Use of Multiple Real-time Sensors for Improved Process Understanding and Control: Cl_2 Etching of Polycrystalline Si

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- Dr. Craig Garvin (now with Inficon)
- Prof. Jessy Grizzle (UofM)
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- Pete I. Klimecky and Fred L. Terry, Jr., “A multi-sensor study of Cl_2 etching of polycrystalline Si,” *Phys. Stat. Sol.* (c) 5, No. 5, 1341–1345 (2008)
- Pete I. Klimecky, J. W. Grizzle, and Fred L. Terry, Jr. “Compensation for transient chamber wall condition using real-time plasma density feedback control in an inductively coupled plasma etcher,” *J. Vac. Sci. Technol*., A 21, pp. 706-17 (2003).

Key Points

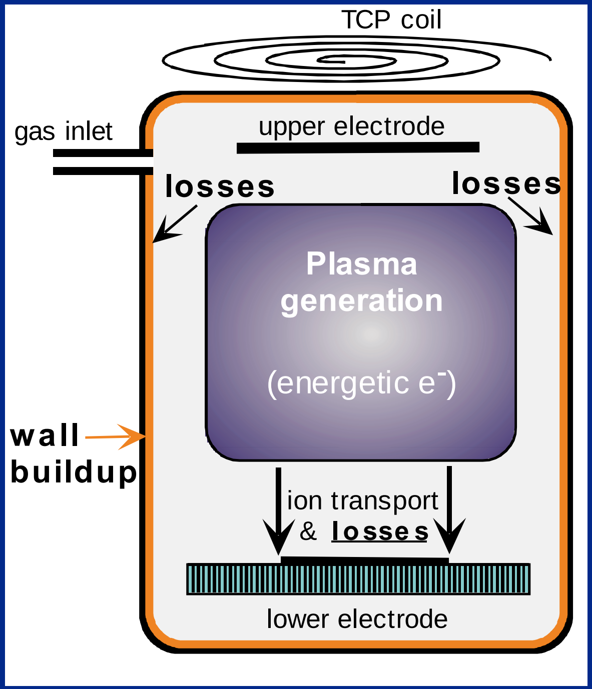
- Real-Time Process and Wafer Sensors, and Feedback Process Control Helped Identify and Quantitatively Prove the Mechanism for Process Disturbance/Run-to-Run Variation (Chamber Conditioning Effects on Etch Rate)
- Simultaneous Analysis of Multiple Process Measurements and A Wafer Measurement Improved the Quantitative Estimation of Process Chemistry Parameters (Cl^+ and Cl_0 Concentrations)

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!*

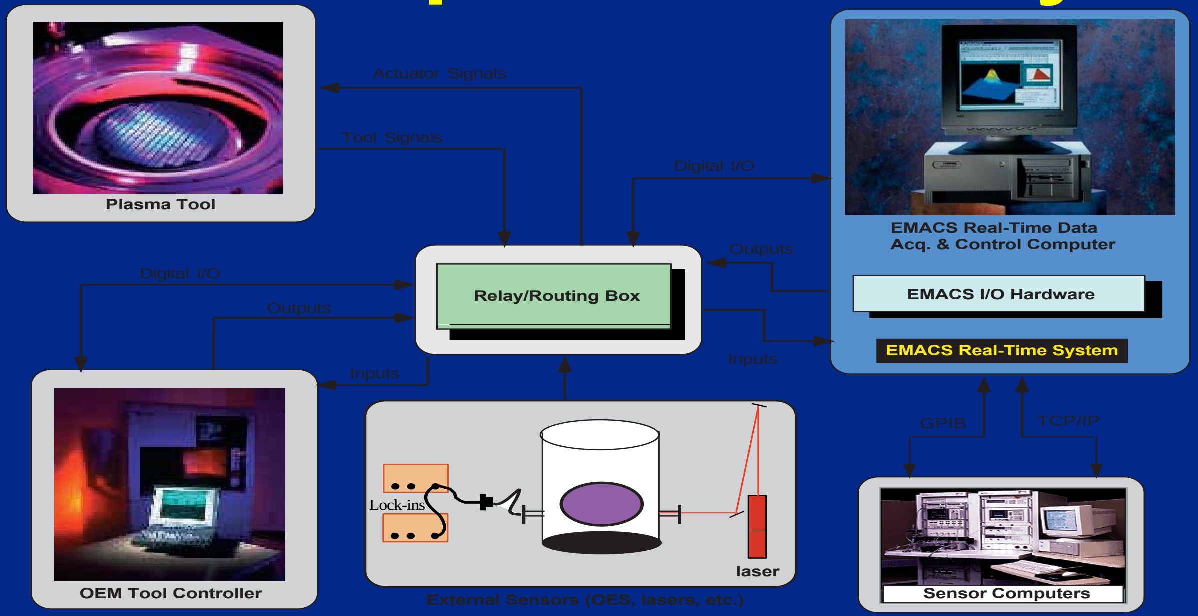
Previous Wall State Work

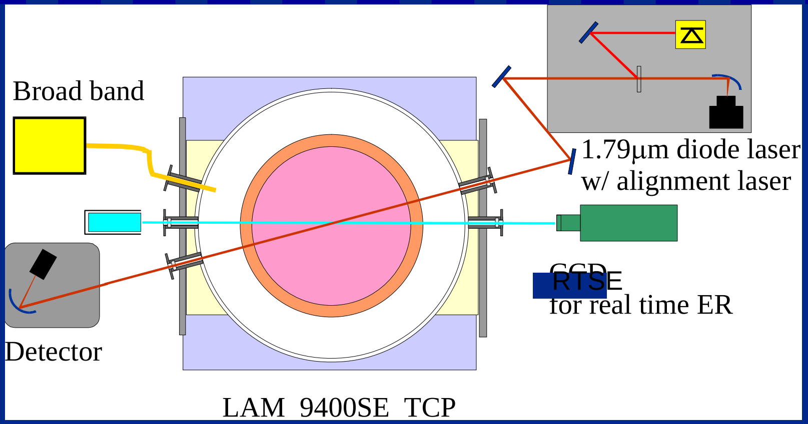
- **Sawin**: 1st reported Etch Rate changes in Cl_2 due to O_2 (↑) & CF_4 (↓) chamber exposure. (*JECS* 1992)
- **Donnelly**: Increasing Cl neutral conc. with time in a quartz tube helical resonator. (*JVSTA* 1996)
- **Aydil**: Atomic Cl drifts due to SiO_2 wall conditioning & SF_6 wall cleans. (*JVSTA*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

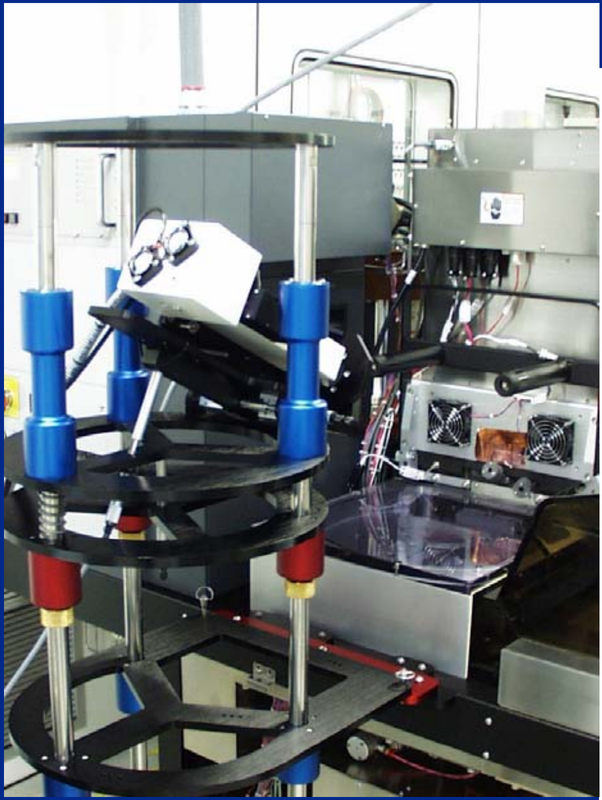

Plasma Tool
Actuator Signals
Tool Signals
Digital I/O
EMACS Real-Time Data Acq. & Control Computer
Outputs
Relay/Routing Box
Digital I/O
Outputs
EMACS I/O Hardware
Inputs
EMACS Real-Time System
Inputs
GPIB
TCP/IP
OEM Tool Controller
Lock-ins
laser
External Sensors (OES, lasers, etc.)
Sensor Computers

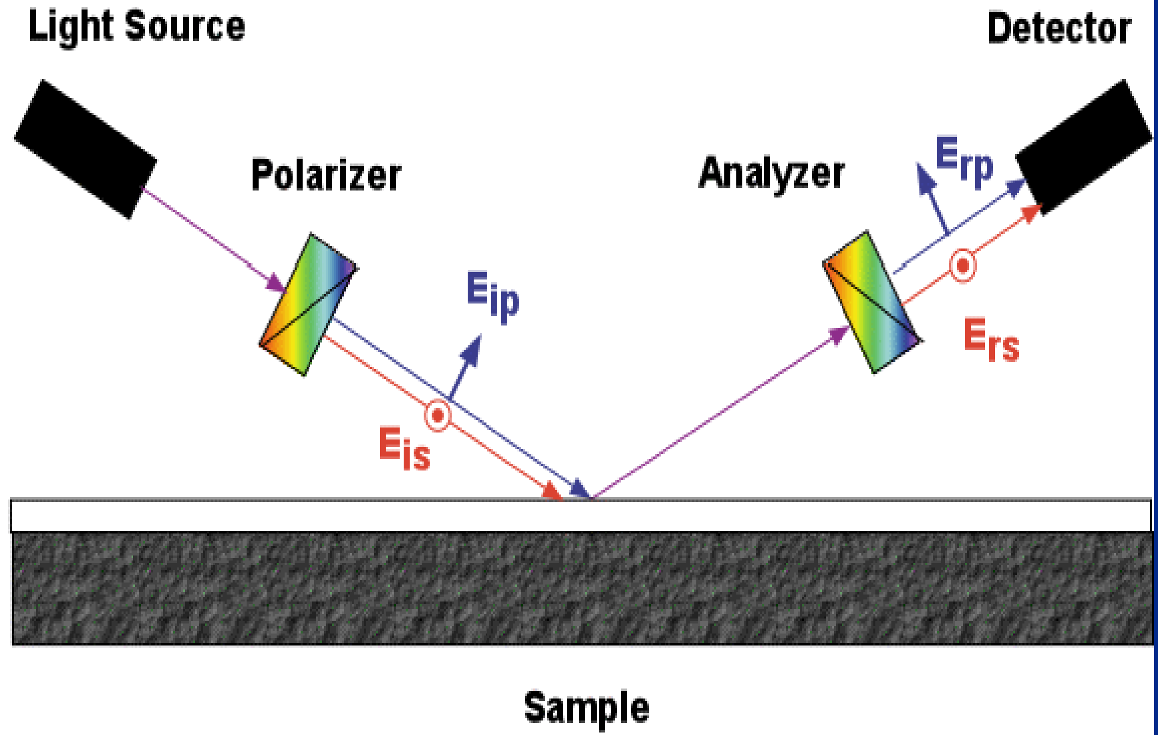


Real-Time Monitors

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

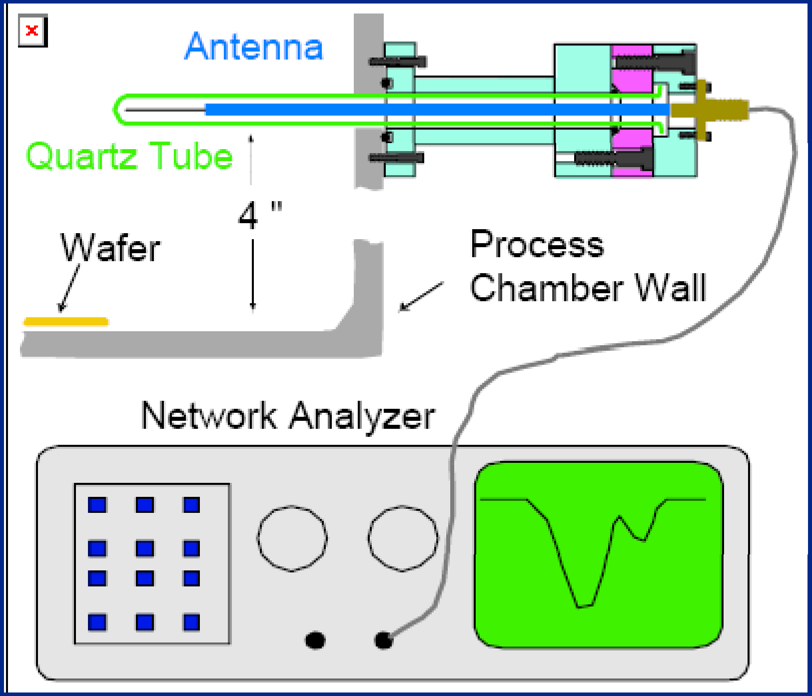
RTSE

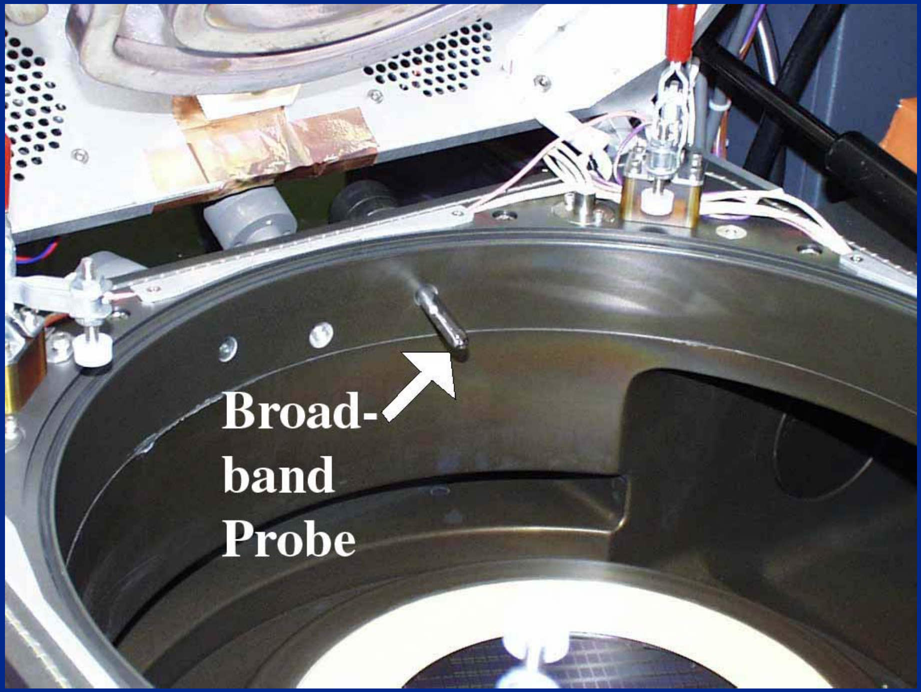




- Real-Time Spectroscopic Ellipsometer (RTSE)
  - Can optically model film etch depth, CD, sidewall slope
  - Use for real-time etch rate monitoring & transients

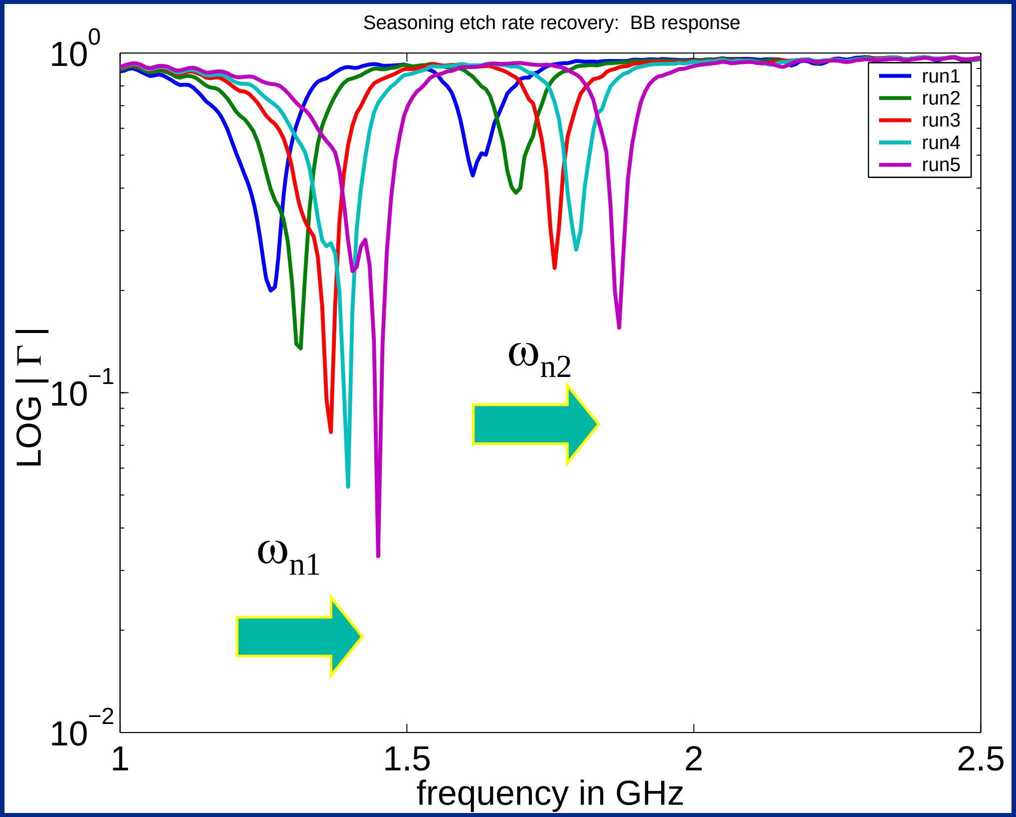
BroadBand RF





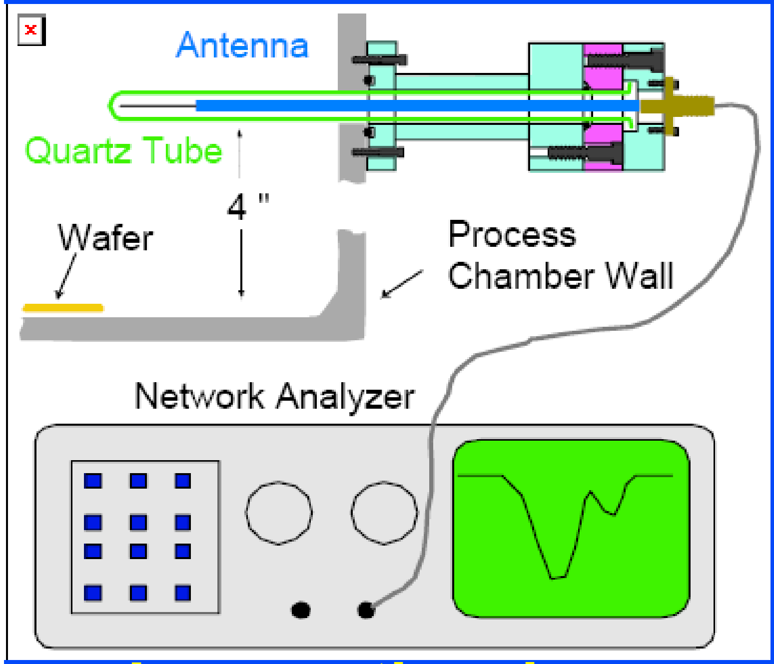
Remarks
- High frequency (GHz), low power (mW) sweep of plasma
- Plasma impedance spectroscopy
- Must analyze broad spectrum of data (Broadband RF Probe)
- Yields plasma density metric

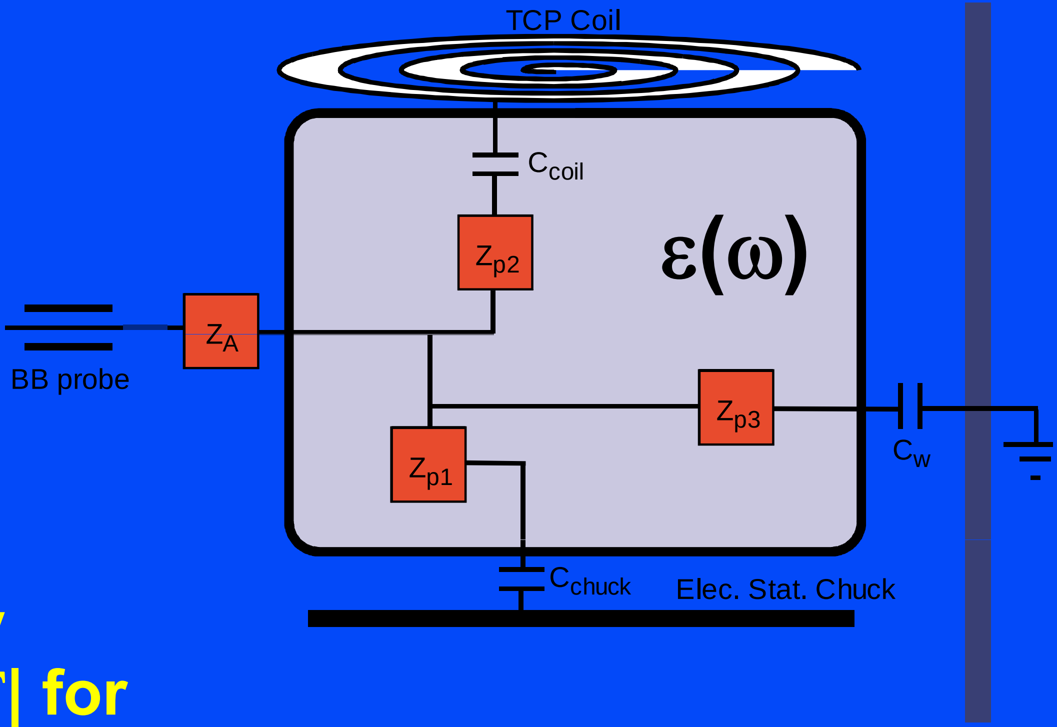
BB Peak Shifts & Density



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

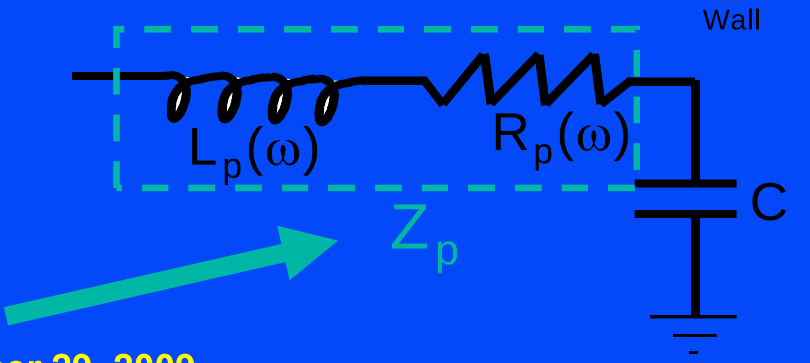
BroadBand RF Circuit Analogy





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

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



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Broadband Interpretation

- The frequencies of maximum RF absorption, ω_{n1} & ω_{n2} , track similarly and are circuit/cavity shifted indicators of the plasma frequency
- The shape of the BBRF signals contain more information, but this is not considered here

$$\omega_{pe} = \left(\frac{q^2 n_e}{\varepsilon_0 m} \right)^2$$

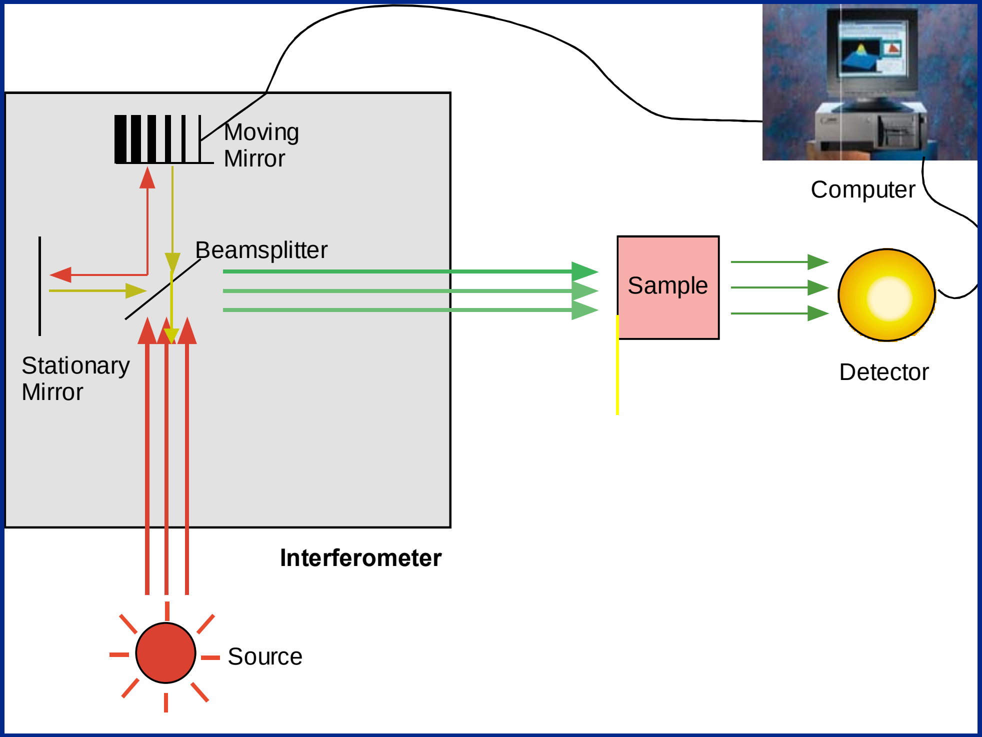
$$\omega_{n1} = A\omega_{pe}$$

$$\omega_{n2} = B\omega_{pe}$$

$$A < B < 1$$

$$n_e = \left(\frac{\varepsilon_0 m}{q^2} \right) \omega_{pe}^2 = \left(\frac{\varepsilon_0 m}{Bq^2} \right) \omega_{n2}^2$$

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. (now MKS)

Etch Conditions

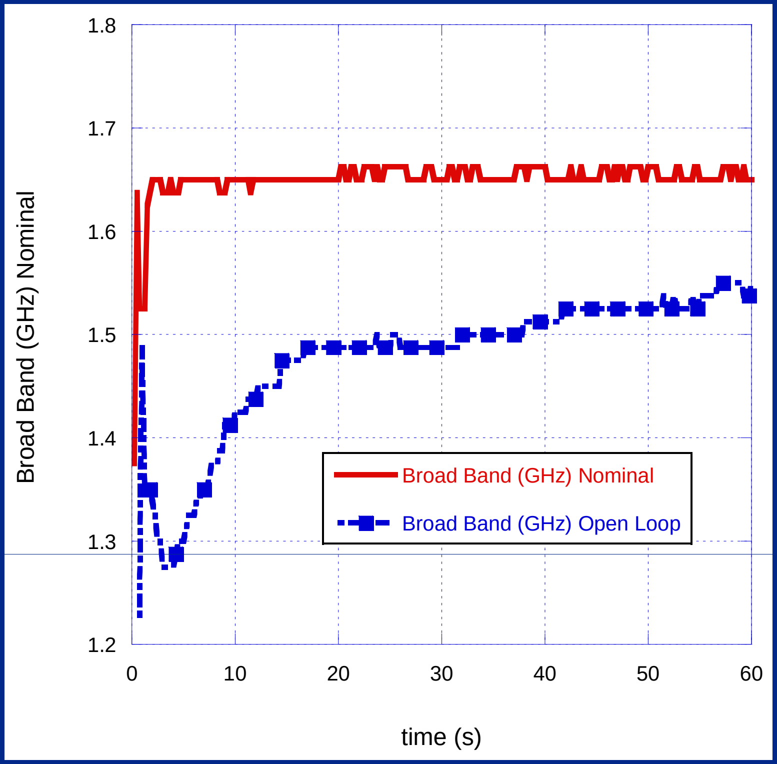
- Lam 9400 TCP SE
- 10 mTorr
- 100 sccm Cl_2 flow
  - 100 sccm total etch gas flow for Cl_2/HBr experiments
- 5 sccm Ar flow
- 250 W TCP Power
  - Varied for Plasma Density Control (Closed Loop) Runs
- 100 W Bias Power
  - Bias Voltage Measurement Not Available
- Unpatterned 150 mm Poly-Si/30nm SiO_2/Si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

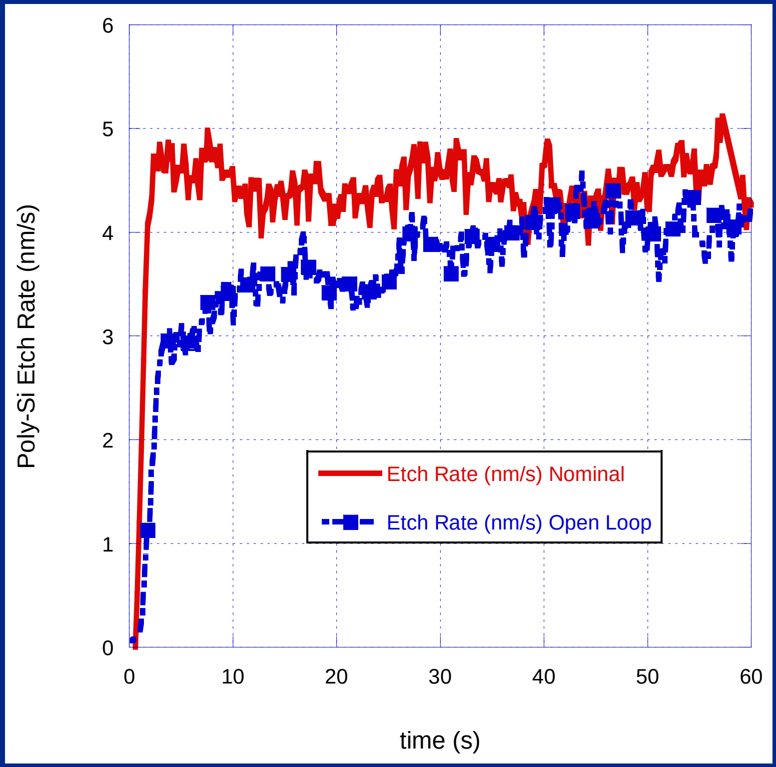
Experimental Definition 1

- 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.**

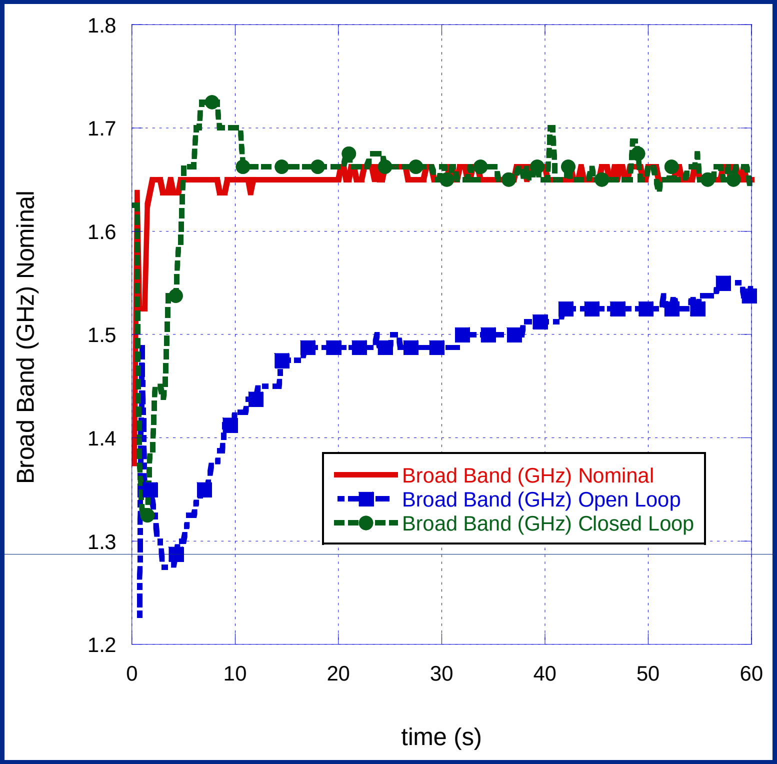
(OL) Open Loop Drift Recovery

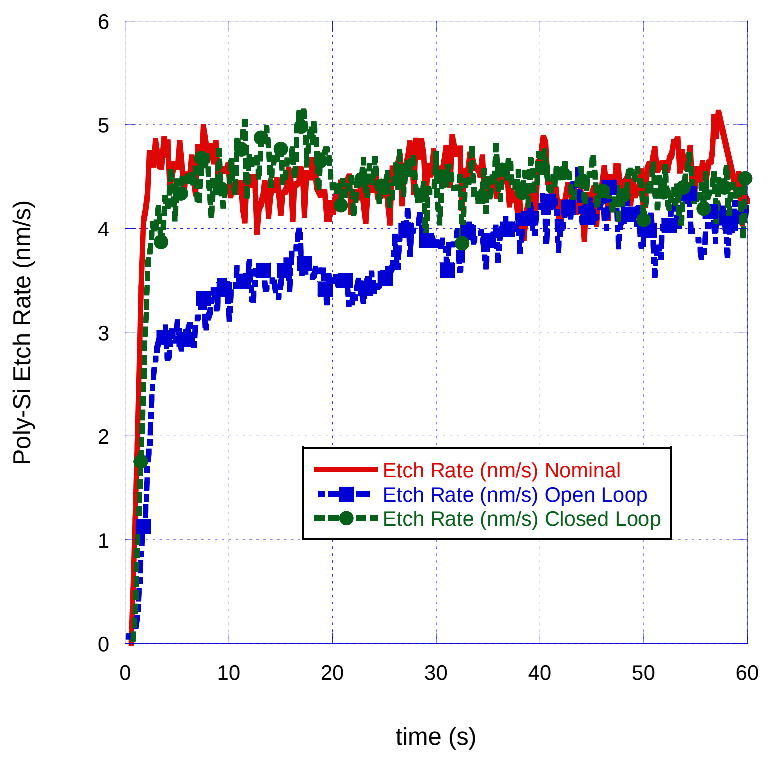




- Nominal etch rate flat, OL rate increasing
- Nominal BroadBand ω_{n2} flat, OL ω_{n2} increasing
- OL signals do not recover in 60sec

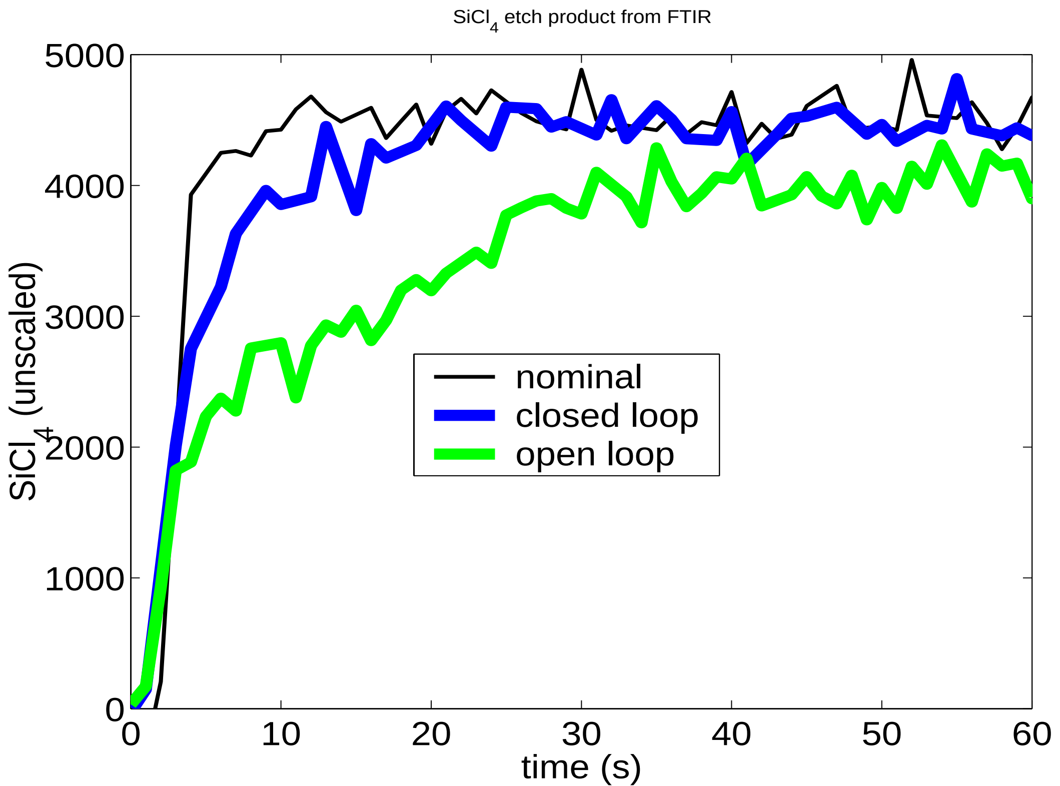
(CL) Closed Loop Recovery





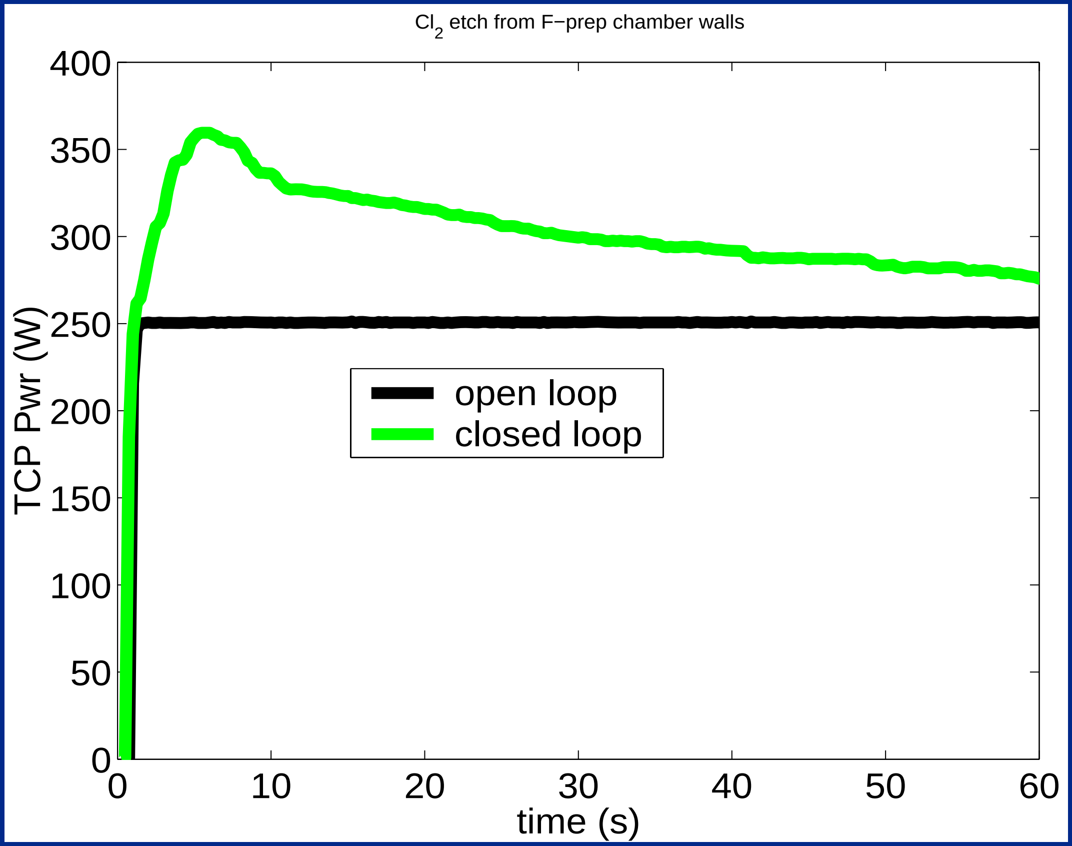
- **Both nominal & CL etch rate flat**
- **Both nominal & CL BroadBand ω_{n2} flat**
- **CL signals recover in ~5sec**

$SiCl_4$ 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



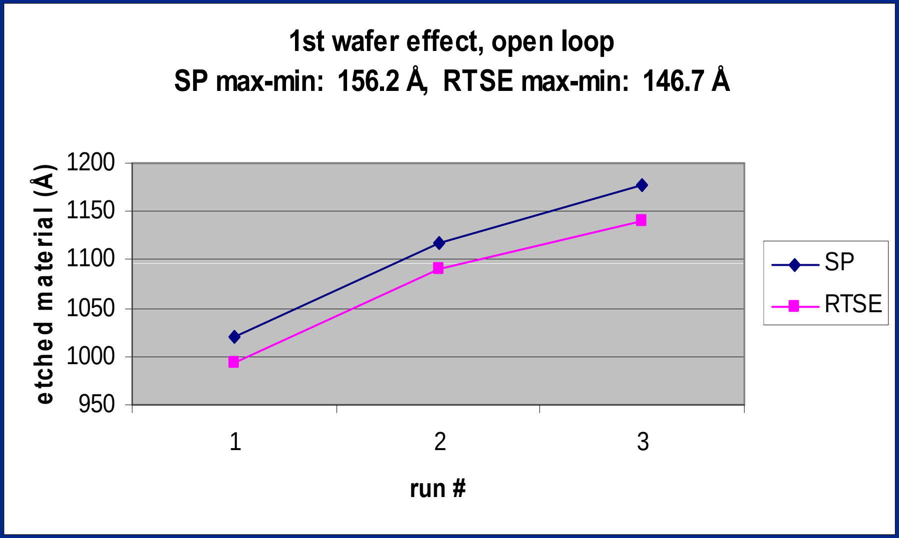
- **TCP power compensation in CL is very high at the start to make up for lost Cl^+ ions to the walls**

Experimental Definition 2

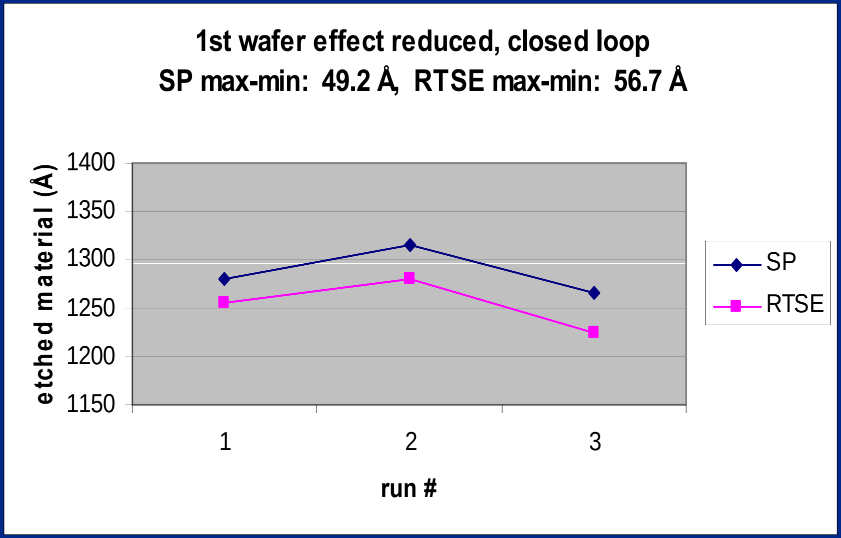
- Second project; 2 experiments, OL vs. CL
- **1st wafer effect elimination with plasma density compensation**
  - **Prep chamber walls using C_2F_6 clean**
  - **Follow with 3 open loop etches for 30s each in Cl_2 and measure etch depth**
  - **Prep chamber with C_2F_6 clean again**
  - **Follow with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



1st wafer effect, open loop
SP max-min: 156.2 Å, RTSE max-min: 146.7 Å

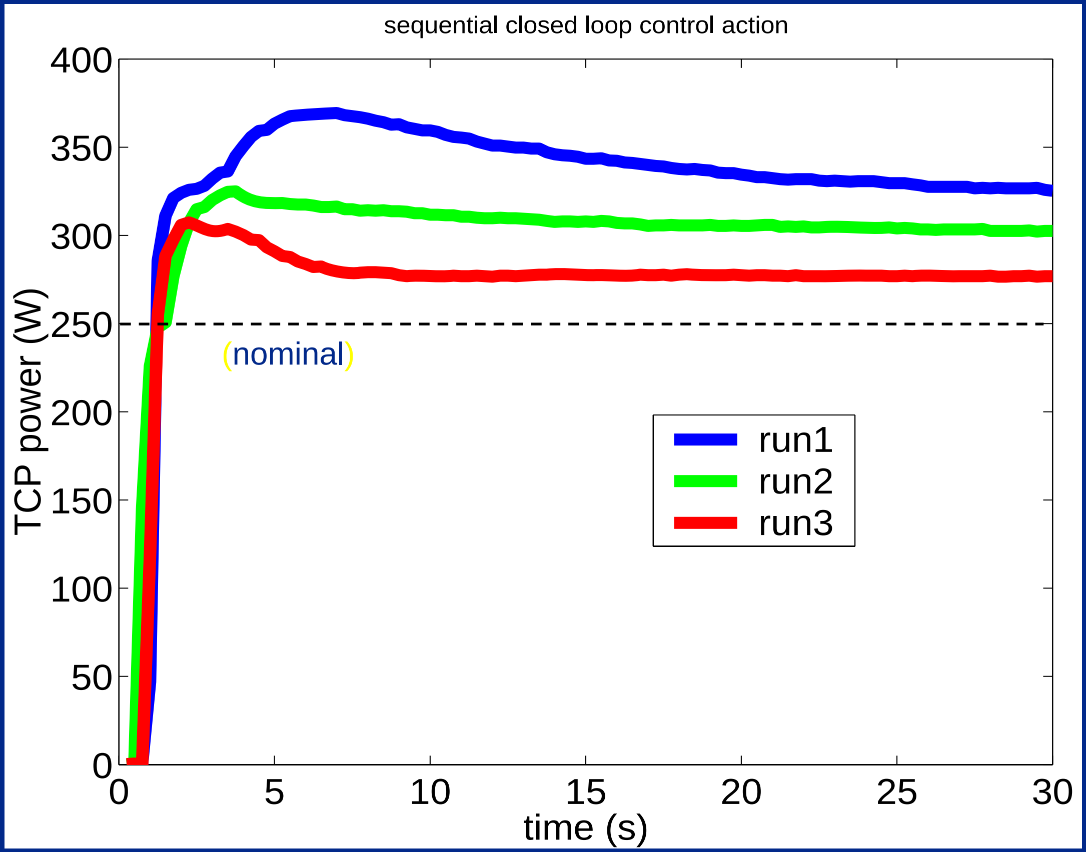


1st wafer effect reduced, closed loop
SP max-min: 49.2 Å, RTSE max-min: 56.7 Å

- **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**

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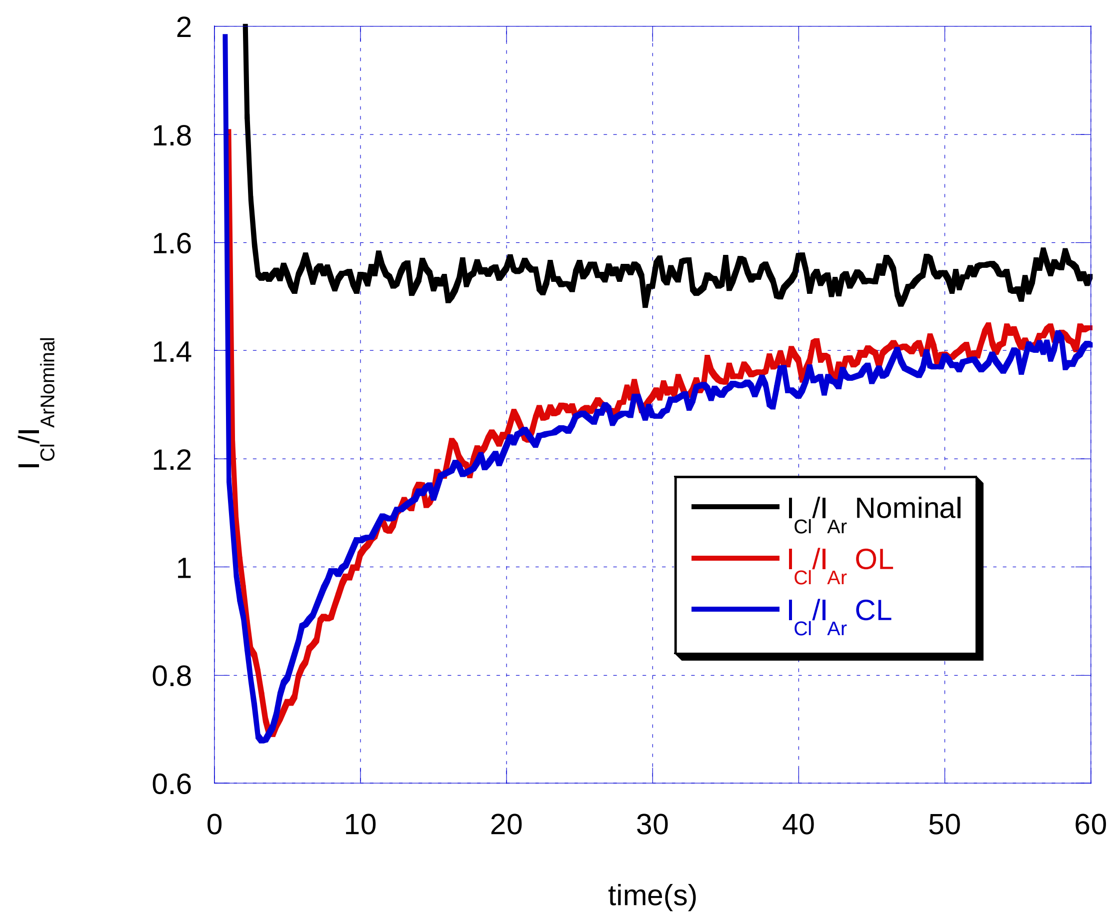
Summary

- 1st evidence of real-time Poly-Si etch rate variation in Cl_2 due to F-exposure.
- 1st 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 1st 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*

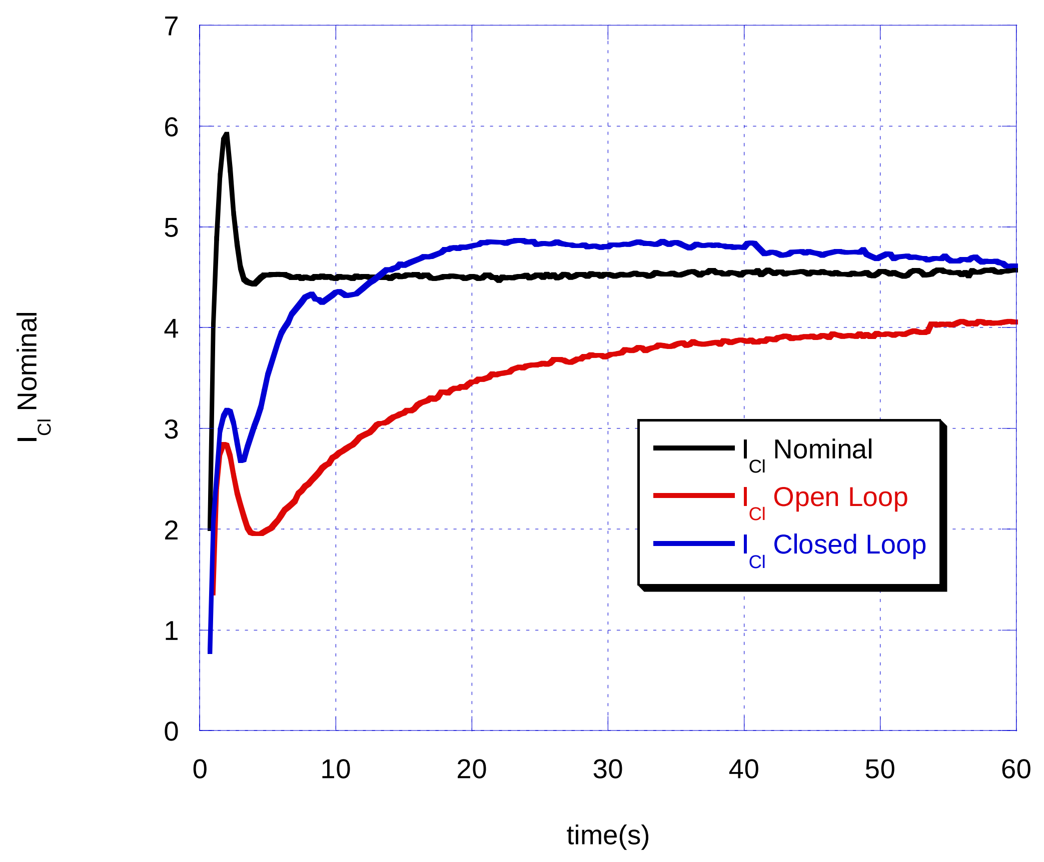
Intensity Ratio I_{Cl}/I_{Ar}

λ_{Ar}: 750.4nm
λ_{Cl}: 822.2nm



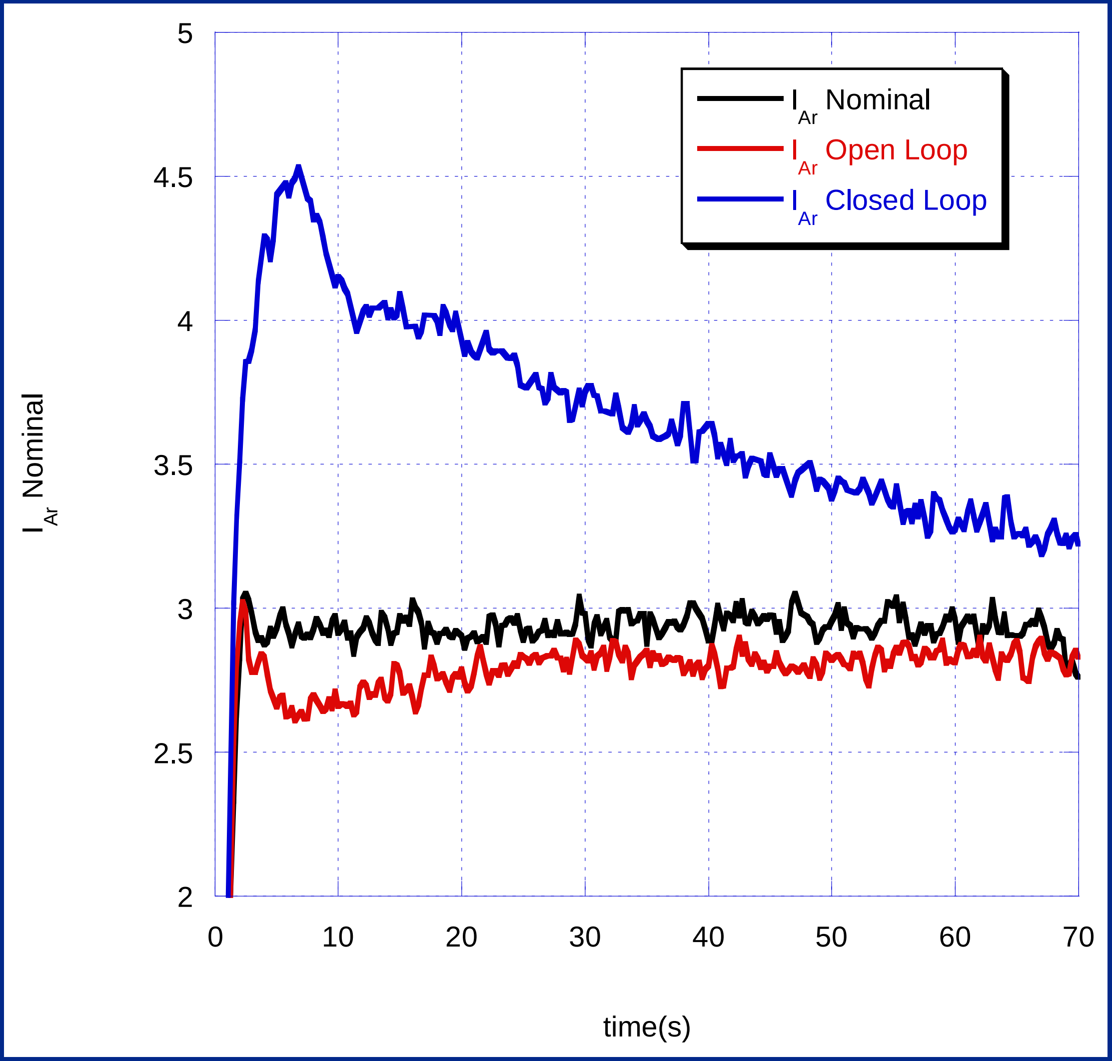
- After F-disturbance, both controlled & uncontrolled cases show similar Cl-neutral suppression and recovery.
- Simple Conclusion is that Ions (not neutrals) control etch rate for this process.

Cl Intensity



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

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:**

$(n_e \propto \omega_n^2)$

$$\boxed{\begin{array}{l} I_{Ar} = K_{Ar}(T_e)\, n_e n_{Ar} \\ I_{Cl} = K_{Cl}(T_e)\, n_e n_{Cl} \end{array}}$$

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

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

Now including the Ar actinometer concentration

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

The concentration of Ar is diluted by Cl_2 dissociation

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

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

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

Thus

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

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 (α_{Cl}’ & K_{Ar}’) possible if d (I_{Cl}/I_{Ar}) changes significantly enough in time

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

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

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

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

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

Fitting of OES Data

Fitting 2 constants (α_{Cl}’ & K_{Ar}’) possible if d (I_{Cl}/I_{Ar}) changes significantly enough in time

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

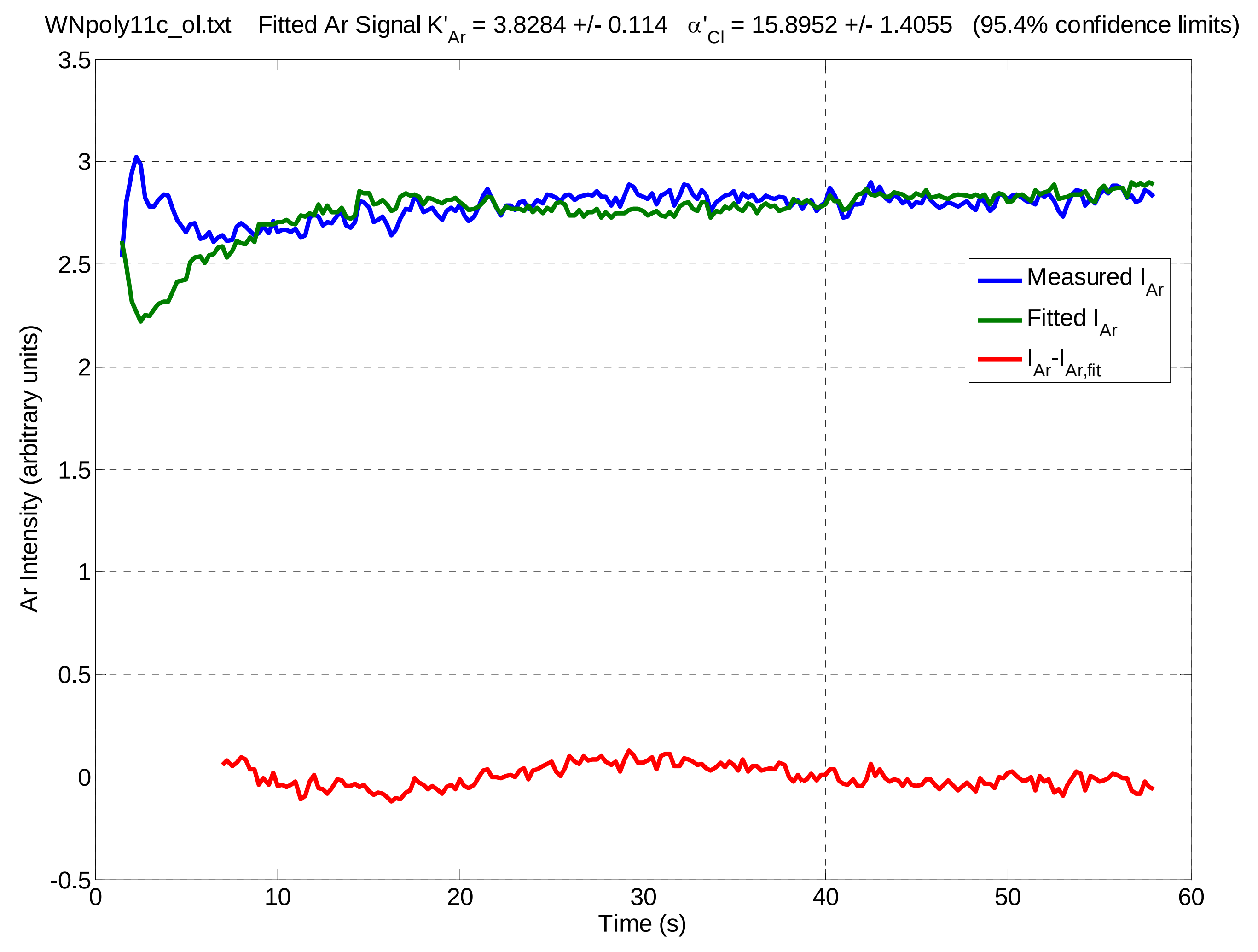
$$I_{Cl} = K_{Ar}'\omega_n^2 \left[\frac{f_{Ar} \left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}}{1+\frac{1}{2}\alpha_{Cl}^{'} f_{Ar} \left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}} \right]$$

$$d = \frac{1}{2}\alpha_{Cl}^{'} \left(\frac{f_{Ar}}{1-f_{Ar}}\right) \left[\frac{I_{Cl}}{I_{Ar}}\right]_{meas}$$

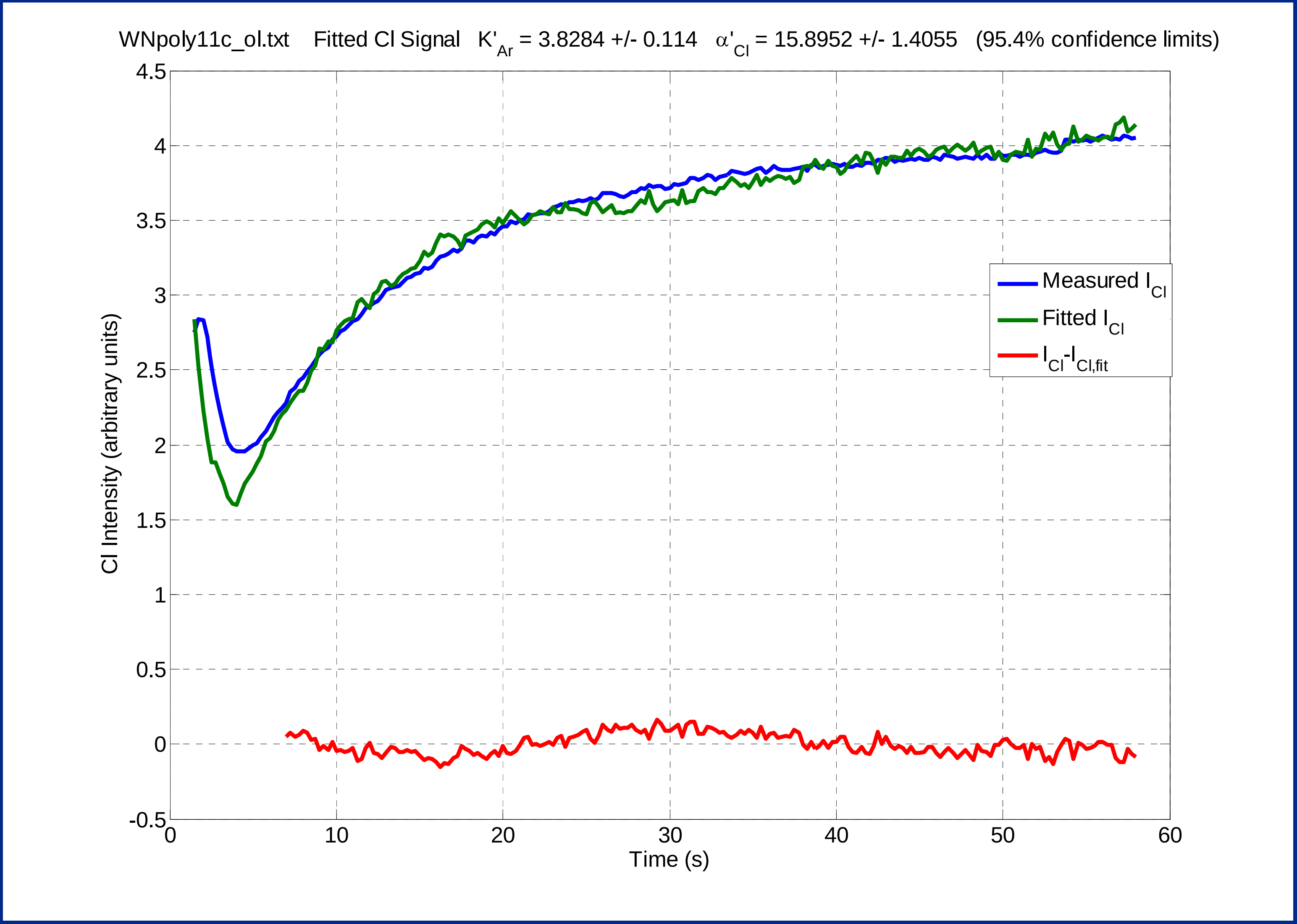
$$\frac{n_{Cl}}{n_g} = \left[\frac{2d\left(1-f_{Ar}\right)}{1+d\left(1-f_{Ar}\right)} \right]$$

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

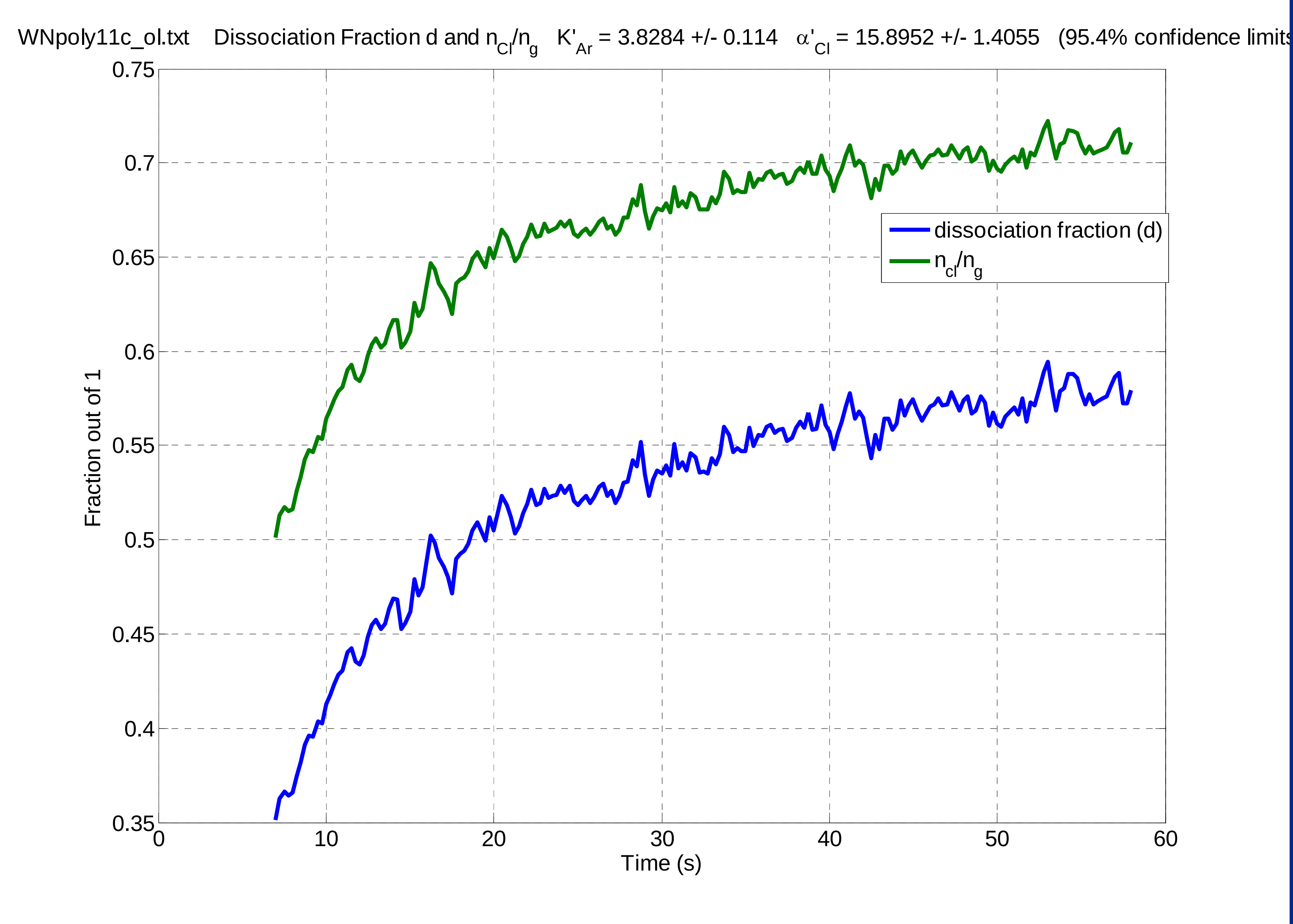
Ar OES Signal & Fit: $SiCl_4$ Ignored



Cl OES Signal & Fit: $SiCl_4$ Ignored



Cl_2 Net Dissociation: $SiCl_4$ Ignored



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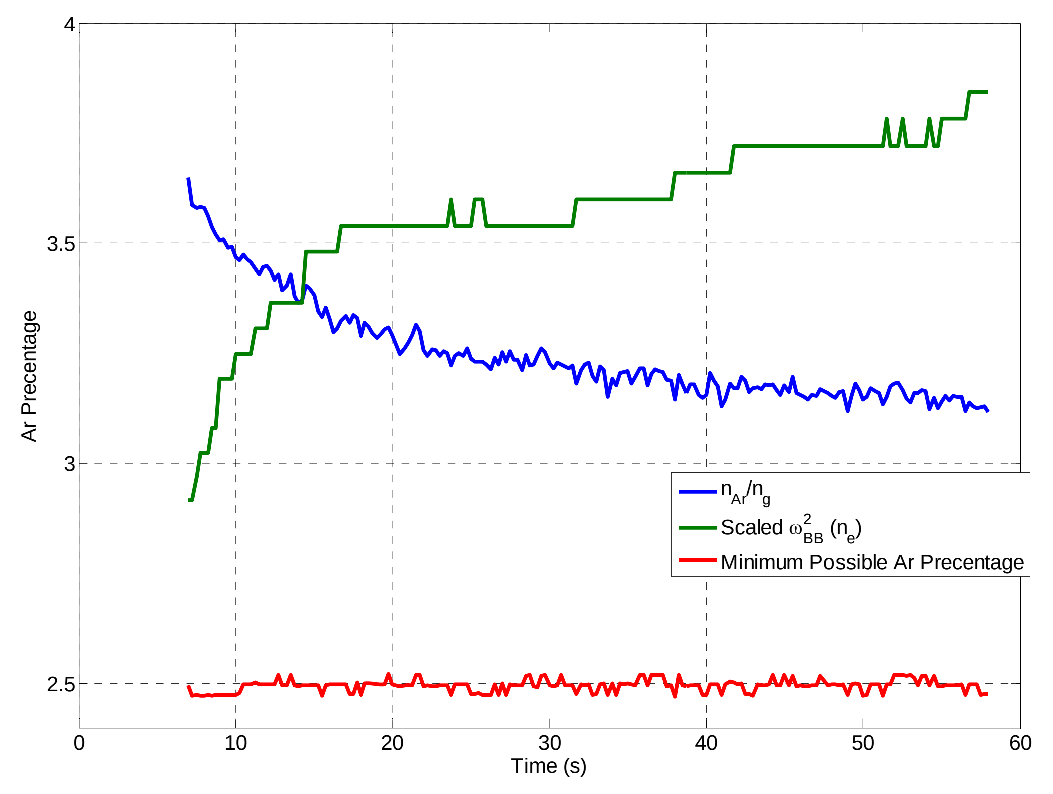
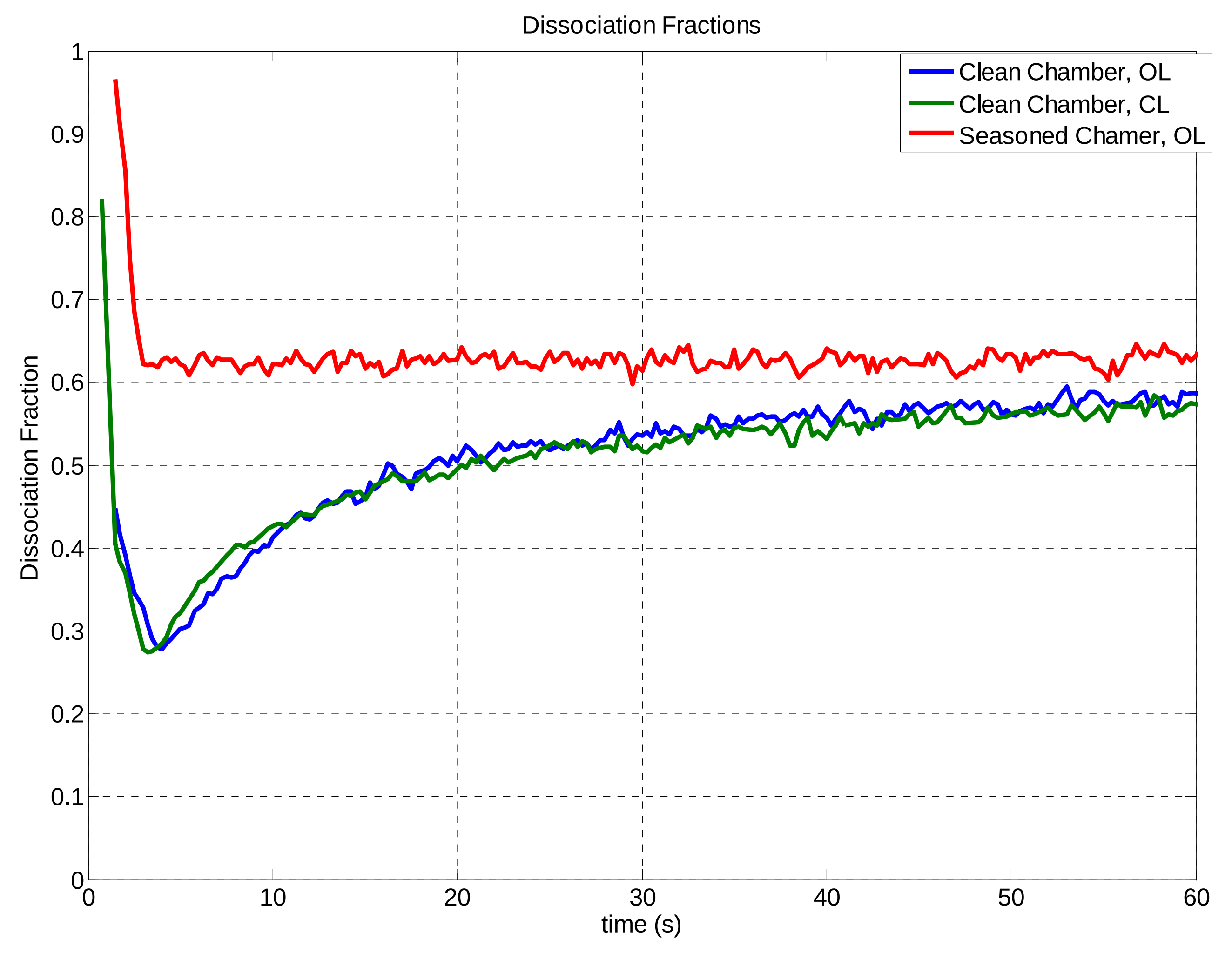
Ar Fraction: $SiCl_4$ Ignored



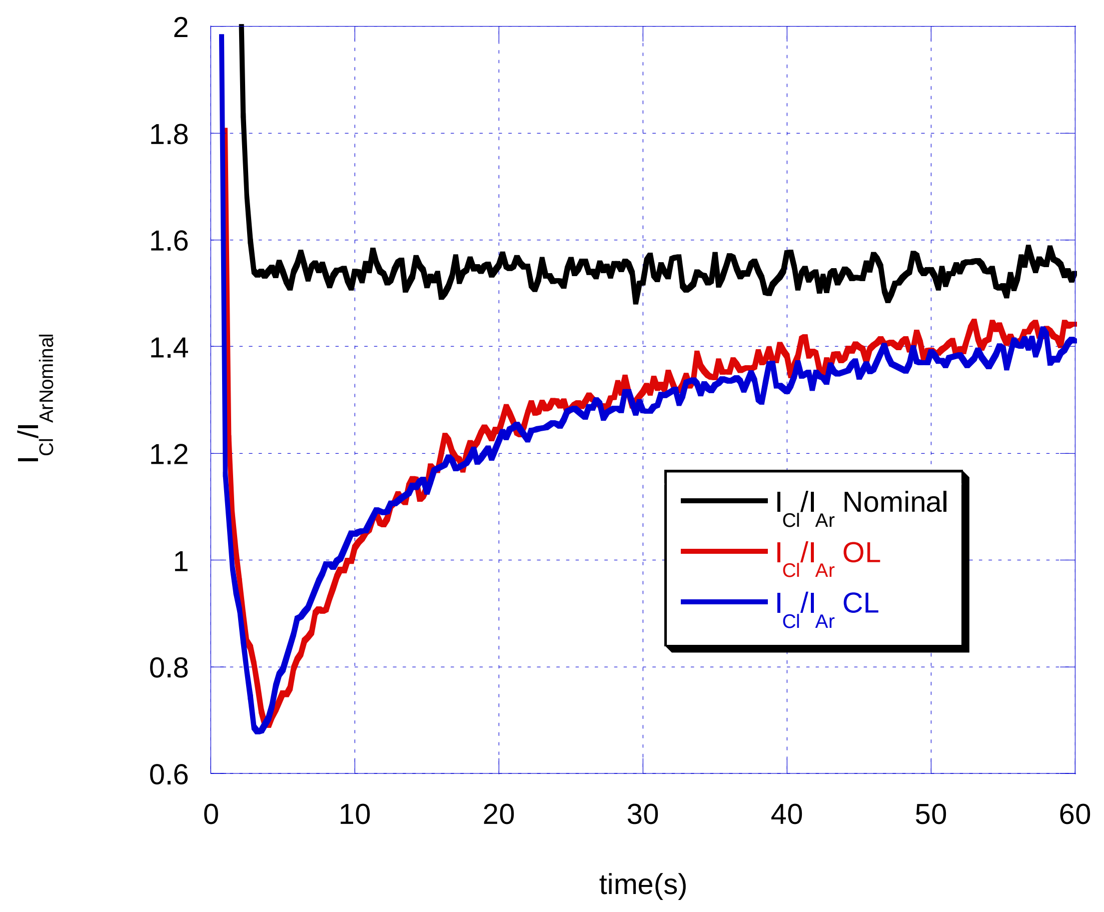
I_{Ar}(t) ~const. due to opposing effects of dilution (↓) & n_e (↑)

Dissociation Fractions: $SiCl_4$ Ignored



Intensity Ratio I_{Cl}/I_{Ar}

λ_{Ar}: 750.4nm
λ_{Cl}: 822.2nm



- Why is feedback controlled I_{Cl}/I_{Ar} still low? : GENERATION of Cl Is Increased but COMSUMPTION by Si Etching & Dilution by $SiCl_4$ Offset Generation

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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
$SiCl_4 + SiO_2 \rightarrow SiO_xCl_y + Cl + Cl_2$	Deposition Reactions (unbalanced)
$SiCl_4 + Al_2O_3 \rightarrow Al_vSi_zO_xCl_y + Cl + Cl_2$	

Simplified Reaction Set

Assuming Cl ionization and Si-species deposition

Reactions have small effects on gas species concentrations,

the other remaining reactions yield:

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

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

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

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

So

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

F_{Si} *(t)* Estimated From Real-Time Etch Rate (Spectroscopic Ellipsometry) and Si Area

Result of Simplified Reaction Set

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

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

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

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

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

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

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

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

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

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

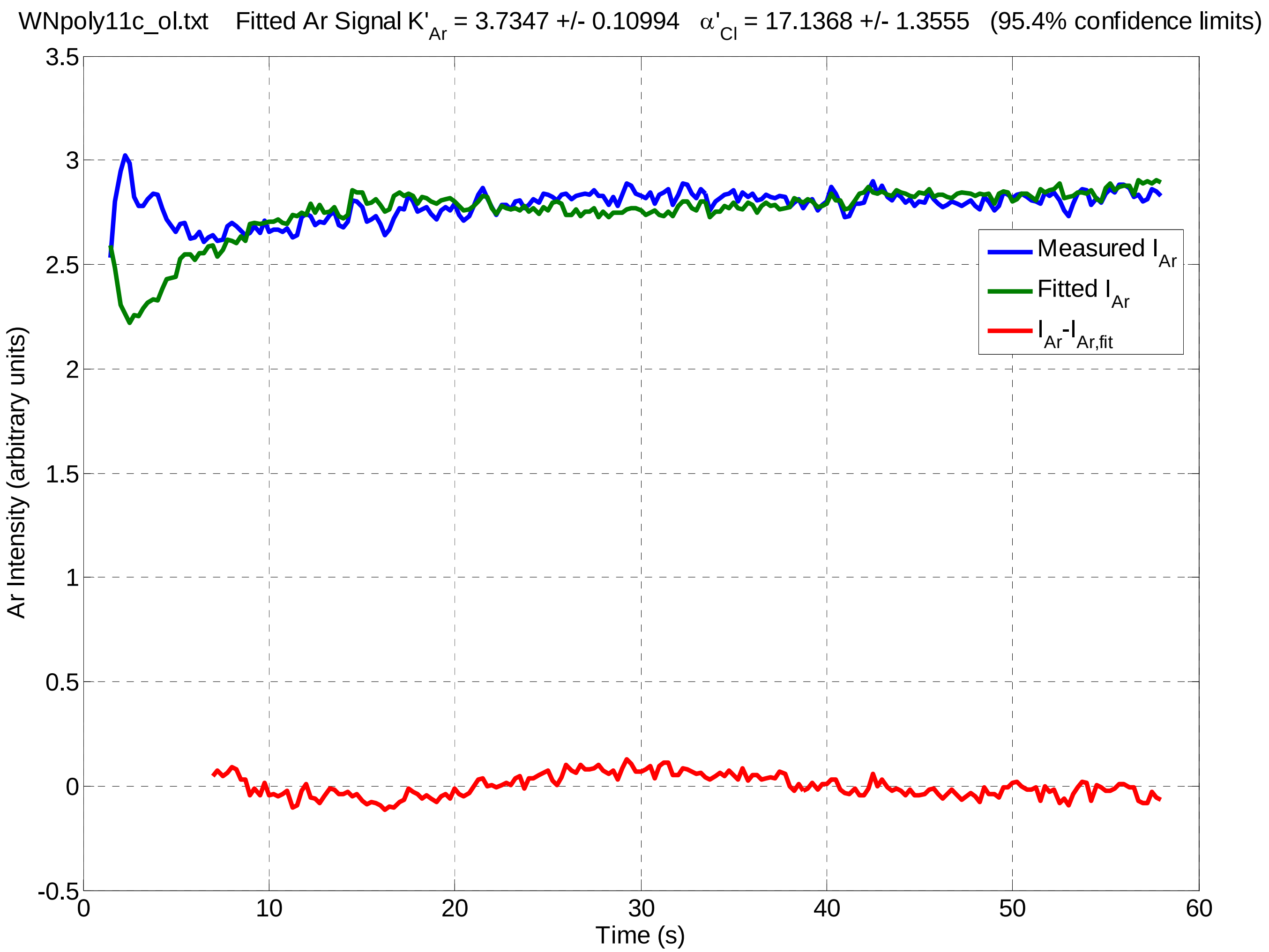
$$= P\omega_{BB}^2 \left[\frac{K'_{Ar} A_m F_{Ar}}{F_{Cl_2} + \left(1 + \frac{1}{2}\alpha'_{Cl} A_m\right) F_{Ar} - F_{Si}} \right]$$

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

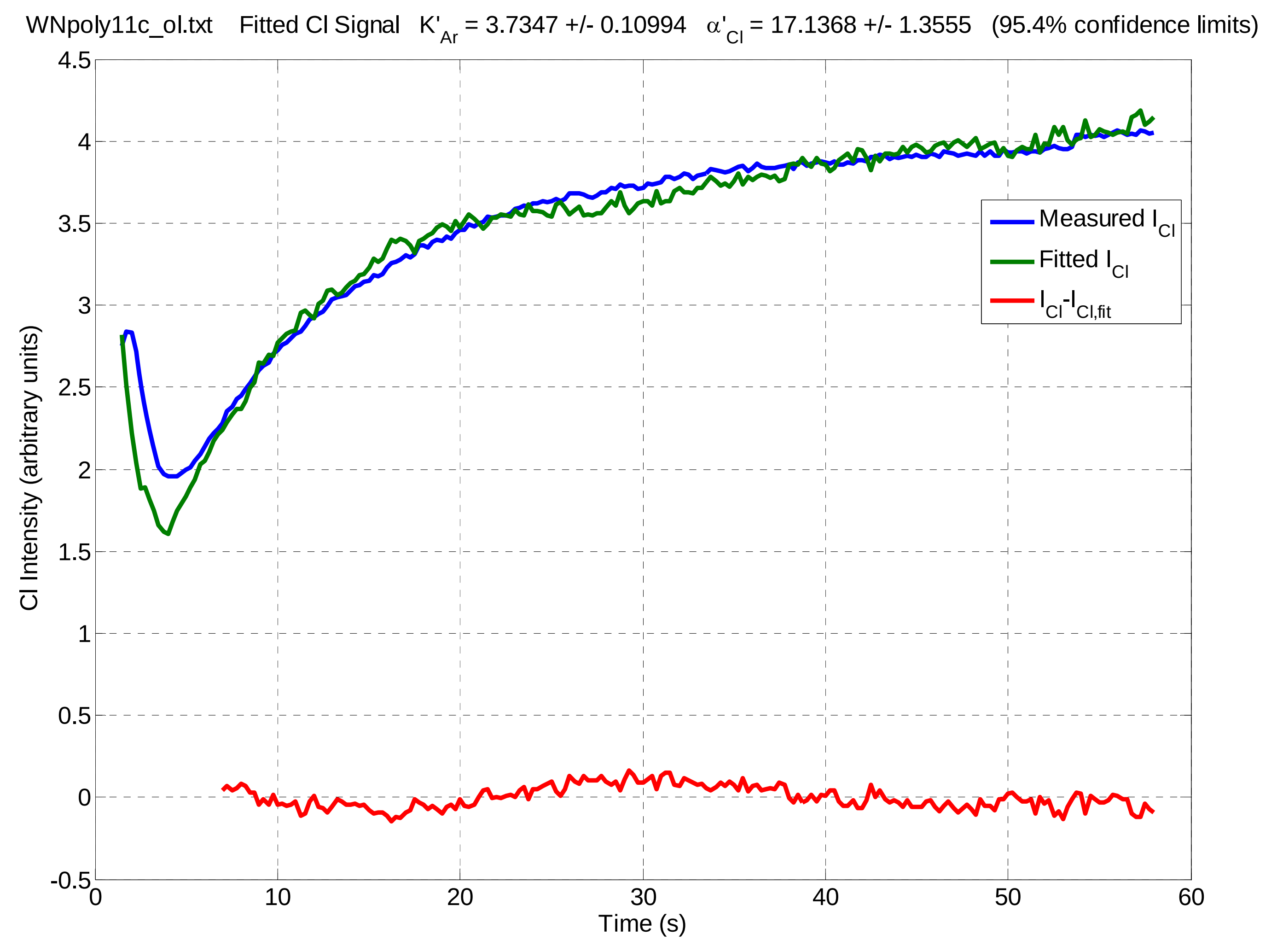
K'_{Ar} & α'_{Cl} are the only unknowns

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



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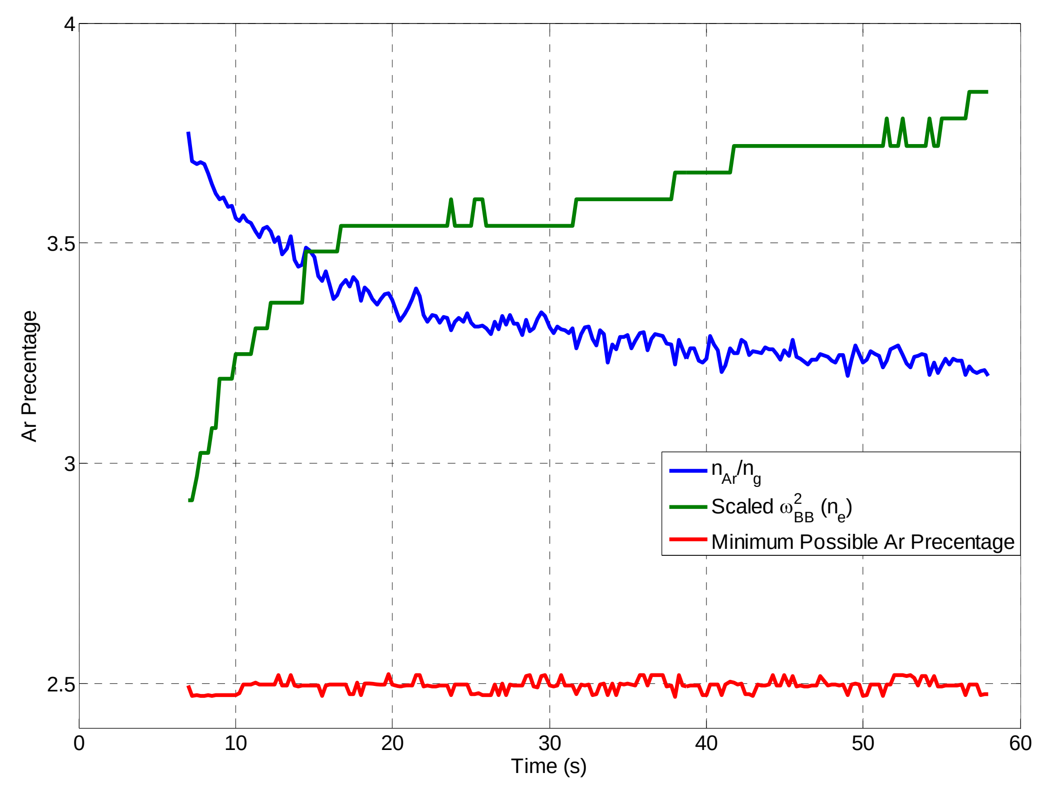
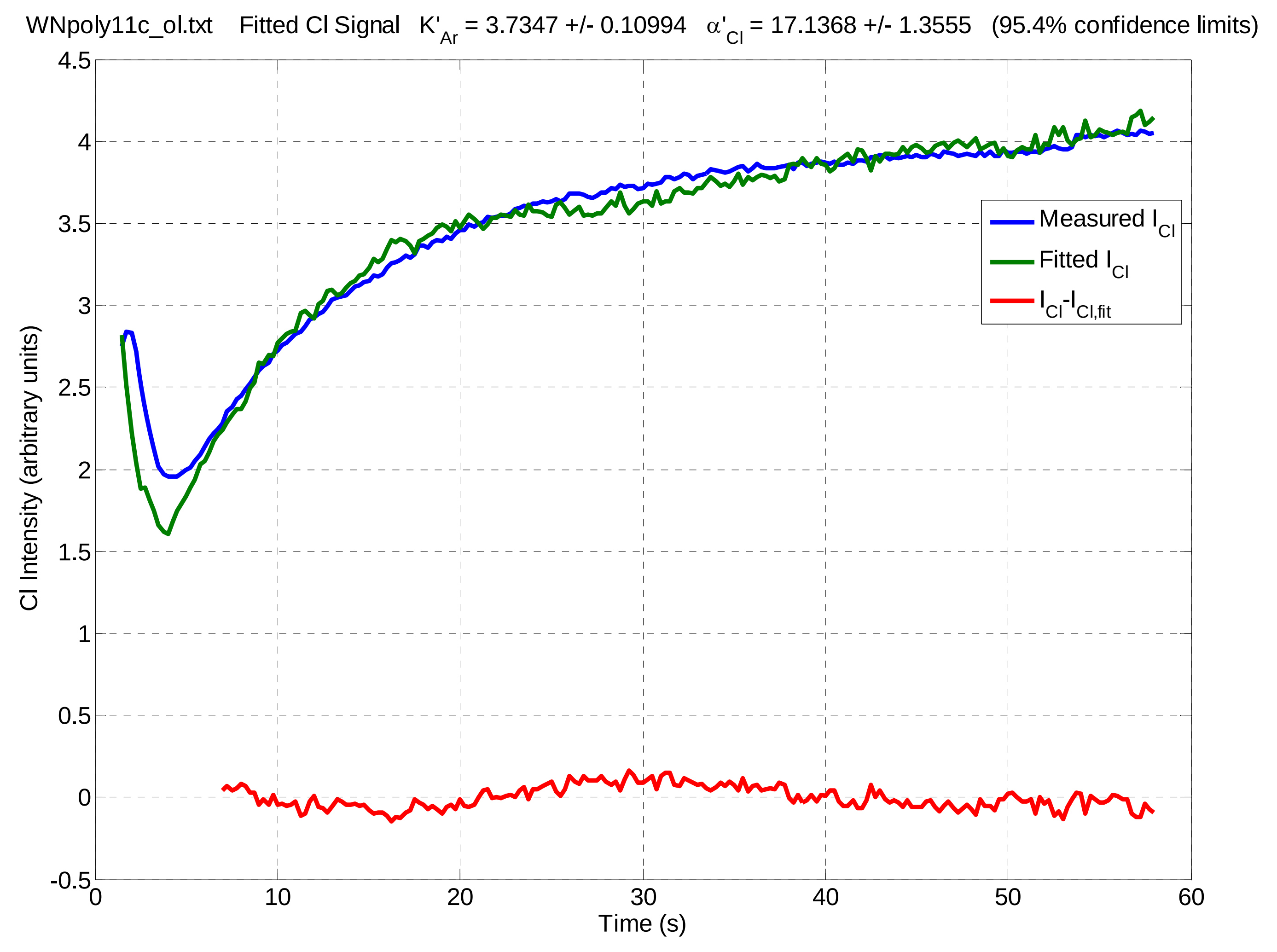
Ar Fraction : $SiCl_4$ Included from RTSE



Dissociation Fraction : $SiCl_4$ Included from RTSE



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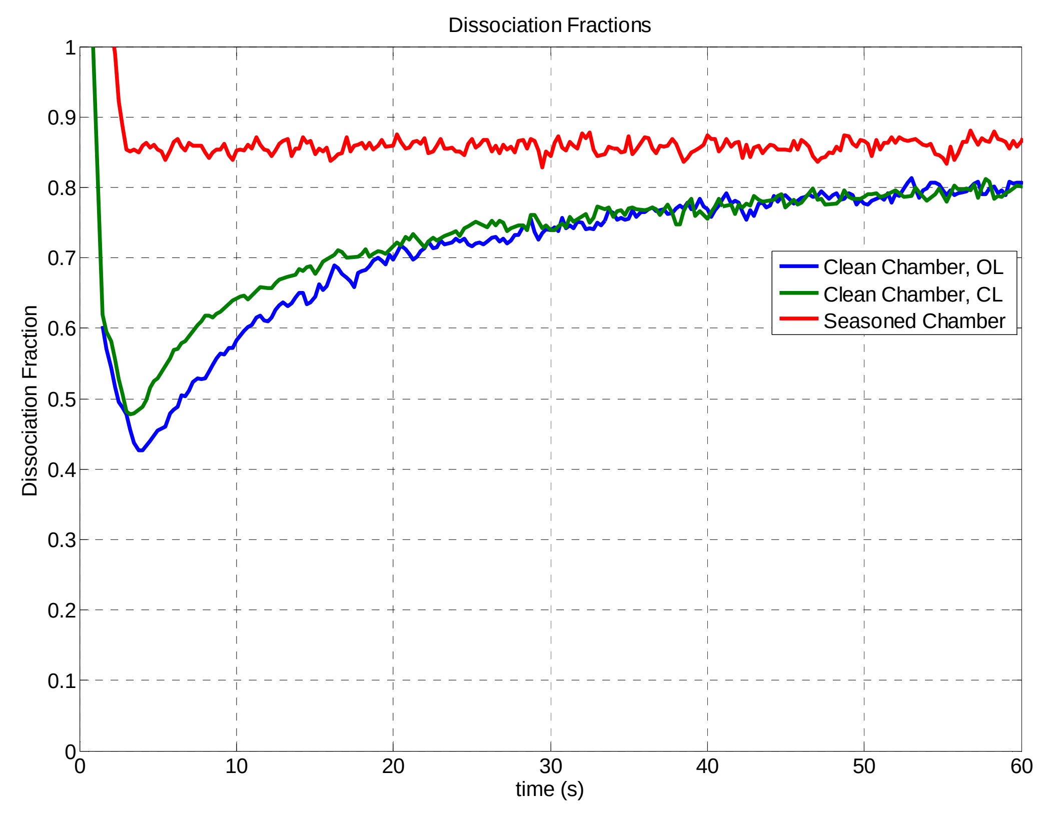
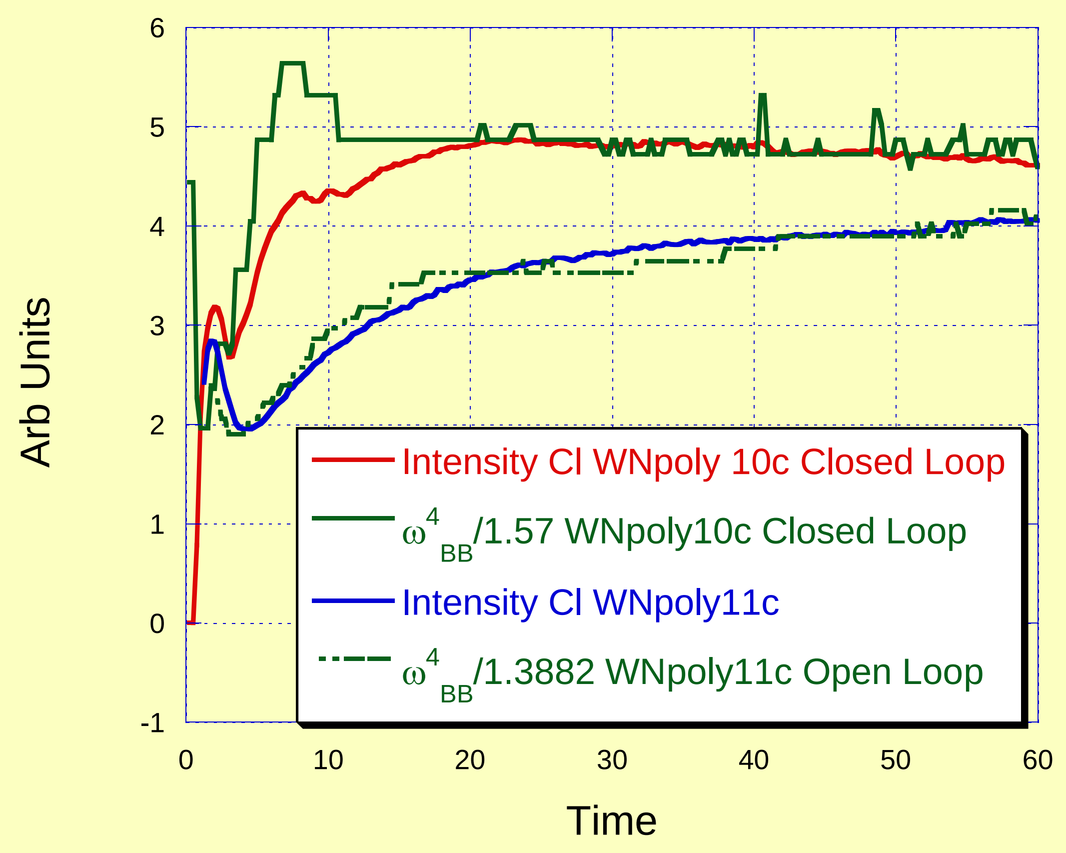
Dissociation Fractions: $SiCl_4$ Included from RTSE



- **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**

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}.

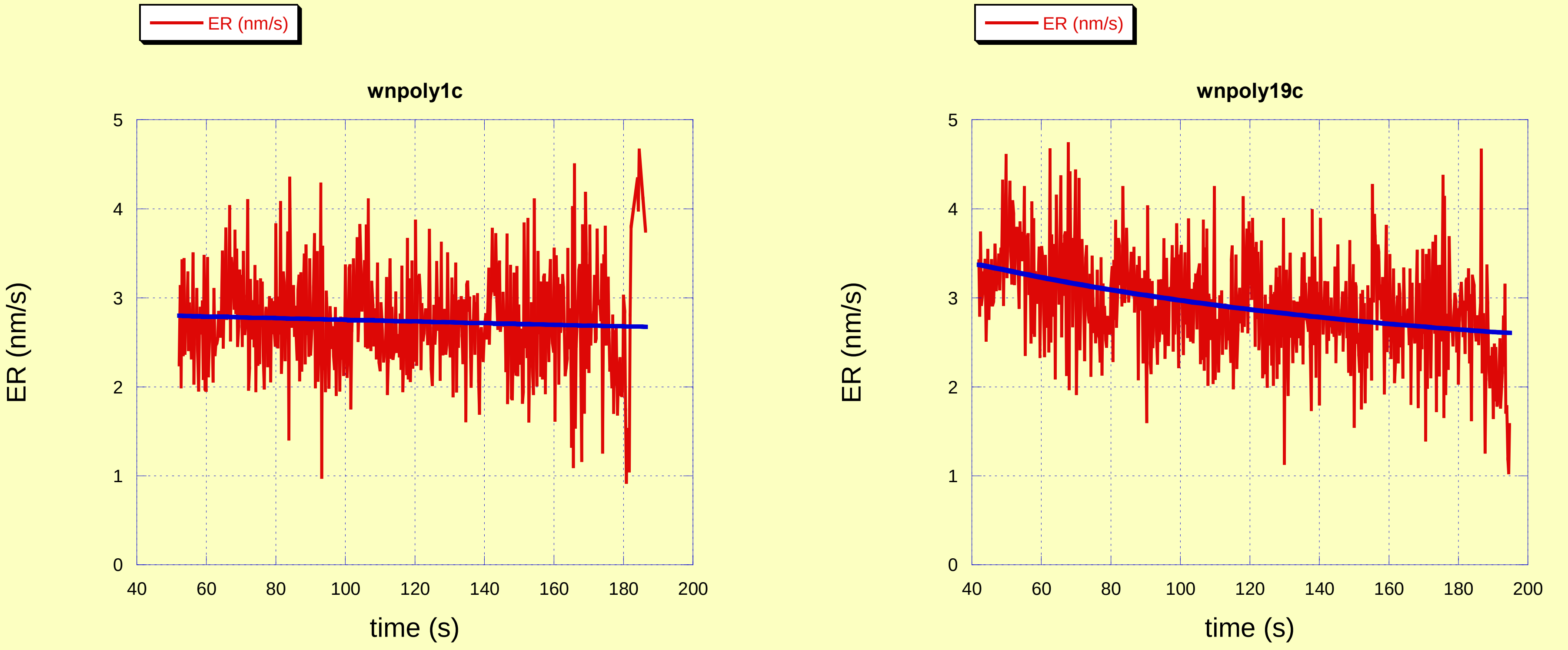
HBr/Cl_2 Etches

- 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 Density Limited & Future Work is Needed

HBr/Cl_2 Etch (80/20)

Open Loop

Closed Loop



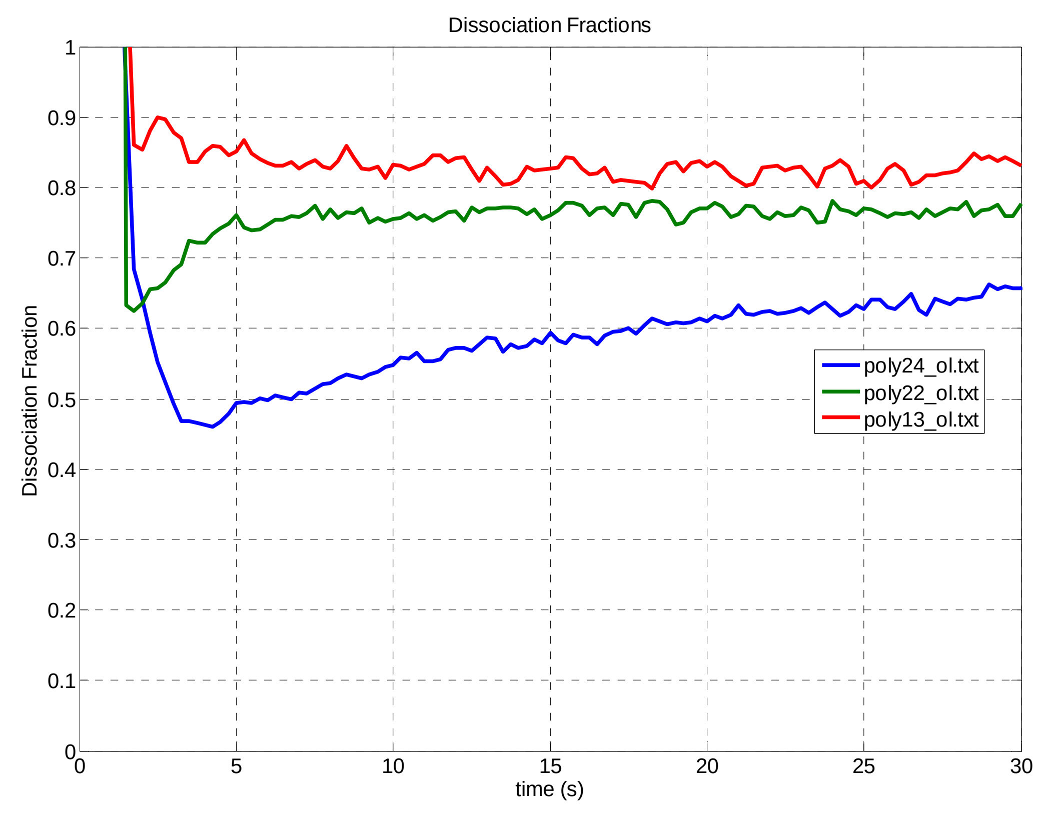
Future Work

- 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.

Supporting Materials

For Possible Q&A

Dissociations Fractions Including $SiCl_4$ from Open Loop Runs



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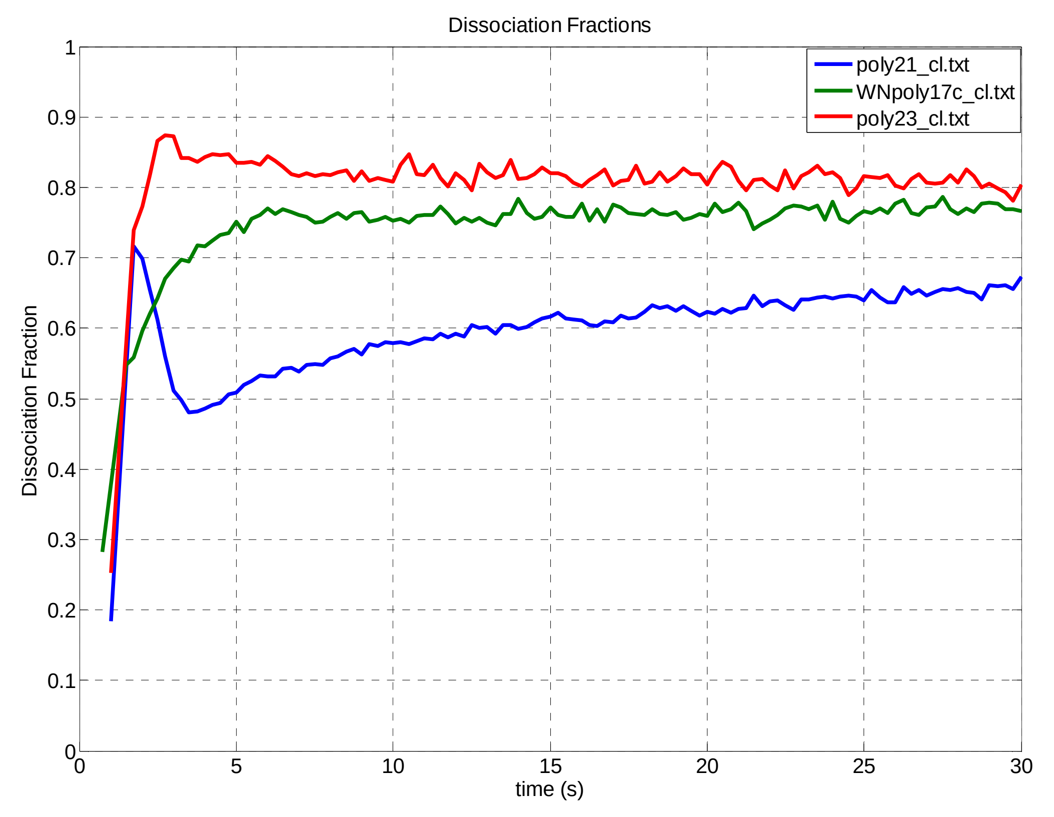
Dissociations Fractions Including $SiCl_4$ from Closed Loop Runs



Te Estimator Slides

For Possible Q&A

Bulk Ionization/Recombination

Generation/Ionization

of Neutral Cl by e's

$$Cl_0 + e^- \rightarrow Cl^+ + 2e^-$$

Bulk Plasma
Recombination
of Ions with e's

$$Cl^+ + e^- \rightarrow Cl_0$$

$$\frac{\partial n_{Cl^+}}{\partial t} = \overbrace{n_e n_{Cl^0}\left[\int_{E_i}^{\infty} \sigma_i(\varepsilon)\varepsilon e^{-\varepsilon/k_B T_e}\, d\varepsilon\right]}^{[Ionization\_Rate]} - \overbrace{\Gamma n_e n_{Cl^+}}^{[Bulk\_\mathrm{Re}combination\_Rate]}$$

$$= \underbrace{n_e n_{Cl^0} X_i(T_e)}_{[Ionization\_Rate]} - \underbrace{\Gamma n_e n_{Cl^+}}_{[Bulk\_\mathrm{Re}combination\_Rate]}$$

Steady-State

Solution

$$\frac{\partial n_{Cl^+}}{\partial t} = 0 \rightarrow n_{Cl^+} = \left[\frac{X_i(T_e)}{\Gamma}\right] n_{Cl^0} \rightarrow n_{Cl^0} = \left[\frac{\Gamma}{X_i(T_e)}\right] n_{Cl^+}$$

Electron Temperature and Broadband I

- Assuming Cl^+ loss rate dominated by bulk Cl^+ - e^- recombination yields steady state solution where $n_{Cl}{}^+$ depends on T_e but not n_e

$$n_{Cl^+} \approx \left[\frac{X_i(T_e)}{\Gamma} \right] n_{Cl^0}$$

- Assuming a Quasi-Neutral Plasma dominated by Cl^+ & e^-

-

$$n_{Cl^+} \approx n_e$$

- Cl Neutral Glow Intensity Coupled to n_e&$n_{Cl}{}^0$

$$I_{Cl} = n_e n_{Cl^0} X_0(T_e) S(\lambda_{cl}) = n_e^2 X_0(T_e) \left[\frac{\Gamma}{X_i(T_e)} \right] S(\lambda_{cl})$$

Electron Temperature and Broadband II

- Assuming Broadband peak frequency is a circuit/path-scaled electron plasma frequency

$$\omega_p^2 = \left(\frac{q^2 n_e}{m_e \varepsilon_0} \right) = D\omega_{BB}^2$$

$$\rightarrow n_e = A\omega_{BB}^2$$

- Combing last 4 equations yields

$$\left(\frac{\omega_{BB}^4}{I_{Cl}} \right) = \left[\frac{X_i(T_e)}{X_0(T_e)} \right] \left[\frac{1}{\Gamma S(\lambda_{cl})A} \right]$$

- Ratio measures relative ratio of ionization rate to metastable glow state excitation
- Sensitive to T_e due to significant difference between excitation thresholds for ionization and glow

Electron Temperature/Cl Glow Equations

Ionization/recombination

$$\frac{\partial n_{Cl^+}}{\partial t} = n_e n_{Cl^0}\left[\int_{E_i}^{\infty}\sigma_i(\varepsilon)\varepsilon e^{-\varepsilon/k_B T_e}\,d\varepsilon\right] - \Gamma n_e n_{Cl^+}$$
$$= n_e n_{Cl^0} X_i(T_e) - \Gamma n_e n_{Cl^+}$$

$\downarrow$

$$\frac{\partial n_{Cl^+}}{\partial t} = 0$$
$$\rightarrow n_{Cl^+} = \left[\frac{X_i(T_e)}{\Gamma}\right] n_{Cl^0}$$
$$\rightarrow n_{Cl^0} = \left[\frac{\Gamma}{X_i(T_e)}\right] n_{Cl^+}$$

Steady

State

$\downarrow$

$$n_{Cl^+} \approx n_e$$

Quasi-

Neutrality

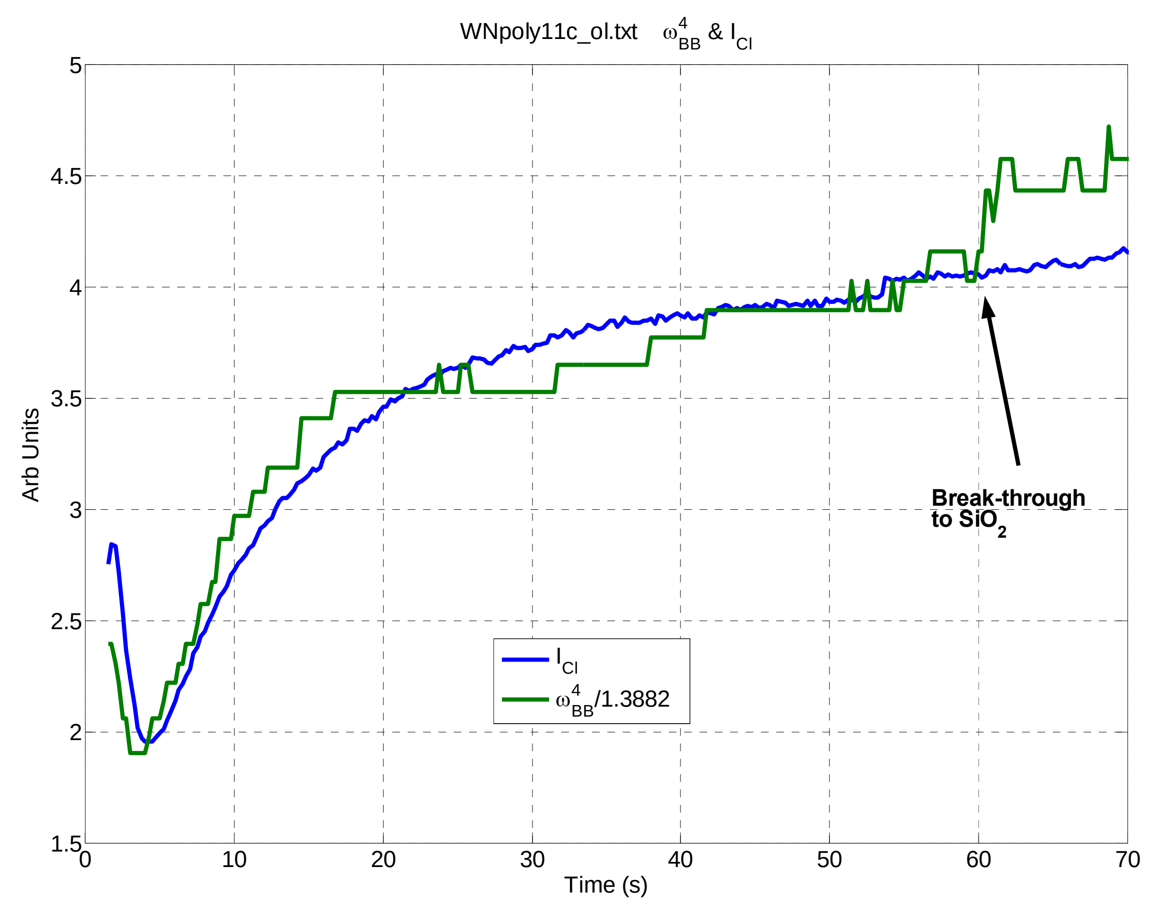
Neutral Glow

$$I_{Cl} = S(\lambda_{cl}) n_e n_{Cl^0}\left[\int_{E_{Cl0}}^{\infty}\sigma_0(\varepsilon)\varepsilon e^{-\varepsilon/k_B T_e}\,d\varepsilon\right]$$
$$= n_e n_{Cl^0} X_0(T_e) S(\lambda_{cl})$$

Combining for ratio

$$= n_e\left[\frac{\Gamma}{X_i(T_e)}\right] n_{Cl^+} X_0(T_e) S(\lambda_{cl})$$
$$= \left[\frac{X_0(T_e)}{X_i(T_e)}\right]\Gamma S(\lambda_{cl}) n_e^2$$
$$= \left[\frac{X_0(T_e)}{X_i(T_e)}\right]\Gamma S(\lambda_{cl}) A\omega_{BB}^4$$
$$\left(\frac{\omega_{BB}^4}{I_{Cl}}\right) = \left[\frac{X_i(T_e)}{X_0(T_e)}\right]\left[\frac{1}{\Gamma S(\lambda_{cl}) A}\right]$$

Cl OES Signal & BB Signal: Open Loop/Clean Chamber



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