Chamber Wall Effects on Polycrystalline-Si Reactive Ion Etching in Cl_2: A Multiple Real-Time Sensors Study

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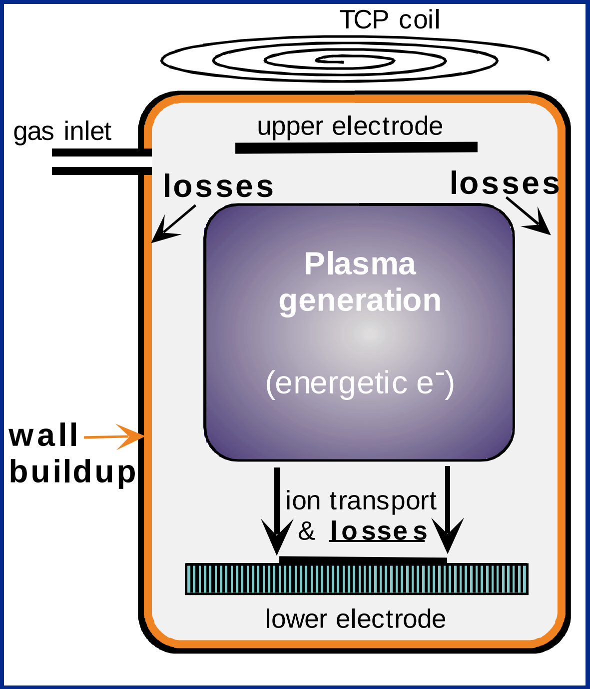
Outline

- Multi-sensor Study of Cl_2 Etching of Poly-Si in Lam 9400 TCP / Variations with F-cleans
  - OES/Actinometry for Cl
  - Broadband RF for Plasma Density
  - RTSE for Poly Si Etch Rate
- Wall Recombination Affects Both Neutral Species and Ion Concentrations
- Ion Density Measurement Control of Cl_2 etch of Si
- Interpretation of Actinometry Results Requires Careful Consideration of Gas Dilution Effects on Actinometer Concentration
- HBr-Cl_2 Mixtures

Motivation

- Chamber wall state as source of transient variations
- Loss rates at walls dependent on wall buildup
- Wall condition dynamically alters chemical and plasma densities
- Solutions for process drift: PMs, additional clean steps, test wafers



➔ *Control of plasma density will improve process tolerance limits & OEE!*

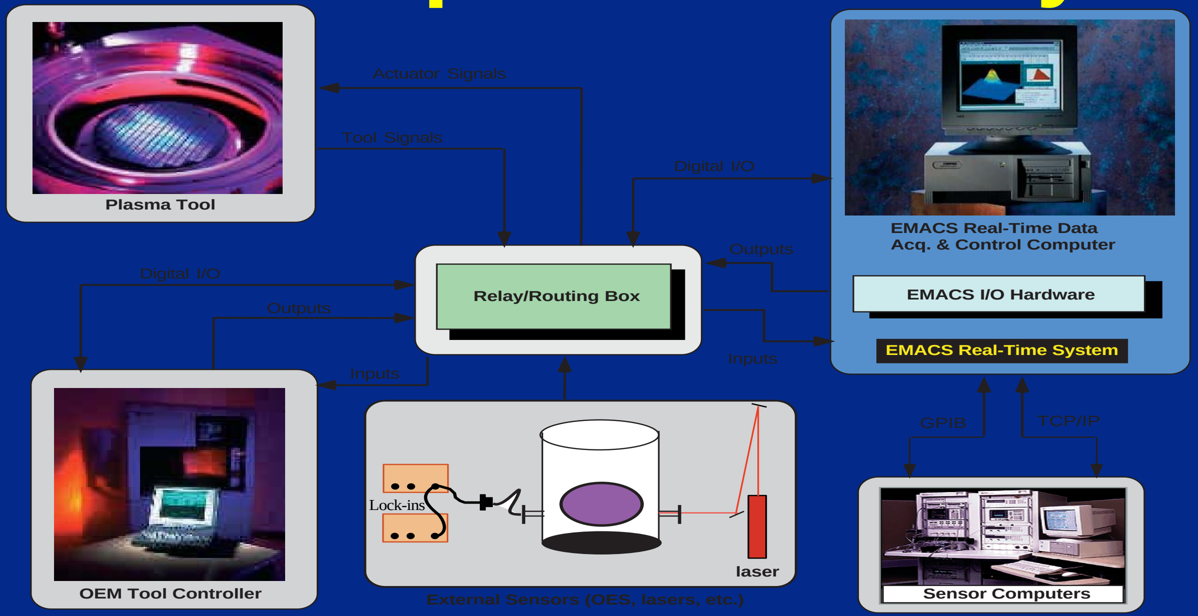
Previous Wall State Work

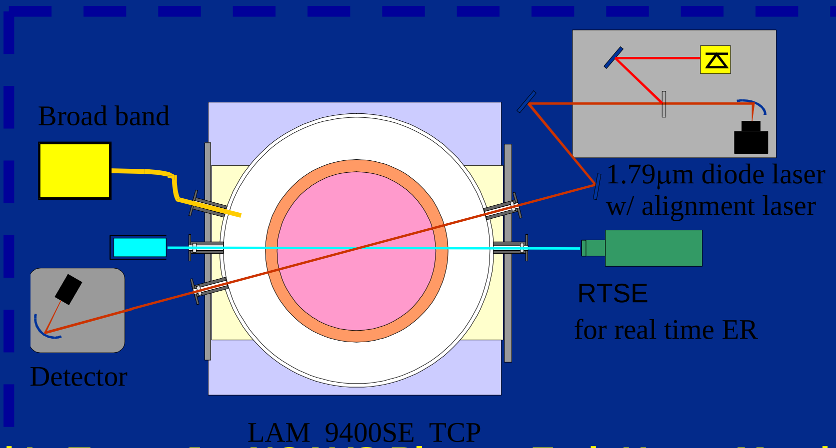
- **Sawin**: 1st reported Etch Rate changes in Cl_2 due to O_2 (↑) & CF_4 (↓) chamber exposure. (*JECS* 1992)
- **Donnelly**: Increasing Cl neutral conc. with time in a quartz tube helical resonator. (*JVSTA* 1996)
- **Aydil**: Atomic Cl drifts due to SiO_2 wall conditioning & SF_6 wall cleans. (*JVSTA* 2002)

This Work

- 1st experimental evidence of Cl_2 plasma density variation with F-cleans/wall prep.
- 1st direct correlation of real-time plasma density & real-time etch rate variations
- 1st direct real-time feedback control of plasma density to stabilize poly-Si etch rate in Cl_2
- Improved Understanding of Wall Effects and Actinometry Results

Time Stamped Sensor System





Real-Time Monitors

a) RTSE – wafer state

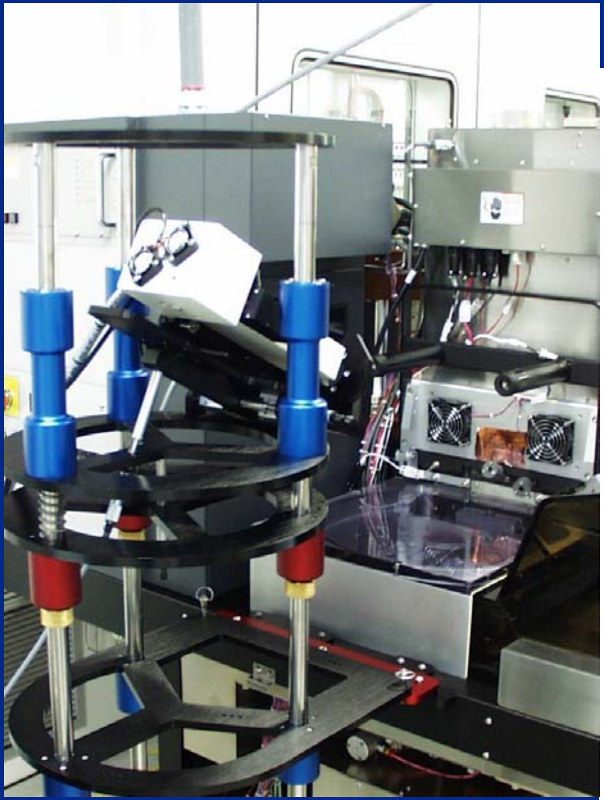
b) BroadBand RF – plasma state

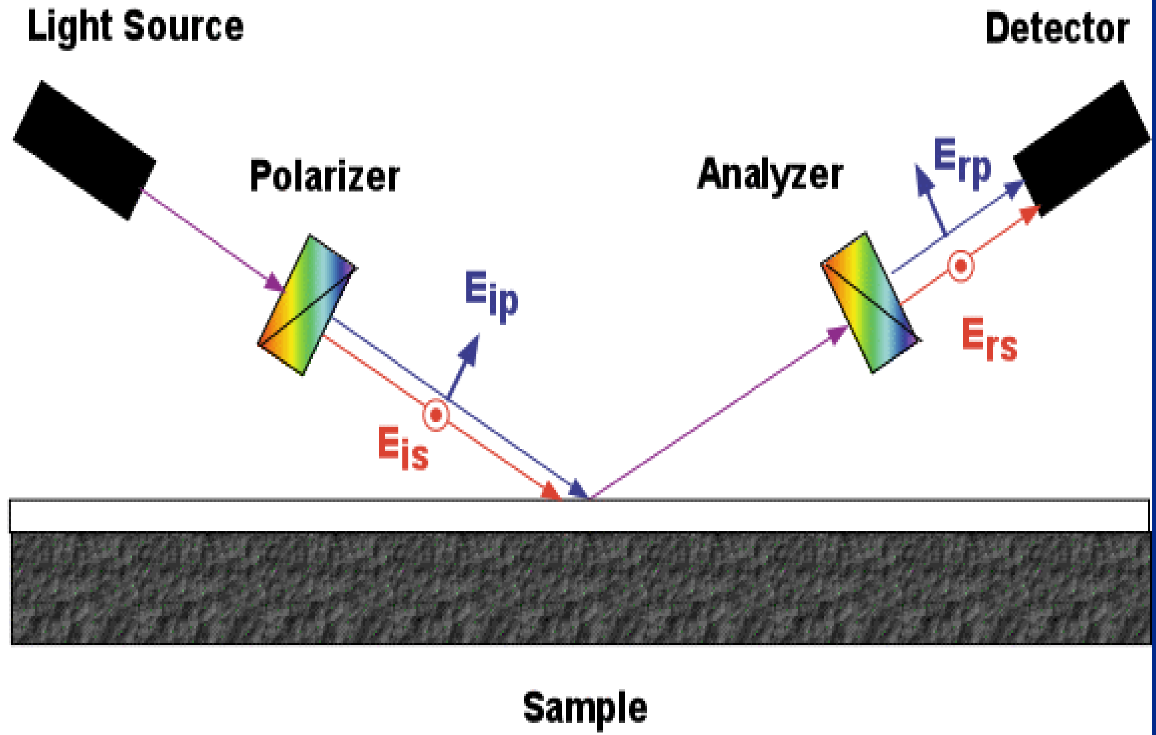
c) FTIR – exhaust chem; $SiCl_4$, SiF_4

d) Diode Laser Absorption – chem state

e) OES – [F], [Cl] intensity in chamber

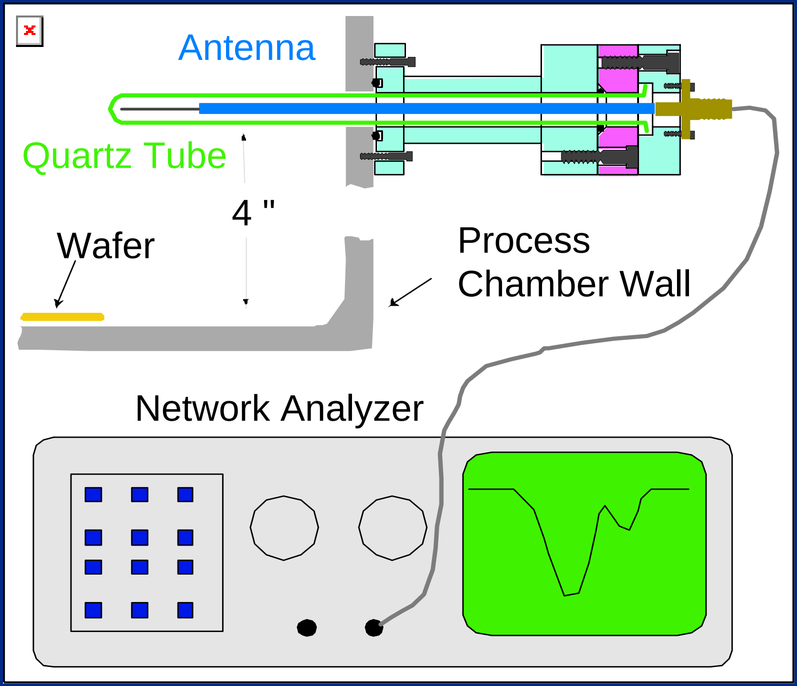
RTSE

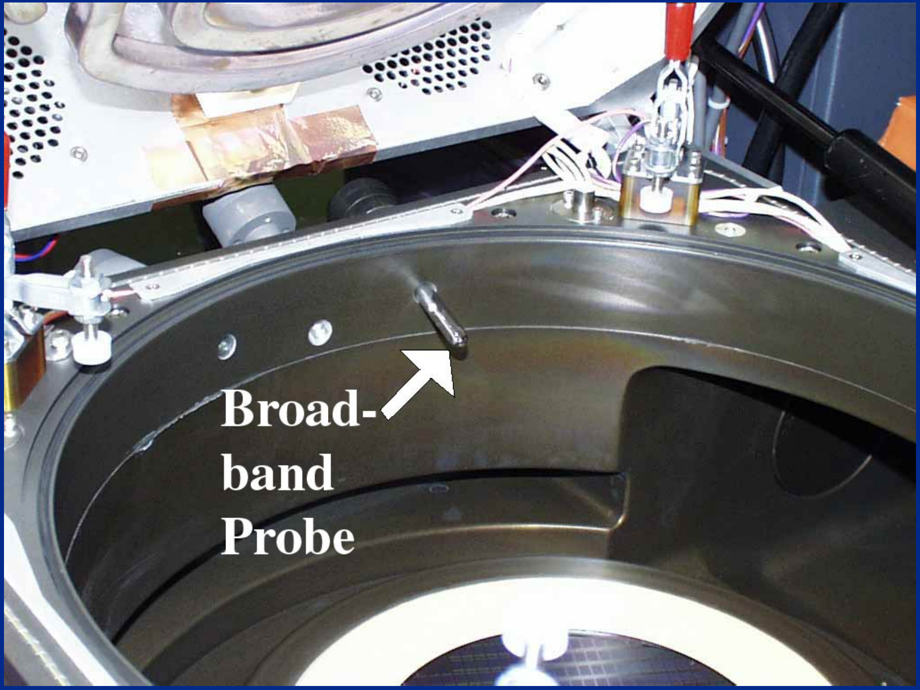




- **Real-Time Spectroscopic Ellipsometer (RTSE)**
  - **Can optically model film etch depth, CD, sidewall slope**
  - **Use for real-time etch rate monitoring & transients**

BroadBand RF

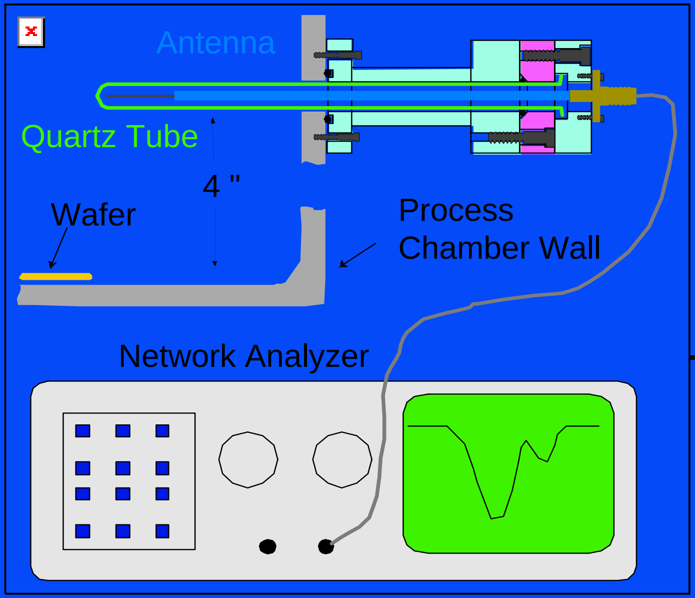


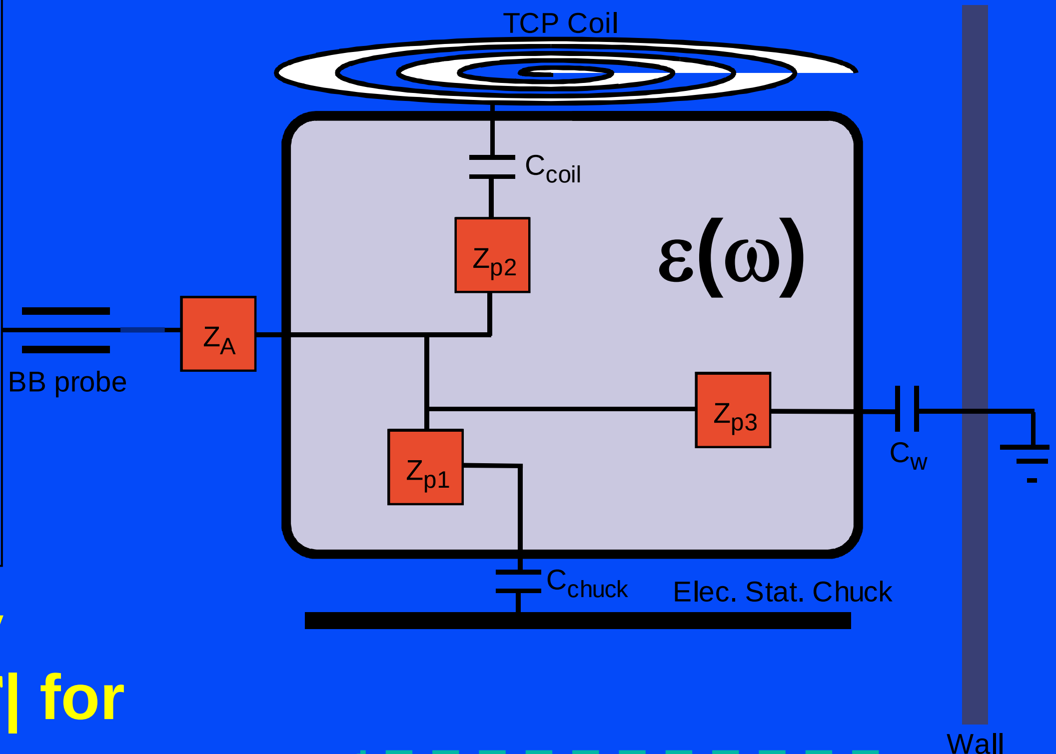


Remarks

- High frequency (GHz), low power (mW) sweep of plasma
- Plasma impedance spectroscopy
- Must analyze broad spectrum of data (Broadband RF Probe)
- Yields plasma density metric

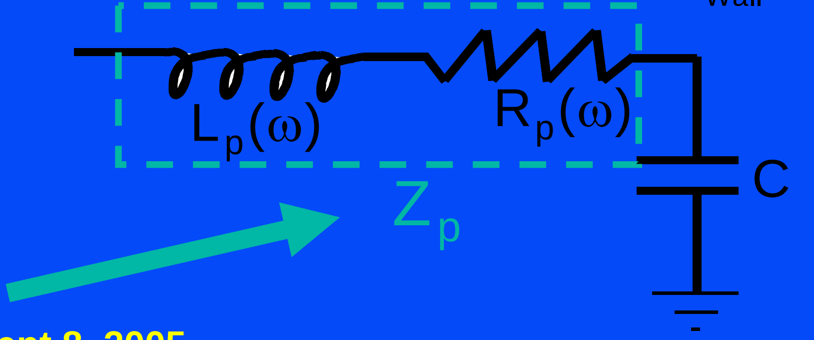
BroadBand RF Circuit Analogy



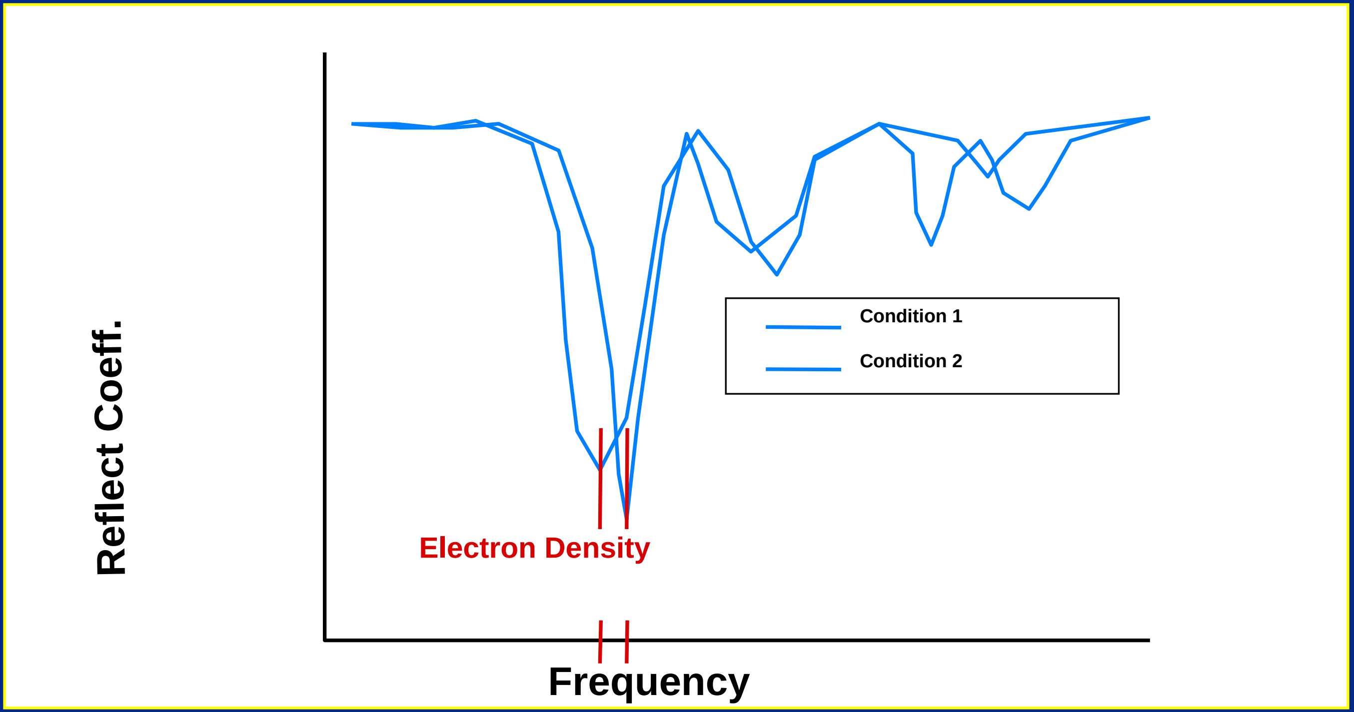


- **Loss paths give many resonance peaks in |Γ| for single ω_p**
- **Model peaks as RLC circuit resonances w/**

$$\omega_{ni} = \frac{1}{\sqrt{LC}}$$

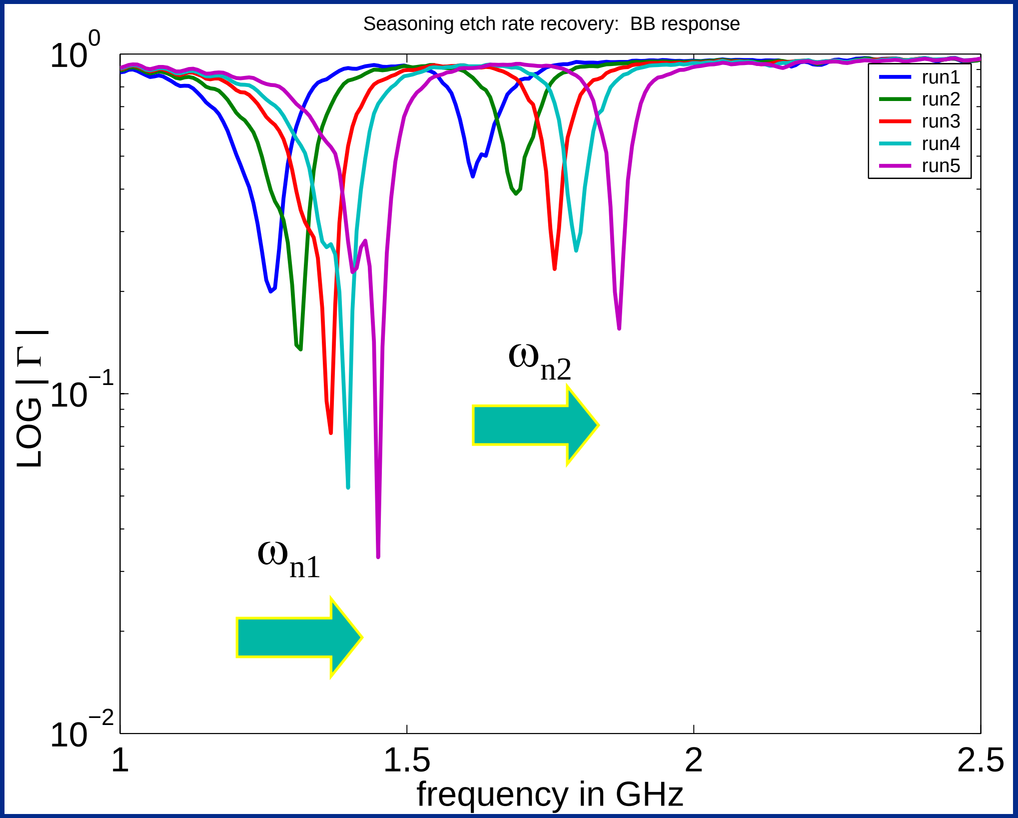


BroadBand Signature



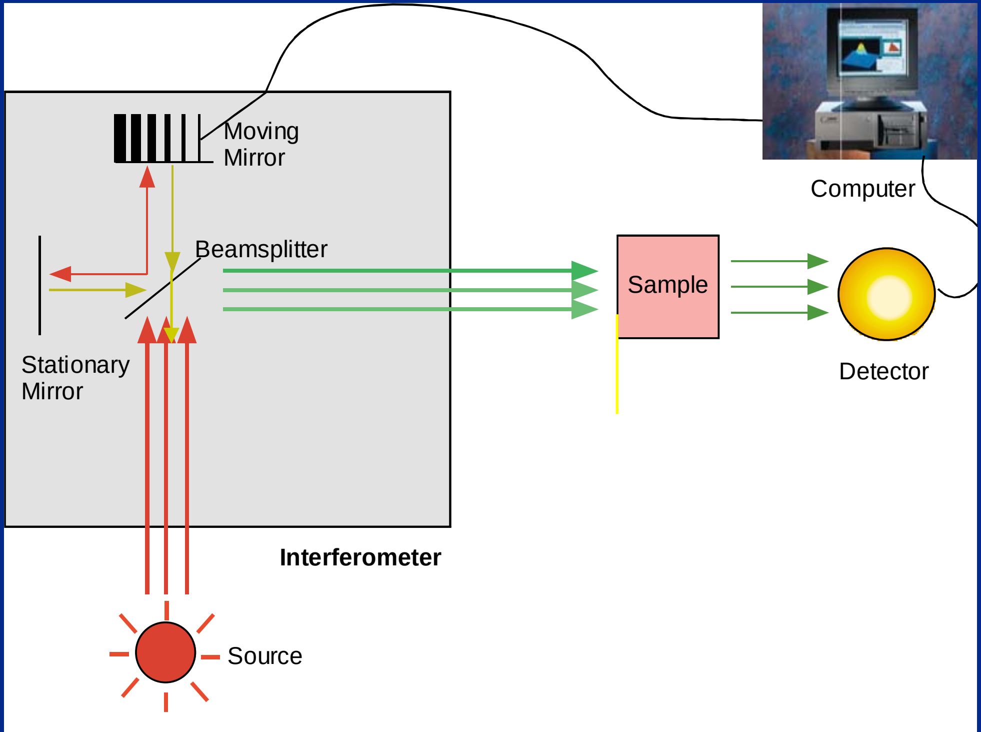
- Signal sensitive to several important plasma outputs
  - **Plasma density**
  - **Delivered plasma power**
  - **Chamber wall state**
  - **Wafer surface chemistry**

BB Peak Shifts & Density



- Two prominent resonance modes, ω_{n1} & ω_{n2}, for these chamber conditions
- Peak frequencies shift right for increasing density

FTIR Effluent Measurements



- Fourier Transform InfraRed (FTIR) spectroscopy measures volatile etch products in foreline exhaust
- Yields dynamic chemical state changes in $SiCl_4$ & SiF_4
- Used commercial INDUCT^{tm} FTIR from On-line Tech.

Etch Conditions

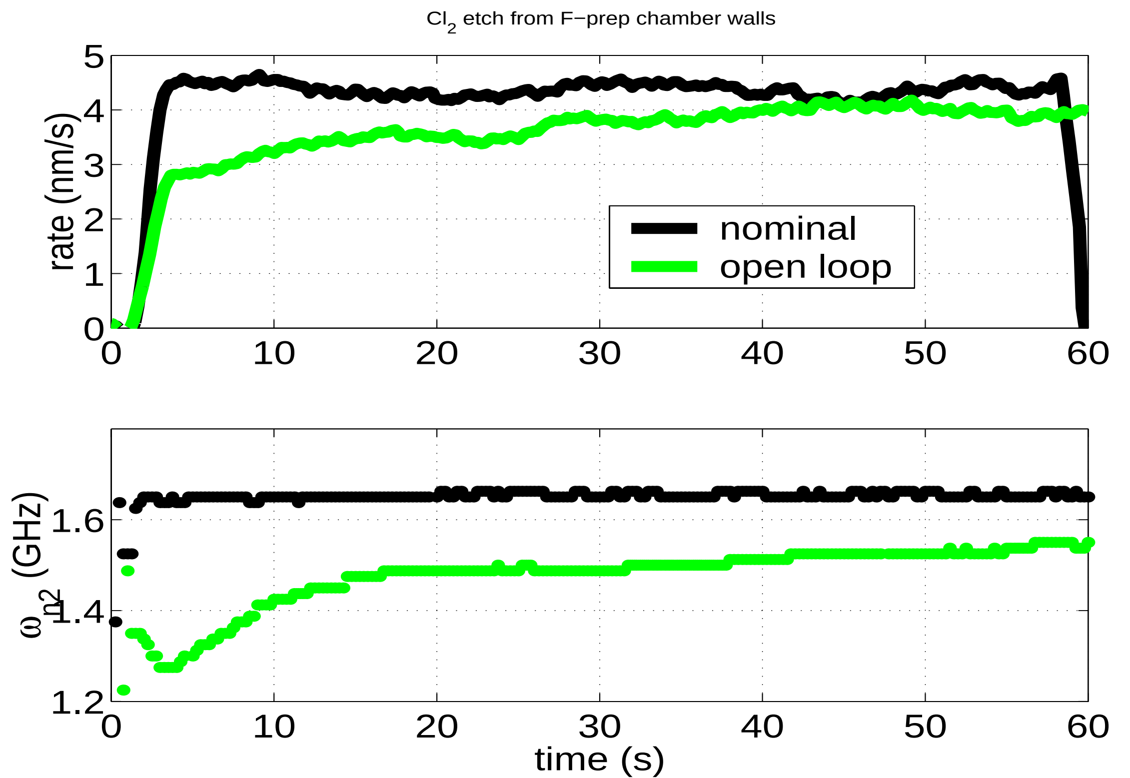
- Lam 9400 TCP SE
- 10 mTorr
- 100 sccm Cl_2 flow
  - 100 sccm total etch gas flow for Cl_2/HBr experiments
- 5 sccm Ar flow
- 250 W TCP Power
  - Varied for Plasma Density Control (Closed Loop) Runs
- 100 W Bias Power
  - Bias Voltage Measurement Not Available
- Unpatterned 150 mm Poly-Si/30nm SiO_2/Si Test Wafers

Experimental Definition 1

- First project; 3 experiments
- **Compensate for ion density losses due to F-cleaning of chamber walls**

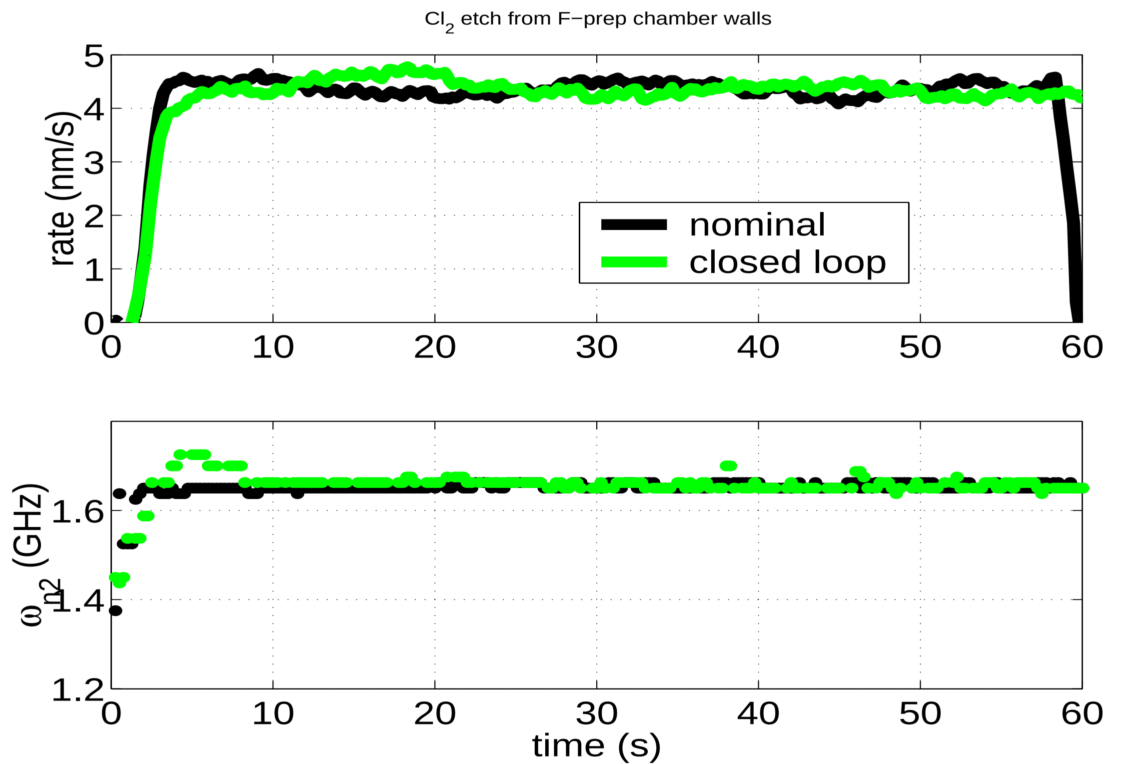
1) **Nominal Etch: Run plasma chamber at steady state chlorine condition to establish real-time etch rate, BB peak position, and $SiCl_4$ effluent level**
2) **Open loop recovery: Prep chamber walls using C_2F_6 clean to strip Silicon Oxychloride buildup, then run identical Cl_2 recipe.**
3) **Closed loop compensation: Run identically as uncontrolled open loop etch, only now use TCP power to maintain BroadBand setpoint.**

(OL) Open Loop Drift Recovery



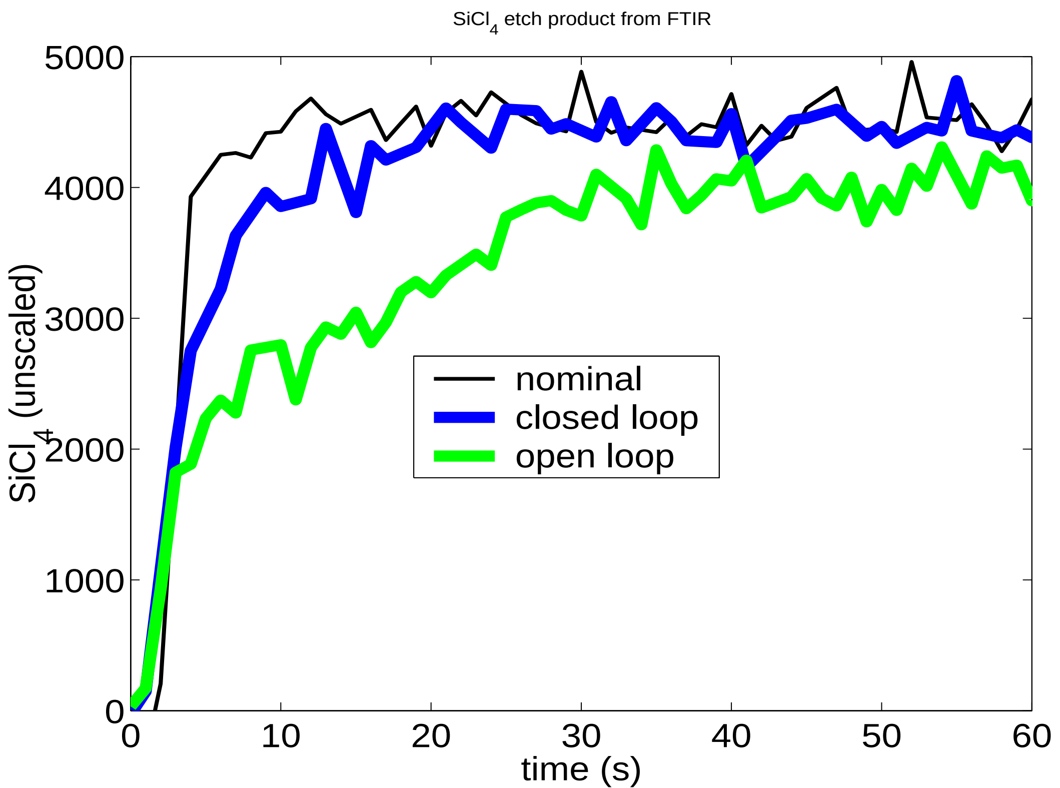
- **Nominal etch rate flat, OL rate increasing (upper plot)**
- **Nominal BroadBand ω_{n2} flat, OL ω_{n2} increasing (lower)**
- **OL signals do not recover in 60sec**

(CL) Closed Loop Recovery



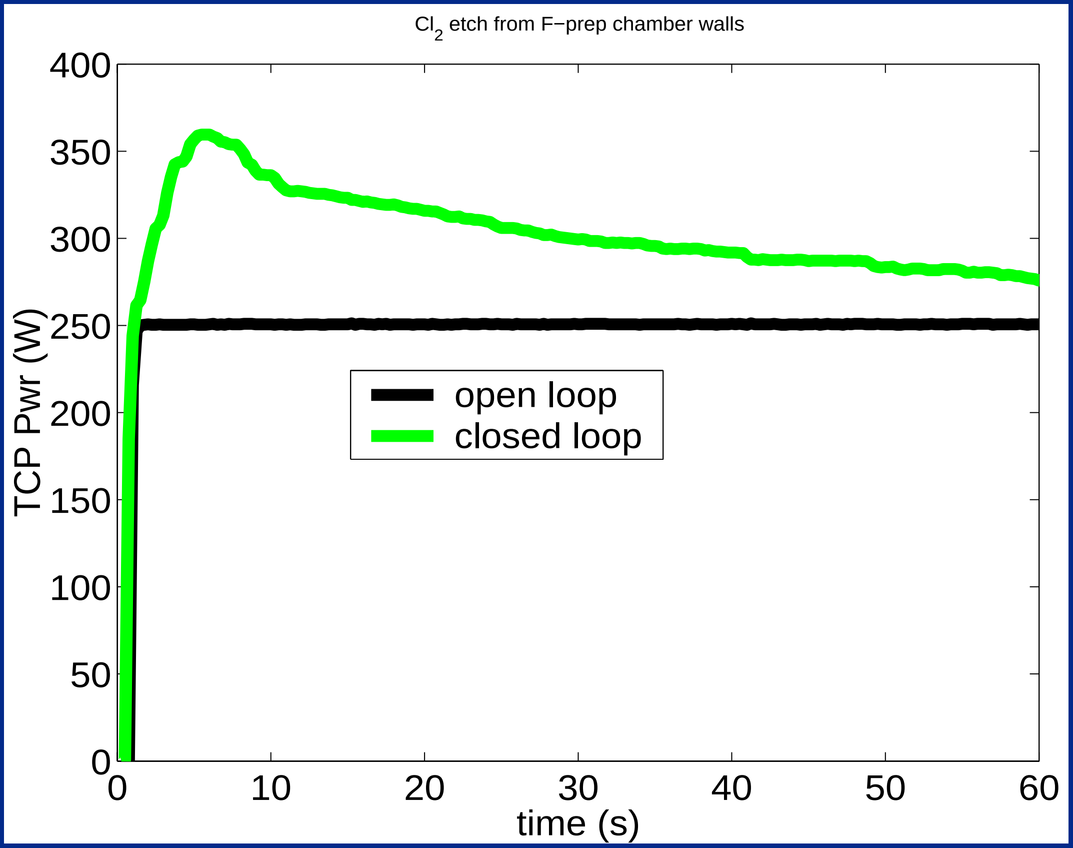
- Both nominal & CL etch rate flat (upper plot)
- Both nominal & CL BroadBand ω_{n2} flat (lower plot)
- CL signals recover in ~5sec

$SiCl_4$ Effluent from FTIR



- Nominal $SiCl_4$ is flat with no disturbance (black)
- OL $SiCl_4$ effluent is suppressed = lower ER (green)
- CL $SiCl_4$ is mostly compensated by controller (blue)

TCP Power OL vs. CL



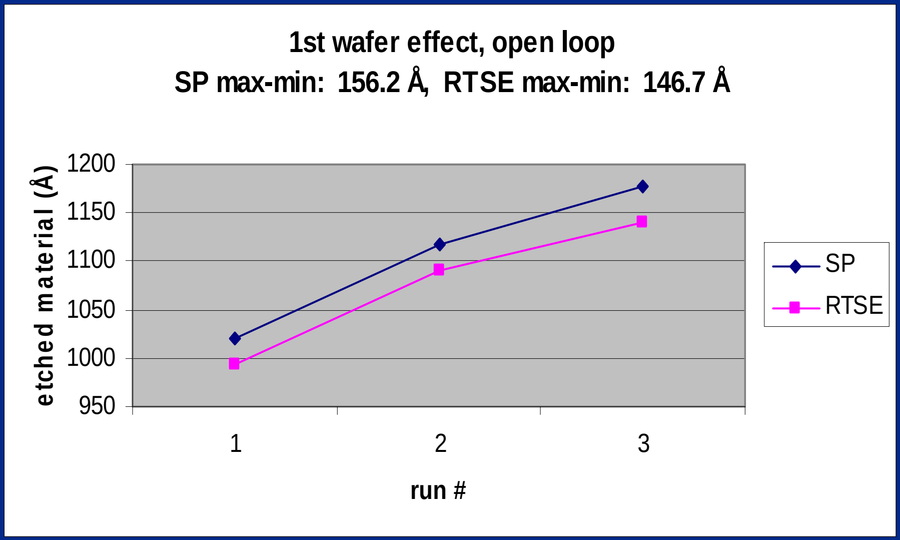
- **TCP power compensation in CL is very high at the start to make up for lost Cl^+ ions to the walls**

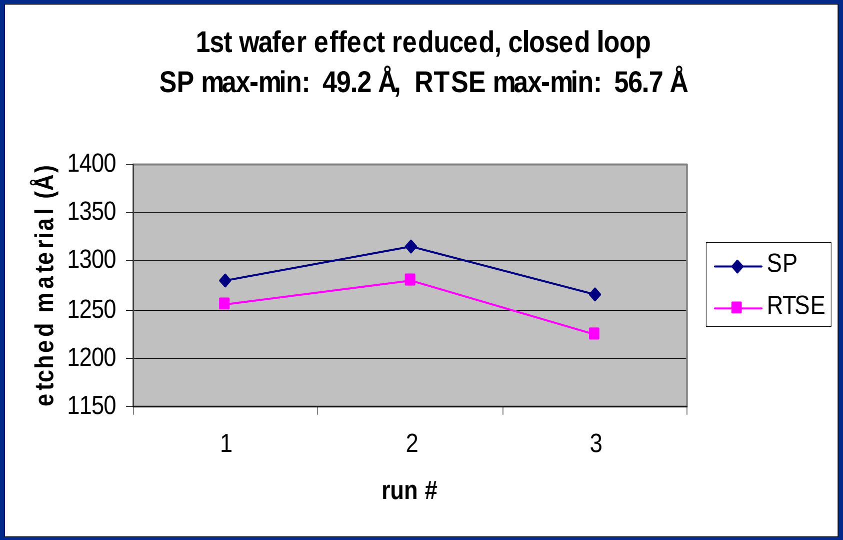
Experimental Definition 2

- Second project; 2 experiments, OL vs. CL
- **1st wafer effect elimination with plasma density compensation**
  - **Prep chamber walls using C_2F_6 clean**
  - **Follow with 3 open loop etches for 30s each in Cl_2 and measure etch depth**
  - **Prep chamber with C_2F_6 clean again**
  - **Follow with 3 closed loop etches for 30s each and compare etch depth variation with that in OL case**

1st Wafer Effect Reduction

Three 30s Cl_2 etches after single F-prep of chamber

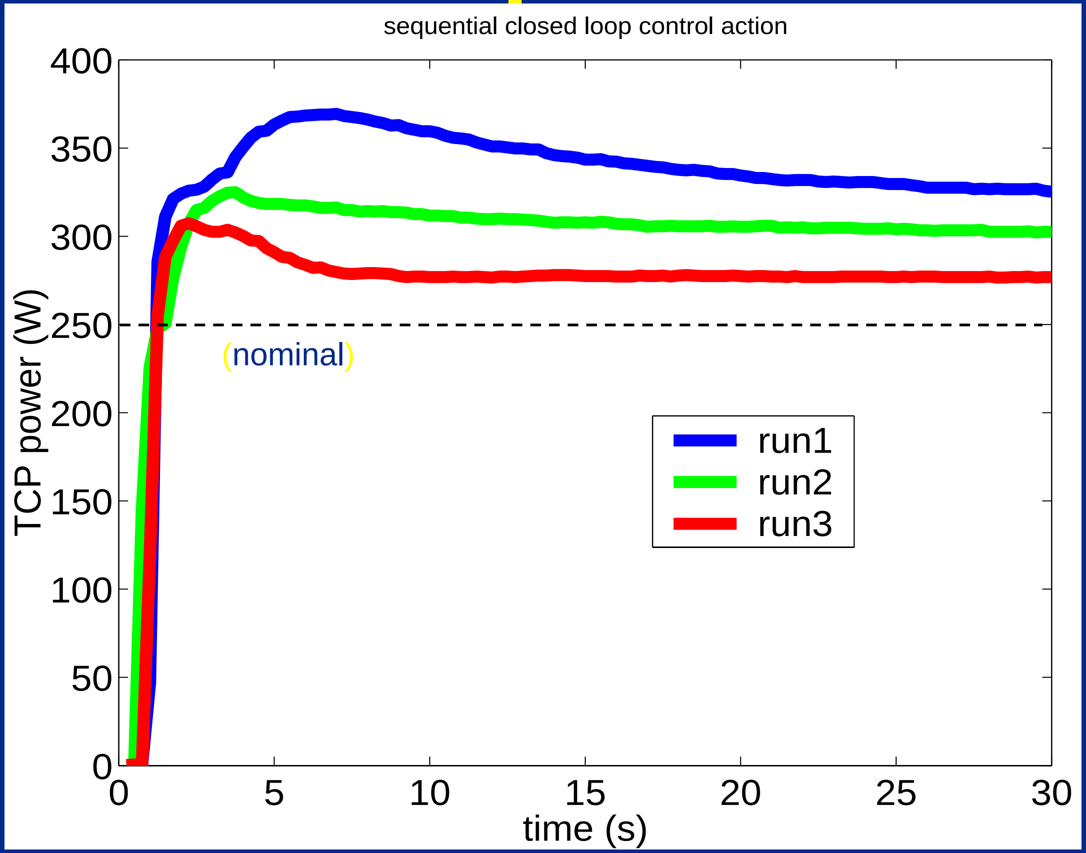




- **Open loop etch depth**
- **Etch rate increases, both *in situ* (RTSE) & *ex situ* (Reflectometer)**
- **Etch depth variation ~150Å**

- Closed loop etch depth with density correction
- Etch depth variation reduced to ~50Å

TCP Compensation R2R



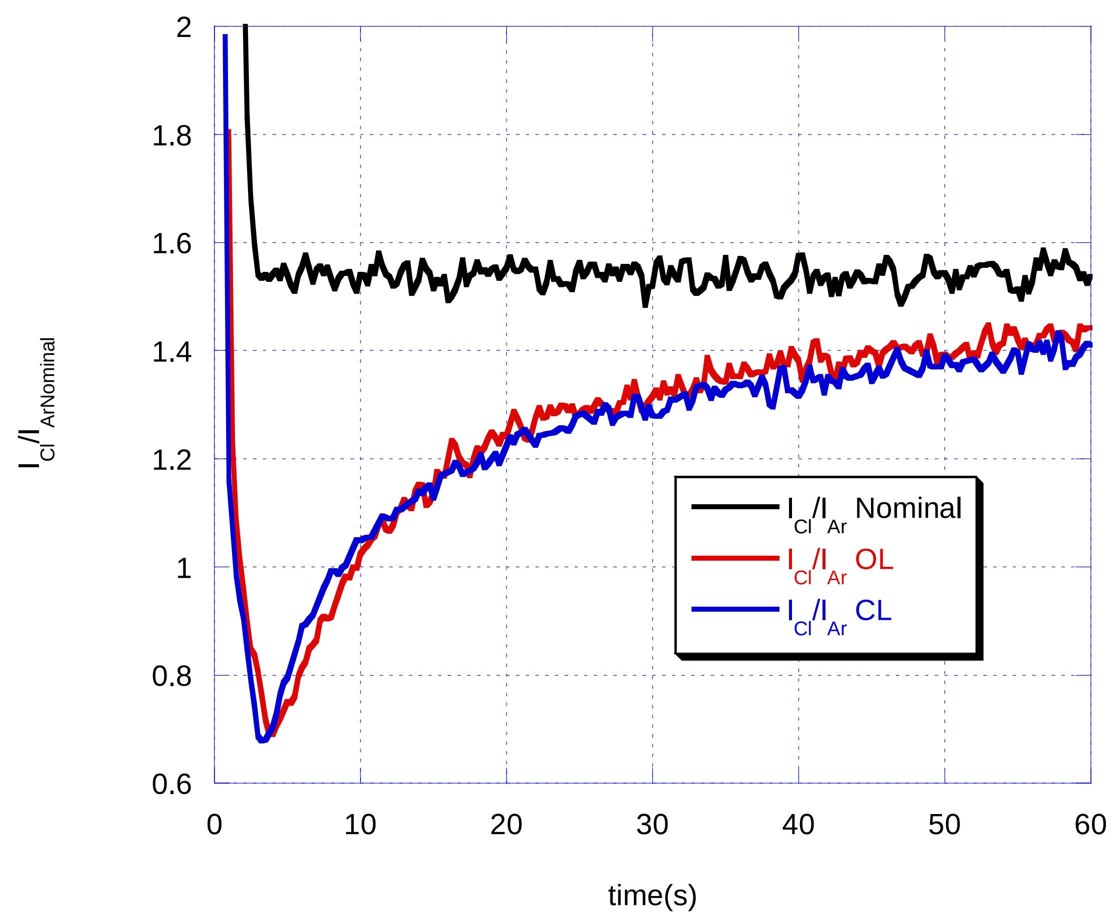
- **Closed loop TCP power compensation reduces with each successive run as chamber begins to season**

Summary

- 1^{st} evidence of real-time Poly-Si etch rate variation in Cl_2 due to F-exposure.
- 1^{st} demonstration of ion density control in Cl_2 to compensate for Poly-Si real-time etch rate transients.
- Effluent $SiCl_4$ chemistry verifies both real-time performance drifts and feedback correction.
- Significant 1^{st} wafer effect reduction after chamber cleans with density feedback control.
- Question: How Do We Explain the Results of Earlier Researchers?
  - Actinometry Results & Interpretations
  - *Key Point Is That Even For Qualitative Conclusions, Actinometry/OES Results Must Be Carefully Analyzed Considering All Gasses Present In Chamber*

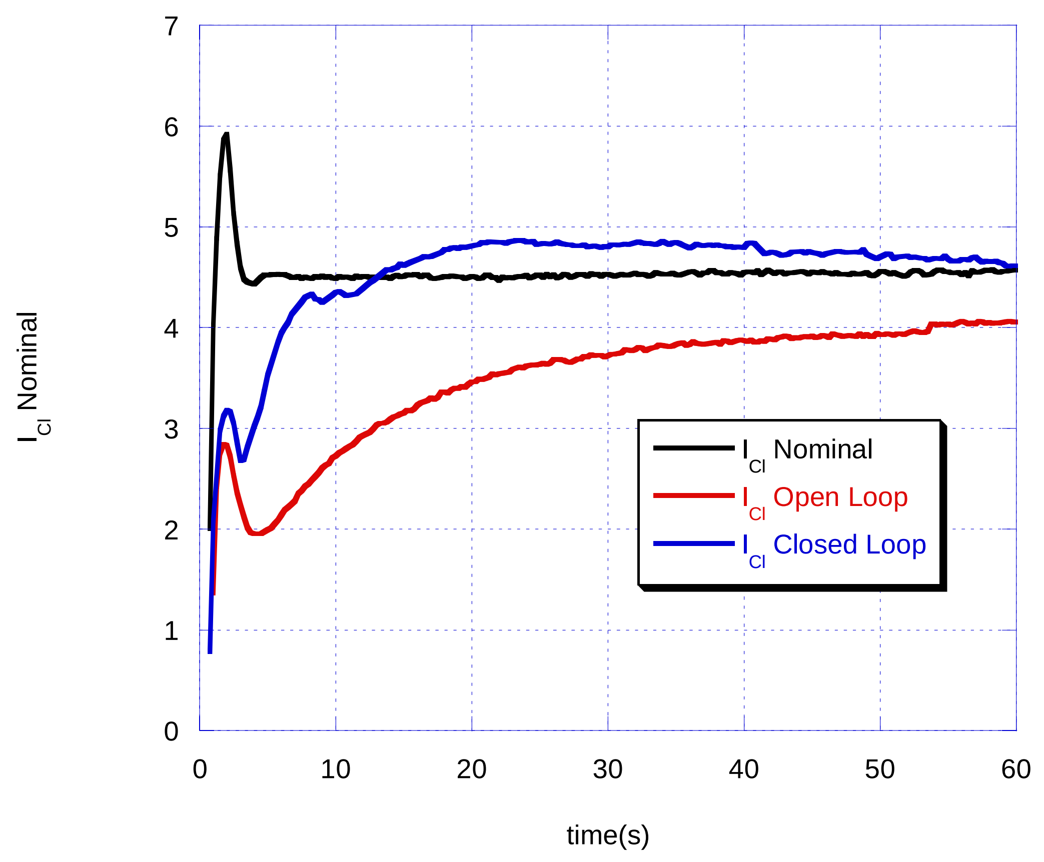
Intensity Ratio I_{Cl}/I_{Ar}

λ_{Ar}: 750.4nm
λ_{Cl}: 822.2nm



- After F-disturbance, both controlled & uncontrolled cases show similar Cl-neutral suppression and recovery.
- Simple Conclusion is that Ions (not neutrals) control etch rate for this process.

Cl Intensity



- **Cl Intensity is Flat in Nominal/Seasoned-wall case & varies in Open Loop and Closed Loop Cases**

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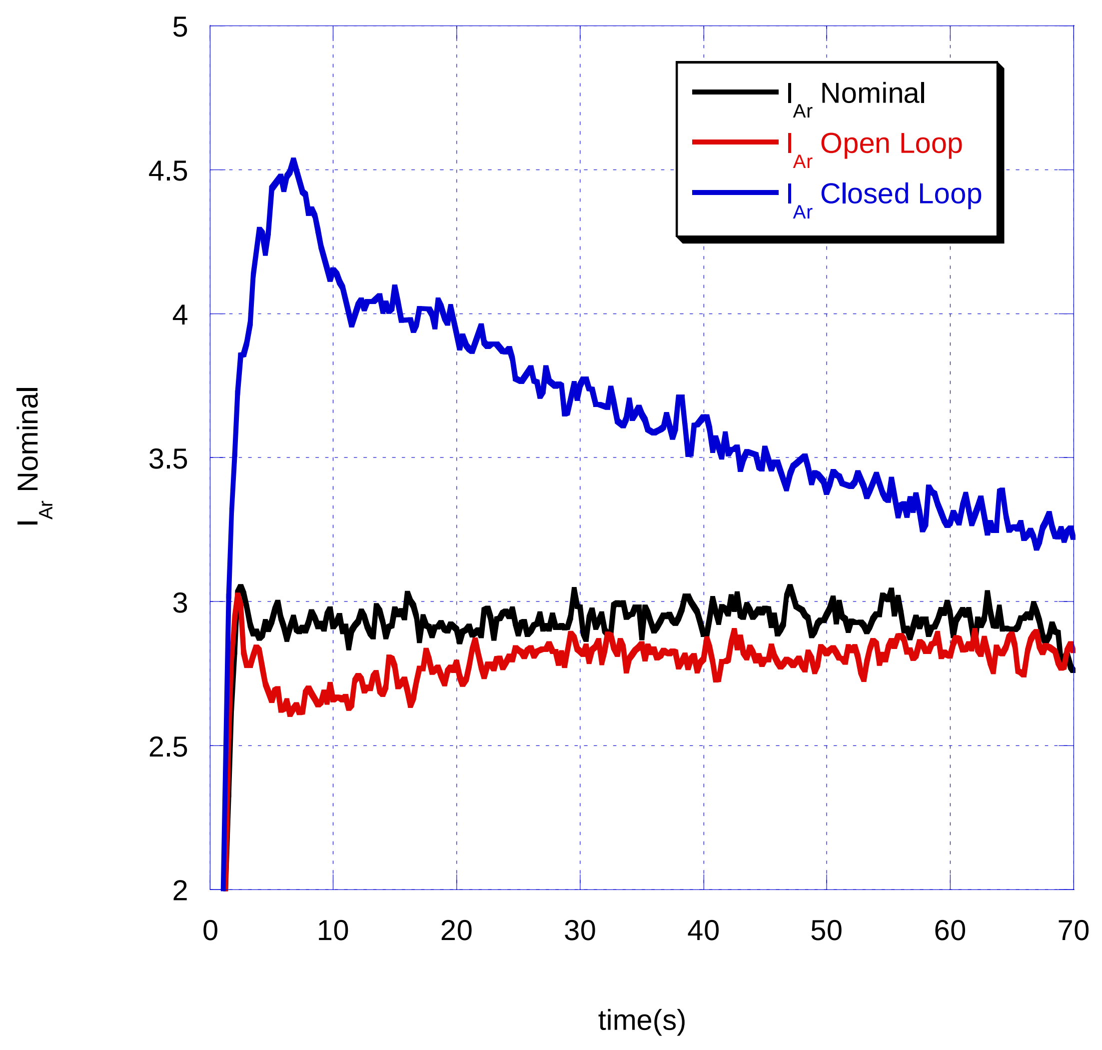
Ar Intensity



- Intensity of Ar Being Nearly Flat Was Previously Taken By Some Researchers To Show that the Plasma Density Was Constant
- This led to the conclusion that neutral Cl loss was responsible for Si etch rate variations
- We have shown that neither of these conclusions can be correct

OES Setup Equations

d = Cl_2 dissociation fraction

f_{Ar} = mole fraction of Ar in feed gas (5%)

- **Mass balance:** $Cl_2 \rightarrow 2dCl + (1-d)Cl_2$
- **Raw optical intensity signals:**

$(n_e \propto \omega_n^2)$

$$\boxed{\begin{aligned} I_{Ar} &= K_{Ar}(T_e)\omega_n^2 n_{Ar} \\ I_{Cl} &= K_{Cl}(T_e)\omega_n^2 n_{Cl} \end{aligned}}$$

coupled simply by d, f_{Ar}

- **Intensity ratio:**

$$\left[\frac{I_{Cl}}{I_{Ar}}\right] = \left(\frac{K_{Cl}}{K_{Ar}}\right)2d\left(\frac{1-f_{Ar}}{f_{Ar}}\right)\underbrace{\cancel{\propto} n_{Cl}}_{if\ d\to 1}$$

$$= \left(\frac{1}{\alpha'_{Cl}}\right)2d\left(\frac{1-f_{Ar}}{f_{Ar}}\right)$$

Detailed Look at Dissociation Diluation Effect on Ar

$$\underbrace{Cl_2}_{\text{input gas mixture}} \rightarrow \underbrace{2dCl+\left(1-d\right)Cl_2}_{\text{gas composition in plasma}} \quad \text{Chlorine Dissociation}$$

Now including the Ar actinometer concentration

$$\underbrace{\left(f_{Ar}\right)Ar+\left(1-f_{Ar}\right)Cl_2}_{\text{input gas mixture}} \rightarrow \underbrace{\left(f_{Ar}\right)Ar+2d\left(1-f_{Ar}\right)Cl+\left(1-d\right)\left(1-f_{Ar}\right)Cl_2}_{\text{gas composition in plasma}}$$

The concentration of Ar is diluted by Cl_2 dissociation

So in the plasma, assuming all molecules, atoms, ions at the same temperature:

$$n_{Ar}=\left[\frac{f_{Ar}}{f_{Ar}+2d\left(1-f_{Ar}\right)+\left(1-d\right)\left(1-f_{Ar}\right)}\right]n_{tot}=\left[\frac{f_{Ar}}{1+d\left(1-f_{Ar}\right)}\right]n_{tot}$$

$$n_{Cl}=\left[\frac{2d\left(1-f_{Ar}\right)}{f_{Ar}+2d\left(1-f_{Ar}\right)+\left(1-d\right)\left(1-f_{Ar}\right)}\right]n_{tot}=\left[\frac{2d\left(1-f_{Ar}\right)}{1+d\left(1-f_{Ar}\right)}\right]n_{tot}$$

Thus

$$\frac{n_{Cl}}{n_{Ar}}=\left[\frac{2d\left(1-f_{Ar}\right)}{f_{Ar}}\right]=2d\left[\frac{\left(1-f_{Ar}\right)}{f_{Ar}}\right]$$

OES Fits

- Clean Chamber / High Recombination Case Yields Actinometry Data with Enough Structure to Extract α_{Cl}' & K_{Ar}' by Nonlinear Regression
- Dissociation Fractions for Other Runs Estimated by Assuming α_{Cl}' is the same as the Clean Chamber Result
  - Possible T_e variations Errors
  - Possible Window Variations

Fitting of OES Data

Fitting 2 constants allows quantitative extraction of d from OES data

$$I_{Ar} = K_{Ar}(T_e)\omega_n^2 n_{Ar} = K_1\omega_n^2\left[\frac{f_{Ar}}{1+d\left(1-f_{Ar}\right)}\right]n_{tot}$$

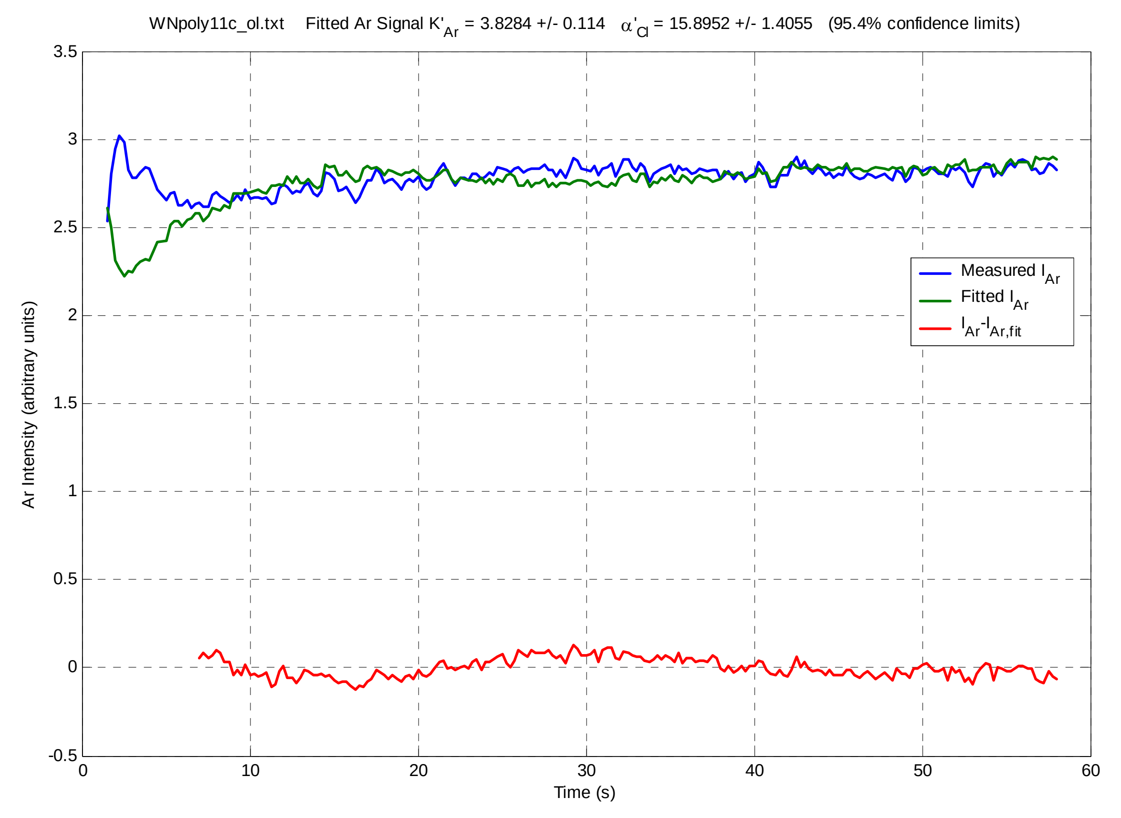
$$I_{Cl} = K_{Cl}(T_e)\omega_n^2 n_{Cl} = K_2\omega_n^2\left[\frac{2d\left(1-f_{Ar}\right)}{1+d\left(1-f_{Ar}\right)}\right]n_{tot}$$

$$\left[\frac{I_{Cl}}{I_{Ar}}\right] = \left(\frac{K_{Cl}}{K_{Ar}}\right)2d\left(\frac{1-f_{Ar}}{f_{Ar}}\right) \rightarrow d = \underbrace{\frac{1}{2}\left(\frac{K_{Ar}}{K_{Cl}}\right)}_{\alpha_{cl}}\left(\frac{f_{Ar}}{1-f_{Ar}}\right)\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}$$

$$I_{Ar} = K_{Ar}n_{tot}\omega_n^2\left[\frac{f_{Ar}}{1+\frac{1}{2}\alpha_{cl}\left(\frac{f_{Ar}}{1-f_{Ar}}\right)\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}\left(1-f_{Ar}\right)}\right] = K_{Ar}n_{tot}\omega_n^2\left[\frac{f_{Ar}}{1+\frac{1}{2}\alpha_{cl}f_{Ar}\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}\right] = K_{Ar}'\omega_n^2\left[\frac{f_{Ar}}{1+\frac{1}{2}\alpha_{cl}f_{Ar}\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}\right]$$

$$I_{Cl} = K_2(T_e)\omega_n^2 n_{Cl} = K_{Cl}n_{tot}\omega_n^2\left[\frac{\alpha_{cl}f_{Ar}\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}{1+\frac{1}{2}\alpha_{cl}f_{Ar}\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}\right] = K_{Cl}'\omega_n^2\left[\frac{\alpha_{cl}f_{Ar}\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}{1+\frac{1}{2}\alpha_{cl}f_{Ar}\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}\right] = K_{Ar}'\omega_n^2\left[\frac{f_{Ar}\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}{1+\frac{1}{2}\alpha_{cl}f_{Ar}\left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}\right]$$

Ar OES Signal & Fit: $SiCl_4$ Ignored



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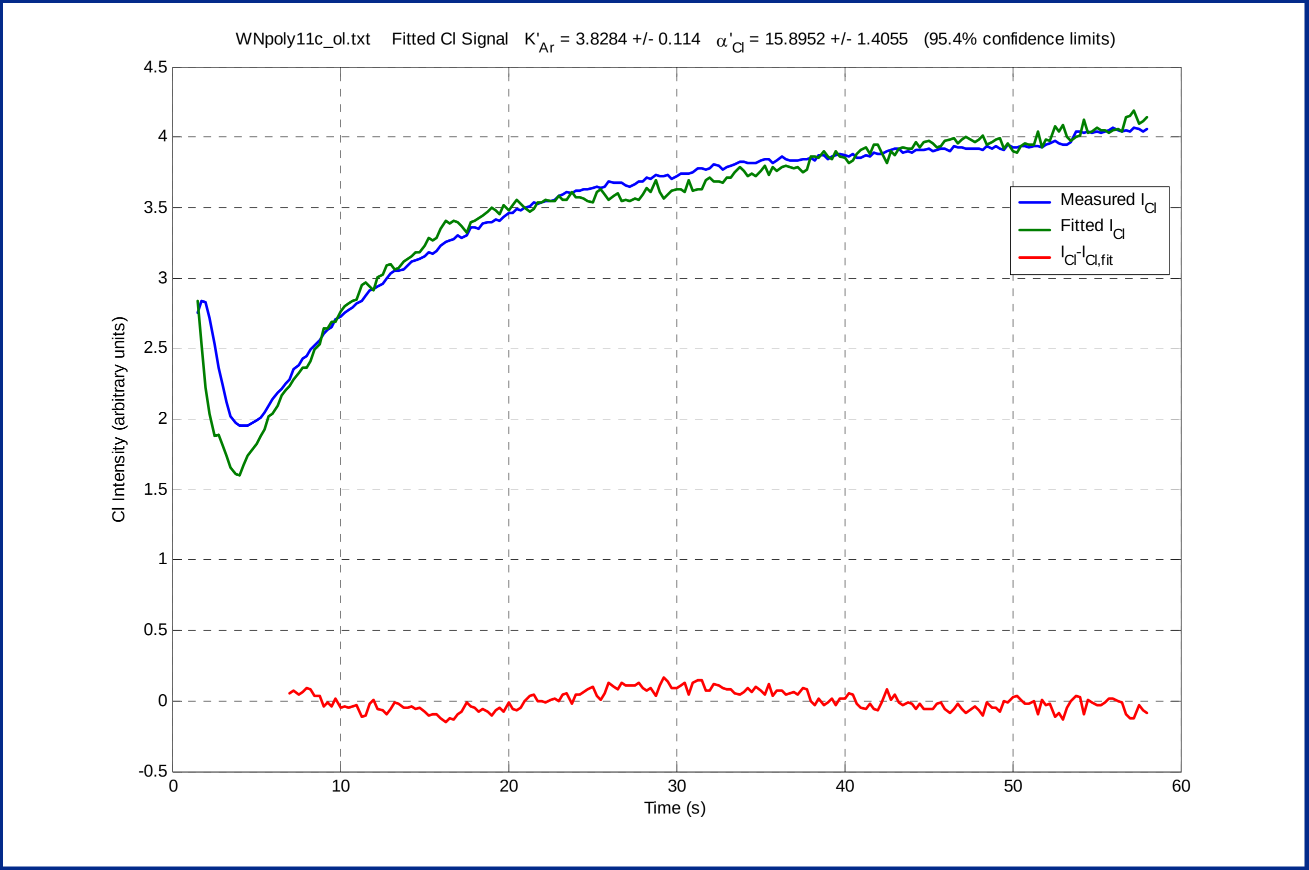
Cl OES Signal & Fit: $SiCl_4$ Ignored



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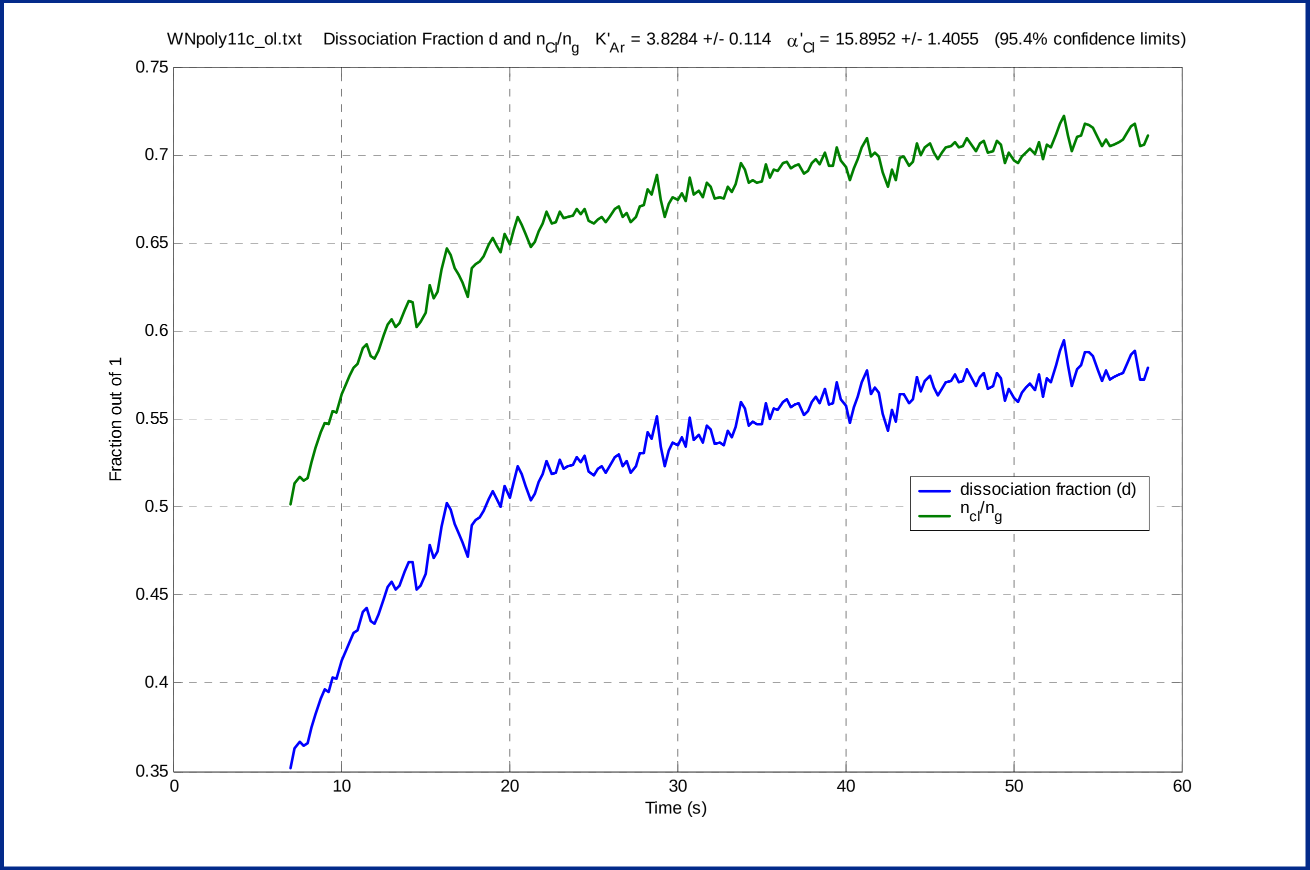
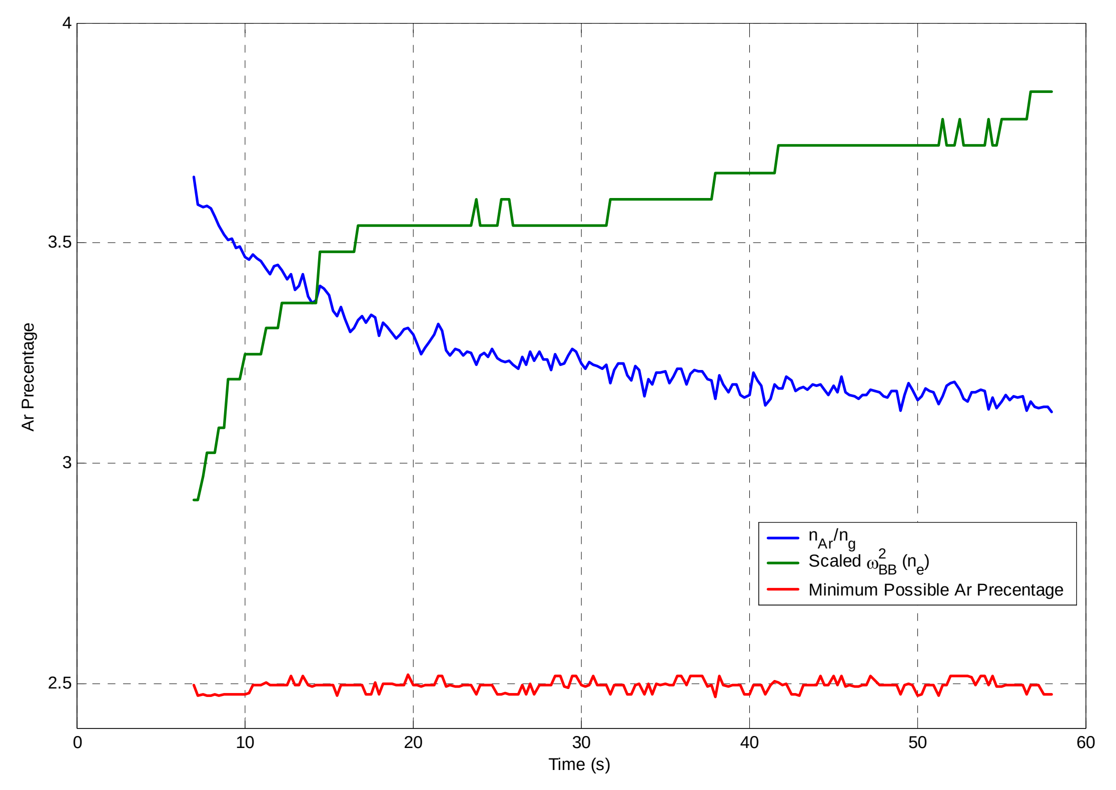
Cl_2 Net Dissociation: $SiCl_4$ Ignored



Ar Fraction: $SiCl_4$ Ignored



$I_{Ar}(t)$ ~const. due to opposing effects of dilution (↓) & ne (↑)

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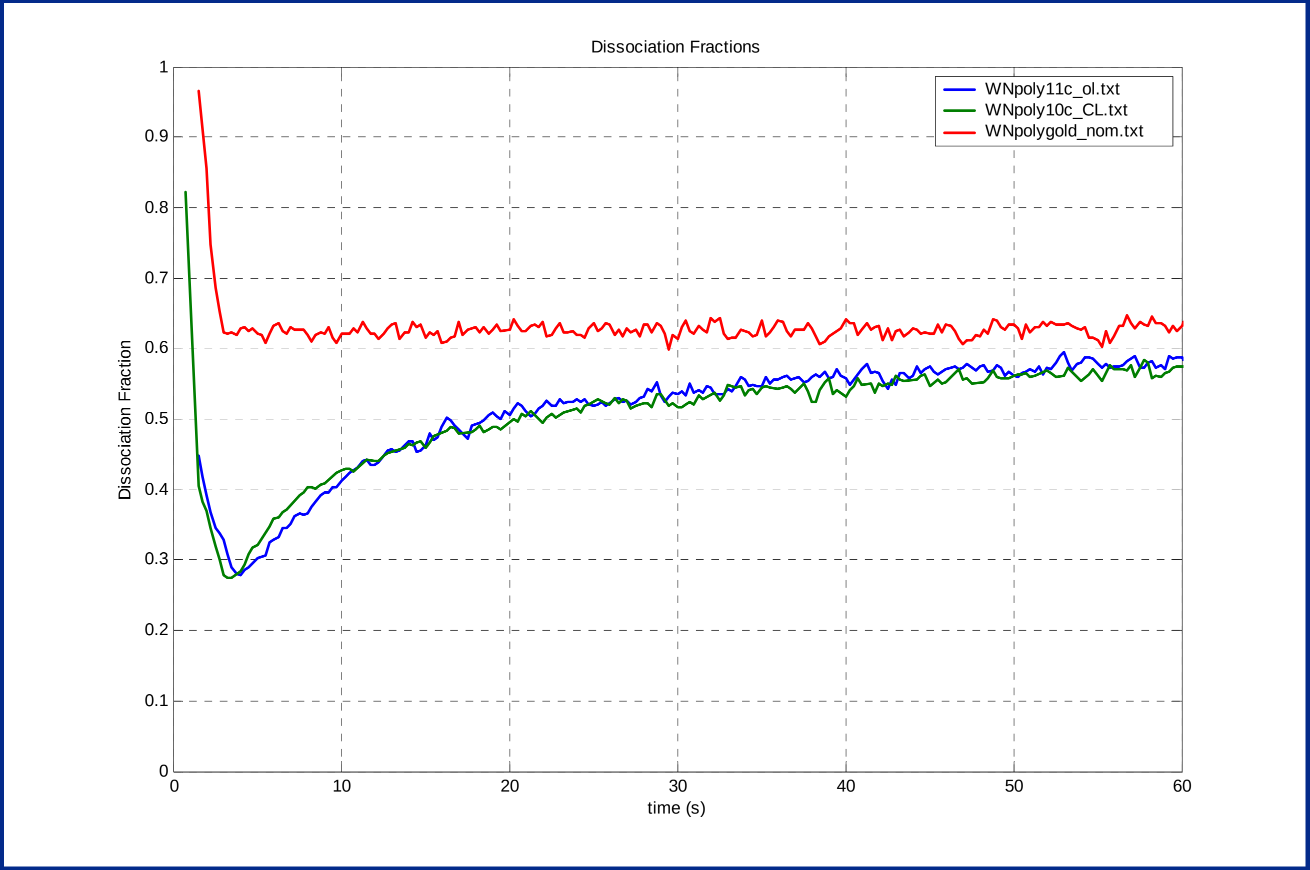
Dissociation Fractions: $SiCl_4$ Ignored



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Intensity Ratio I_{Cl}/I_{Ar}

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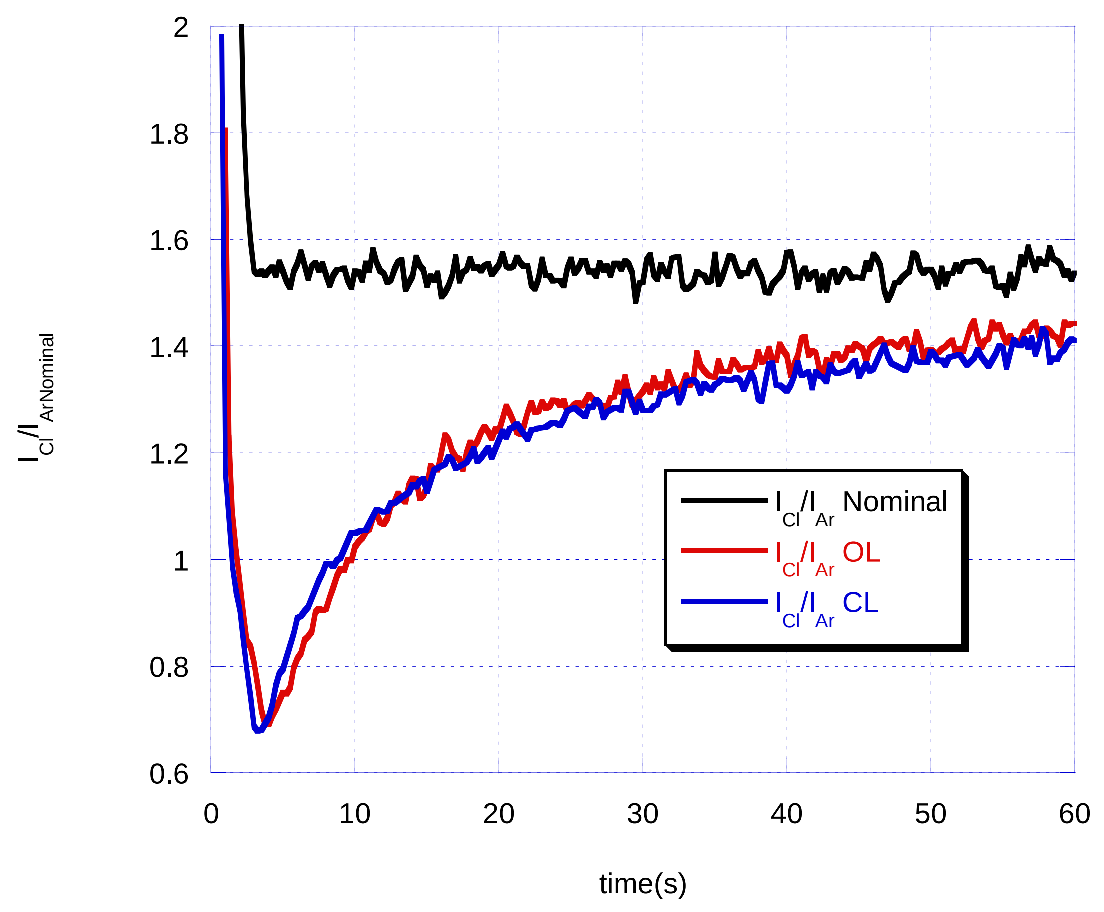


- Why is feedback controlled I_{Cl}/I_{Ar} still low? – <u>Our Next AVS Paper</u> : GENERATION of Cl Is Increased but COMSUMPTION by Si Etching & Dilution by $SiCl_4$ Offset Generation

Key Reactions

$Cl_2 \rightarrow 2Cl$	Dissociation
$2Cl \rightarrow Cl_2$	Recombination (wall & bulk gas phase)
$Cl + e^- \rightleftarrows Cl^+ + 2e^-$	Ionization & Bulk Deionization
$Si + 4Cl \rightarrow SiCl_4$	Etch

$$\left.\begin{array}{l} SiCl_4 + SiO_2 \rightarrow SiO_xCl_y + Cl + Cl_2 \\ SiCl_4 + Al_2O_3 \rightarrow Al_vSi_zO_xCl_y + Cl + Cl_2 \end{array}\right\} \text{Deposition Reactions (unbalanced)}$$

Simplified Reaction Set

Assuming Cl ionization and Si-species deposition

Reactions have small effects on gas species concentrations,

the other remaining reactions yield:

$$\underbrace{F_{Cl_2}Cl_2 + F_{Ar}Ar + F_{Si}Si}_{\text{molecules in}} \rightarrow \underbrace{xCl + yCl_2 + F_{Si}SiCl_4 + f_{Ar}Ar}_{\text{chamber gas phase molecules}}$$

$$\frac{1}{2}x + y + 2F_{Si} = F_{Cl_2} \text{ for } Cl_2 \text{ mass balance}$$

$$y = (1-d)F_{Cl_2} \text{ where } d = \text{Net Dissociation Fraction of } Cl_2$$

$$F_{Si} = \{Si \text{ atoms/s consumed by etching}\} \text{ known from measured etch rate \& flows}$$

So

$$x = \left[2dF_{Cl_2} - 4F_{Si}\right]$$

Result of Simplified Reaction Set

$$n_g \propto x + y + F_{Si} + F_{Ar}$$

$$n_g \propto 2dF_{Cl_2} - 4F_{Si} + \left(1 - d\right)F_{Cl_2} + F_{Si} + F_{Ar}$$

$$n_g \propto \left(1 + d\right)F_{Cl_2} + F_{Ar} - 3F_{Si}$$

$$n_{Cl} = \left[\frac{x}{x + y + F_{Si} + F_{Ar}}\right] n_g = \left[\frac{2dF_{Cl_2} - 4F_{Si}}{\left(1 + d\right)F_{Cl_2} + F_{Ar} - 3F_{Si}}\right] n_g$$

$$n_{Ar} = \left[\frac{F_{Ar}}{x + y + F_{Si} + F_{Ar}}\right] n_g = \left[\frac{F_{Ar}}{\left(1 + d\right)F_{Cl_2} + F_{Ar} - 3F_{Si}}\right] n_g$$

$$I_{Cl} = K_{Cl} n_{Cl} n_e \qquad\qquad I_{Ar} = K_{Ar} n_{Ar} n_e$$

Measured Actinometry Ratio:

$$\left[\frac{I_{Cl}}{I_{Ar}}\right]_m \equiv A_m = \frac{K_{Cl} S_{Cl} n_{Cl} n_e}{K_{Ar} S_{Ar} n_{Ar} n_e} = \frac{1}{\alpha'_{Cl}}\left[\frac{2dF_{Cl_2} - 4F_{Si}}{F_{Ar}}\right]$$

Cl Actinometry Signal Suppressed by Etch/Loading

$$PV = n_g R T_g \rightarrow n_g = \frac{PV}{RT_g}$$

Assume T_g is constant & $n_e = C\omega_{BB}^2$ where C is a portionality constant fixed during the etch run.

$$I_{Cl} = P\omega_{BB}^2 \left[\frac{K_{Cl}^{'}\alpha_{Cl}^{'}A_m F_{Ar}}{F_{Cl_2} + \left(1 + \frac{1}{2}\alpha_{Cl}^{'}A_m\right)F_{Ar} - F_{Si}} \right]$$

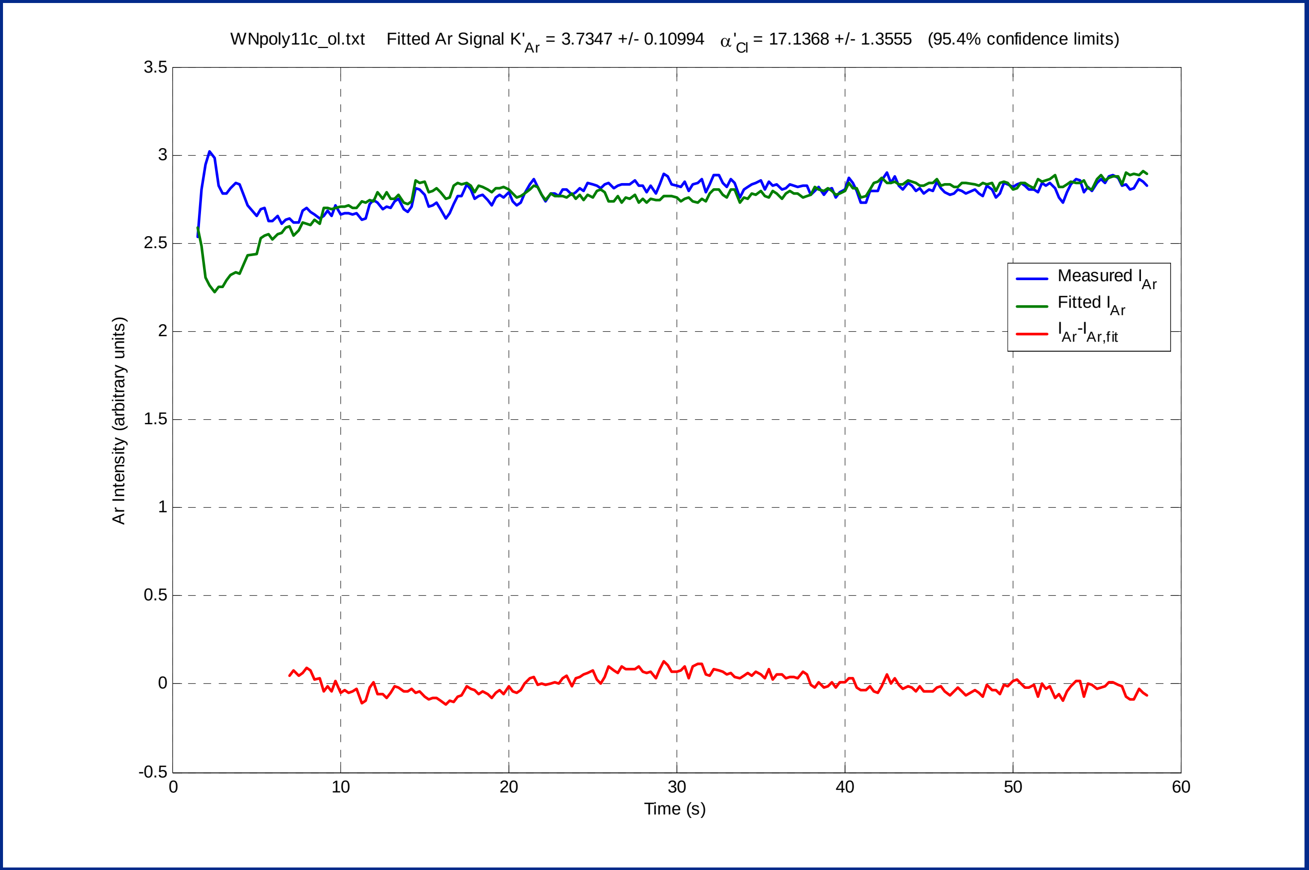
$$= P\omega_{BB}^2 \left[\frac{K_{Ar}^{'}A_m F_{Ar}}{F_{Cl_2} + \left(1 + \frac{1}{2}\alpha_{Cl}^{'}A_m\right)F_{Ar} - F_{Si}} \right]$$

$$I_{Ar} = P\omega_{BB}^2 \left[\frac{K_{Ar}^{'}F_{Ar}}{F_{Cl_2} + \left(1 + \frac{1}{2}\alpha_{Cl}^{'}A_m\right)F_{Ar} - F_{Si}} \right]$$

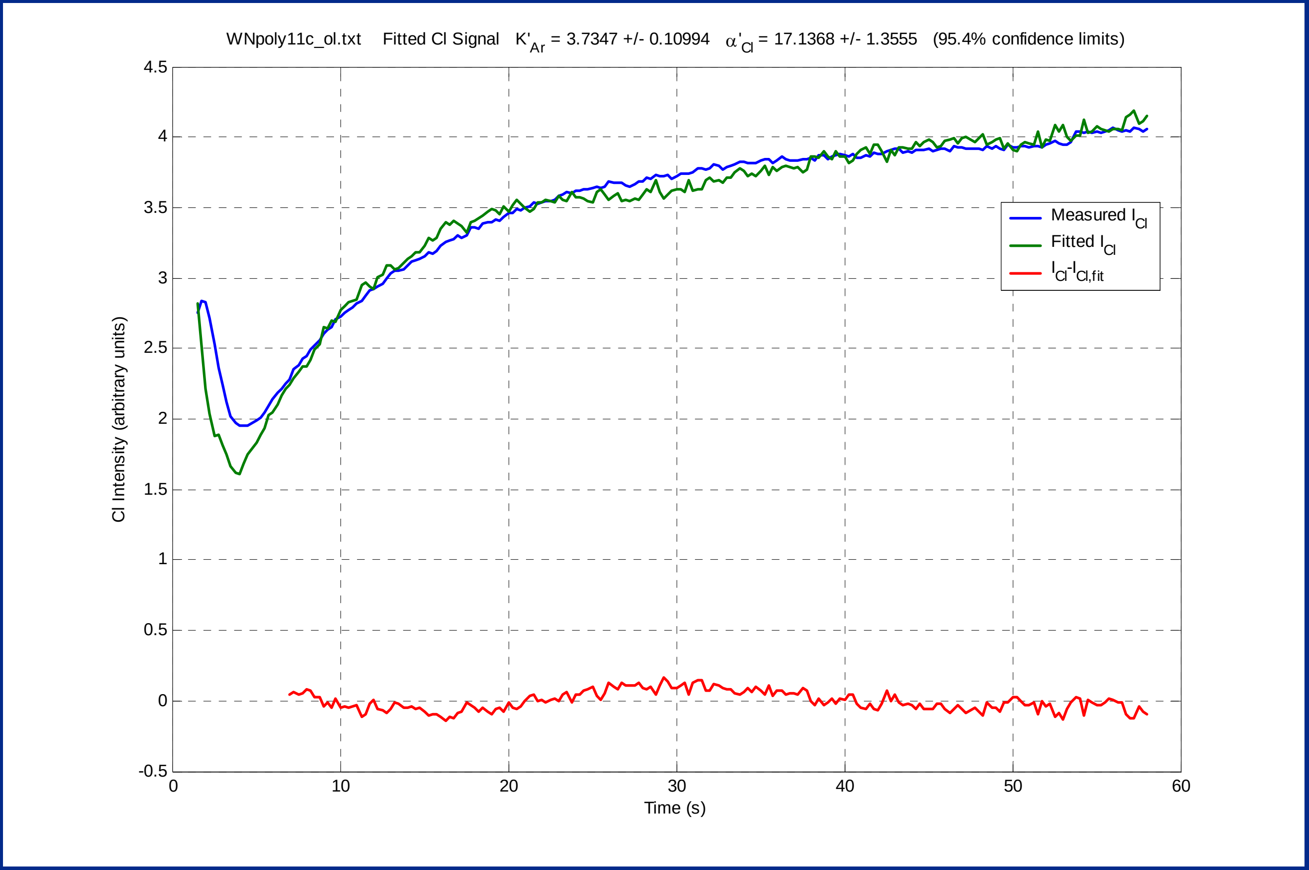
$K_{Ar}^{'}$ & $\alpha_{Cl}^{'}$ are the only unknowns

They can be extracted if there is sufficient variation in $I_{Cl}(t)$ & $I_{Ar}(t)$

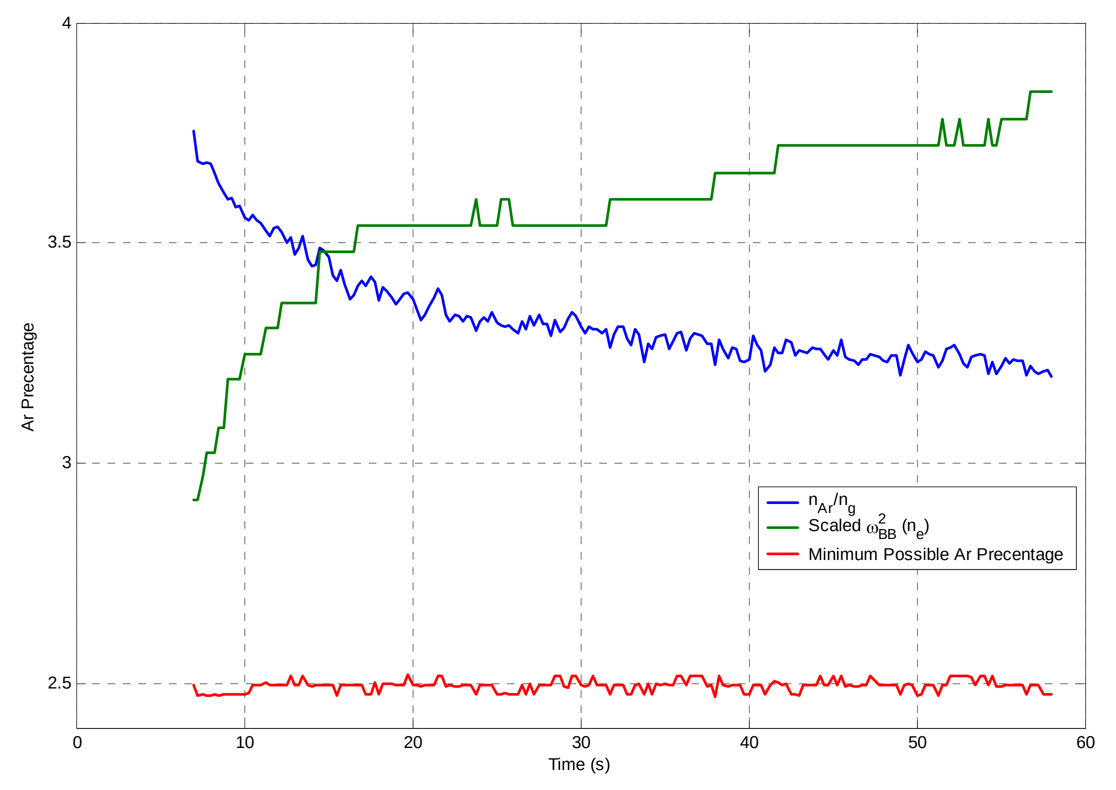
Ar OES Intensity & Fit: $SiCl_4$ Included from RTSE



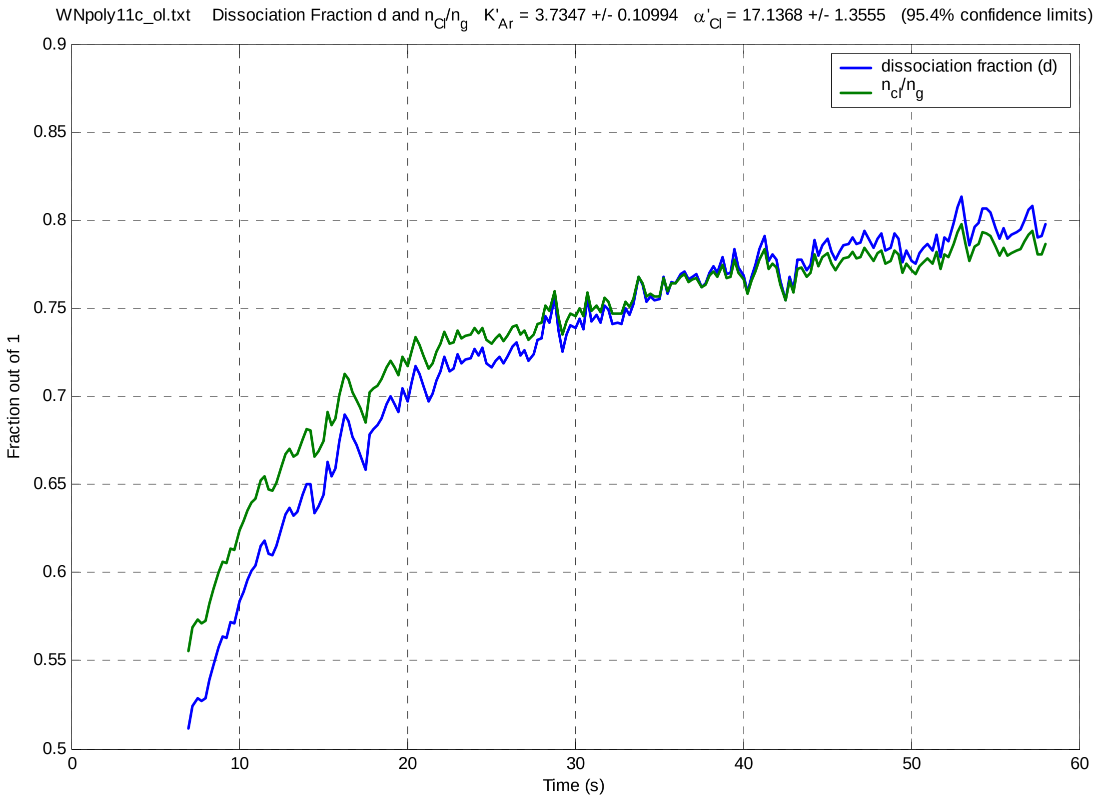
Cl OES Intensity & Fit: $SiCl_4$ Included from RTSE



Ar Fraction : $SiCl_4$ Included from RTSE

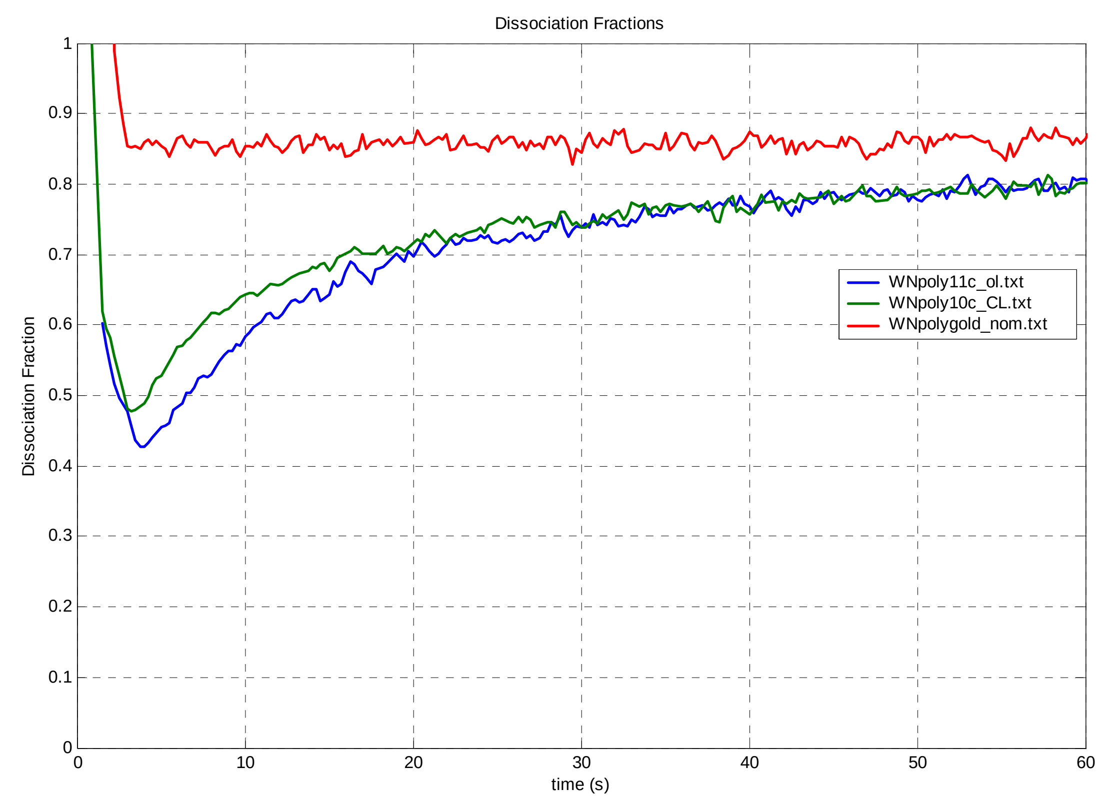


Dissociation Fraction : $SiCl_4$ Included from RTSE



Fred L. Terry, Jr., NCAVS Plasma Etch Users Meeting Sept 8, 2005

Dissociation Fractions: $SiCl_4$ Included from RTSE



- **Net Dissociation Fraction (d) Is Increased by Higher TCP Power in Closed Loop Run**
- **Net d is higher than estimated from procedure ignoring $SiCl_4$**
- **Wall Recombination Still Suppresses Cl, d**

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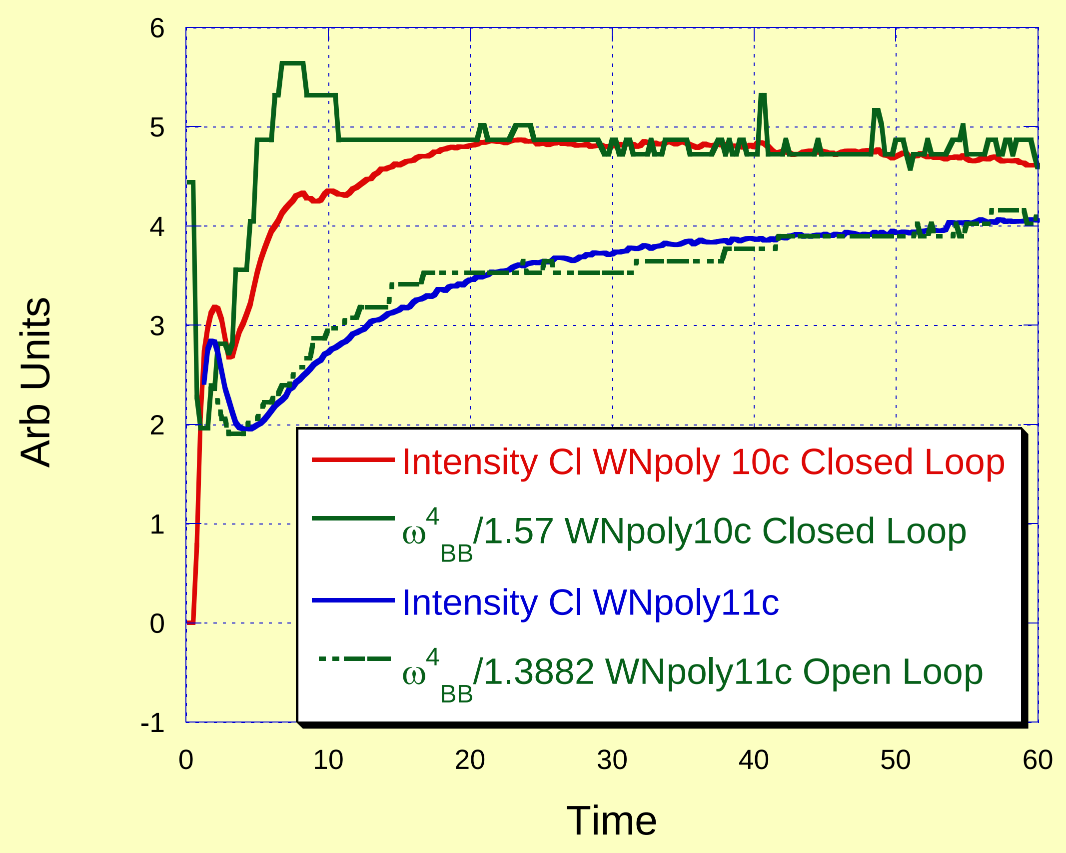
T_e (EEDF) Issue



With some assumptions which we believe are justified:

$$\left[\frac{\omega_n^4}{I_{Cl}}\right] = f\left(T_e\, only\right)$$

T_e for open loop case appears ~constant

T_e is increased initially for closed loop case (constant α_{Cl}' assumption may not be accurate)

Wall-State Effects Model

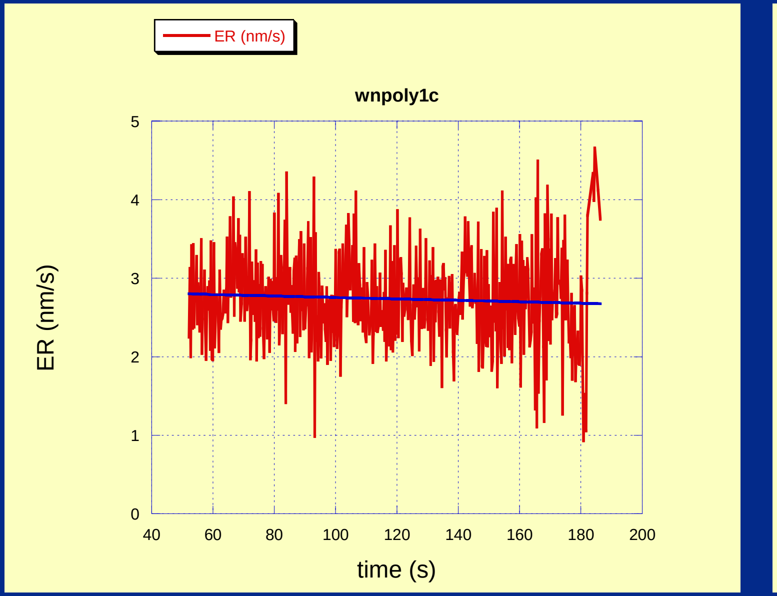
- **n_{Cl} reduced due to recombination on F-cleaned walls.**
- **n_{Cl+} reduced due to lower availability of n_{Cl} precursor. ER decreases due to lower ion bombardment.**
- **Real-time feedback control corrects for $n_e \approx n_{Cl+}$ losses by increasing T_e, but does not fully recover n_{Cl}.**
- **Model supports ion dominated etch of Si w/ Cl_2;** $n_{Cl+} \Leftrightarrow ER \neq n_{Cl}$. **High n_{Cl} keeps surface Cl-saturated. $\therefore$ ion bombardment is rate limiting step.**
- **Extracted d varies significantly, causing constant I_{Ar}.**

HBr/Cl_2 Etches

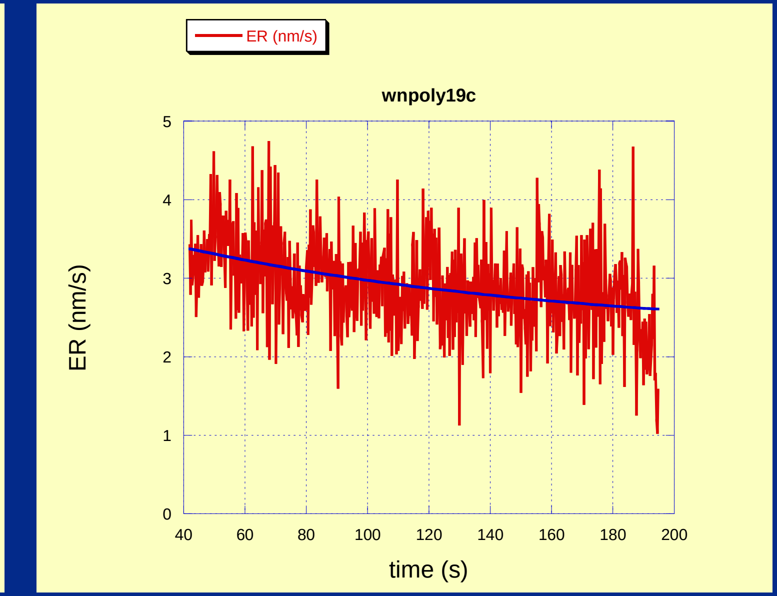
- HCl Is Formed In Mixing Manifold By HBr/Cl_2 Reaction
- Collaboration With Stanford Group Shows Similar Plasma/Gas Chemistry Trends To Cl_2 Only Cases
  - HCl absolute concentration was measured by laser diode absorption
  - HCl Dissociation follows BB-RF/plasma density trends
  - Chamber cleaning suppresses dissociation of HCl & increases plasma density variation
- Open Loop Etch Rates Become More Constant With Increasing HBr & Show Less Sensitivity to Chamber Wall Condition
- Closed Loop Plasma Density Control Causes More Time Variation In Etch Rate for High HBr Concentration Cases
- HBr/Cl_2 Etch Rates Are Not Directly Ion Limited & Future Work is Needed
  - Wafer Surface Temperature?

HBr/Cl$_2$ Etch (80/20)

Open Loop



Closed Loop



Future Work

- Modeling of BB Signals to extract more from the shape of the data
  - collision parameters
  - Possible T_e/EEDF Information
- Improved antenna designs for BB System
- Lower-cost electronics for BB reflectometry
- Apply density control to topography & profile variations.
- Expand to other ion-dominated etches besides Cl_2 etching of Poly-Si.
- Larger scale, multi-wafer tests to verify control improvements.
- Ion density control most effective when etch is ion dominated. Chemically dominated etches do not show same effects.
- Combine ion density control with ion energy control.

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  - Projected Ended August, 2001
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  - Project Ended June, 2002

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