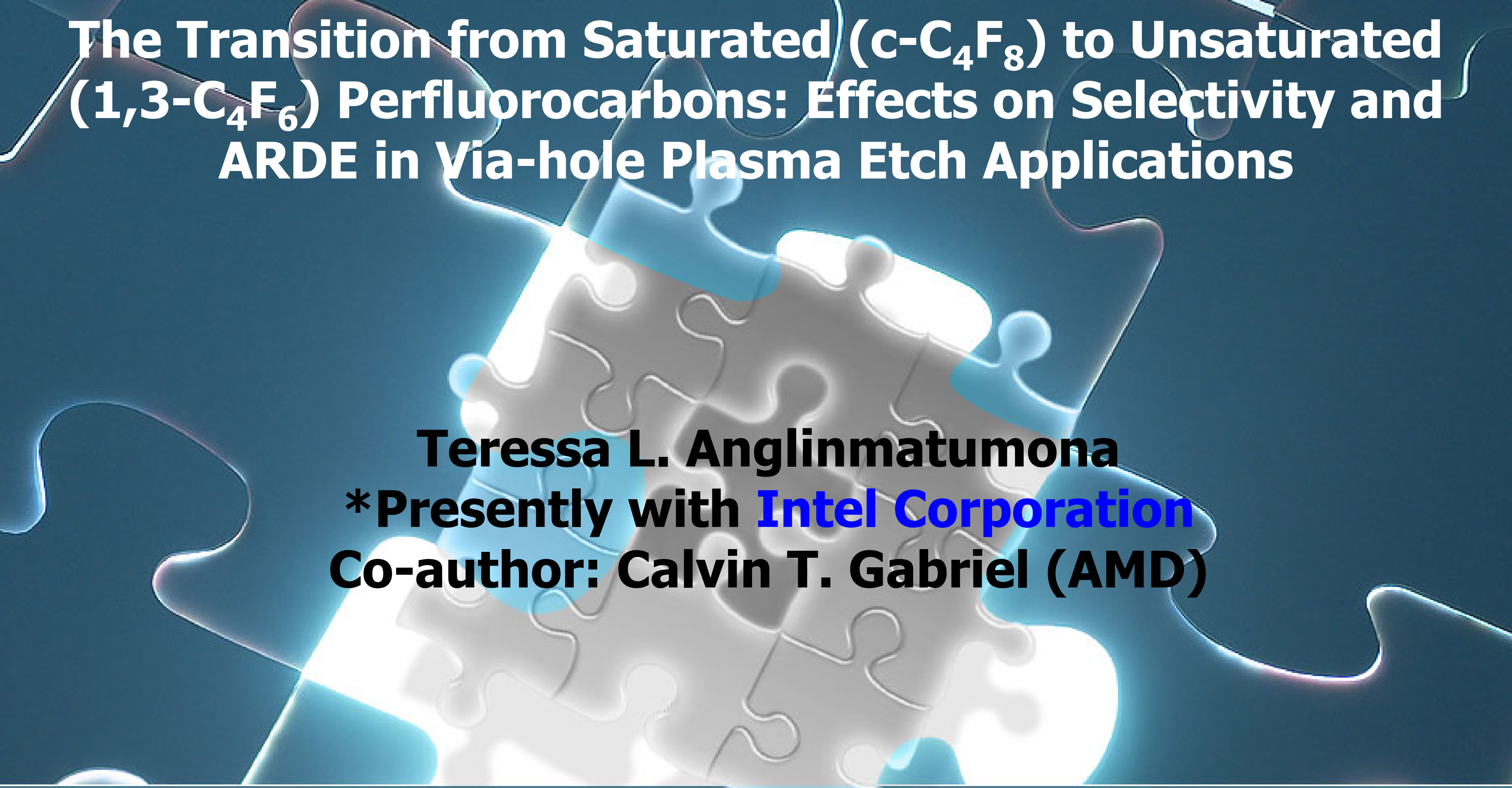
The Transition from Saturated (c-C_4F_8) to Unsaturated (1,3-C_4F_6) Perfluorocarbons: Effects on Selectivity and ARDE in Via-hole Plasma Etch Applications



Teressa L. Anglinmatumona
***Presently with Intel Corporation**
Co-author: Calvin T. Gabriel (AMD)

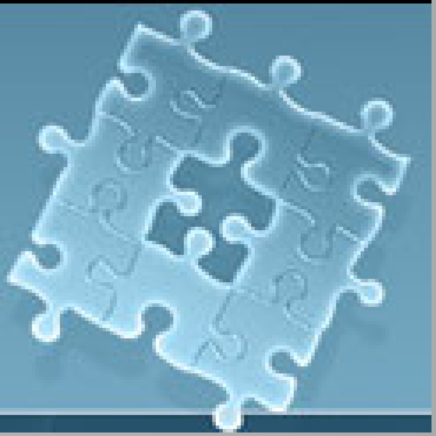
NCCAVS PEUG, Sunnyvale, CA
May 11, 2006

Research Funding
2002-2003

AMD

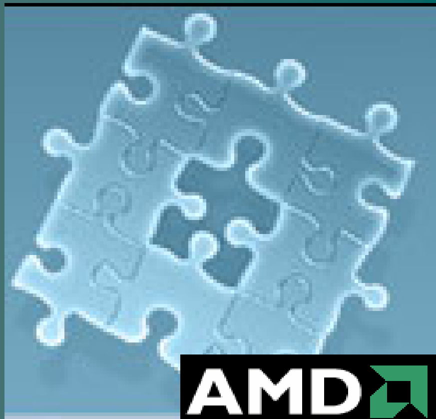
(Submicron Development Center)

Etch Module

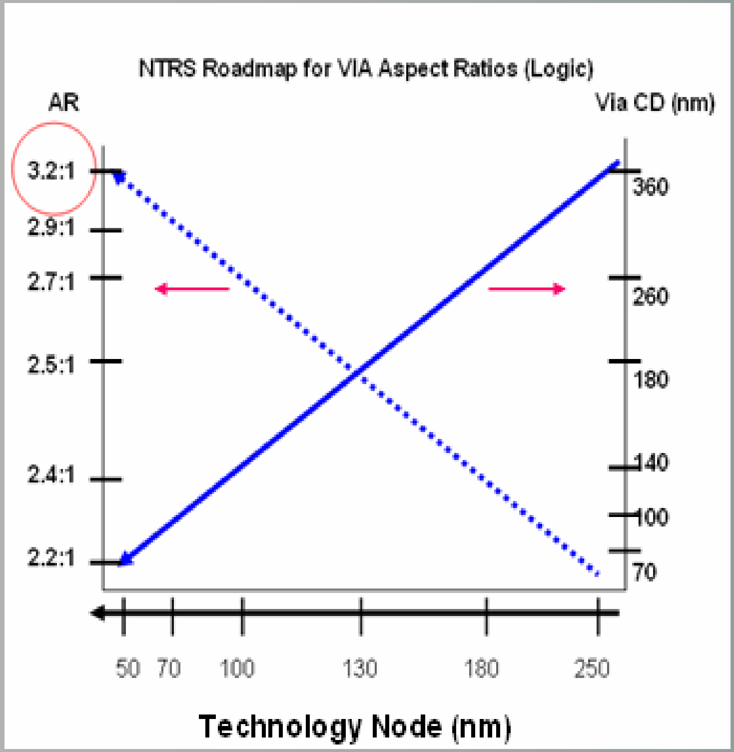


Outline

- Research Motivation
- Experimental Set-up
- 1,3-C_4F_6 Characterization
- 1,3-C_4F_6 vs. c-C_4F_8



Motivation: Plasma Chemistry for HAR Dielectric Etching Beyond 65 nm Node



At a technology node of 50 nm:
AR=3.2:1 and Via CD = 70 nm

Challenges:

- Mass transport limitation due to higher molecular-weight radicals.
- Thin 193 nm Resist (low etch resistance)
- Low Etch Selectivity
- ARDE

In this research, the transition from a saturated (c-C_4F_8, C-C bond) to an unsaturated (1,3-C_4F_6, C=C bond) plasma gas was found to lessen the challenges of low selectivity, anisotropy and ARDE..

.

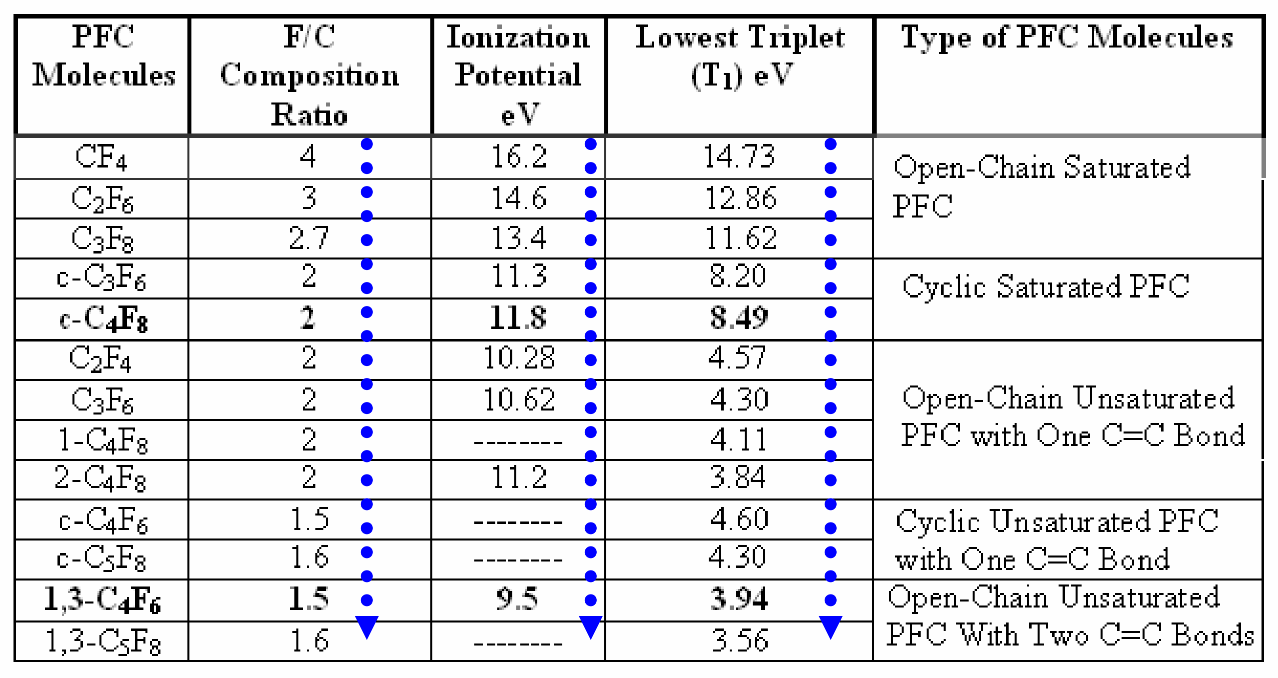
Ref. L. Ling, J. Vac. Sci. Technol. **B22** (2004) 2594.
S. Samukawa and T. Mukai: J. Vac. Sci. Technol. **B18** (2000) 166.

Evolution of Dielectric Etch Chemistries

Saturated

Transition

Unsaturated



PFC Molecules	F/C Composition Ratio	Ionization Potential eV	Lowest Triplet (T_1) eV	Type of PFC Molecules
CF_4	4	16.2	14.73	Open-Chain Saturated PFC
C_2F_6	3	14.6	12.86	
C_3F_8	2.7	13.4	11.62	
c-C_3F_6	2	11.3	8.20	Cyclic Saturated PFC
c-C_4F_8	**2**	**11.8**	**8.49**	
C_2F_4	2	10.28	4.57	Open-Chain Unsaturated PFC with One C=C Bond
C_3F_6	2	10.62	4.30	
1-C_4F_8	2	--------	4.11	
2-C_4F_8	2	11.2	3.84	
c-C_4F_6	1.5	--------	4.60	Cyclic Unsaturated PFC with One C=C Bond
c-C_5F_8	1.6	--------	4.30	
1,3-C_4F_6	**1.5**	**9.5**	**3.94**	Open-Chain Unsaturated PFC With Two C=C Bonds
1,3-C_5F_8	1.6	--------	3.56	

1,3-C_4F_6 Process-Multiple Advantages are Driven By:

- ❖Unique cleaving mechanism which allows a better bond decomposition scheme (CF2 & CF3)
- ❖Lower energy thresholds (i.e., ionization, dissociation and excitation).
- ❖Lower fluorine-to-carbon (F/C) ratio.
- ❖More polymer-initiating radicals

[1] T. Nakamura, H. Motomura and K. Tachibana: Jpn. J. Appl. Phys. **40** (2001) 847.
[2] S. Samukawa, T. Mukai, and K. Tsuda: J. Vac. Sci. Technol. A**17** (1999) 2551.
[3] G.K. Jarvis, K.J. Boyle, C.A. Mayhew and R.P. Tuckett: J. Phys. Chem. A **102** (1998) 3230.
[4]U.S. Secretary of Commerce on Behalf of the USA, "NIST Chemistry Webbook" http://webbook.nist.gov/chemistry/.

Experimental Set-up

Phase I

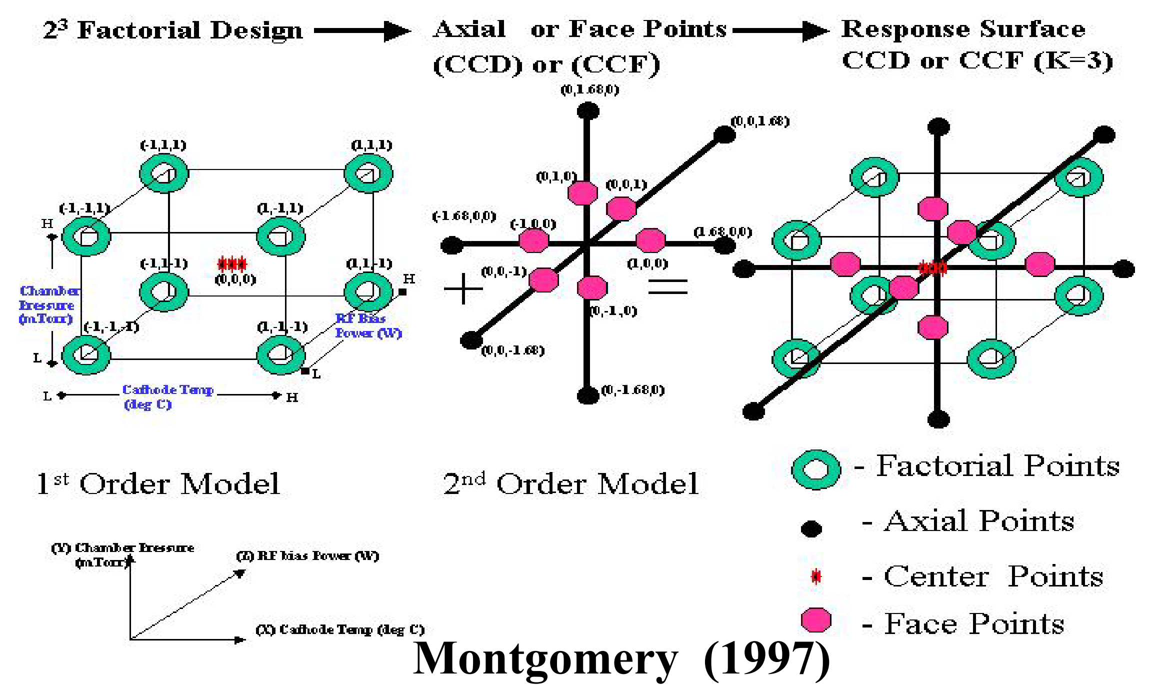
❖1,3-C_4F_6 Characterization
❖Identify Process Window in design space w/ Trade-offs

Phase II

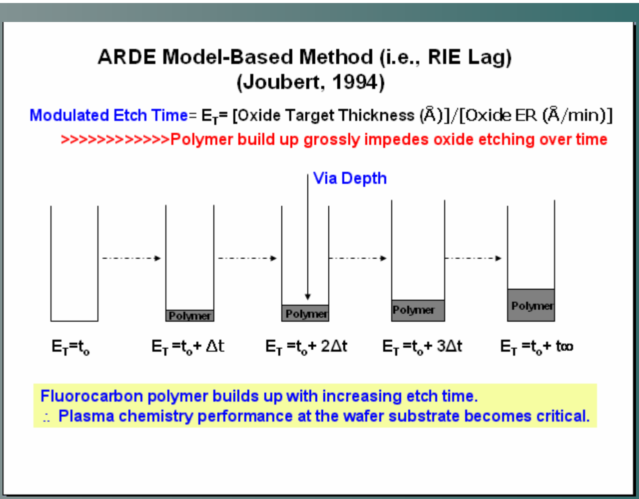
1,3-C_4F_6 vs. c-C_4F_8
(Etch Performance)

Phase III

Develop ARDE Models
(1,3-C_4F_6 vs. c-C_4F_8)
❖ Critical Aspect Ratio



Montgomery (1997)

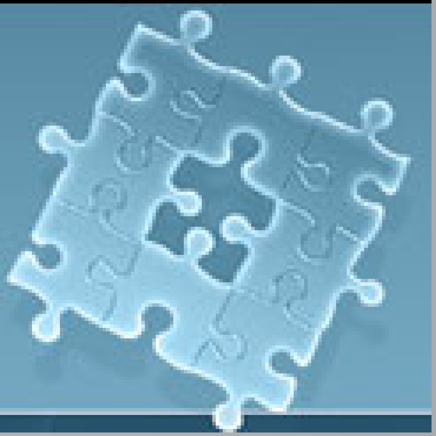


ARDE Model-Based Method (i.e., RIE Lag)
(Joubert, 1994)

Modulated Etch Time= E_T= [Oxide Target Thickness (Å)]/[Oxide ER (Å/min)]
>>>>>>>>>>>>Polymer build up grossly impedes oxide etching over time

Fluorocarbon polymer builds up with increasing etch time.
∴ Plasma chemistry performance at the wafer substrate becomes critical.

Plasma Etch System:
AMAT® IPS Etcher



Trade-Offs

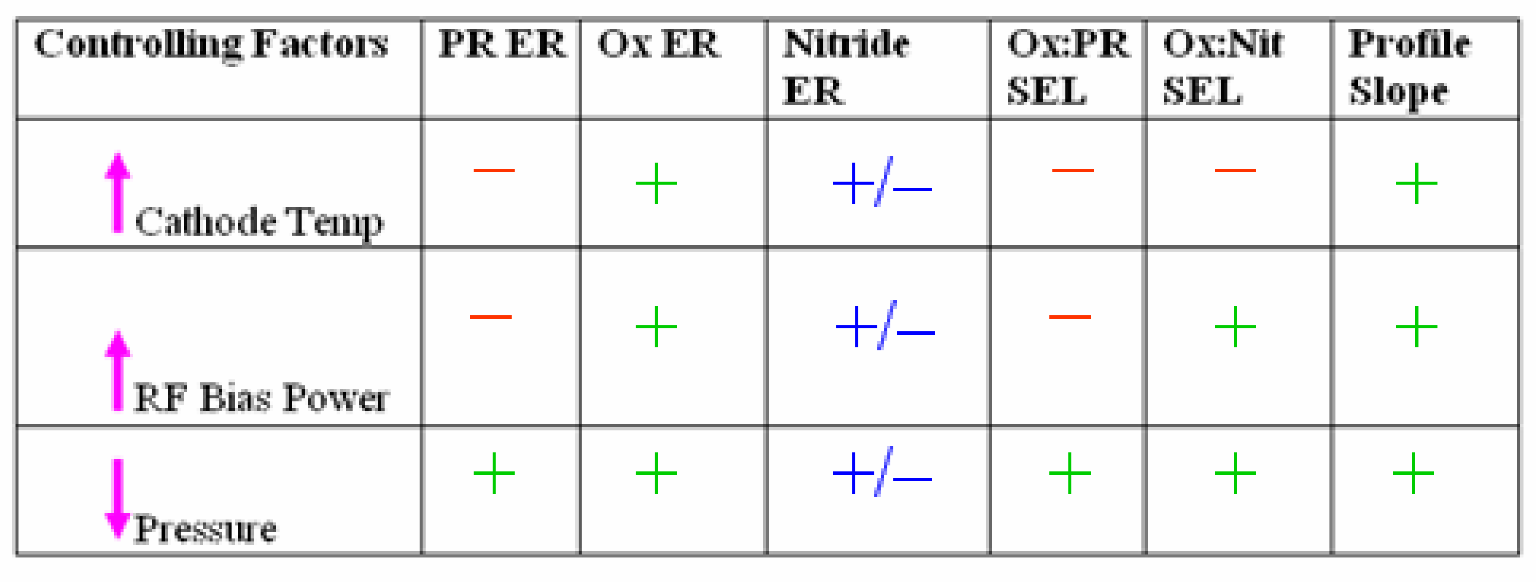
Order of Priority

1. **Anisotropy**

(most critical parameter to control)

2. **Oxide:Resist SEL**
3. **Oxide:Nitride SEL**
4. **Oxide Etch Rate**

Process Trends Using 1,3-C_4F_6



Controlling Factors	PR ER	Ox ER	Nitride ER	Ox:PR SEL	Ox:Nit SEL	Profile Slope
↑ Cathode Temp	–	+	+/–	–	–	+
↑ RF Bias Power	–	+	+/–	–	+	+
↓ Pressure	+	+	+/–	+	+	+

Favorable (+) and Unfavorable (–)

*****With interaction influence**

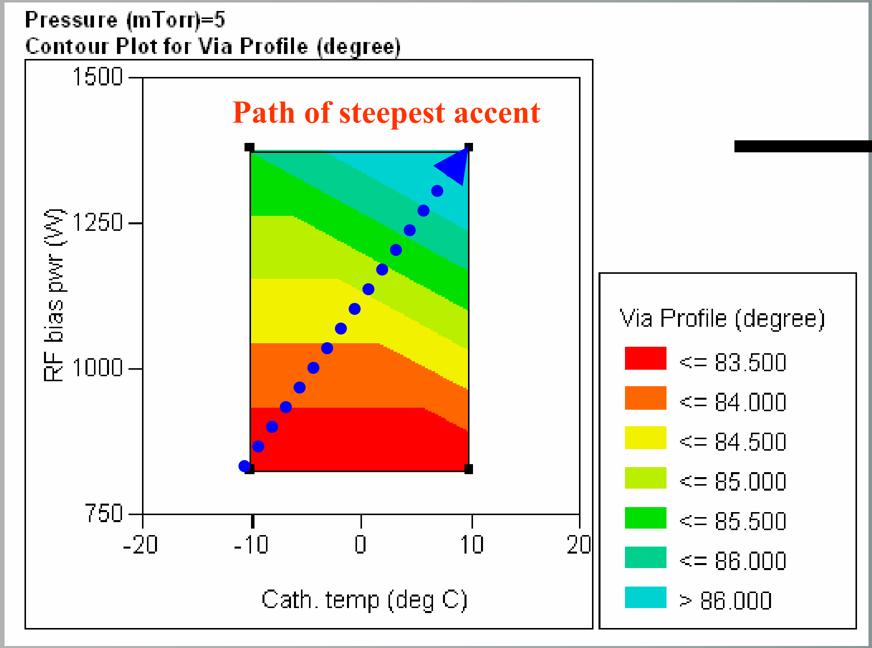
Cathode Temp $1/\propto$ Polymer deposition rate

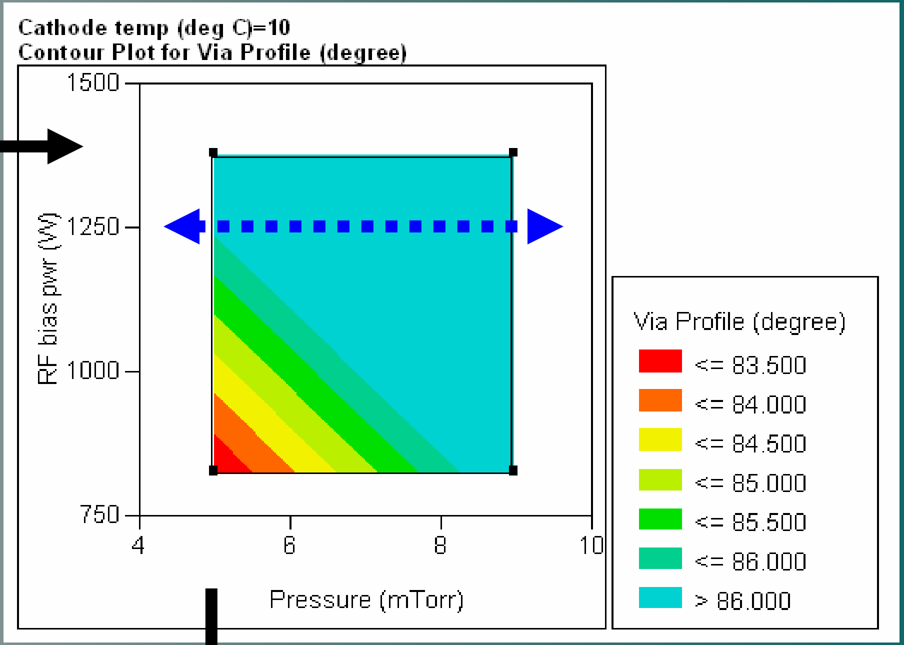
Pressure $1/\propto$ Ion Energy Flux

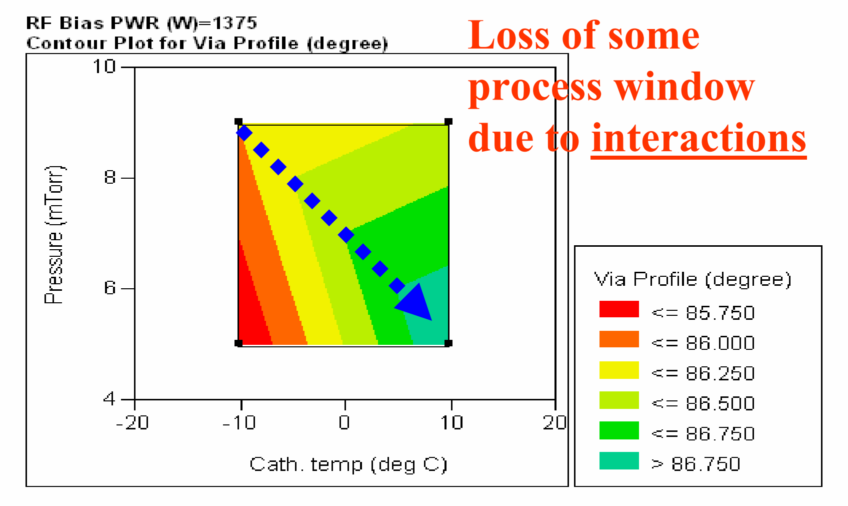
RF Bias Power $\propto$ Ion Energy Flux

Lower pressure → Longer mean free path- Improved directionality

Profile Slope (i.e., Anisotropy) Using 1,3-C_4F_6







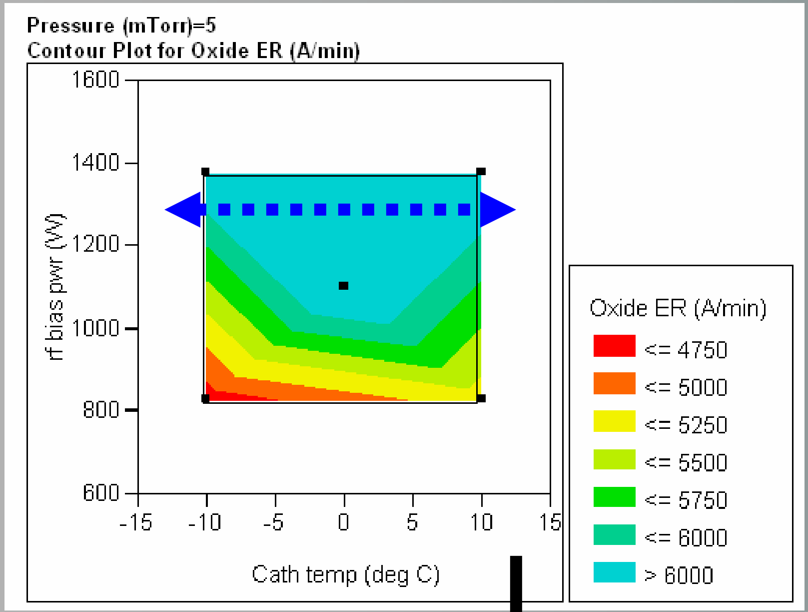
Loss of some process window due to <u>interactions</u>

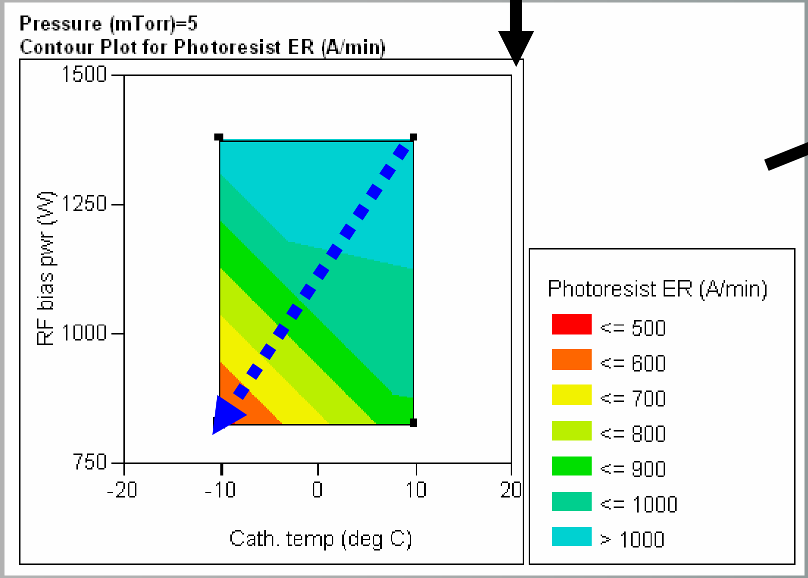
At 5 mTorr, profile slope increases with RF bias power at low/high cathode temp.

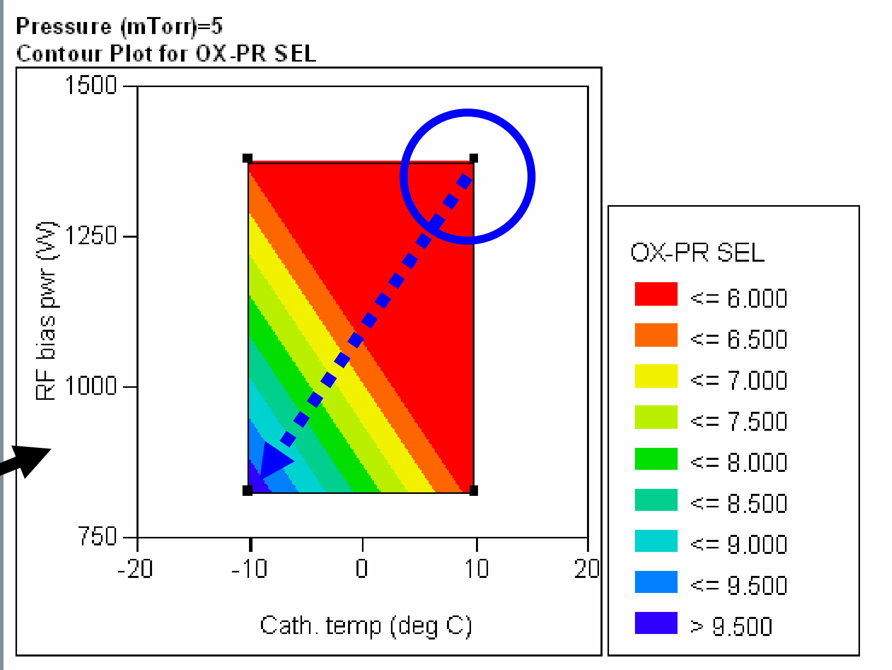
Above 1250 W and 10 deg C, profile slope is independent of pressure.

At a RF bias power of 1375 W, profile slope increases with lower pressure and higher cathode temp.

Oxide:Resist Selectivity Using 1,3-C_4F_6

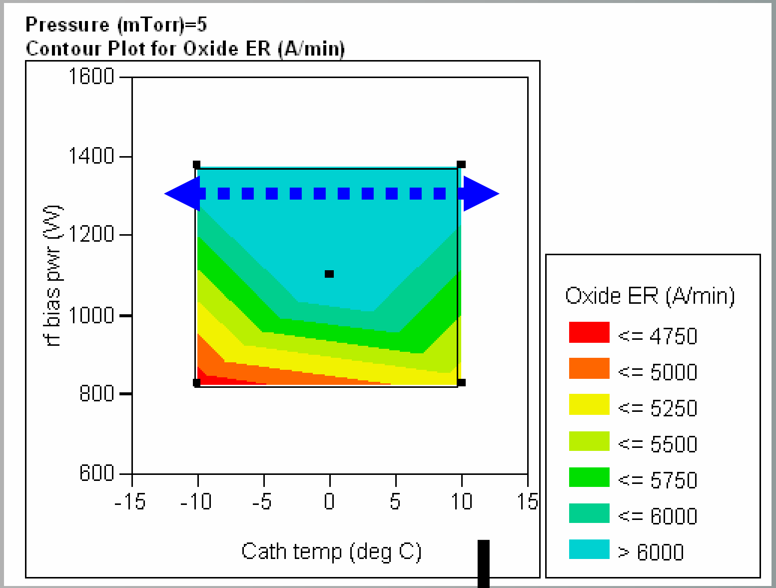

Pressure (mTorr)=5
Contour Plot for Oxide ER (A/min)

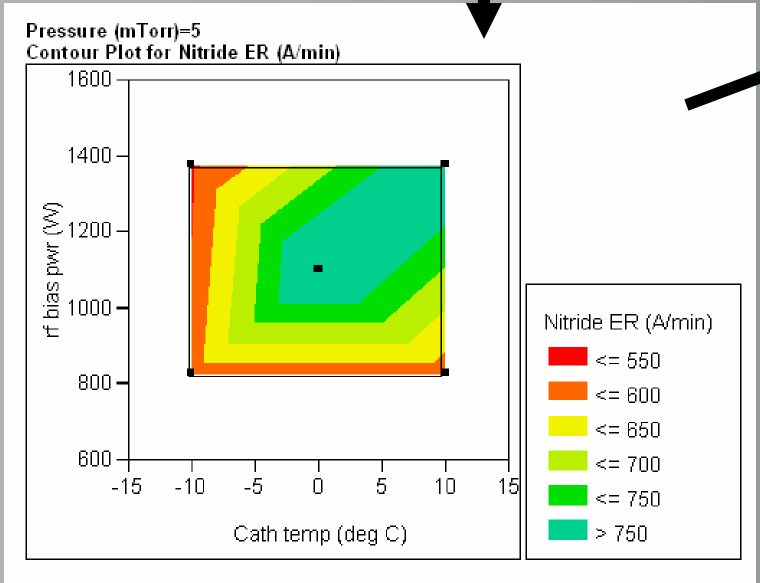

Pressure (mTorr)=5
Contour Plot for Photoresist ER (A/min)

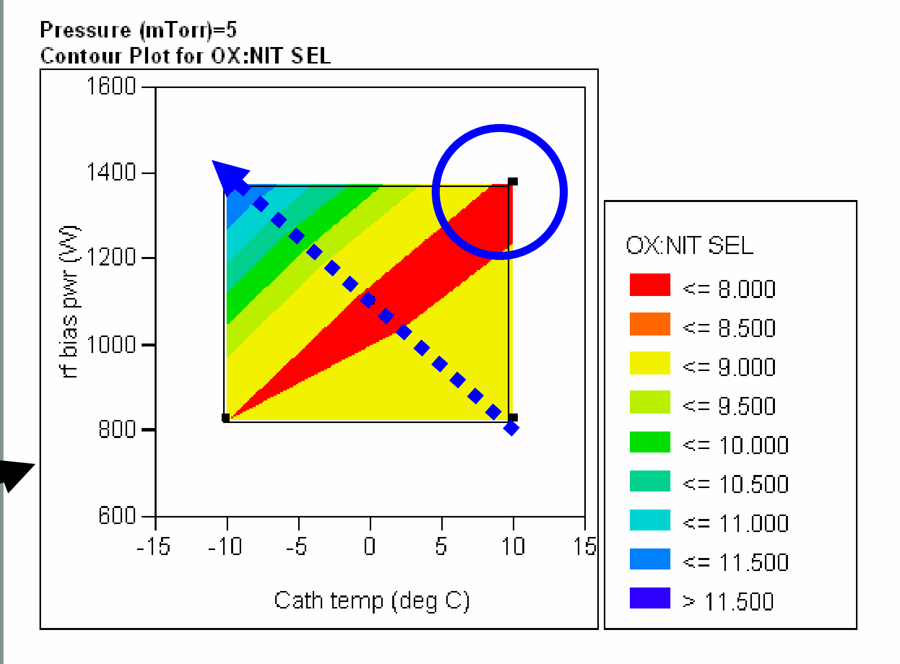

Pressure (mTorr)=5
Contour Plot for OX-PR SEL

- ❖**Lower cathode temp/Lower rf bias power compromise anisotropy.**
- ❖ **An acceptable selectivity at most 6:1 can be obtained at high rf bias power and cathode temp.**

Oxide:Nitride Selectivity Using 1,3-C_4F_6







- ❖ Above 1300 W, Oxide ER is independent of cathode temp.
- ❖ Nitride has non-linear etch rate behavior.
- ❖ With no compromise to anisotropy an acceptable selectivity of at most 8:1 can be obtained at high power and cathode temp.

Process Conditions Based on Trade-Offs

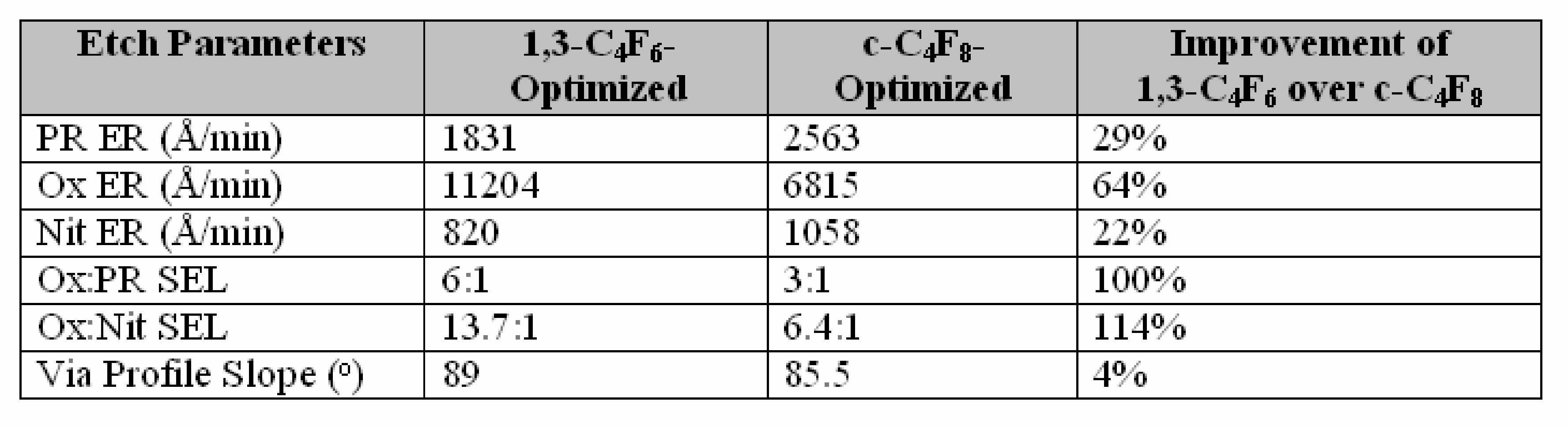
Cathode Temp (High)/RF Bias (High)/Pressure (Low)

1,3-C_4F_6 with 90% Ar Using DOE: 1, 1, -1

Etch Parameter	Data Output
Via Profile Slope	87 ^{o}
Oxide-Photoresist Selectivity	5.8:1
Oxide-Nitride Selectivity	7.7:1
Oxide Etch Rate	6315 Å/min
Photoresist Etch Rate	1097 Å/min
Silicon Nitride Etch Rate	820 Å/min

* Based on patterned test wafers with dielectric 1

c-C_4F_8 vs. 1,3-C_4F_6 Saturated vs. Unsaturated



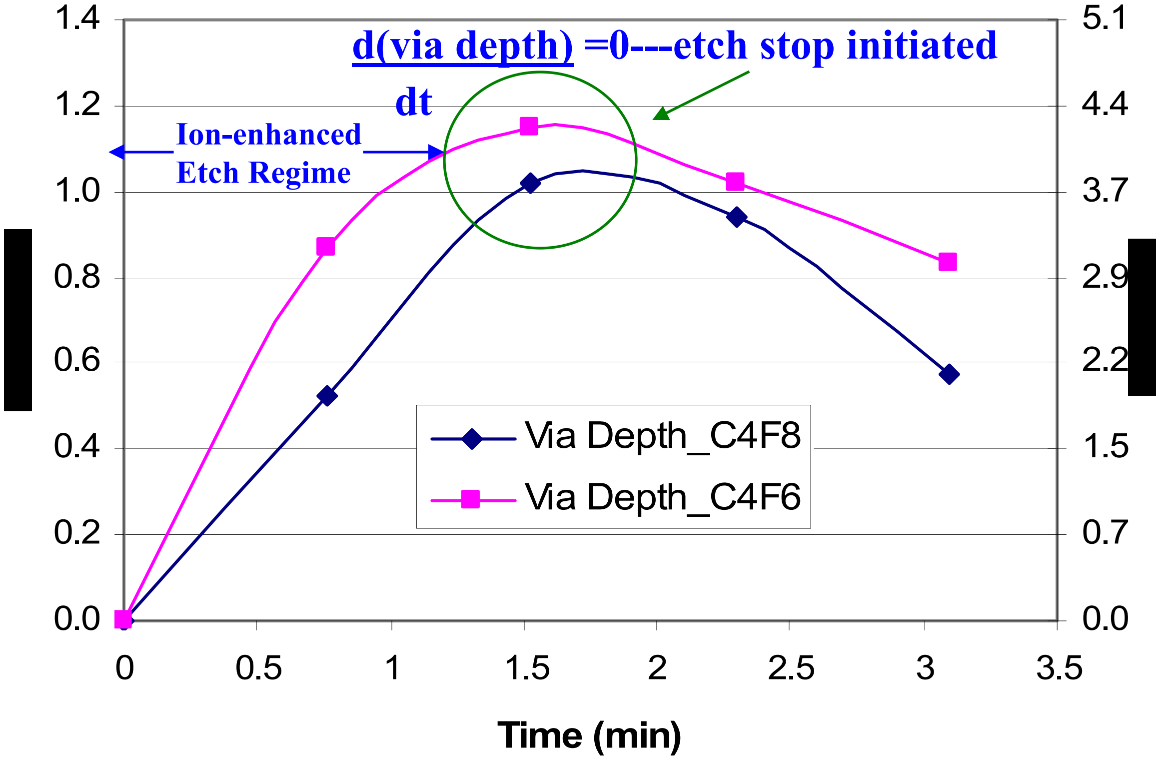
Etch Parameters	1,3-C_4F_6-Optimized	c-C_4F_8-Optimized	Improvement of 1,3-C_4F_6 over c-C_4F_8
PR ER (Å/min)	1831	2563	29%
Ox ER (Å/min)	11204	6815	64%
Nit ER (Å/min)	820	1058	22%
Ox:PR SEL	6:1	3:1	100%
Ox:Nit SEL	13.7:1	6.4:1	114%
Via Profile Slope (°)	89	85.5	4%

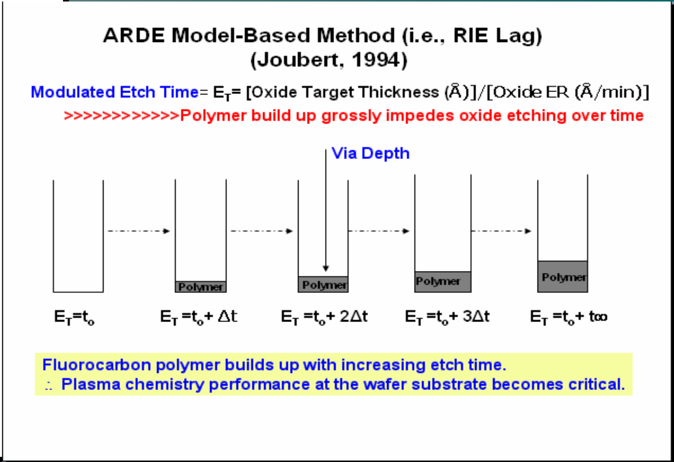
1,3-C_4F_6 etch performance is more favorable than c-C_4F_8

* Based on patterned test wafers with dielectric 2

Etch Performance (ARDE) vs. Plasma Chemistry

Via-hole diameter= 0.273 μm





ARDE Model-Based Method (i.e., RIE Lag)
(Joubert, 1994)

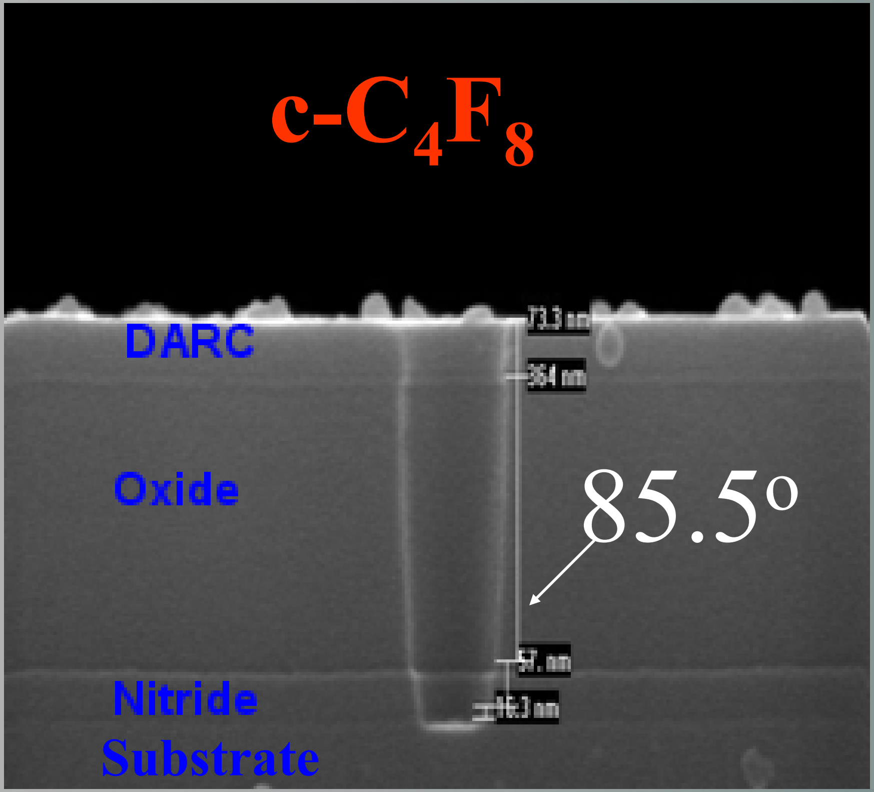
Modulated Etch Time= E_T= [Oxide Target Thickness (Å)]/[Oxide ER (Å/min)]

>>>>>>>>>>>>Polymer build up grossly impedes oxide etching over time

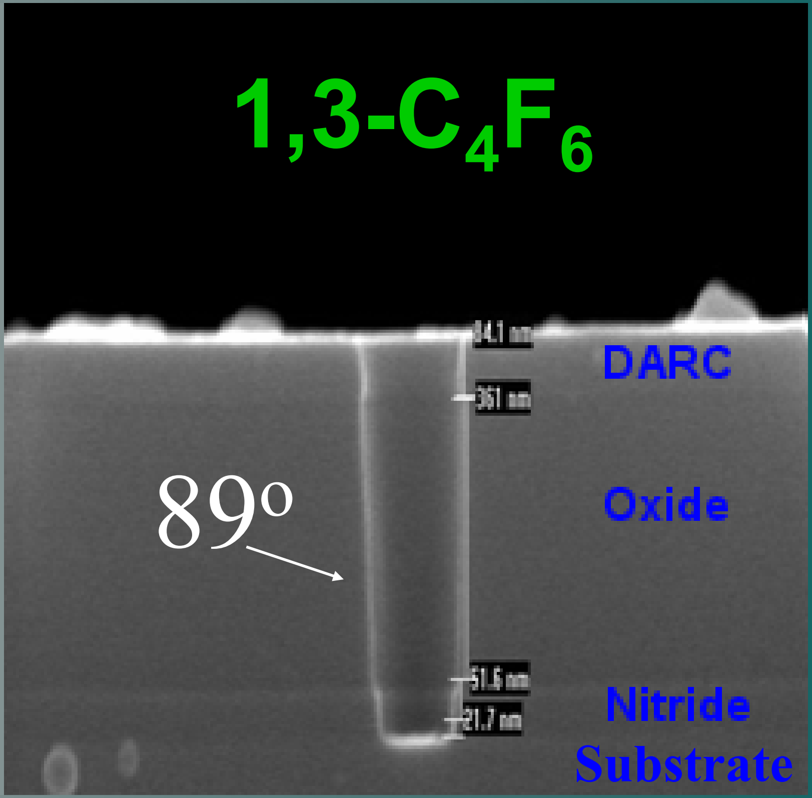
Fluorocarbon polymer builds up with increasing etch time.
∴ Plasma chemistry performance at the wafer substrate becomes critical.

- ❖Etch rate is much faster between 0-1.5 min for C_4F_6 than C_4F_8.
- ❖At 1.5 min etch stop is initiated and critical AR is defined.
- ❖ At this point, it is believed that the oxide ER transitions to the fluorocarbon suppression regime.
- ❖ Ion energy flux drops and the oxide etch eventually leads to permanent etch stop.
- ❖**Critical Aspect Ratio is improved by 11.4% for C_4F_6.**

Via Profile vs. Plasma Chemistry



$c\text{-}C_4F_8$



$1,3\text{-}C_4F_6$

Profile slope shows improvement with $1,3\text{-}C_4F_6$

* Based on full stack wafers

Conclusions

- The transition from saturated to unsaturated PFC gases display promise in improving the etch performance for increasing aspect ratios.

- Data results showed 1,3-C_4F_6 to increase the oxide-photoresist selectivity by 2 to 1 and the oxide-nitride selectivity by nearly the same. The via profile slope was enhanced (89 ^{o}) when using 1,3-C_4F_6. Aspect ratio dependent etch (ARDE) was favorably reduced due to the intrinsic characteristics of 1,3-C_4F_6 and optimized process conditions.

- This research addressed a possible resolution to the complexities associated with scaling high-aspect-ratios in via structures. Hexafluorobutadiene (1,3-C_4F_6) is being proposed as an alternative gas to octafluorocyclobutane (c-C_4F_8) in a high-density inductively coupled plasma system.

Acknowledgements

- AMD, Submicron Development Center (SDC) for funding this research (Dave Refuerzo, Etch Module Manager)
- Dr. Emily Allen and Dr. Stacy Glexiner from San Jose State University for their inputs, etch discussions and research support.
- Oscar Del Carpio from AMD for conducting SEM work.