Non-PFC Plasma Chemistries for Patterning Low-k Dielectric Materials

(*Task Number: 425.038*)

PIs:

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Graduate Students:

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Objectives

- Screen candidate etch chemistries through the use of thermodynamic analysis, including Gibbs free energy minimization

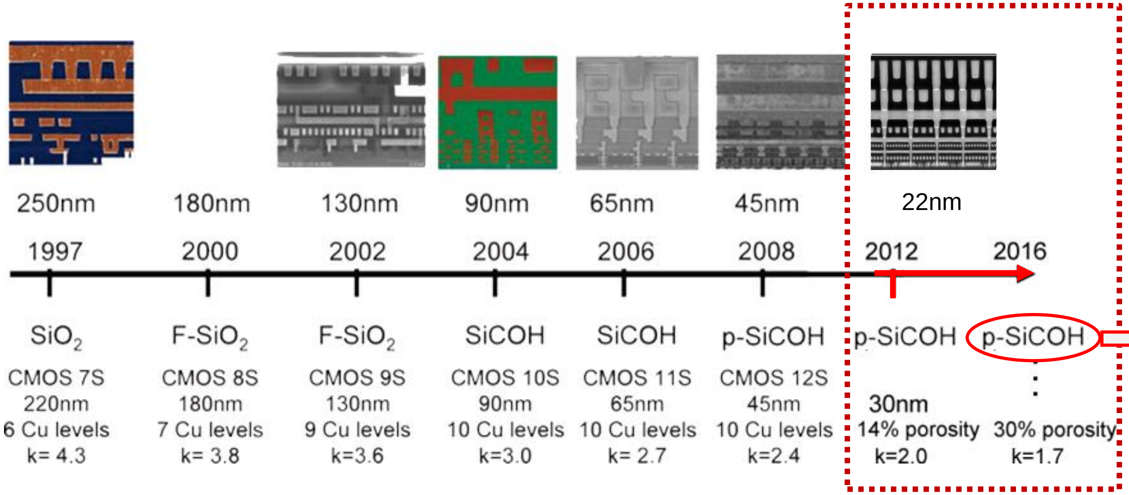
- Identify non-PFC gases that can be used (due to facility limitations, alternative locations are being explored)

- Reduce amount of PFC etchants through additive gases such as H_2

- Assess the feasibility of non-PFC chemistries in patterning low-k dielectric thin films

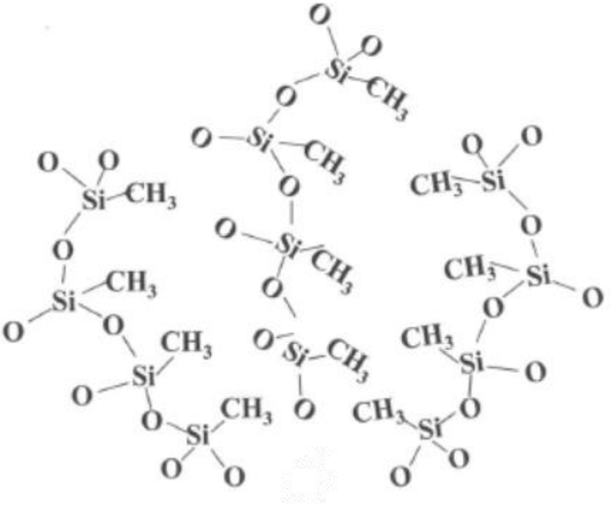
Composition of Low-k Dielectrics[1]

Dielectric materials used in IBM CMOS microprocessors as feature sizes decrease.[2]



250nm	180nm	130nm	90nm	65nm	45nm	22nm	
1997	2000	2002	2004	2006	2008	2012	2016
SiO_2	$F\text{-}SiO_2$	$F\text{-}SiO_2$	SiCOH	SiCOH	p-SiCOH	p-SiCOH	p-SiCOH
CMOS 7S 220nm 6 Cu levels k= 4.3	CMOS 8S 180nm 7 Cu levels k= 3.8	CMOS 9S 130nm 9 Cu levels k=3.6	CMOS 10S 90nm 10 Cu levels k=3.0	CMOS 11S 65nm 10 Cu levels k= 2.7	CMOS 12S 45nm 10 Cu levels k=2.4	30nm 14% porosity k=2.0	: 30% porosity k=1.7

Porous carbon-doped silica, a promising low-k dielectric.



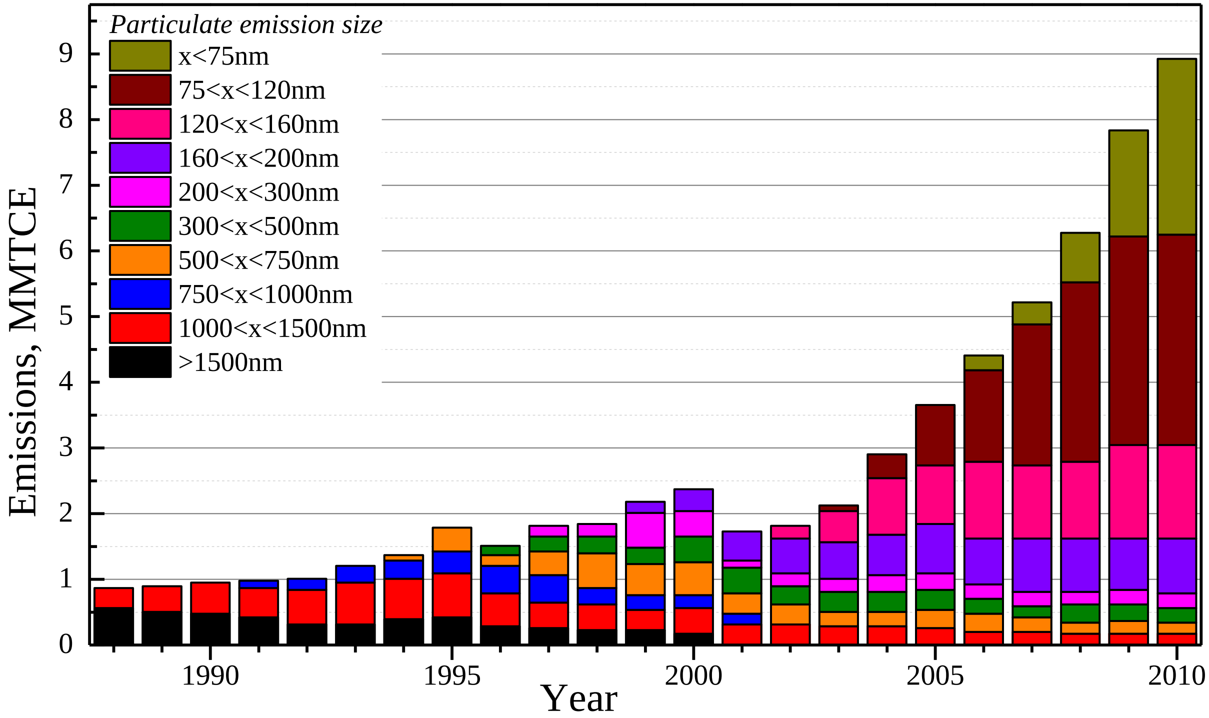
- **Previously explored trend of fluorine, carbon, and pore incorporation into low-k dielectrics**
- **Extension of porosity (k = 1) into the film, thereby realizing a lower dielectric constant**

[1] Vasarla, 2012 [2] W. Volksen, 2010

PFC Usage in BEOL

US EPA's PFC emission model* shows average PFC emissions from semiconductor manufacturing for the evolution of complex devices[3]

MMTCE = Million metric tons of carbon



***Assumes no abatement action taken**

- **Perfluorocarbon gases are used in BEOL for two major plasma processes: wafer patterning of thin films, especially dielectric films, and the in-situ cleaning of PECVD chambers**

[3] PFC reduction/Climate partnership for the semiconductor industry, US EPA, (2008) [18] W. Worth, PFC Technical Update Session, SEMICON/WEST(1995)

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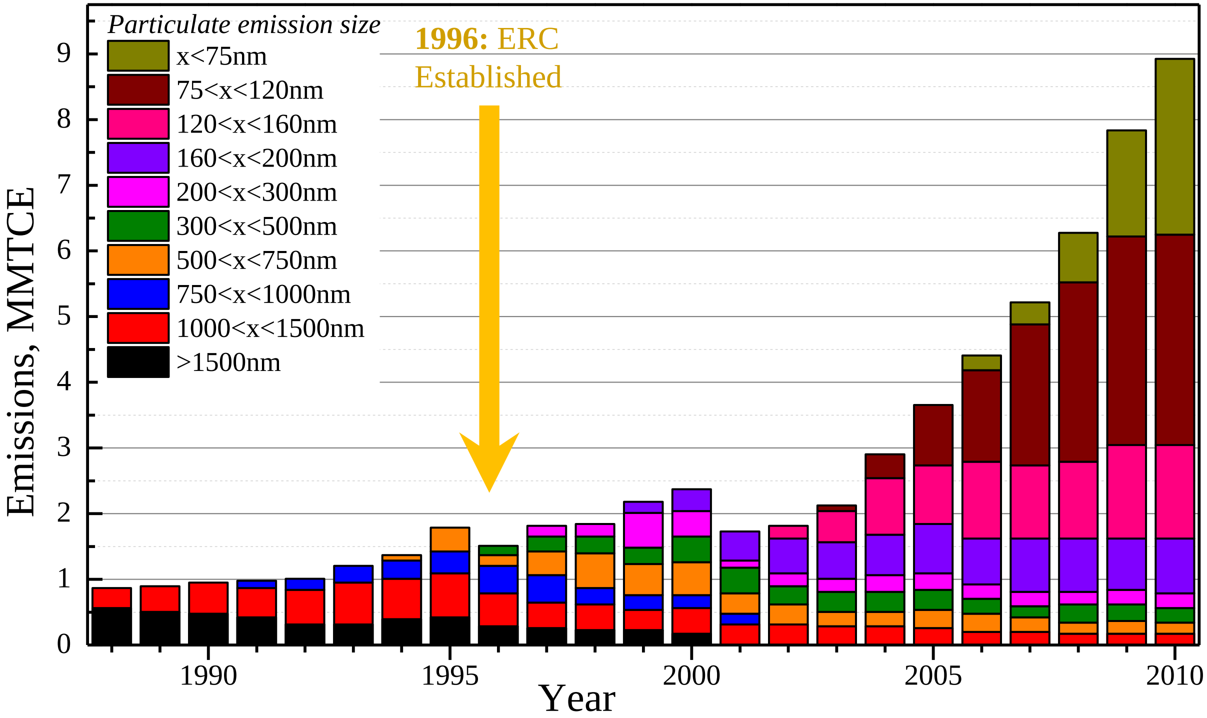

***Assumes no abatement action taken**

- **1996—Engineering Research Center (ERC) established with goal of combating trend of increased PFC usage**

[3] PFC reduction/Climate partnership for the semiconductor industry, US EPA, (2008) [18] W. Worth, PFC Technical Update Session, SEMICON/WEST(1995)

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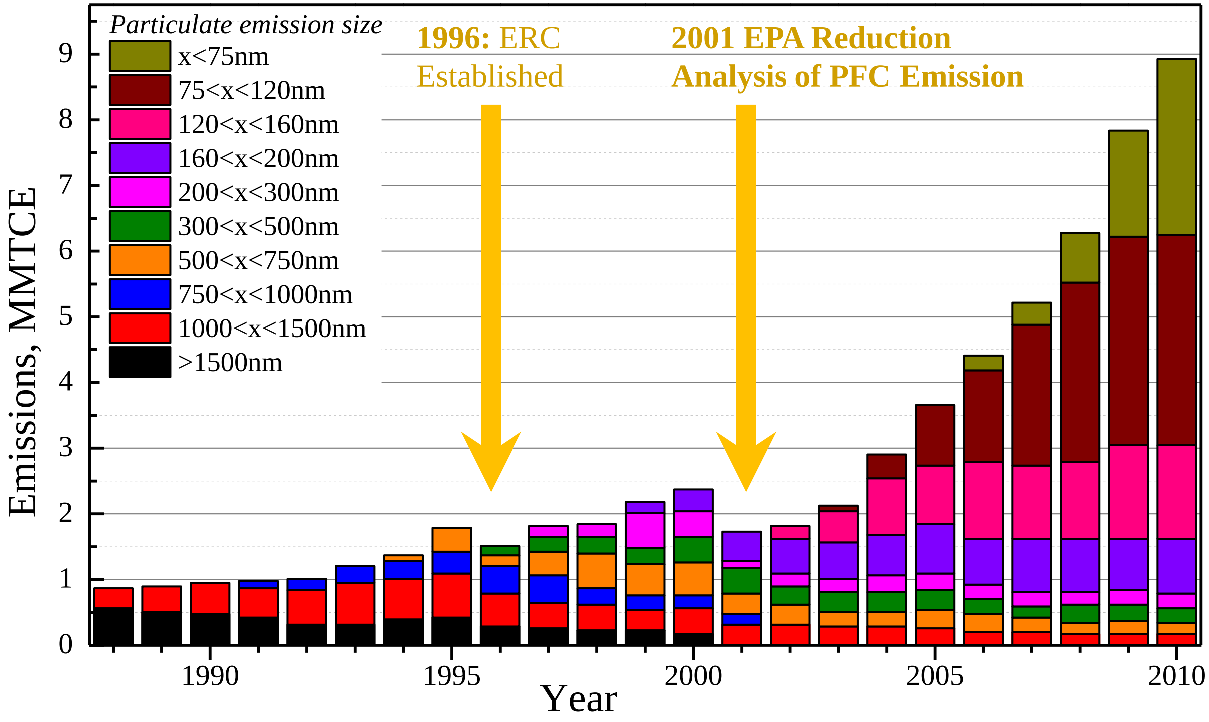

1996: ERC Established

2001 EPA Reduction Analysis of PFC Emission

***Assumes no abatement action taken**

- **2001—EU and EPA release reports analyzing pathways to reduce overall PFC emissions in Europe and United States, introducing stricter environmental policies**

[3] PFC reduction/Climate partnership for the semiconductor industry, US EPA, (2008) [18] W. Worth, PFC Technical Update Session, SEMICON/WEST(1995)

PFC Usage in BEOL

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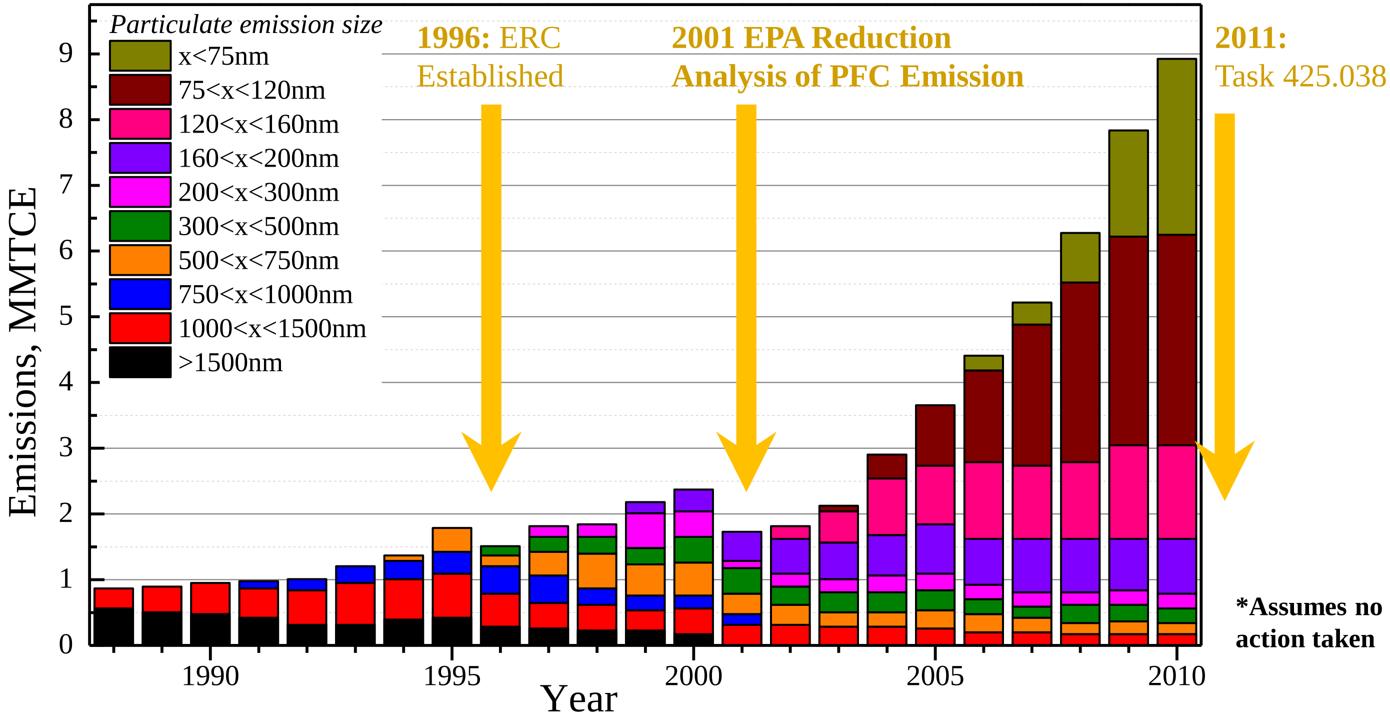


1996: ERC Established

2001 EPA Reduction Analysis of PFC Emission

2011: Task 425.038

***Assumes no abatement action taken**

- **2011—Task 425.038 introduced to investigate the potential reduction of PFC usage**

SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

[3] PFC reduction/Climate partnership for the semiconductor industry, US EPA, (2008) [18] W. Worth, PFC Technical Update Session, SEMICON/WEST(1995)

Global Warming Potential

Chemistries	Atmospheric conc. in 2015 (ppt)	Atmospheric conc. in 2005 (ppt)	Con. since 1994 & 1998 (ppt)	Annual emission in late 1990s (Gg)	Radiative efficiency ($W/m^2/ppb$)	Lifetime (year)	Global Warming Potential	Ref.
CO_2	$403x10^6$	$379x10^6$	$358x10^6$*	-	-	variable	1	[12]
CH_4	$7.22x10^5$	$7x10^5$	$1.7x10^5$*	-	-	12.2	21	[12]
N_2O	$326x10^5$	$275x10^3$	$311x10^3$*	-	-	120	310	[12]
$CHClF_2$	-	-	$105x10^3$*	-	-	12.1	1400	[12]
CF_4	76	74	-	~15	0.1	50,000	6500	[13]
CCl_2F_2	-	-	$503x10^3$*	-	-	102	7100	[12]
C_2F_6	-	2.9	3.4	~2	0.26	10,000	9200	[13]
CHF_3	21	18	22	~7	0.19	270	11700	[12]
SF_6	-	5.6	7.1	~6	0.52	3,200	23900	[13]
NH_3	-	-	-	0.054	-	2 hrs	0	[14]
NF_3	<0.1	-	-	~2.3	0.21	740	16800	[13]
C_2F_4	-	-	-	-	-	1.9 days	<1	[15]
C_6F_6	-	-	-	-	-		<1	[16]
CF_3I	-	-	-	-	-	2 days	1	[10]

- **GWP is a simplified index based on radiative properties that estimates the potential impacts of gases on global warming**

Target of Carbon-doped SiO_2 Etch

*Material Metrics as Specified by Intel (Dr. Suri)

Intel specified

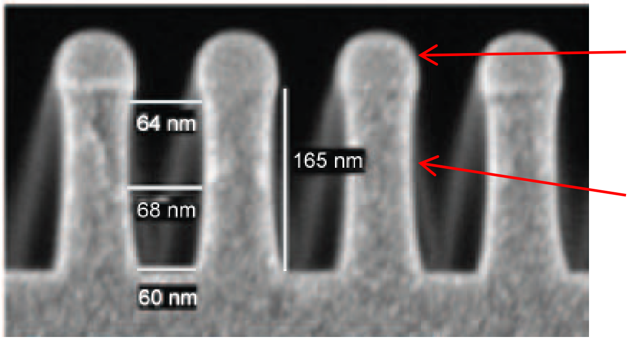
Elements	Range(%)
Si	20%
O	40%
C	15-40%
Porosity	20-25%
Thickness	100nm

Focus on:

1	Trench etch (later via)
2	Selectivity to PR
3	Sidewall damage

Target	Carbon doping level	Composition				Unit
		Si (%)	O (%)	C (%)	H (%)	
1	Low	15.4	23.1	15.4	46.1	$SiO_{1.5}CH_3$
2	↑	20	20	20	40	$SiOCH_2$
3	↓	12.5	12.5	25	50	$SiO(CH_2)_2$
4	High	18.2	27.2	36.4	18.2	$SiO_{1.5}C_2H$

- **SEM of C-doped SiO_2 pre-metal dielectric layer[4]**



SiO_2 hard mask rounding

Bowed profiles

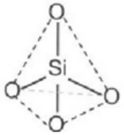
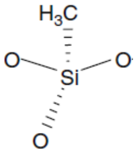
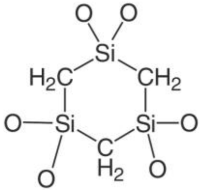
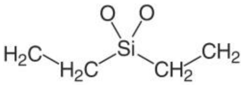
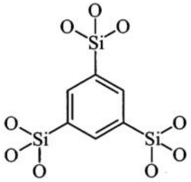
[4] S. Rimal, et al., Evaluation of Plasma Damage to Low-k dielectric Trench Structures, *ECS Solid State Letters*, **3,** N1-4 (2014)

Systematic Approach - Thermodynamic

- **Thermodynamic approach can be systematic**
  - **If such data is available**
    - **NIST-JANAF Thermo-chemical tables**
    - **HSC Chemistry for Windows, chemical reaction and equilibrium software with extensive thermo-chemical database**
    - **FACT, Facility for Analysis of Chemical Thermodynamics**
    - **Barin and Knacke tables (thermo-chemical data for pure substances and inorganic substances)**
  - **Determination of dominant surface/gas-phase species**
  - **Assessment of possible reactions**

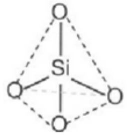
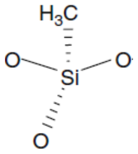
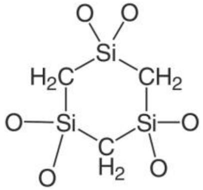
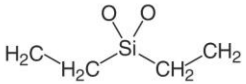
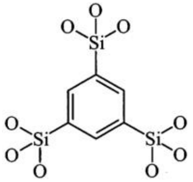
- **Graphical Representation of thermodynamic analysis**
  - **Richardson Ellingham diagram**
  - **Pourbaix diagram**
  - **Volatility diagram**
  - **Gibbs free energy minimization**

Data for C-doped Silica is Limited

C-doped silica		**$\Delta_f H$ (kJ/mol)**	**$\Delta_f S$ (J/mol)**	**$\Delta_f G$ (kJ/mol)**
SiO_2[4]		-910.87	-182.53	-856.11
$SiO_{1.5}CH_3$[4,5] (15.4%)				
$SiOCH_2$[4,5] (20%)		No data is available		
$SiO(CH_2)_2$[4,5] (25%)				
$SiO_{1.5}C_2H$[4,5,6] (36.4%)				

[5] NIST-JANAF Thermochemical (2013) [6] S. W. Benson, ACS Symposium series 677, (1988)

Data for C-doped Silica is Needed

C-doped silica		**$\Delta_f H$ (kJ/mol)**	**$\Delta_f S$ (J/mol)**	**$\Delta_f G$ (kJ/mol)**
SiO_2[4]		-910.87	-182.53	-856.11
$SiO_{1.5}CH_3$[4,5] (15.4%)				
$SiOCH_2$[4,5] (20%)			No data is available	
$SiO(CH_2)_2$[4,5] (25%)				
$SiO_{1.5}C_2H$[4,5,6] (36.4%)				

Group / Bond	No. in $SiO_{1.5}CH_3$	Enthalpy[5] (kJ/mol)	Entropy[5] (J/mol*K)
SiO_2[6]	3/4	-910.866	-
CH_4[6]	3/4	-50.618	-
Si-C	1	-25.1	57.91
Si-O	3	-	-5.19
C-H	3	-	53.97
Total	-	-746.2	204.25

T=300K	SiO_2[4]	$SiO_{1.5}CH_3$
$\Delta_f H$(kJ/mol)	-910.866	-746.2
$\Delta_f S$(J/mol)	-182.53	-324.77
$\Delta_f G$(kJ/mol)	$\boxed{-856.106}$	$\boxed{-648.8}$

$$\Delta_f S_{C-SiO_2} = S^\circ_{C-SiO_2} - (nS^\circ_{Si} + xS^\circ_{O_2} + yS^\circ_{C} + zS^\circ_{H_2})$$

$$\Delta_f G_{C-SiO_2} = \Delta_f H_{C-SiO_2} - T \times \Delta_f S_{C-SiO_2}$$

- **The bond additivity and group additivity methods[6] is used to determine the energy of formation for C-doped silica**

[5] NIST-JANAF Thermochemical (2013) [6] S. W. Benson, ACS Symposium series 677, (1988)

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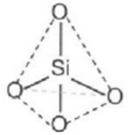
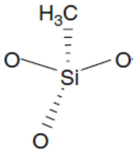
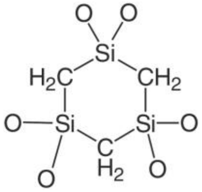
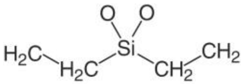
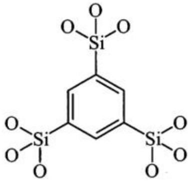
SiO_2[4]		-910.87	-182.53	-856.11
$SiO_{1.5}CH_3$[4,5] (15.4%)		-746.20	-324.77	-648.80
$SiOCH_2$[4,5] (20%)		-517.40	-44.88	-503.90
$SiO(CH_2)_2$[4,5] (25%)		-538.00	-141.84	-495.50
$SiO_{1.5}C_2H$[4,5,6] (36.4%)		-662.70	-328.86	-564.10

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CH_4[6]	3/4	-50.618	-
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Total	-	-746.2	204.25

T=300K	SiO_2[4]	$SiO_{1.5}CH_3$
$\Delta_f H$(kJ/mol)	-910.866	-746.2
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$$\Delta_f S_{C-SiO_2} = S^{\circ}_{C-SiO_2} - (nS^{\circ}_{Si} + xS^{\circ}_{O_2} + yS^{\circ}_{C} + zS^{\circ}_{H_2})$$

$$\Delta_f G_{C-SiO_2} = \Delta_f H_{C-SiO_2} - T \times \Delta_f S_{C-SiO_2}$$

- **The bond additivity and group additivity methods[6] is used to determine the energy of formation for C-doped silica**

SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

[5] NIST-JANAF Thermochemical (2013) [6] S. W. Benson, ACS Symposium series 677, (1988)

Selection of Chemistry

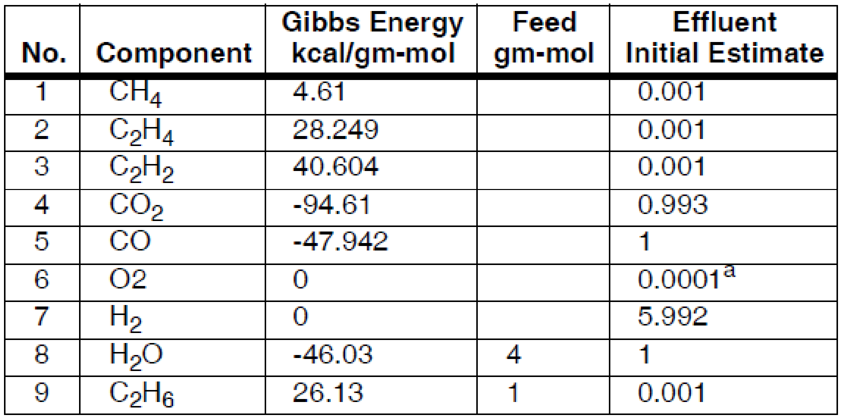
Reaction	ΔG (eV)
SiO_2	
$SiO_2(c) + \mathbf{2CF_4(g)} \rightarrow SiF_4(g) + 2COF_2(g)$	-1.92
$SiO_2(c) + \mathbf{2CF_4(g)} + \mathbf{H_2(g)} \rightarrow SiF_4(g) + 2COF(g) + 2HF(g)$	1.51
$SiO(CH_2)_2(c)$ (Medium-doped silica)	
$SiO(CH_2)_2(c) + \mathbf{CF_4(g)} \rightarrow SiF_4(g) + CO(g) + C_2H_4(g)$	-2.67
$SiO(CH_2)_2(c) + \mathbf{CF_4(g)} + 2\mathbf{H_2}(g) \rightarrow SiF_4(g) + CO(g) + 2CH_4(g)$	-4.43

- **Comparison of non-PFC and PFC in C-doped silica etch**
- **Consider additives such as H_2 to facilitate the formation of volatile C-containing compounds from highly-doped silica (>15%C)**

[5] NIST-JANAF Thermochemical (2013)

Gibbs Free Energy Minimization

- **T=1000K, P=1atm, input: H_2O 4mole, CH_4 1mole**



No.	Component	Gibbs Energy kcal/gm-mol	Feed gm-mol	Effluent Initial Estimate
1	CH_4	4.61		0.001
2	C_2H_4	28.249		0.001
3	C_2H_2	40.604		0.001
4	CO_2	-94.61		0.993
5	CO	-47.942		1
6	O2	0		0.0001[a]
7	H_2	0		5.992
8	H_2O	-46.03	4	1
9	C_2H_6	26.13	1	0.001

- R, T, P, and P_o are known constants
- G_j^o is provided by the NIST-JANAF and HSC thermochemical tables
- Set G_{tot} as objective function to be minimized
- Compute finite set of n_j to reach global minimum of G_{tot}

Two criteria need to be achieved:

1: Elemental balance

Oxygen Balance $g_1 = 2n_4 + n_5 + 2n_6 + n_7 - 4 = 0$

Hydrogen Balance $g_2 = 4n_1 + 4n_2 + 2n_3 + 2n_7 + 2n_8 + 6n_9 - 14 = 0$

Carbon Balance $g_3 = n_1 + 2n_2 + 2n_3 + n_4 + n_5 + 2n_9 - 2 = 0$

2: Minimization of Gibbs free energy

$$G_{tot} = \sum_j n_j \mu_j$$

Sum of chemical potentials

$$\mu_j = G_j^0 + RT \ln\left(a_j\right)$$

Definition of chemical potential

$$a_j = \left(\frac{P}{P_0}\right) y_j ; y_i = \frac{n_j}{\sum_j n_j}$$

Activity and gas mole fraction

$$\min_{n_i}\left\{\frac{G_{tot}}{RT} = \sum_j n_j\left(\frac{G_j^0}{RT} + \ln\left[\left(\frac{P}{P_0}\right)\frac{n_j}{\sum_j n_j}\right]\right)\right\}$$

Gibbs Free Energy Minimization Approach

Gibbs free energy minimization $Cr(s) + Cl_2(g) + O_2(g) \rightarrow \boxed{CrCl_2O_2(g),\ CrO_2(s),\ Cr_2O_3(s)\ldots}$

$$G_{tot} = \sum_j n_j \mu_j = \sum_j n_j \left(\Delta G_j^{\,0} + RT \ln\left[\left(\frac{P}{P_0}\right) \frac{n_j}{\sum_j n_j} \right] \right)$$

1. **Linear constraint of atomic mass conservation**

$$\begin{array}{r} \textbf{Cr balance} \\ \textbf{Cl balance} \\ \textbf{O balance} \end{array} \begin{pmatrix} n_{Cr,Cr} & n_{Cr,Cl_2} & n_{Cr,O_2} & n_{Cr,CrCl_2O_2} & n_{Cr,CrO_2} & n_{Cr,Cr_2O_3} \\ n_{Cl,Cr} & n_{Cl,Cl_2} & n_{Cl,O_2} & n_{Cl,CrCl_2O_2} & n_{Cl,CrO_2} & n_{Cl,Cr_2O_3} \\ n_{O,Cr} & n_{O,Cl_2} & n_{O,O_2} & n_{O,CrCl_2O_2} & n_{O,CrO_2} & n_{O,Cr_2O_3} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} n_{Cr,in} \\ n_{Cl,in} \\ n_{O,in} \end{pmatrix}$$

2. **Feed: 1 mol Cr(s), 130 mol Cl_2(g), 5 mol O_2(g)**

$$\begin{array}{r} \textbf{Cr balance} \\ \textbf{Cl balance} \\ \textbf{O balance} \end{array} \begin{pmatrix} 1 & 0 & 0 & 1 & 1 & 2 \\ 0 & 2 & 0 & 2 & 0 & 0 \\ 0 & 0 & 2 & 2 & 2 & 3 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} 1 \\ 260 \\ 10 \end{pmatrix}$$

3. **Minimize total Gibbs free energy function**

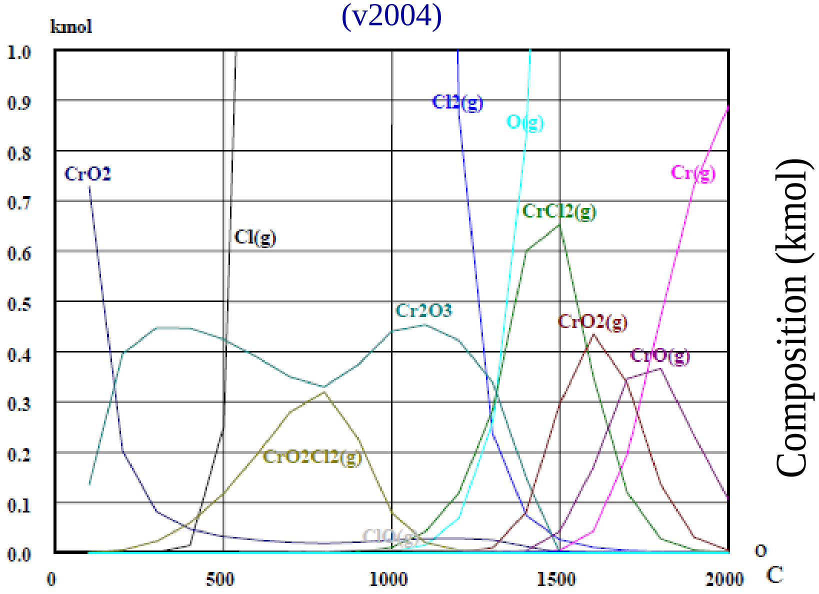
$$\min_{n_j} \left\{ \frac{G_{tot}}{RT} = \sum_j n_j \left(\frac{\Delta G_j^{\,0}}{RT} + \ln\left[\left(\frac{P}{P_0}\right) \frac{n_j}{\sum_j n_j} \right] \right) \right\}$$

[17] B. Wu, "Thermodynamic study of photomask plasma etching", *Proc. SPIE* 5567 (2004)

Commercially Available Software

- Feed: Cl_2 = 200, He = 50, O_2 = 20, Cr = 1 kmol
- **HSC** in Literature [Wu, SPIE]
- **HSC** in lab

(v2004)



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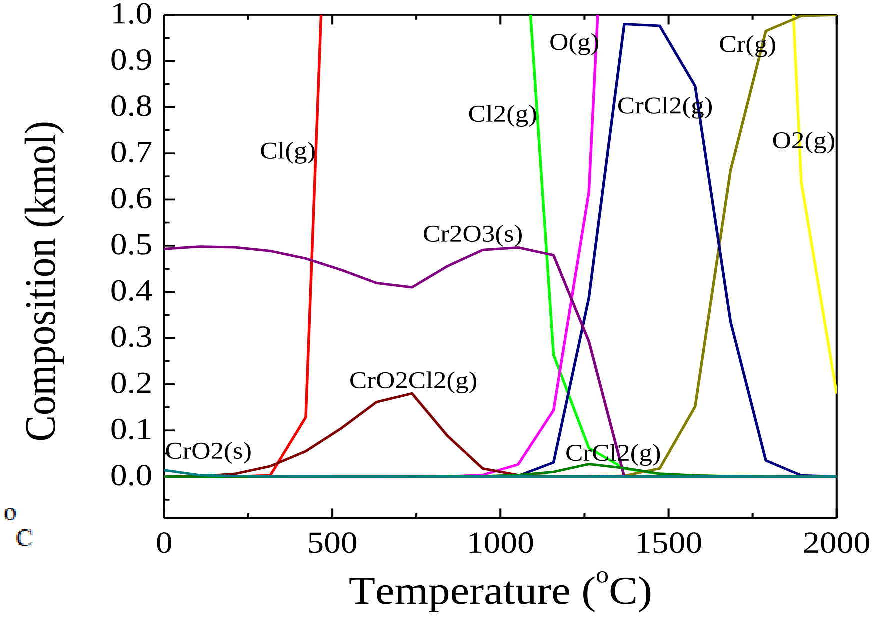


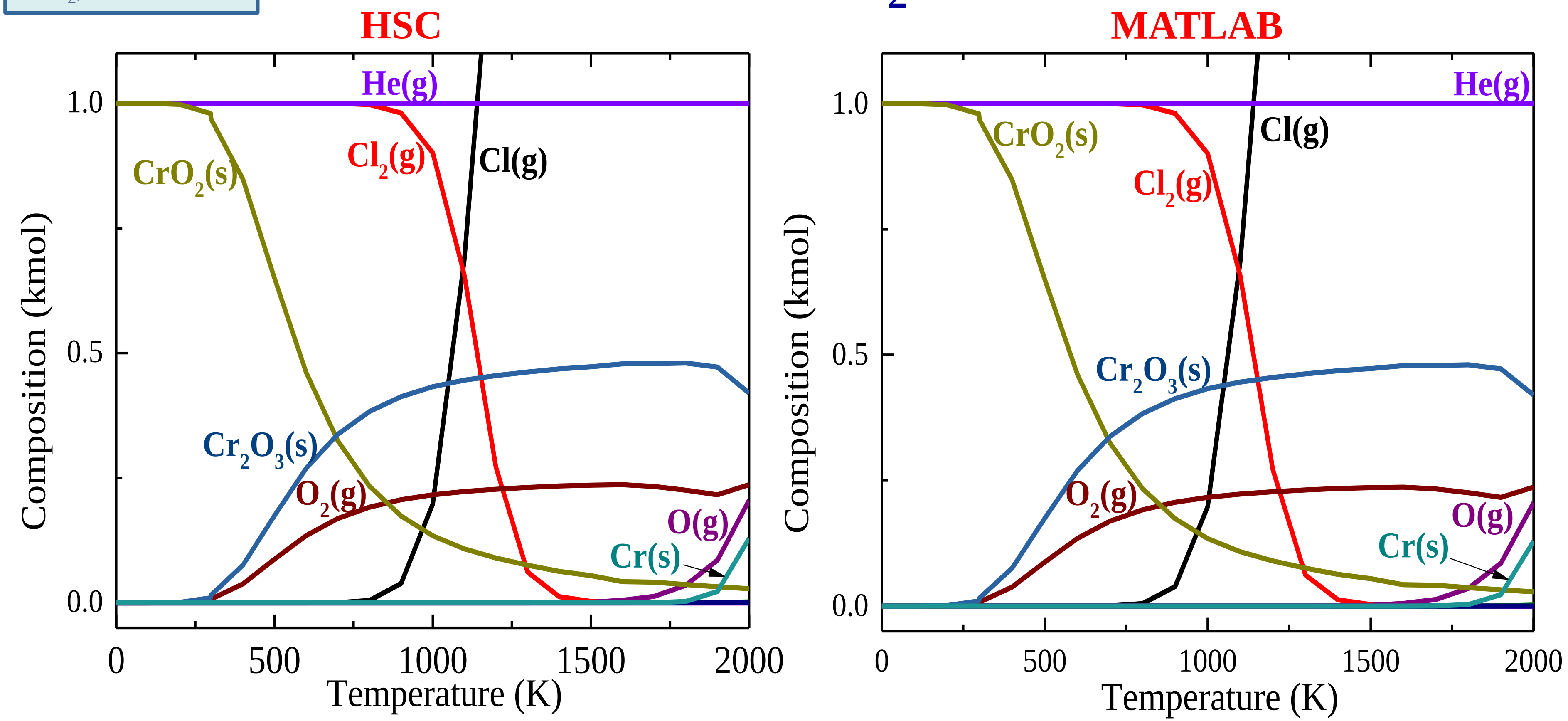
- **Refinements were made to HSC program between 2004 and 2013; however, no details were given about exact changes**

[17] B. Wu, “Thermodynamic study of photomask plasma etching”, *Proc. SPIE* 5567 (2004)

Validating the MATLAB Code

$P = 10^{-5}$ atm
Feed: 1 kmol Cr,
1 Cl_2, 1 He

Cr in Cl_2



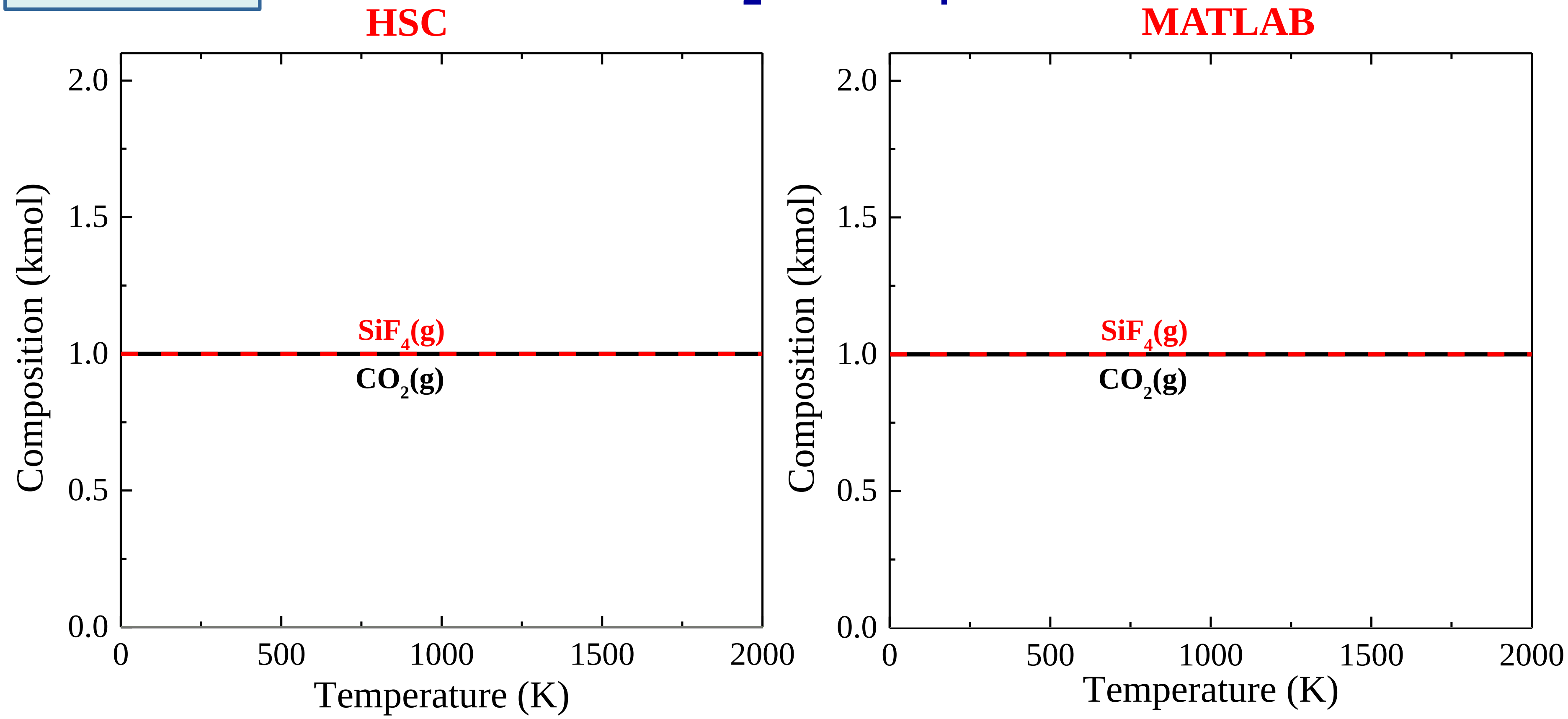
- **Through incorporation of gas and condensed phase data, MATLAB code was able to reproduce HSC results**

[17] B. Wu, "Thermodynamic study of photomask plasma etching", *Proc. SPIE* 5567 (2004)

Validating the MATLAB Code

P = 10^{-5} atm
Feed: 1 kmol SiO_2,
1 CF_4

SiO_2 in CF_4



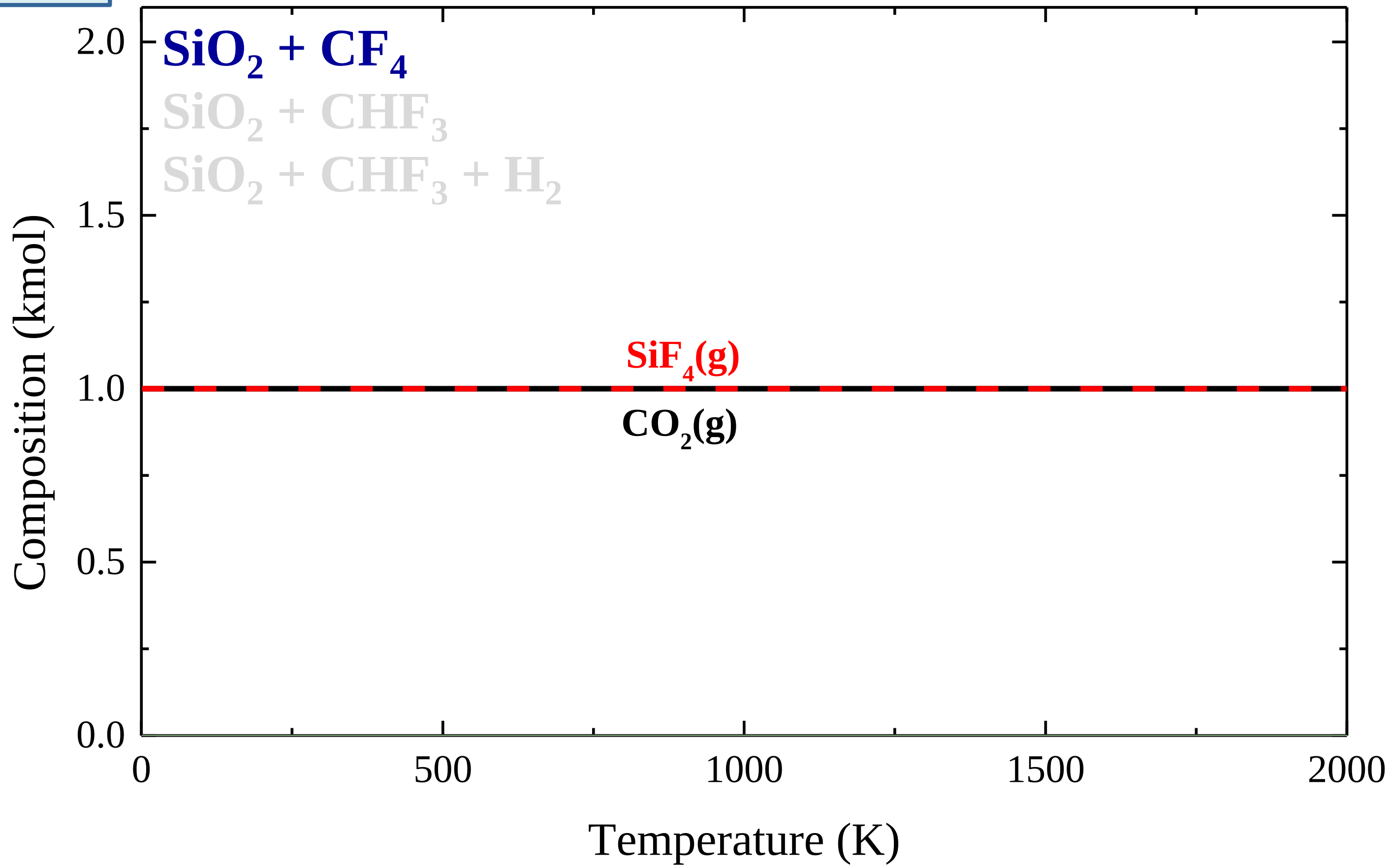
- **The most favorable reaction pathway for SiO_2 with CF_4 is to form SiF_4 and CO_2**

[17] B. Wu, "Thermodynamic study of photomask plasma etching", *Proc. SPIE* 5567 (2004)

Gibbs Minimization Analysis

P = 10^{-5} atm
Feed: 1 kmol SiO_2,
1 CF_4

MATLAB



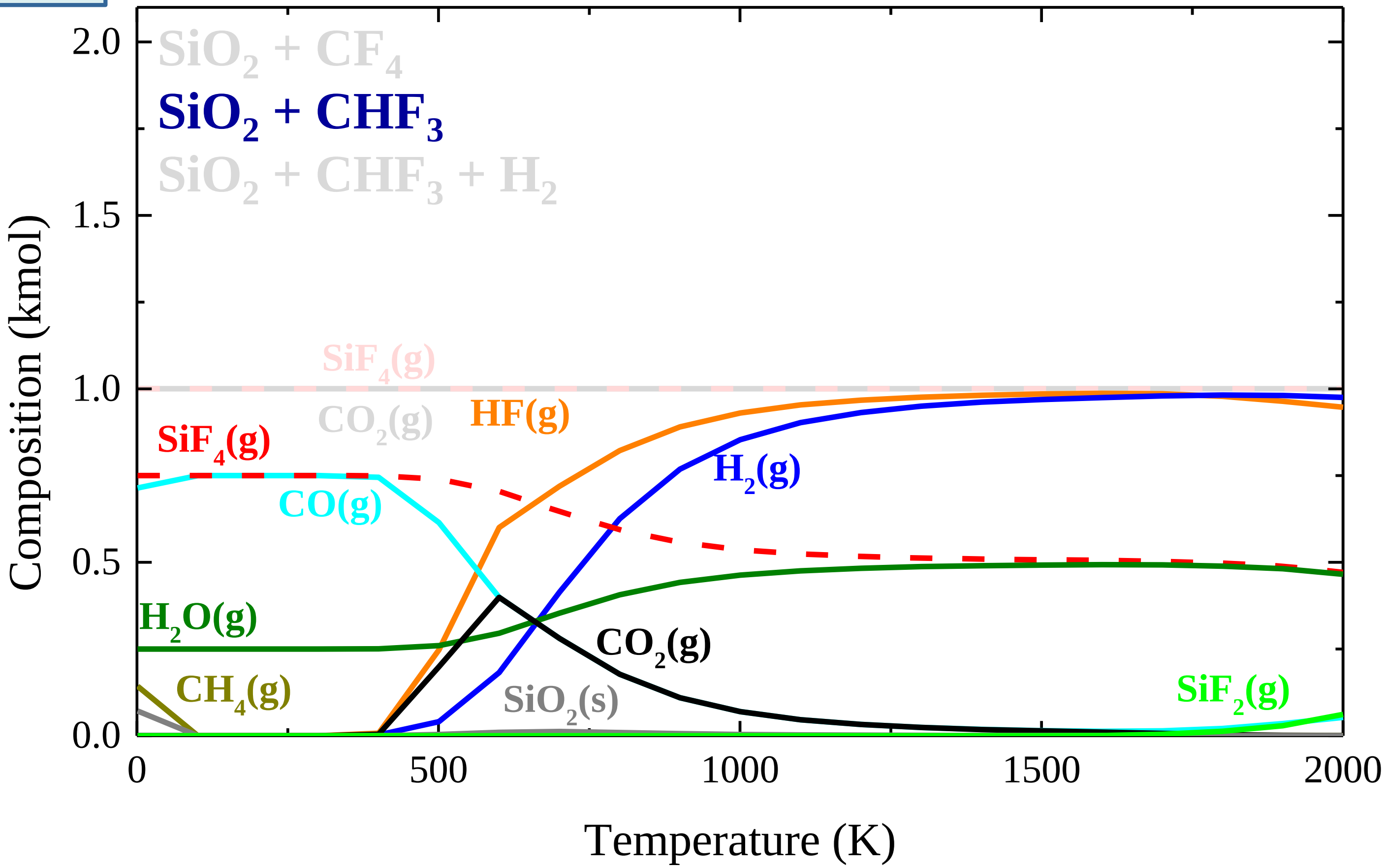
- **SiO_2 and CF_4 was taken as a baseline condition to examine the change in product distribution**

[17] B. Wu, "Thermodynamic study of photomask plasma etching", *Proc. SPIE* 5567 (2004)

Gibbs Minimization Analysis

P = 10^{-5} atm
Feed: 1 kmol SiO_2,
1 CHF_3

MATLAB



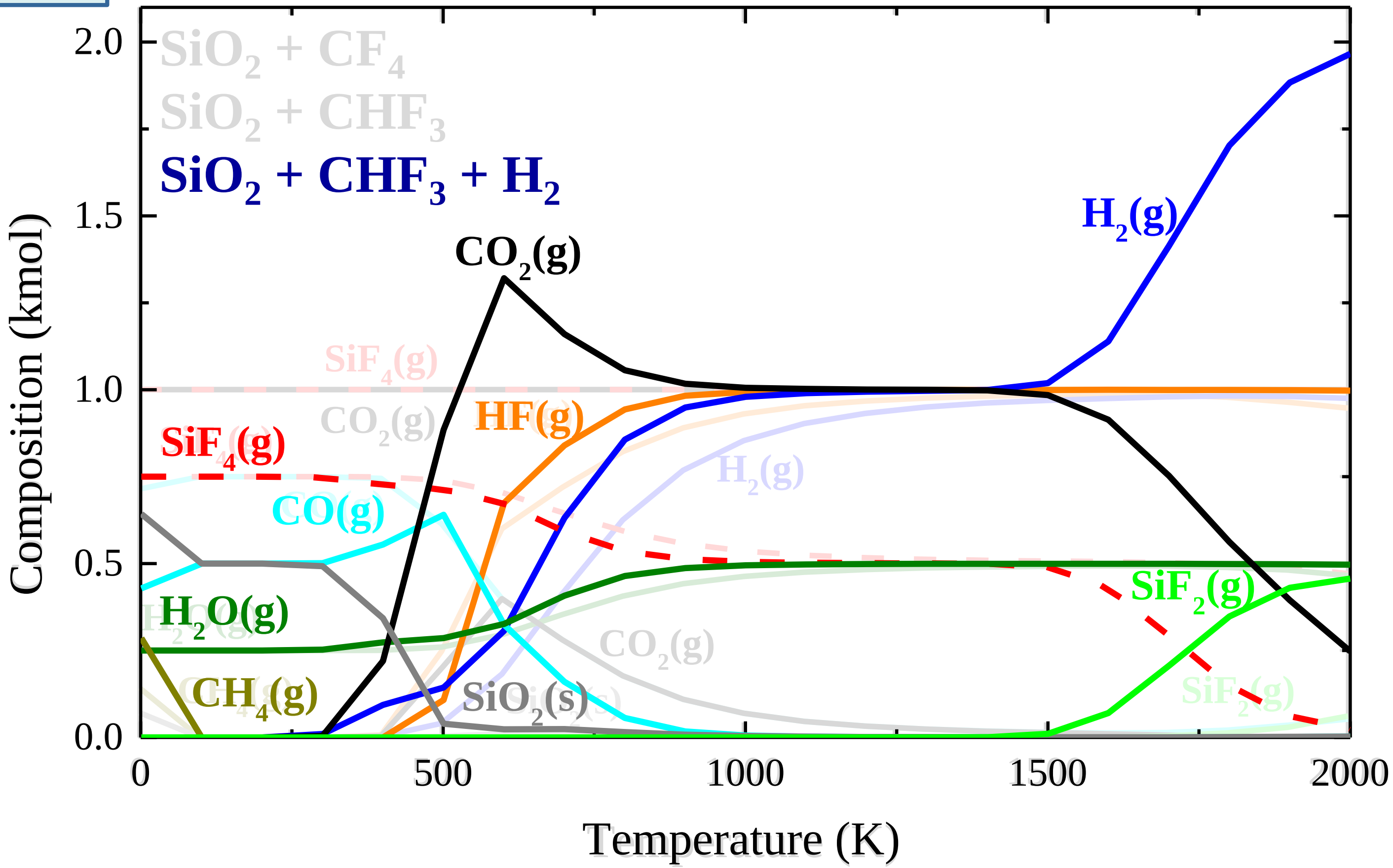
- **Hydrogen can first be incorporated by switching to a partially hydrogenated etchant (CHF_3), causing the product distribution to become significantly more complex**

[17] B. Wu, “Thermodynamic study of photomask plasma etching”, *Proc. SPIE* 5567 (2004)

Gibbs Minimization Analysis

P = 10^{-5} atm
Feed: 1 kmol SiO_2,
1 CHF_3 + 1 H_2

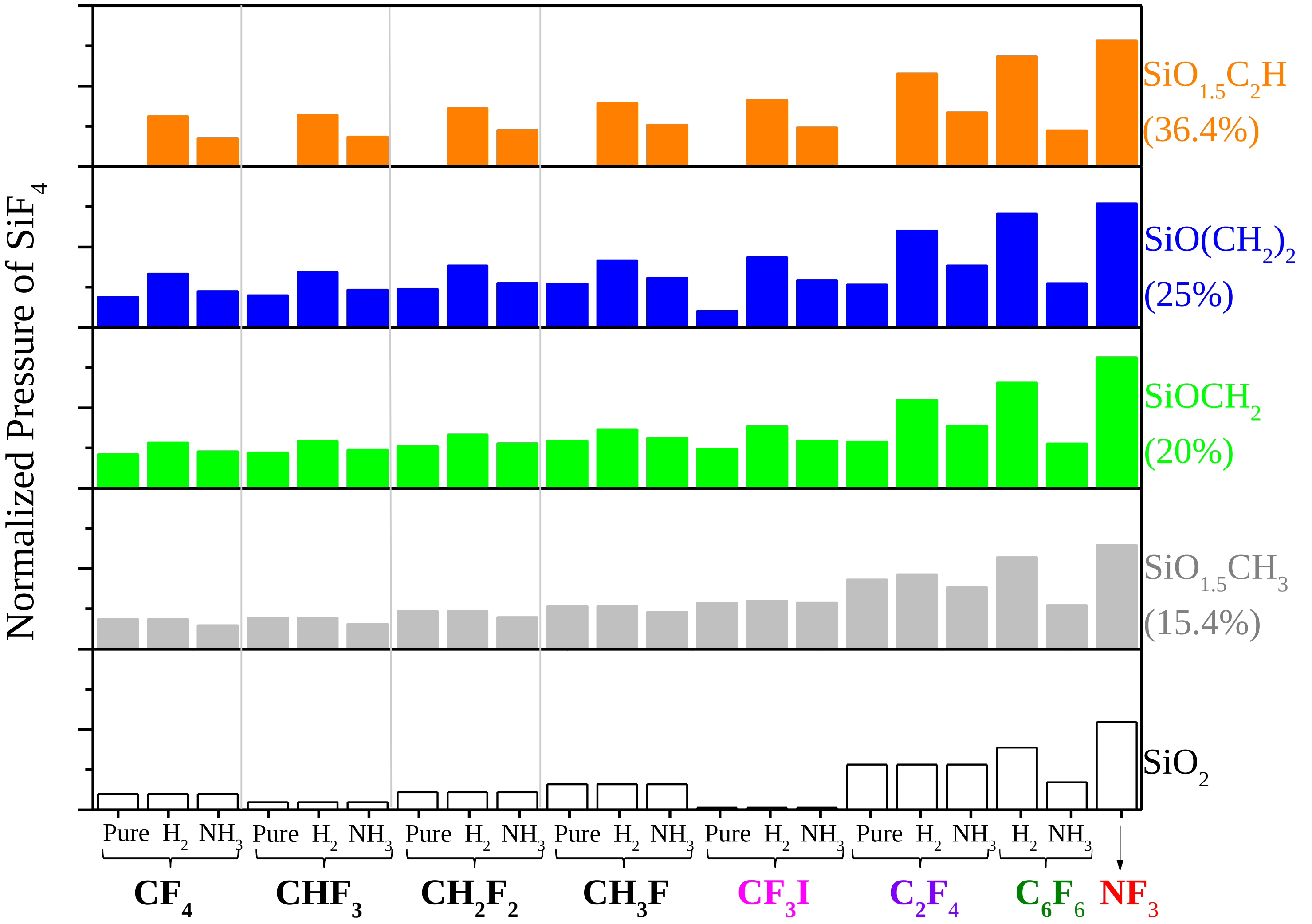
MATLAB



- **Molecular hydrogen can also be added to allow for independent control of the F/H ratio beyond the fixed composition of the etchant molecule**

[17] B. Wu, “Thermodynamic study of photomask plasma etching”, *Proc. SPIE* 5567 (2004)

Comparison of Etchant Chemistries



The y-axis represents the normalized partial pressure of SiF4, one of the primary products. The normalization is with respect to the partial pressure of SiF4 generated in CF4 etching SiO2 where all the thermodynamics data are from NIST JANAF Thermodynamics Table, 2013

[5] NIST-JANAF Thermochemical (2013)

Process Chemistry Availability

Ulvac NE-550

Available gases:

- **H_2**
- O_2
- Ar
- Cl_2
- SF_6
- **CF_4**

STS Advanced Oxide ICP Etcher

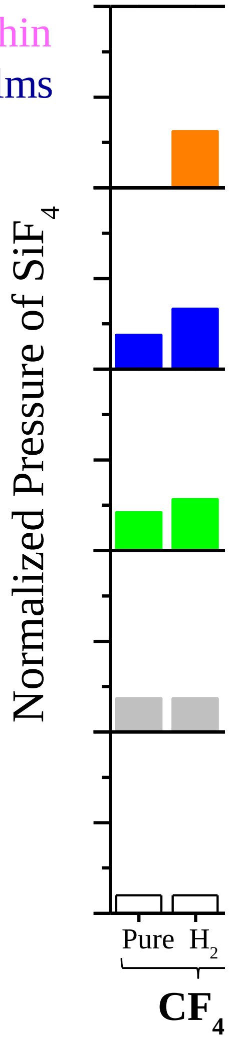
Available gases:

- **H_2**
- O_2
- Ar
- SF_6
- **CF_4**
- **CHF_3**
- C_4F_8

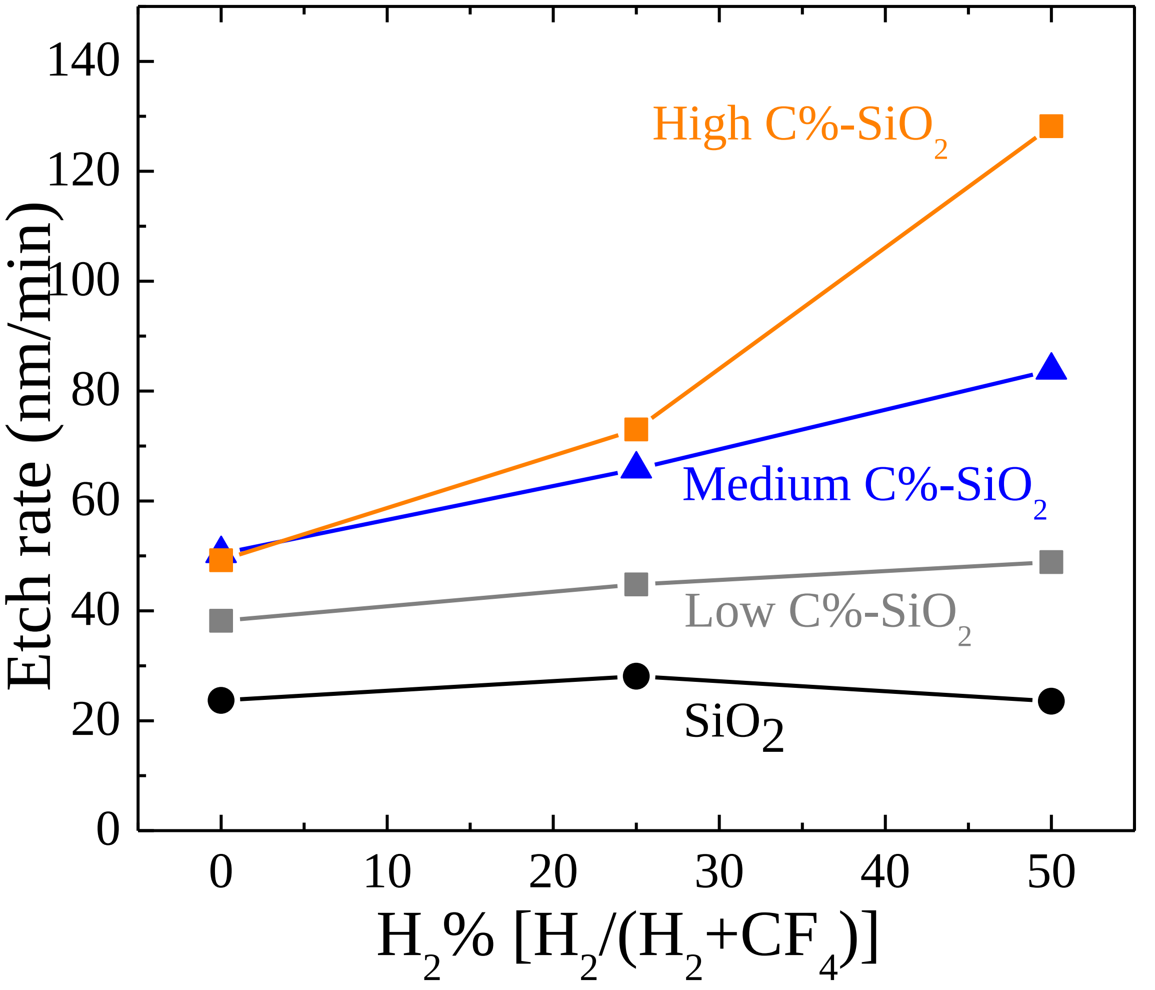
- **CF_4 and H_2 were the only fluorocarbon chemistries available for previous studies using Ulvac NE-550**
- **Transition to STS Oxide etcher allowed for comparison of CF_4 and CHF_3 chemistries with additive H_2**

C%-SiO_2 Etched in CF_4 (Ulvac etcher)

Blanket thin
C-SiO_2 films



Plasma power = 100W, P = 30mtorr, Bias power = 20 W, CF_4 flow rate = 20 sccm

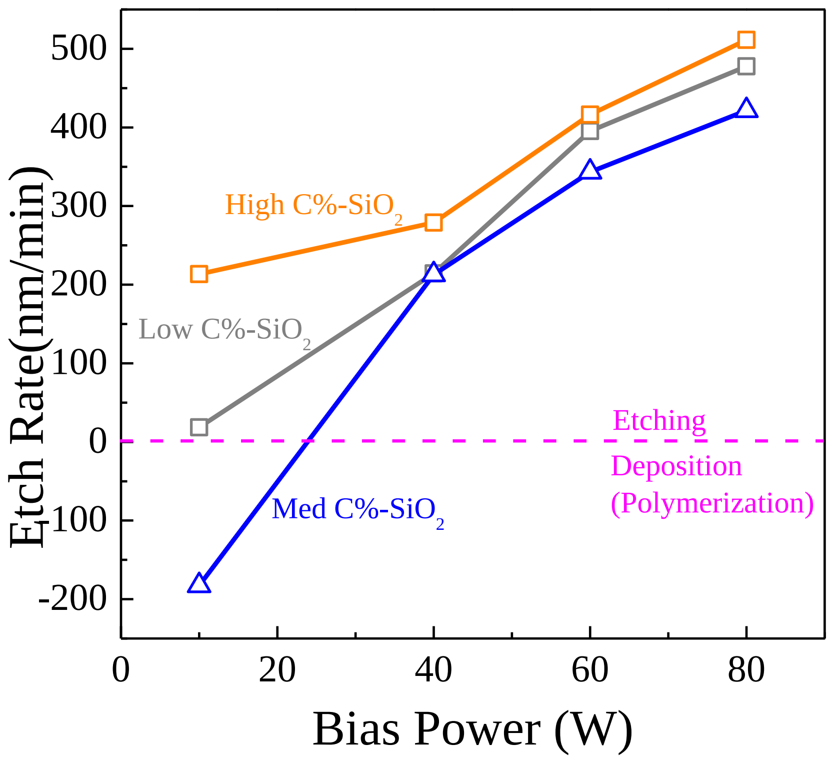


- **Previous results show agreement between etch rate studies and thermodynamic analysis, H_2 addition causes increase in etch rate**

Bias Power Dependence

Plasma power = 1400W, P = 6mtorr, CF_4 flow rate = 20 sccm

Blanket C-SiO_2 thick films



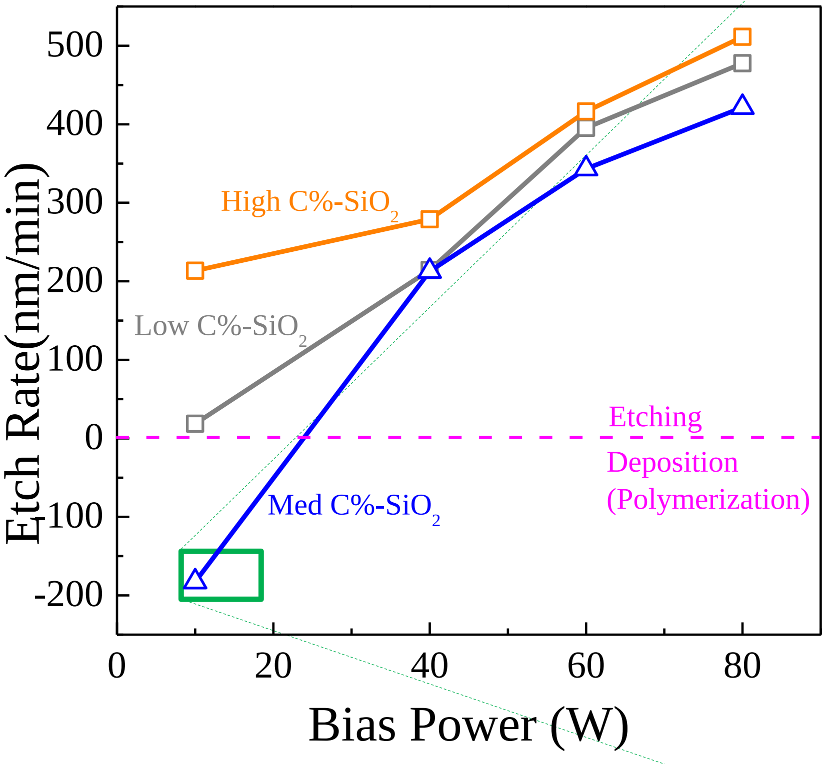
- **Bias power also have significant effect, particularly on medium C% SiO_2 films (in addition to studying the effects of hydrogen chemistry)**

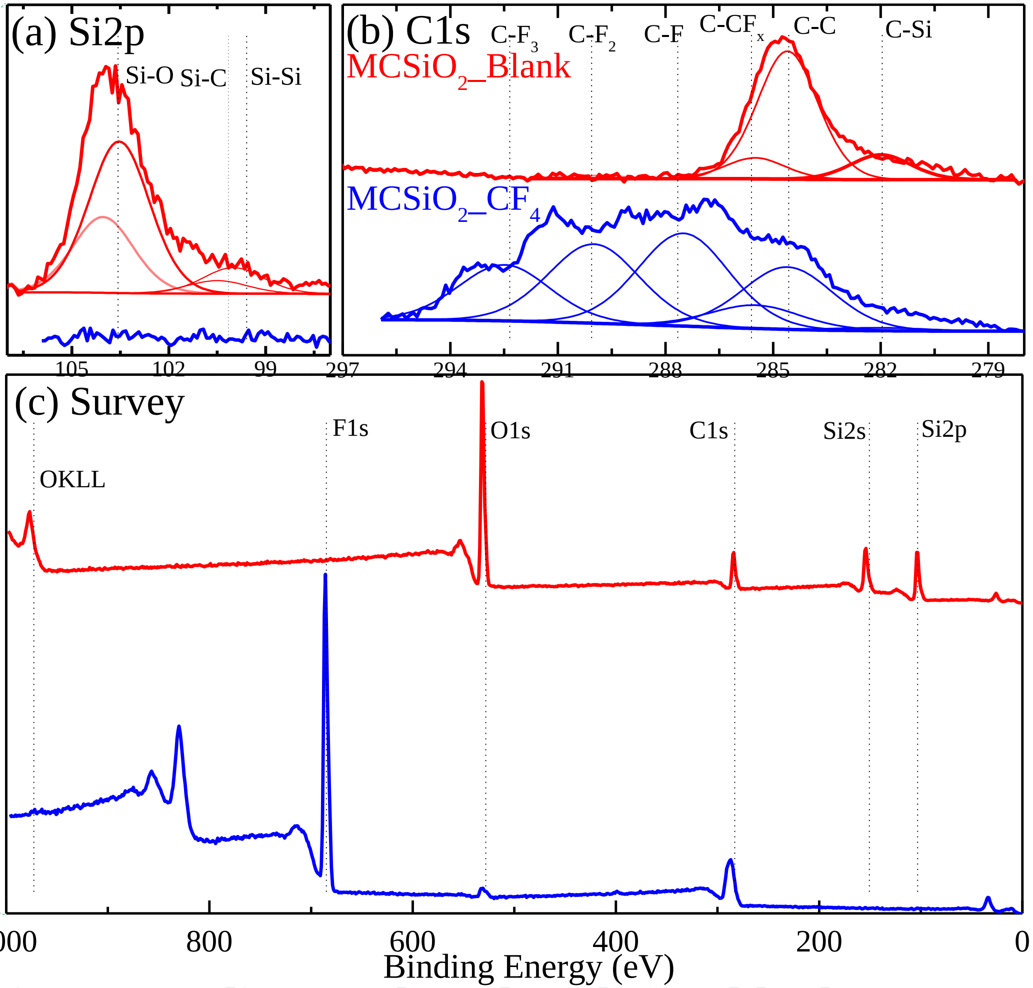
Bias Power Dependence

Plasma power = 1400W, P = 6mtorr, CF_4 flow rate = 20 sccm

XPS surface analysis: $MCSiO_2$_blank(red); $MCSiO_2$_CF_4(blue)

Blanket C-SiO_2 thick films

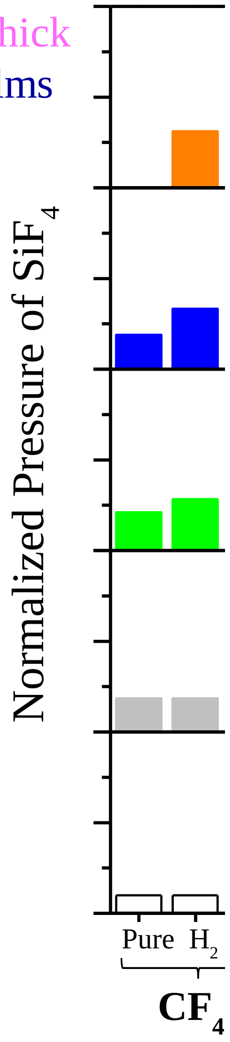


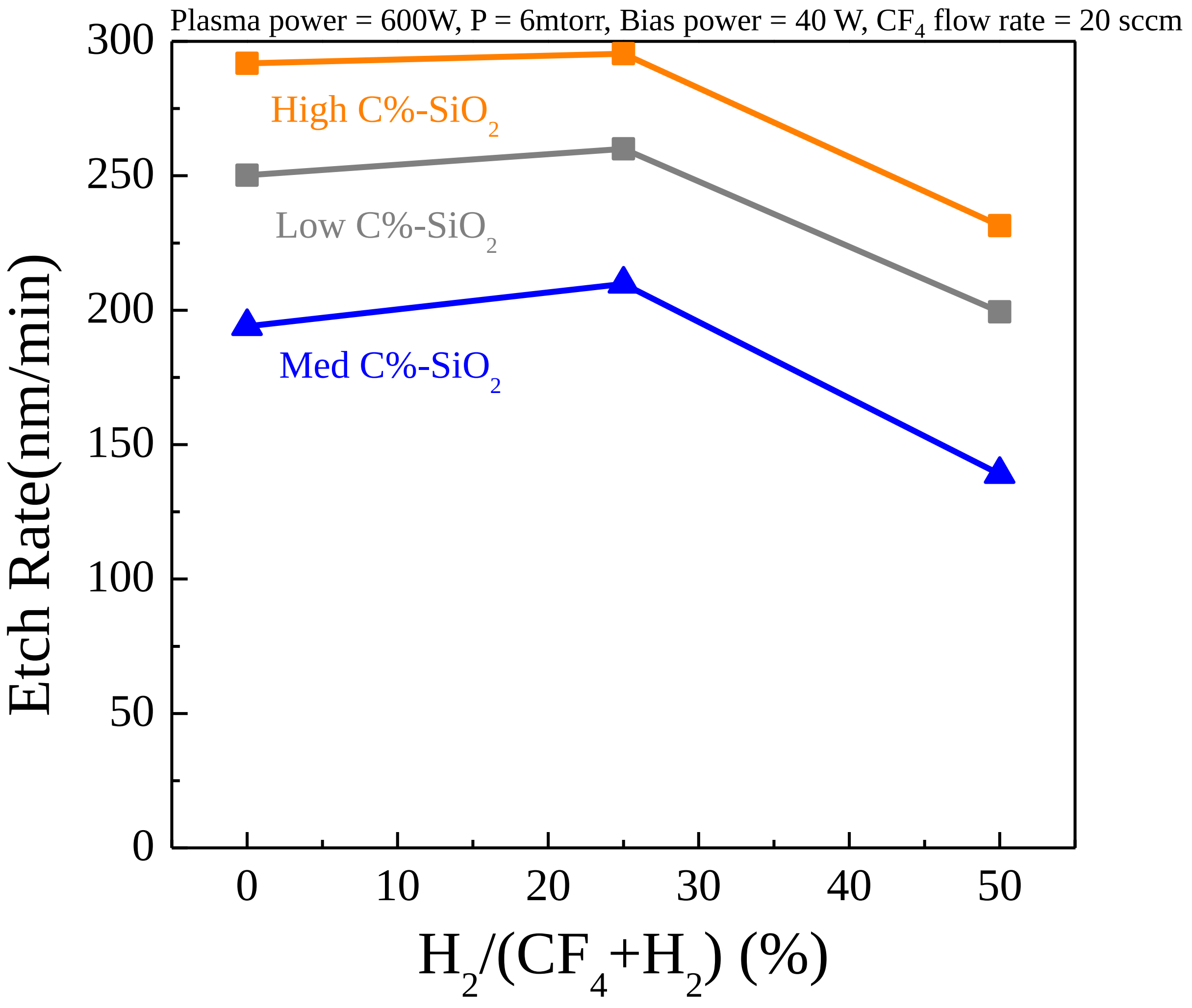


- **Surface characterization of deposition on medium carbon doped SiO_2 blanket films was performed using x-ray photoelectron spectroscopy (XPS)**

C%-SiO_2 Etched in CF_4 (STS etcher)

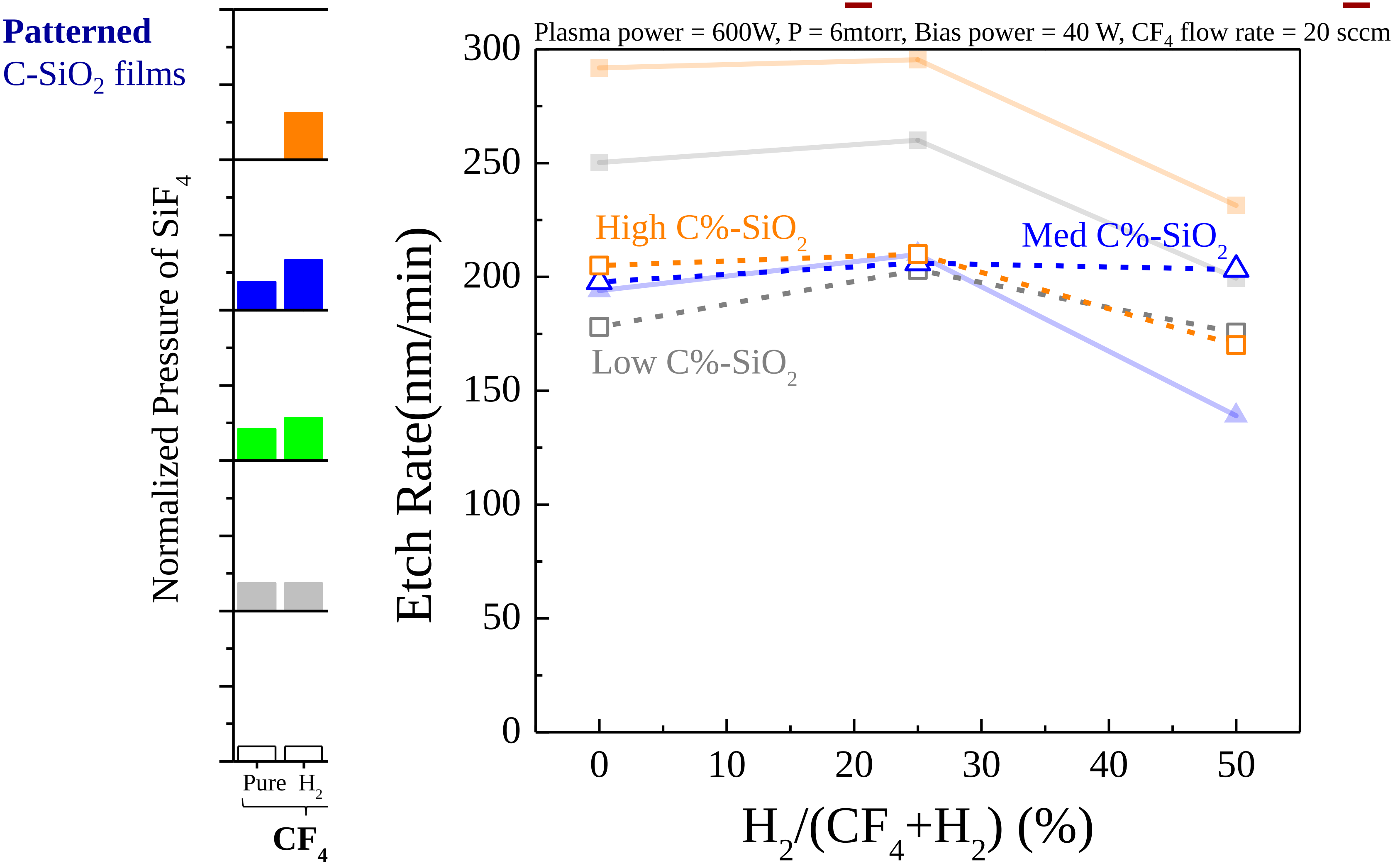
Blanket thick C-SiO_2 films




Plasma power = 600W, P = 6mtorr, Bias power = 40 W, CF_4 flow rate = 20 sccm

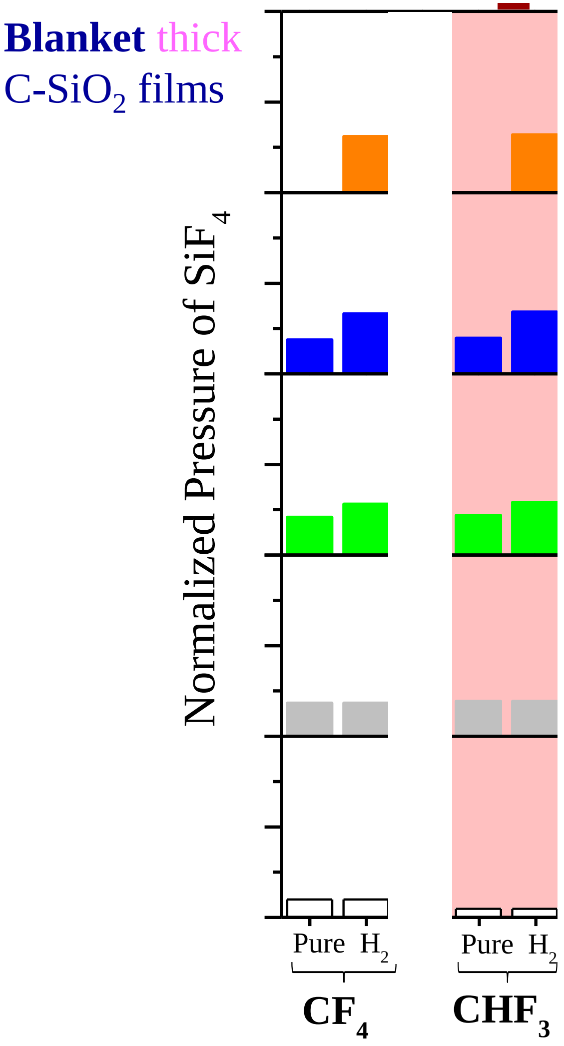
- **Plasma conditions were changed, and experiments performed in a separate etcher that could accommodate both CF_4 and CHF_3 with H_2**

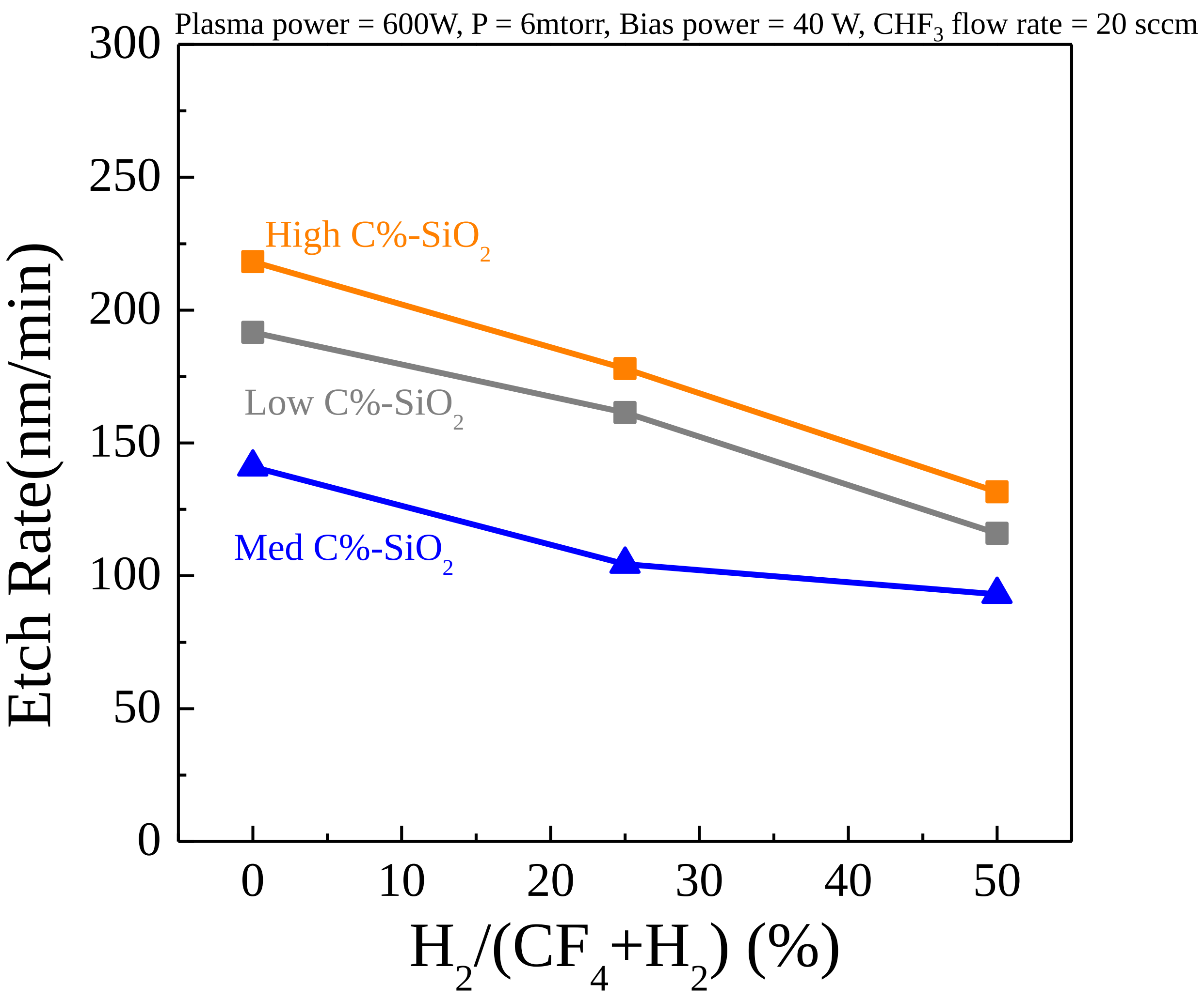
Patterned C%-SiO_2 Etched in CF_4



- **Both blank and patterned carbon doped films exhibit maximum etch rates upon addition of ~25% hydrogen**

C%-SiO_2 Etched in CHF_3 (STS etcher)

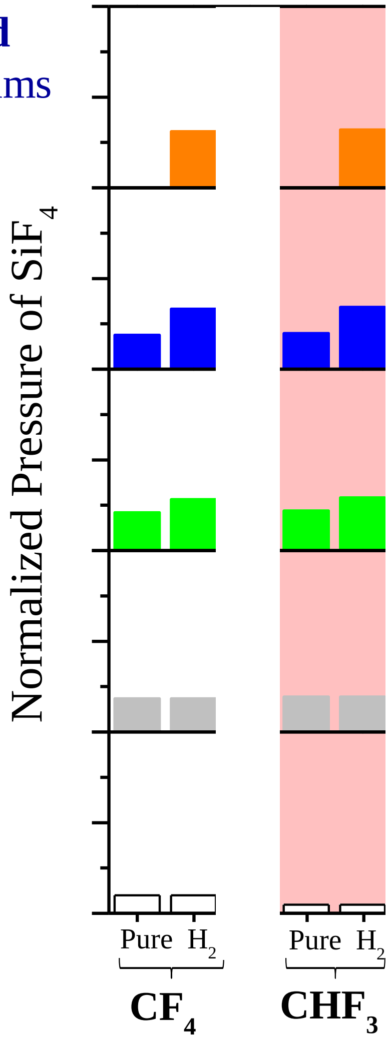


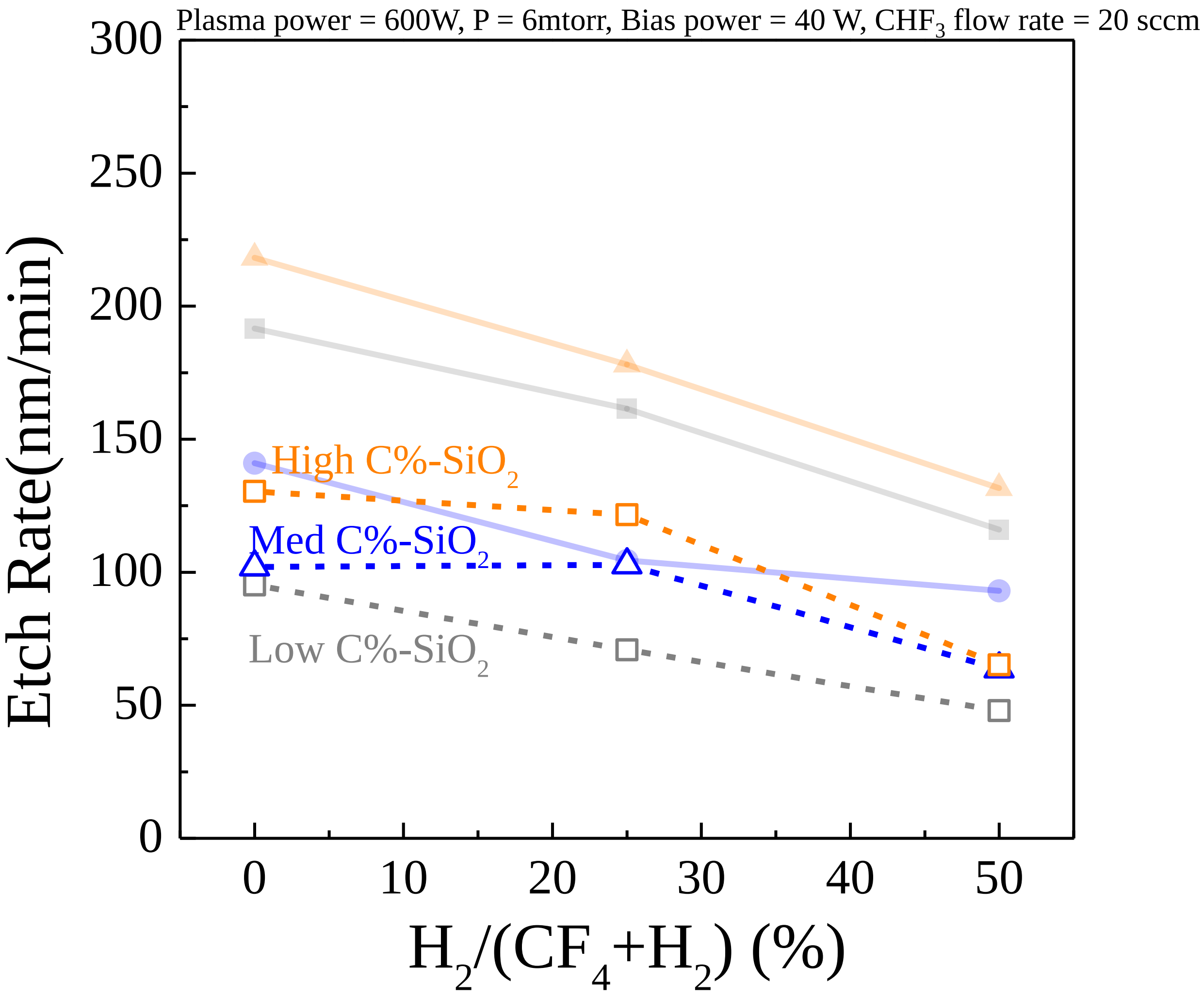


- **Addition of hydrogen to CHF_3 shows negative effect on etch rate of blank carbon doped film**

Patterned C%-SiO_2 Etched in CHF_3

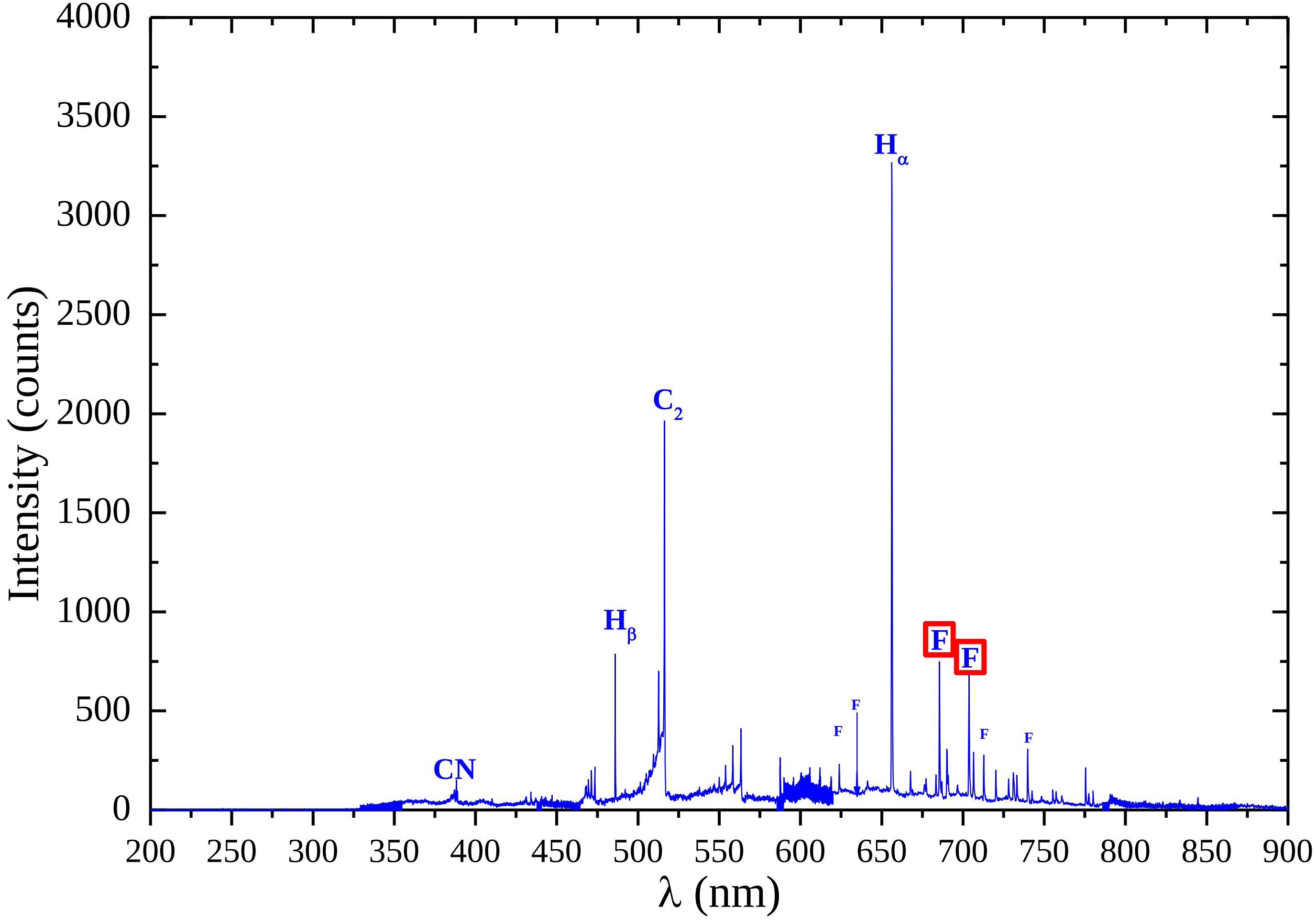
Patterned
C-SiO_2 films




Plasma power = 600W, P = 6mtorr, Bias power = 40 W, CHF_3 flow rate = 20 sccm

- **A similar effect is seen for etchant feed composition on patterned films**

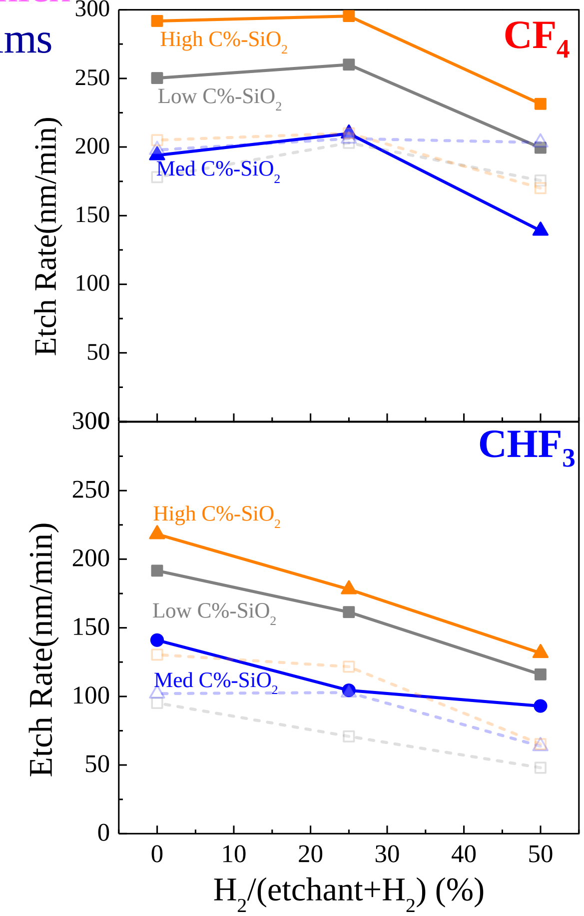
OES of CHF_3



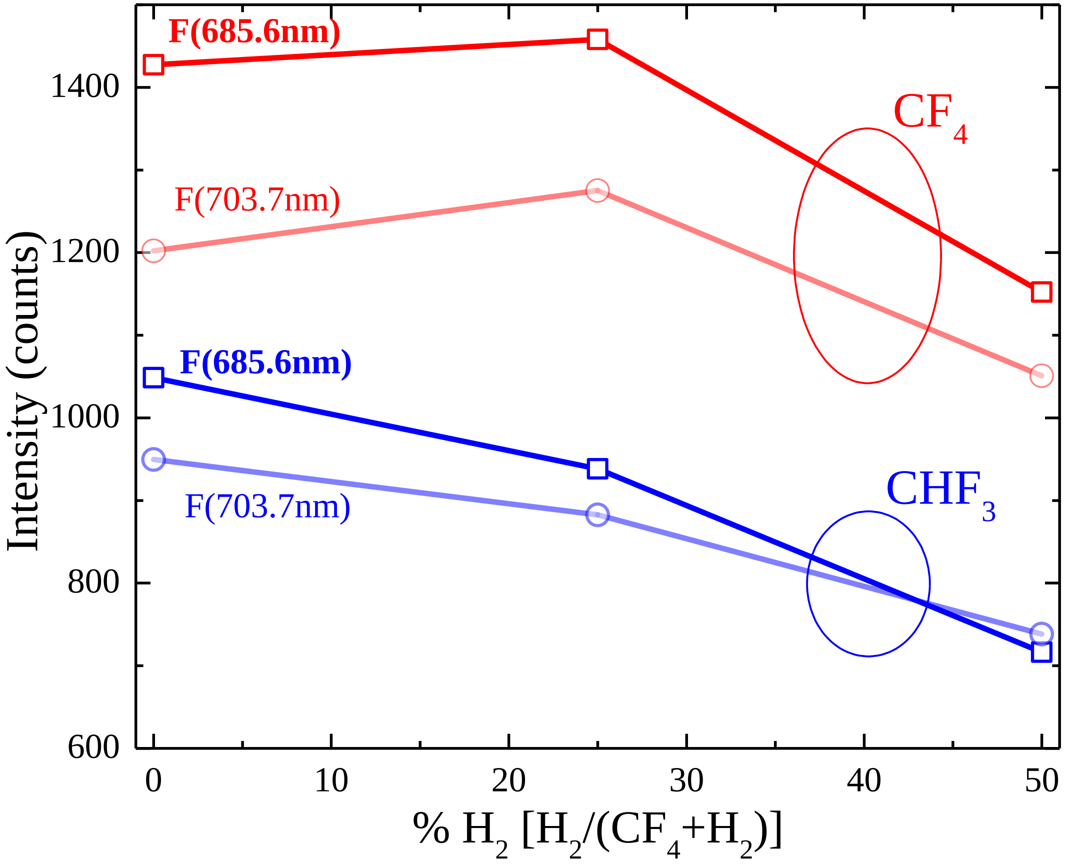
- **Optical emission spectroscopy (OES) measurements showing emission from atomic fluorine at 685.6nm and 703.7nm**

OES of CF_4/CHF_3

Blanket thick
$C\text{-}SiO_2$ films



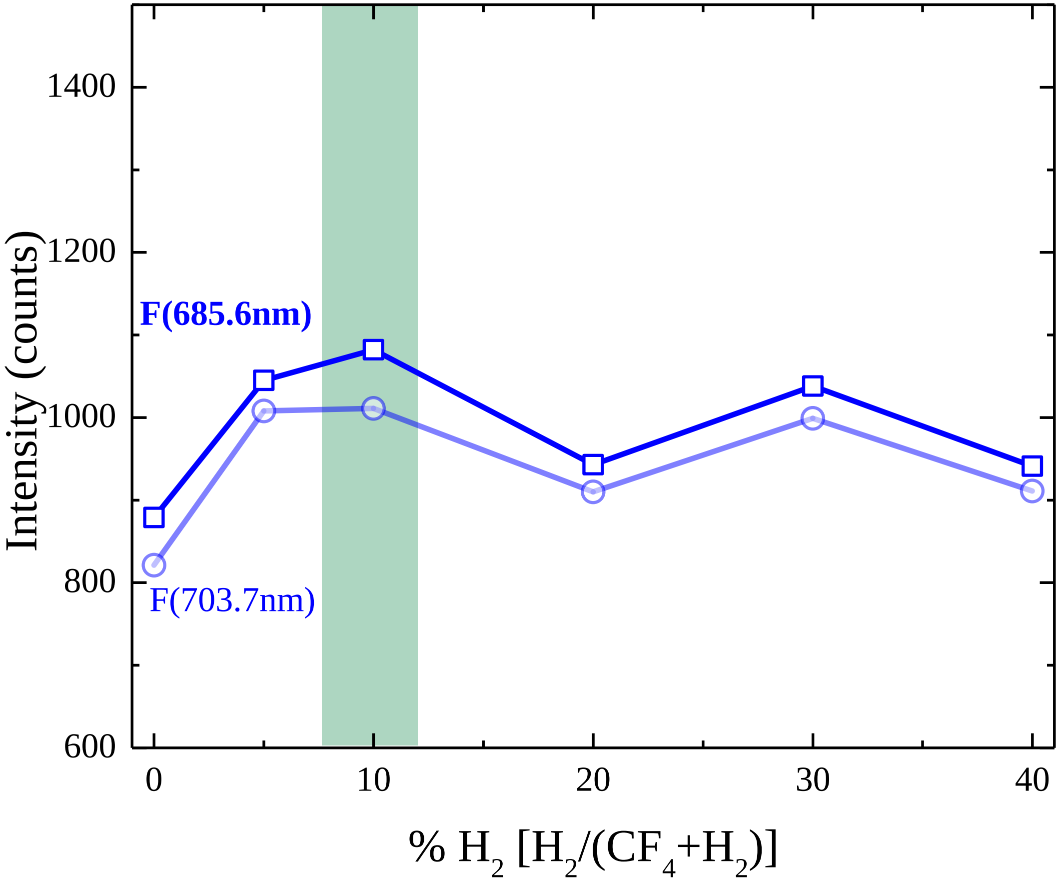
Intensity of F emission lines (685.6, 703.7 nm)



- **OES measurements confirm similar trend of F radical intensities with increasing H_2, correlating to changes in etch rate for blanket films**

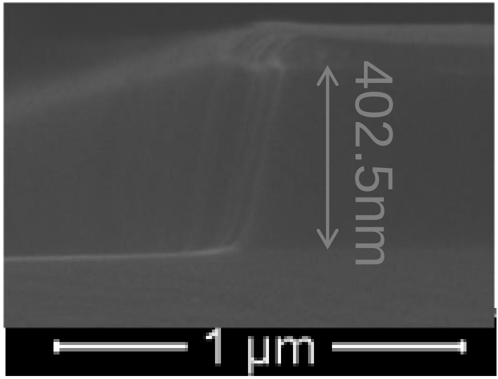
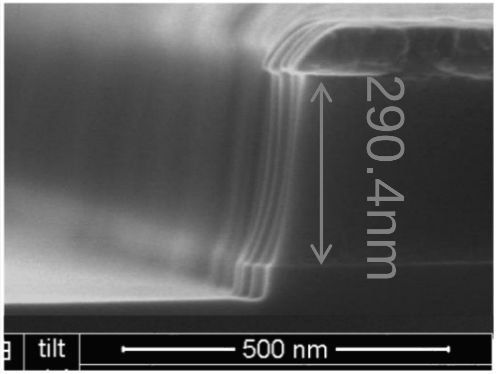
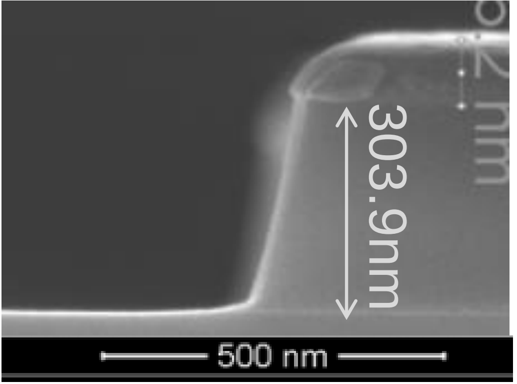
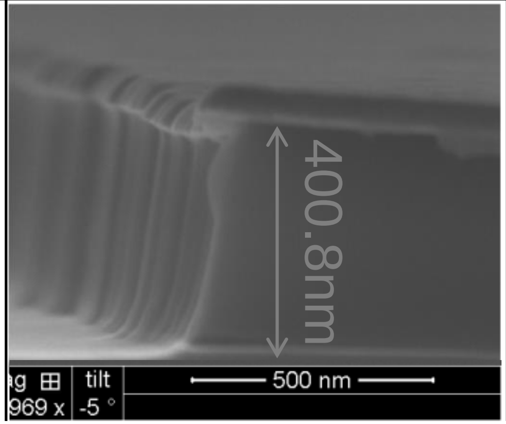
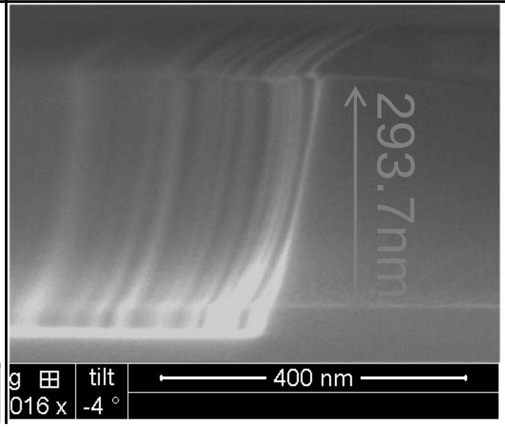
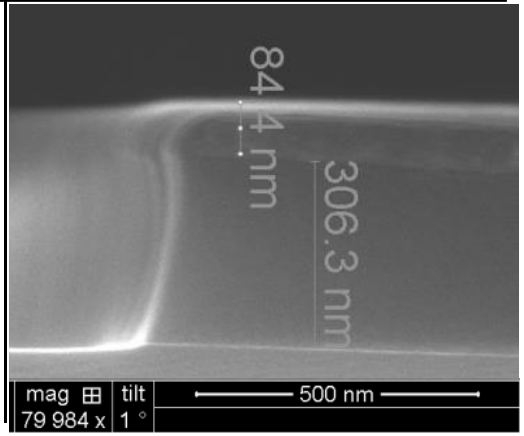
Optimized H_2 Amount in CHF_3

Intensity of F emission lines (685.6, 703.7 nm)



- **CHF_3 with smaller amounts of additive H_2 was probed with OES**
- **Future studies will focus on etch rate measurements to determine optimized F intensity in CHF_3 with H_2**

SEM of Etching Profile

	High C% doped SiO_2	Low C% doped SiO_2		Med. C% doped SiO_2
CF_4			CHF_3	
CF_4 / 20%H_2			CHF_3 / 20%H_2	

- **Carbon doped silica films can be patterned successfully using Ti hard mask and combination of different chemistries**

[5] NIST-JANAF Thermochemical (2013)

References

[1] Vasarla Nagendra Sekhar (2012). Mechanical Characterization of Black Diamond (Low-k) Structures for 3D Integrated Circuit and Packaging Applications, Nanoindentation in Materials Science, Dr. Jiri Nemecek (Ed.), ISBN: 978-953-51-0802-3, InTech, DOI: 10.5772/53198. Available from: http://www.intechopen.com/books/nanoindentation-in-materials-science/mechanical-characterization-of-black-diamond-low-k-structures-for-3d-integrated-circuit-and-packaging

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[3] PFC reduction/Climate partnership for the semiconductor industry, US EPA (U.S. Environmental Protection Agency), (2008) (http://www.epa.gov/semiconductor-pfc/basic.html).

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[5] NIST-JANAF Thermochemical Tables. http:// http://kinetics.nist.gov/janaf/ (accessed 2013).

[6] S. W. Benson and Norman Cohen, “Chapter 2, Current Status of Group Additivity” compiled by Karl K. Irikura and David J. Frurip, in “Computational Thermochemistry,” ACS Symposium series 677, (1988).

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[13] W. Tsai, J. Hazard. Mater., 2008.

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[17] B. Wu, “Thermodynamic study of photomask plasma etching”, *Proc. SPIE* 5567 (2004)

[18] B. Wu, “An investigation of Cr etch kinetics,” *Proc. SPIE 5256 (2003)*

Industrial Interactions and Technology Transfer

- **Conference call with Intel, June 12, 2014 (Satyarth Suri)**
- **Conference call with Intel, July 9, 2014 (Satyarth Suri)**
- **Conference call with Intel, August 14, 2014 (Satyarth Suri)**
- **Conference call with Intel, September 11, 2014 (Satyarth Suri)**
- **Conference call with Intel, October 30, 2014 (Satyarth Suri)**
- **Conference call with Intel, December 18, 2014 (Satyarth Suri)**
- **Conference call with Intel, February 19, 2015 (Satyarth Suri)**

Future Plans

Next Year Plans

- Establish point of contact with industrial sponsor to study etching efficacy of NF_3 and CF_3I not currently available in facilities (exploring possibility at IM Flash Technologies)
- Utilize optical emission measurements to determine etch rate correlation with atomic fluorine intensity

Long-Term Plans

- Formulate the models to predict etch product from plasma processes
- Suggest viable plasma chemistries
- Experimental validation and assessment of EHS impact

Publications, Presentations, and Recognitions/Awards

Presentation:

- **Contributed talk at AVS International Symposium, November 2014**
  (J.K. Chen, N. Altieri, M. Paine, and J.P. Chang, “Non-PFC Plasma Chemistries for Patterning Low-k Dielectric Materials”)

- **SRC ERC EHS TeleSeminar, March 5, 2015**

Publication:

- **“Thermodynamic assessment and experimental verification of reactive ion etching of magnetic metal elements”, June 2014**
- **“Viable chemical approach for patterning nanoscale magnetoresistive random access memory”, January 2015**
- **Deliverable Report, P065582, “Non-PFC Plasma Chemistries for Patterning Complex Materials/Structures”, January 2014**