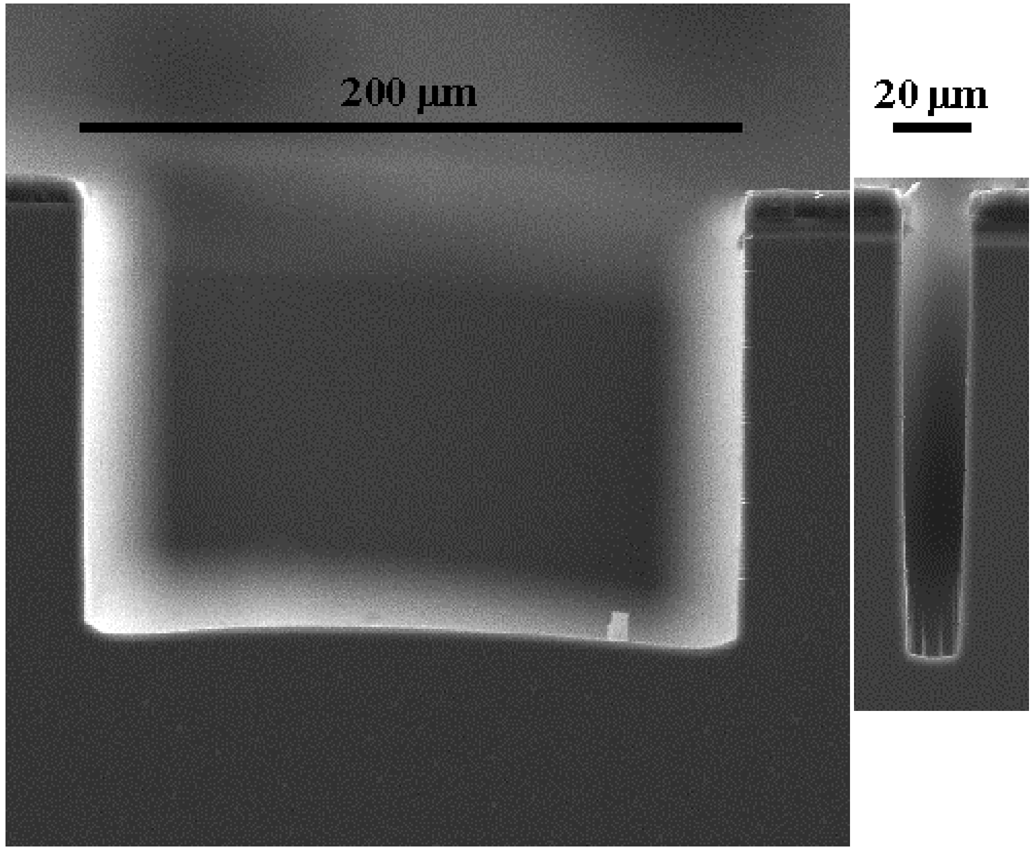
Lag or ARDE (1)





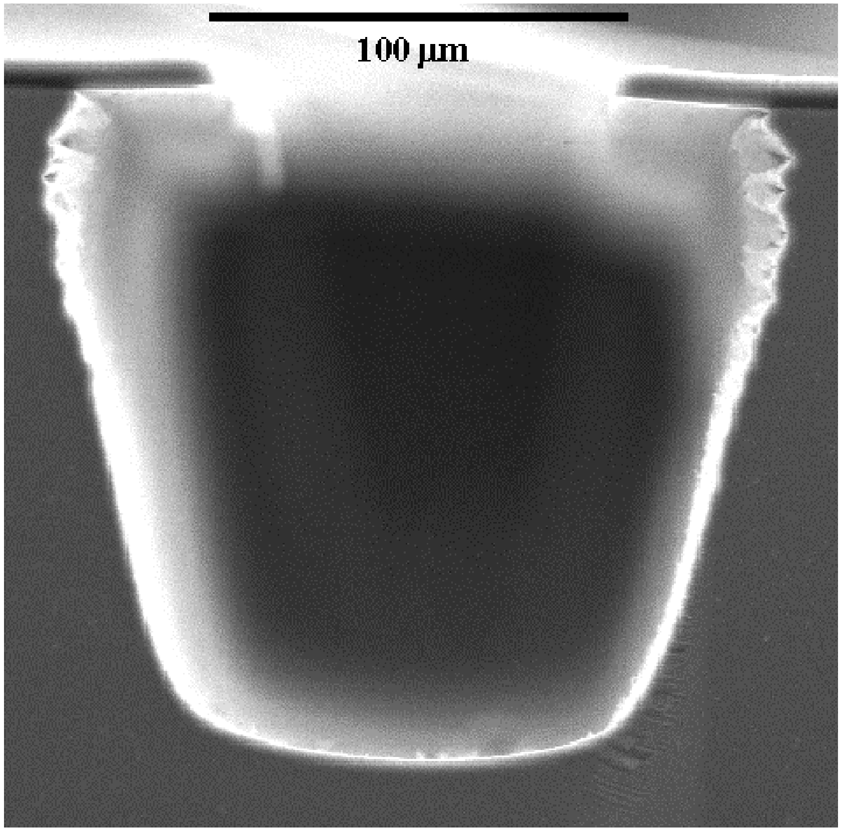
- Lag is measured as percentage difference between the etch depths of the 200 μm and 20 μm trenches
- R^2_{adj}=97% , R^2_{pred}=80%
- “Deposition Lag” during the deposition cycle will translate as reverse etch lag

Lag or ARDE (2)



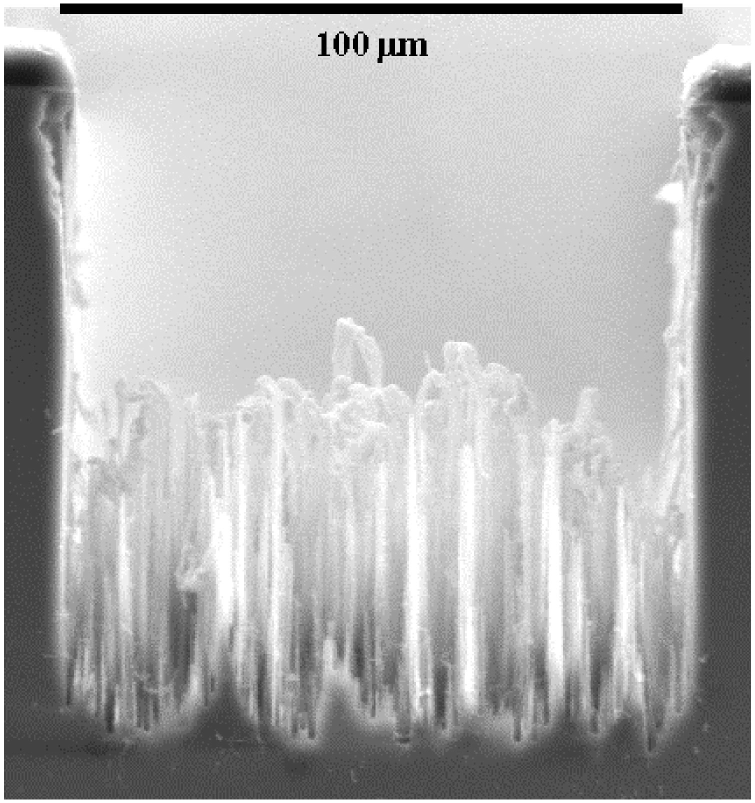
- The “Deposition Lag” can be used for decreasing the overall lag amount
- There is a trade-off between lag amount and etch rate
- For the above profile: Lag = -7% , Etch rate = 1.1 µm/min , Selectivity to resist = 130

Undercut



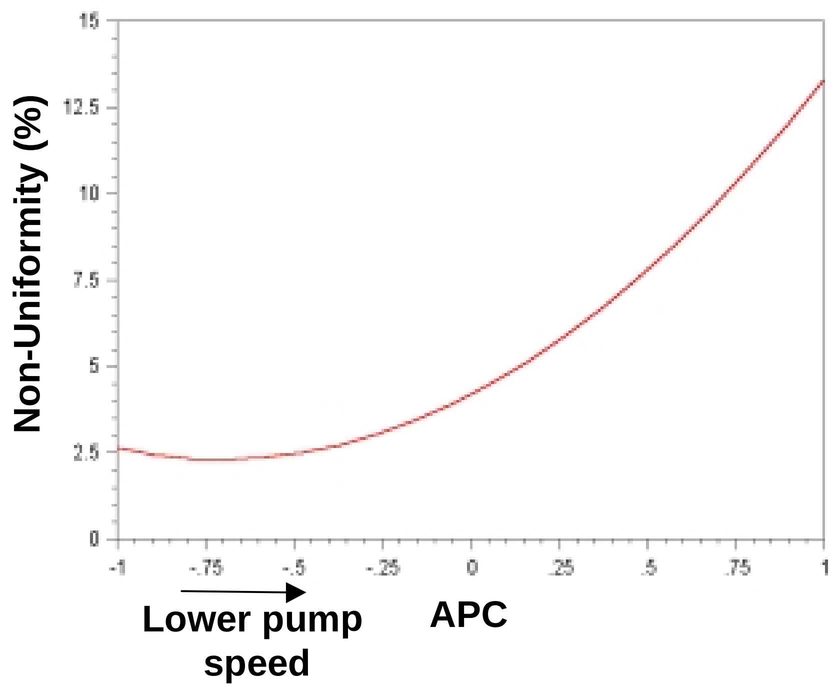
- Undercut is caused by:
  1- Increasing the pressure during the etch cycle
  2- Increasing the etch cycle time to deposition cycle time ratio

Micrograss



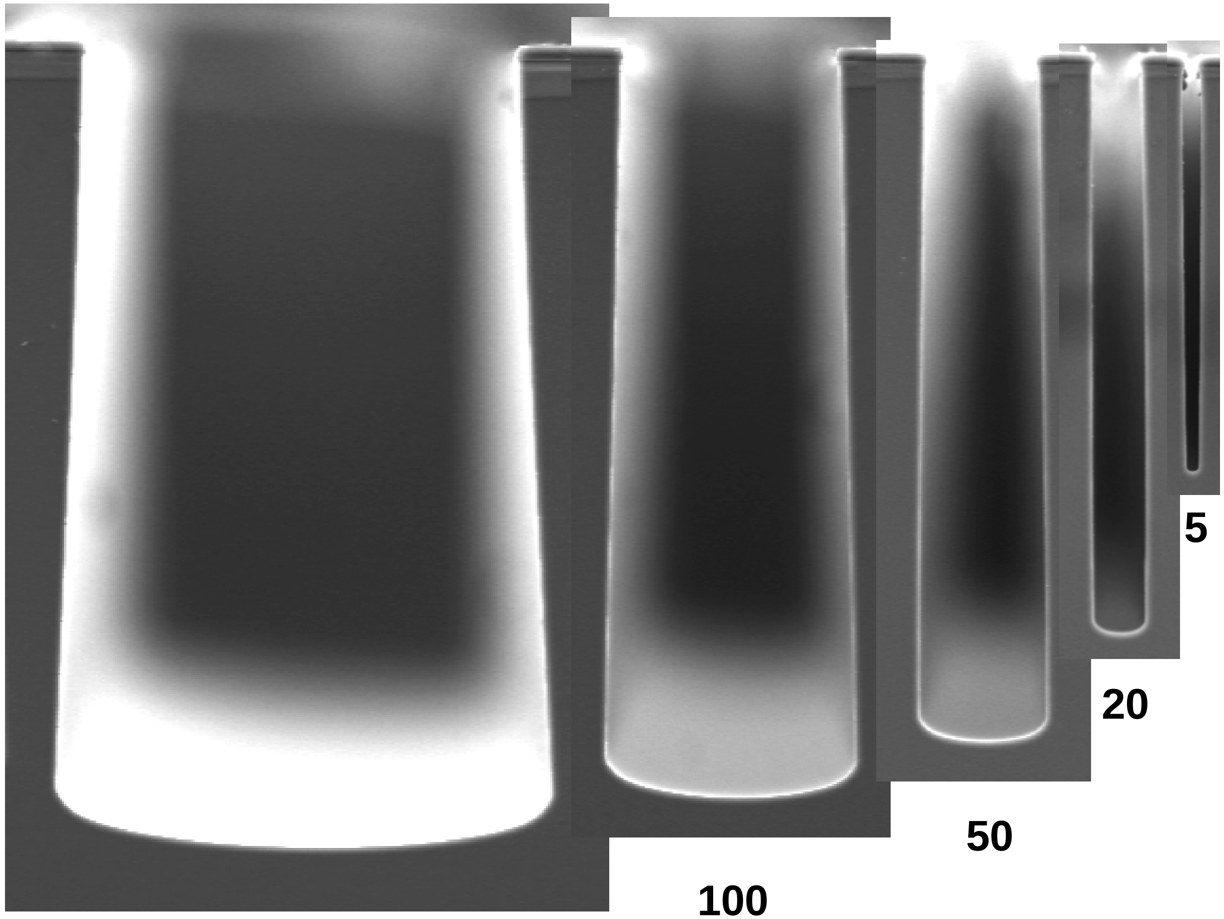
- A combination of high APC (low pump speed, high residence time) and high deposition to etch ratio causes micrograss formation
- If APC is high, higher Bias power (etch or deposition) increases micrograss formation

Non-Uniformity



- Non-uniformity is measured as the percentage difference between the etch rate of the 200 μm trenches at the edge and center of the wafer
- APC is the most important factor in increasing etch rate non-uniformity across the wafer

Sidewall Angle and Trench Width



- Any factor which increases the etch rate, tends to make the profile more re-entrant
- More negative sidewall angles with the increase in the trench width

Summary

- The Bosch deep trench etch process was characterized with respect to the input parameters, using statistical techniques
- Etch lag can be controlled by adjusting the ratio of the etch cycle time to the deposition cycle time, at the expense of the etch rate
- Etch profiles become more re-entrant as the etch rate increases, this is true even for trenches with different widths etched with the same etch recipe

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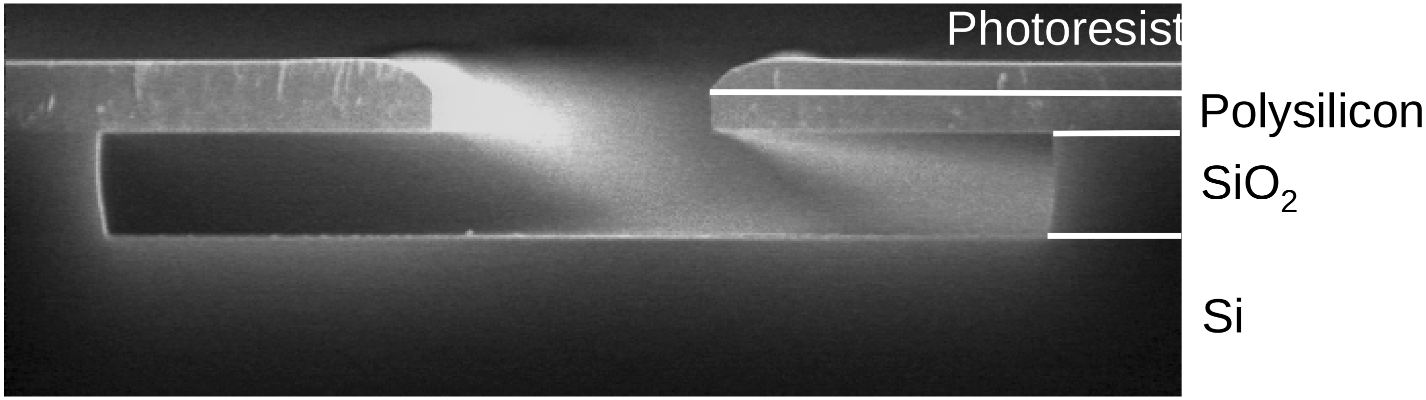
- **Effects of ions on the deposition process**

❑ Summary

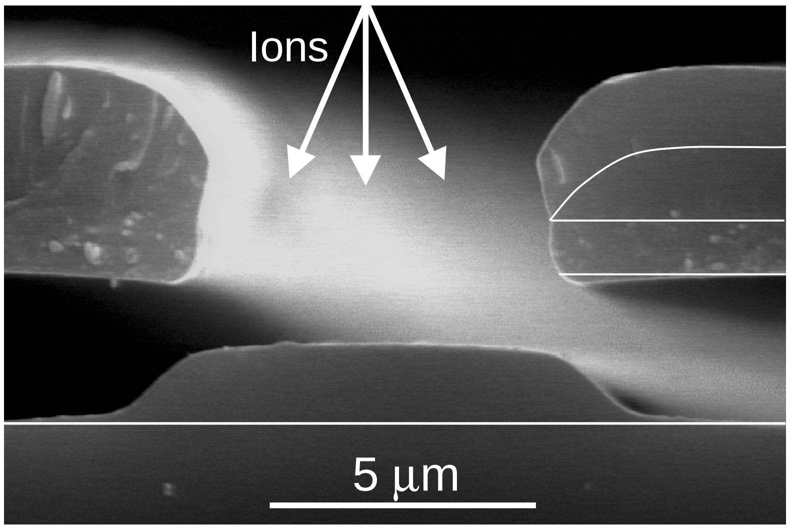
Overhang Test Structure



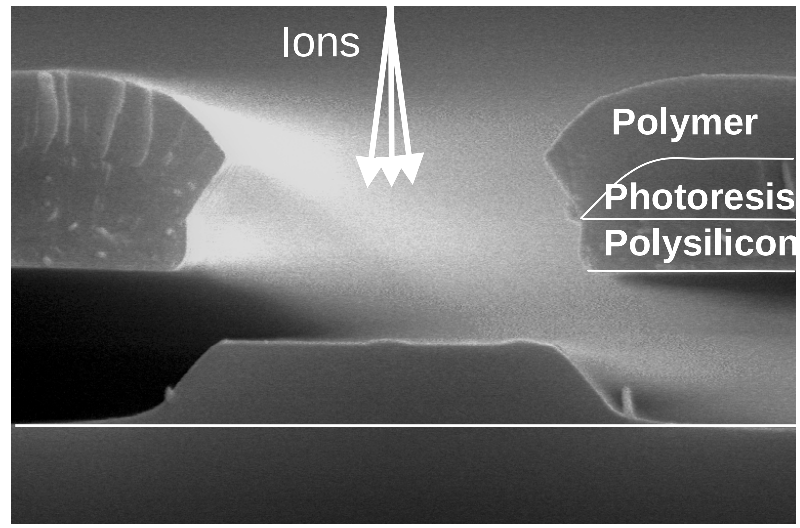
- Separates the effects of the ion flux and neutral fluxes

Polymer Deposition (Wide Opening Overhang)

- C_4F_8 flow rate = 85 sccm, P = 15 mTorr, Coil Power = 600W for 15 min.



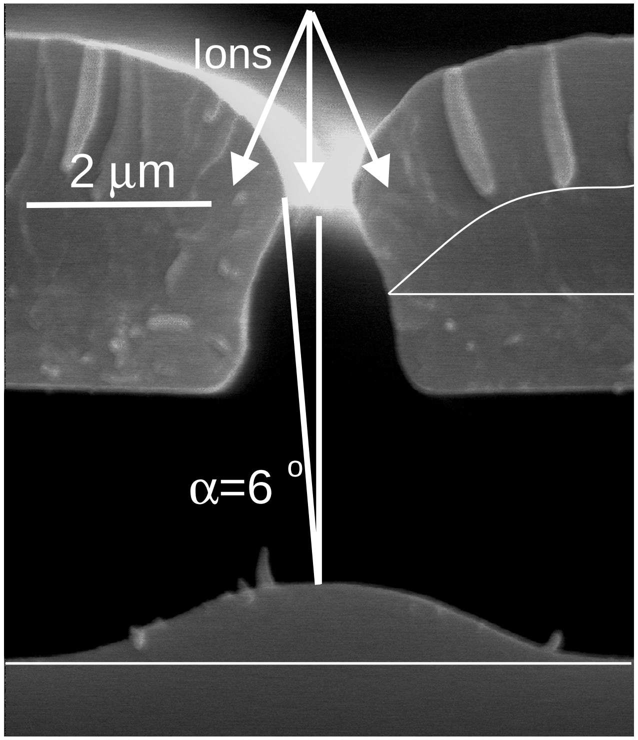
Bias Power = 0 W



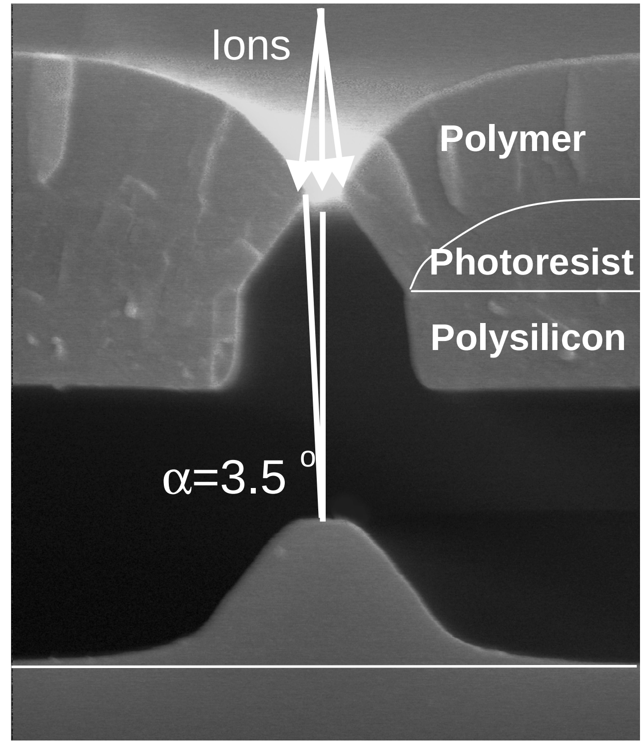
Bias Power = 8W

- Less spread for deposition with higher Bias power
- Deposition thickness is almost the same (10% more for high bias power)
- No definitive conclusion

Polymer Deposition (Narrow Opening Overhang)



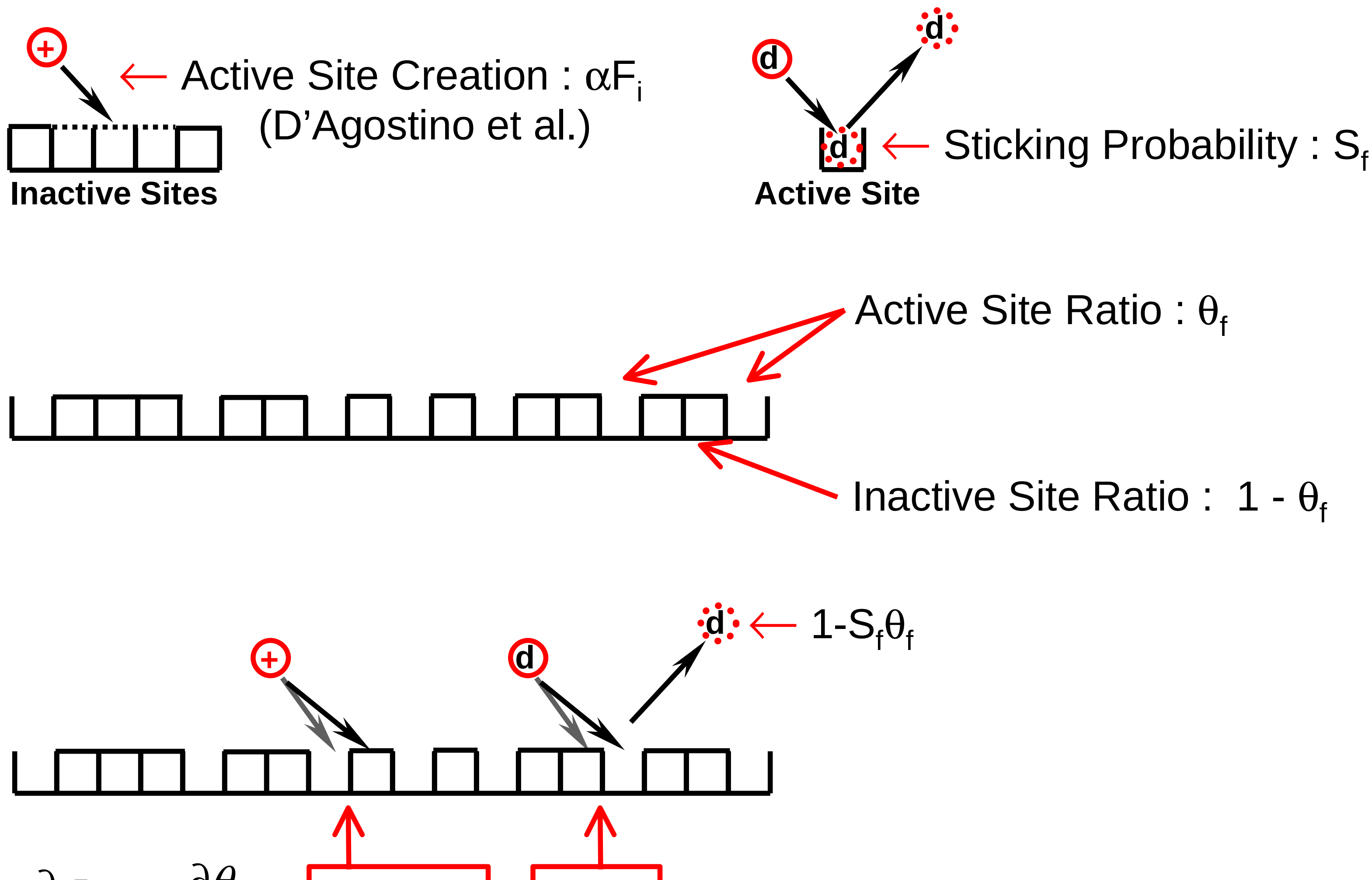
Bias Power = 0 W



Bias Power = 8W

- Conclusion: Polymer deposition should be ion-driven
- D'Agostino et al. (1983, 1997) proposed a model in which $S_d \propto F_i$ and so deposition rate $\propto F_i F_d \Rightarrow$ Can not model our experimental profiles

Site Balance Equation



$$\frac{\partial \sigma}{\partial t} = \sigma_T \frac{\partial \theta_f}{\partial t} = \alpha F_i (1-\theta_f) - F_d S_f \theta_f = 0$$

Modeling Ion Enhanced Polymer Deposition (cont'd)

- Solving the site balance equation:

$$\theta_f = \frac{\alpha F_i}{\alpha F_i + F_d S_f}$$

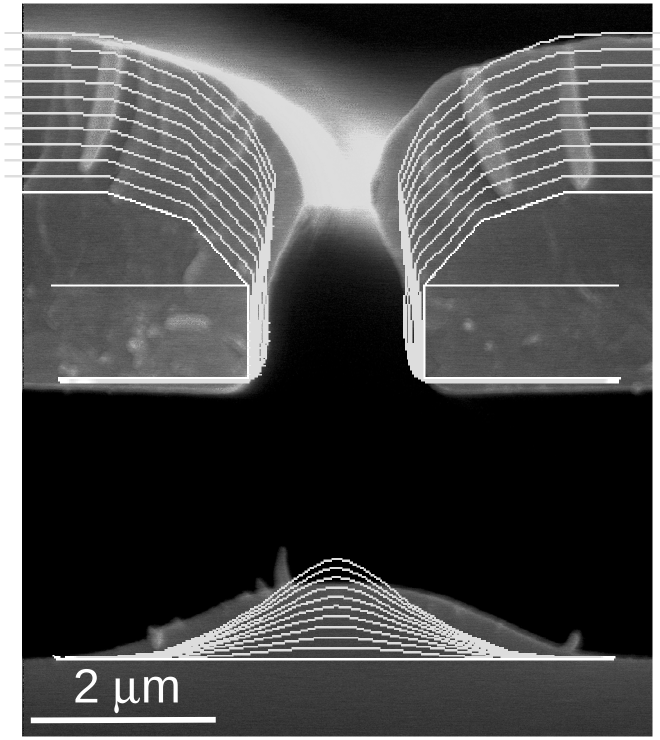
Effective Sticking Probability = $S_d = S_f \theta_f$

Deposition Rate = $\dfrac{F_d S_f \theta_f}{Density}$

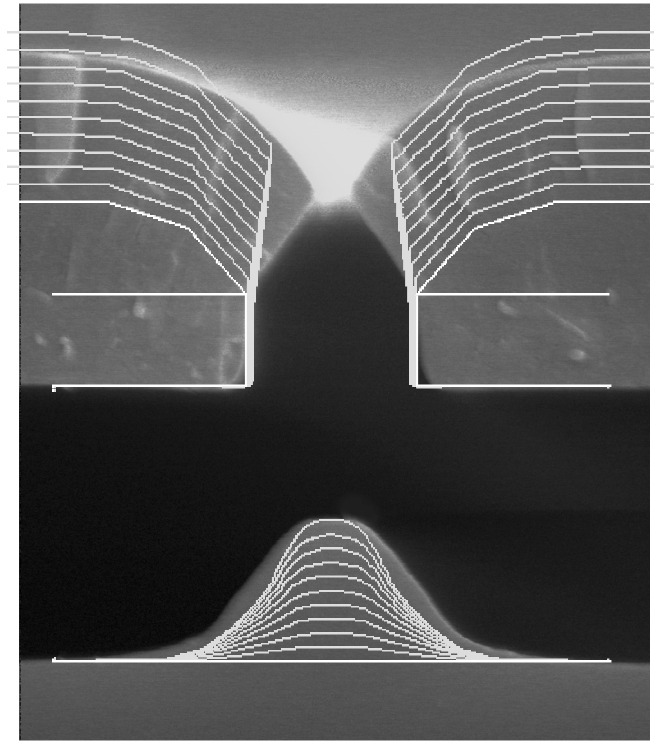
- For our case $F_d S_f >> F_i$:

Deposition Rate $\approx \dfrac{\alpha F_i}{Density}$

Initial Simulation Results



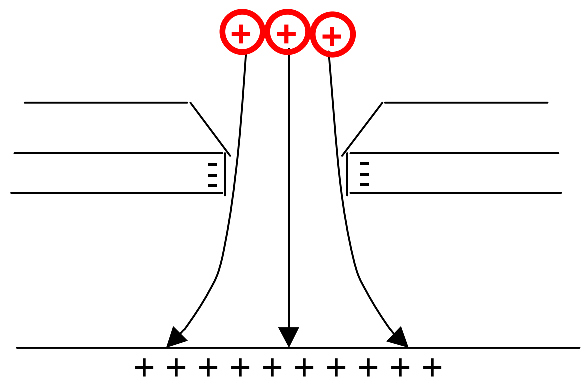
Low Bias Power



High Bias Power

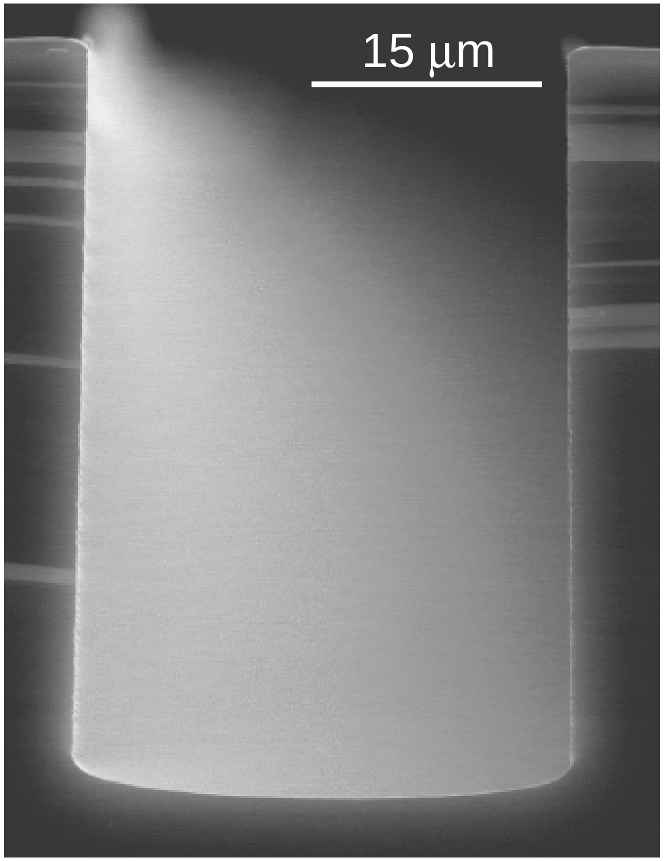
Possible Reasons for Discrepancy

- The simulation could not capture the spread of the profile for low bias case. This could be because of the following reasons:
  - There is a partial CVD component which was not considered in the model
  - Charging effects can change the trajectory of ions and spread them out

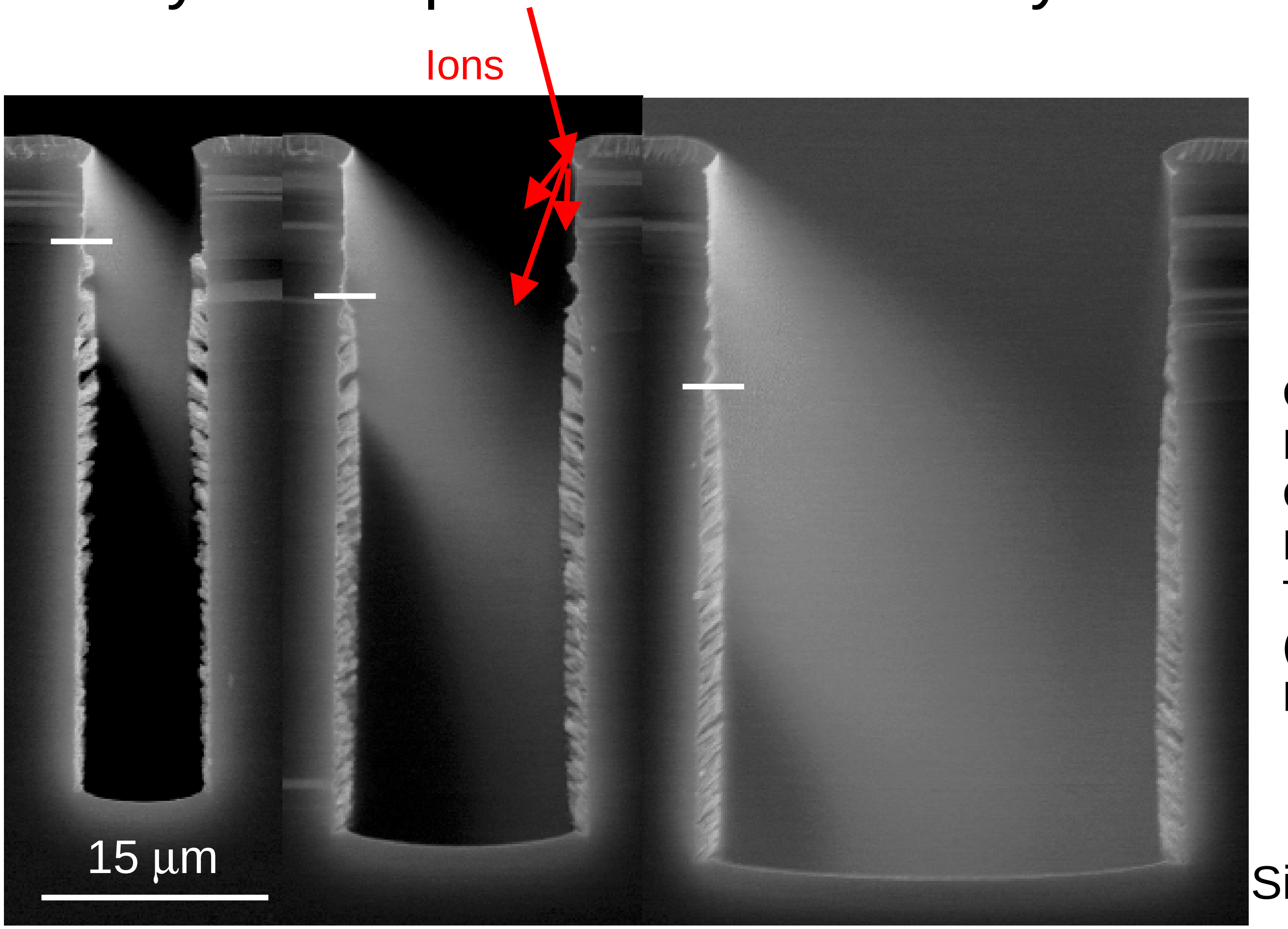


  - Possible ion enhanced surface mobility

Trench Before Deposition



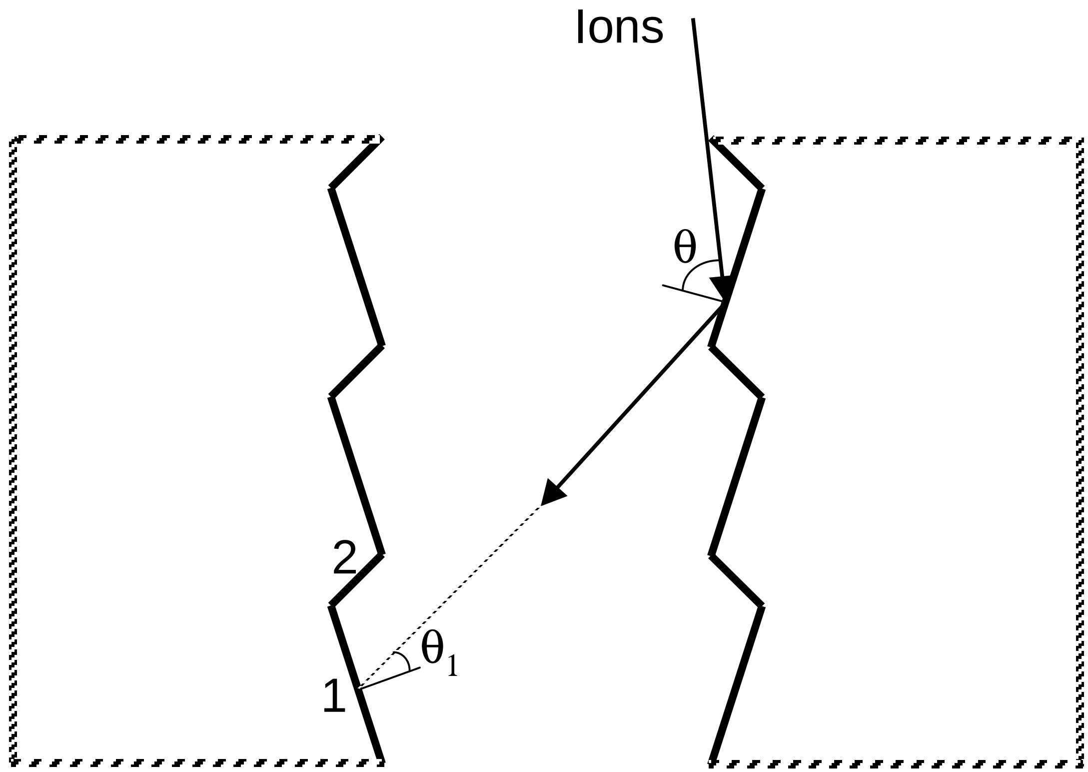
Polymer Deposition in Previously Etched Trenches



C_4F_8 Flow = 85 sccm
P = 15 mTorr
Coil Power = 600W
Bias Power = 8W
Time = 15 min.
(No switching, Deposition only)

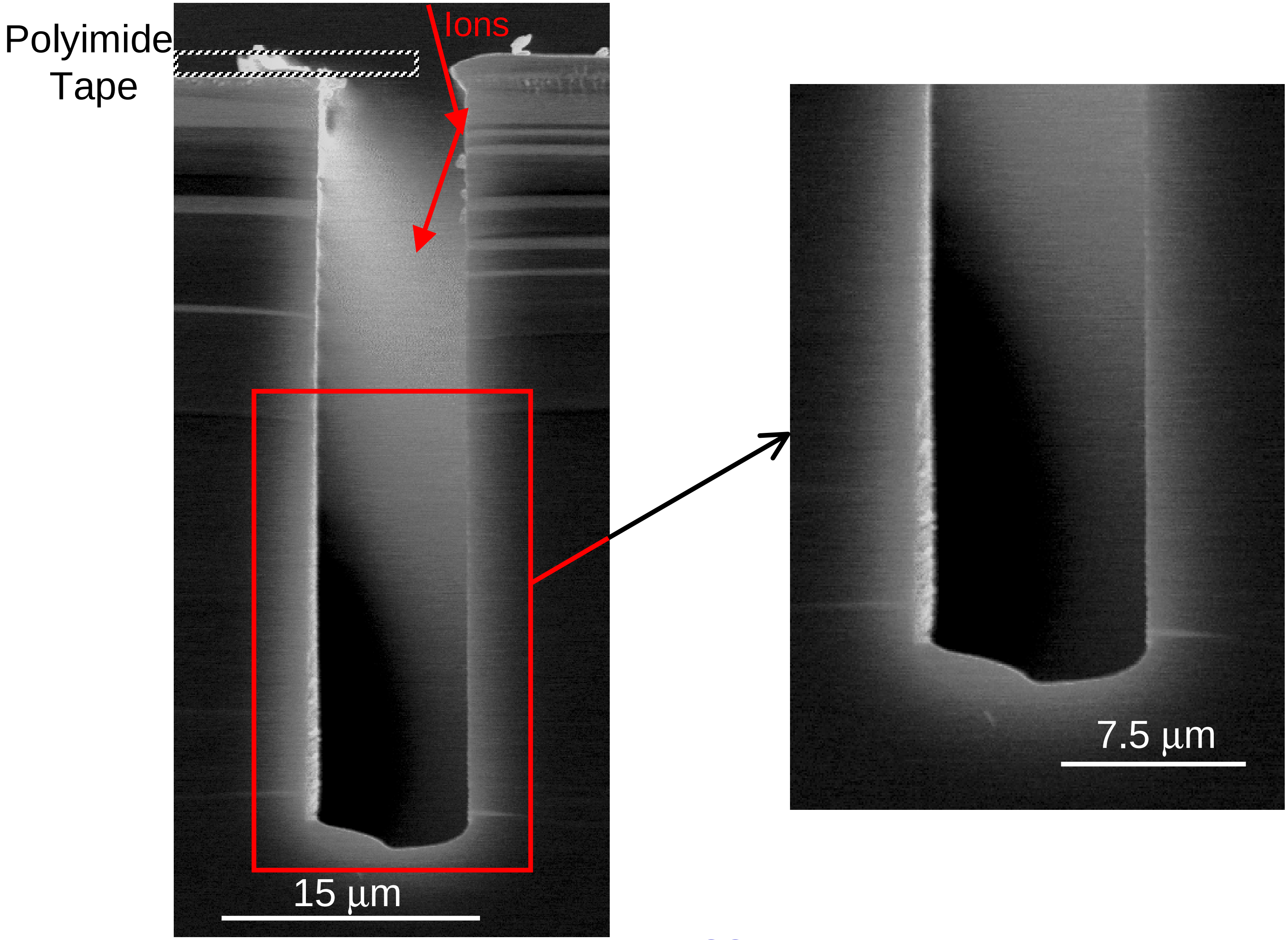
- The starting point of significant deposition on the sidewalls depends on the trench width

Ion Reflection and Sidewall Shape



- If $\theta = 90 - \alpha$ then $\theta_1 = 90 - 3\alpha$
- Much more ion flux , direct or reflected, on slope 1 than slope 2

Ion Reflection and Polymer Deposition



Summary

- Polymer deposition is an ion-driven process
- A monolayer model for polymer deposition process was developed
- Ion reflection plays an important role in the polymer deposition on the sidewalls of trenches

Acknowledgments

- TRW NovaSensor
- DARPA and SRC