Application of insitu Plasma Measurement Techniques on Etch Hardware Design and Process Development for 60nm Structures

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Outline

- *Challenges in Dry Etch Technology today*
- Paradigm Shift in Process Development
- *Insitu* Plasma Measurement Techniques for Hardware Design and Process Development
- Application on Chamber and Process Development
  - Power dissipation and RF frequencies
  - Chamber conditioning
  - Process development
- Conclusions and Summary

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Demands of Dry Etch Technology Development

DRAM Dry Etch Challenge	Feature Size		
	6x nm	5x nm	4x nm
Deep Trench Mask Open Aspect Ratio	30	35	40
Deep Trench Aspect Ratio	80	100	120
Deep Trench CD control	6nm	5nm	4nm

- Main challenges for future dry etch technology development:
  - Increasing aspect ratio
  - Tight CD control
  - Mask selectivity
  - Uniformity improvement on 300mm wafers

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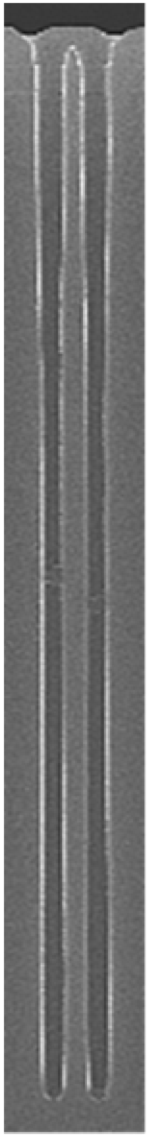
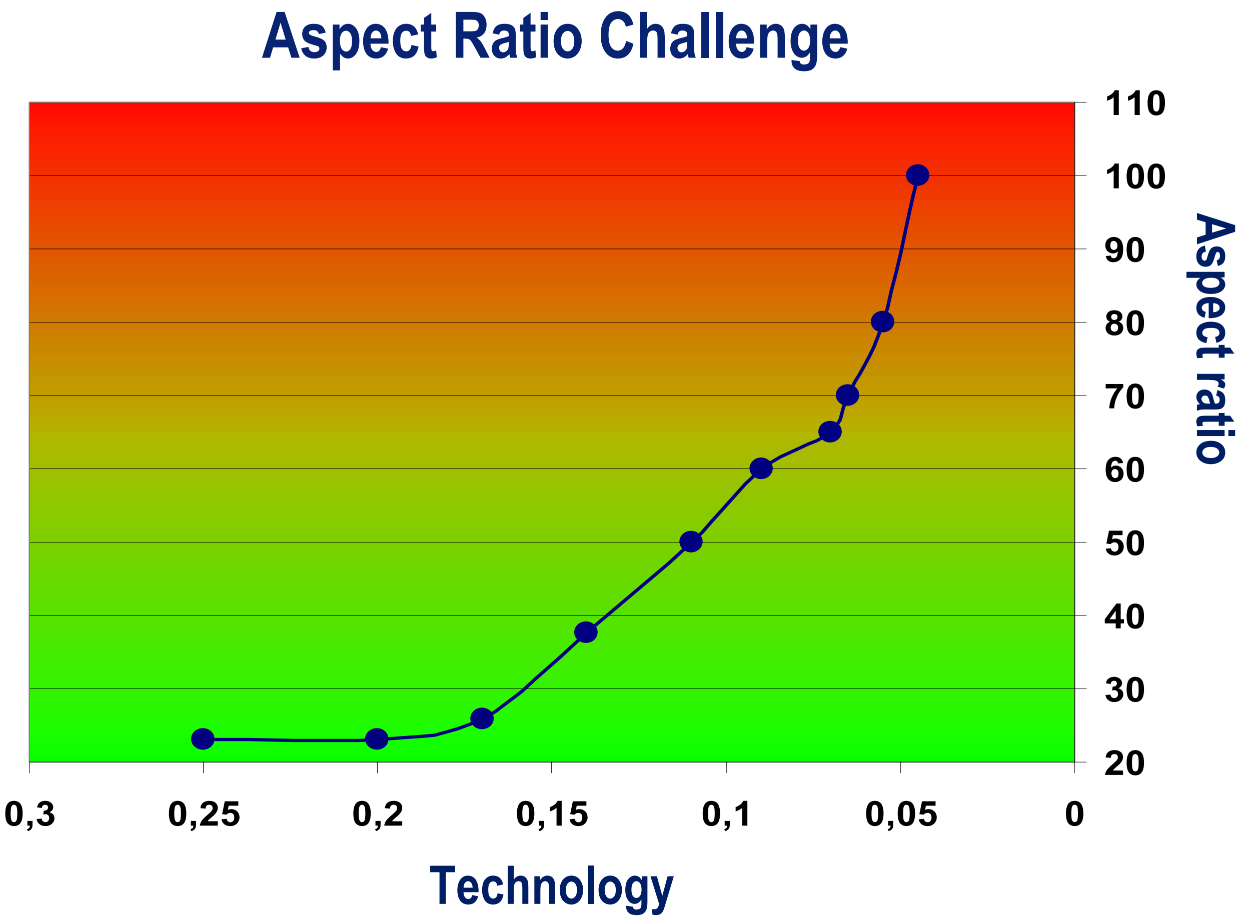
Example of Technology Challenge: Deep Trench Aspect Ratio at DRAM





- Aspect ratio increases exponentially !

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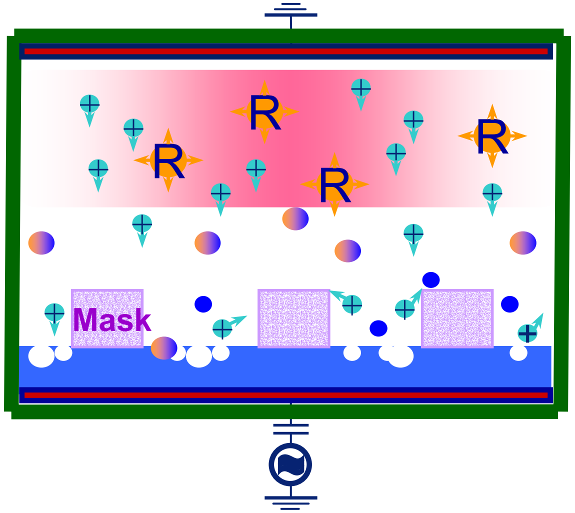
Conventional Methodology at Plasma Process Development



Chamber = Toolbox
Plasma = Tool:
in non-equilibrium and non-linear
Transport processes:
non-linear
Reactions on wafer:
non-equilibrium chemistry

- Present Methodology:
  - Offline measurements on blank and patterned wafers after process
  - Experience and statistical analysis (DOE)
  - *Insitu* measurement methods are rarely used
- Needed:
  - Sufficient characterization and control of wafer surface conditions
  - Significantly improved “tool” = plasma characterization

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Paradigm Shift at Plasma Process Development

- Paradigm shift:
  - **Joint development** of chamber hardware and process **by tool vendors and customers**
  - **Joint application of *insitu* and *exsitu* measurement methods** for chamber hardware design and process development
- Goal: Process development excellence
  - Increase of process development efficiency
  - Reliable tool hardware and process as basic requirement **of AEC/APC**
- The following measurement methods have been used:
  - Quadrupol Mass Spectroscopy (QMS)
  - Optical Emission Spectroscopy (OES) with high and low resolution
  - Self-Excited Electron Resonance Spectroscopy (SEERS)
  - RF voltage, current and phase measurement (V,I Probe)
  - RF Network Analysis

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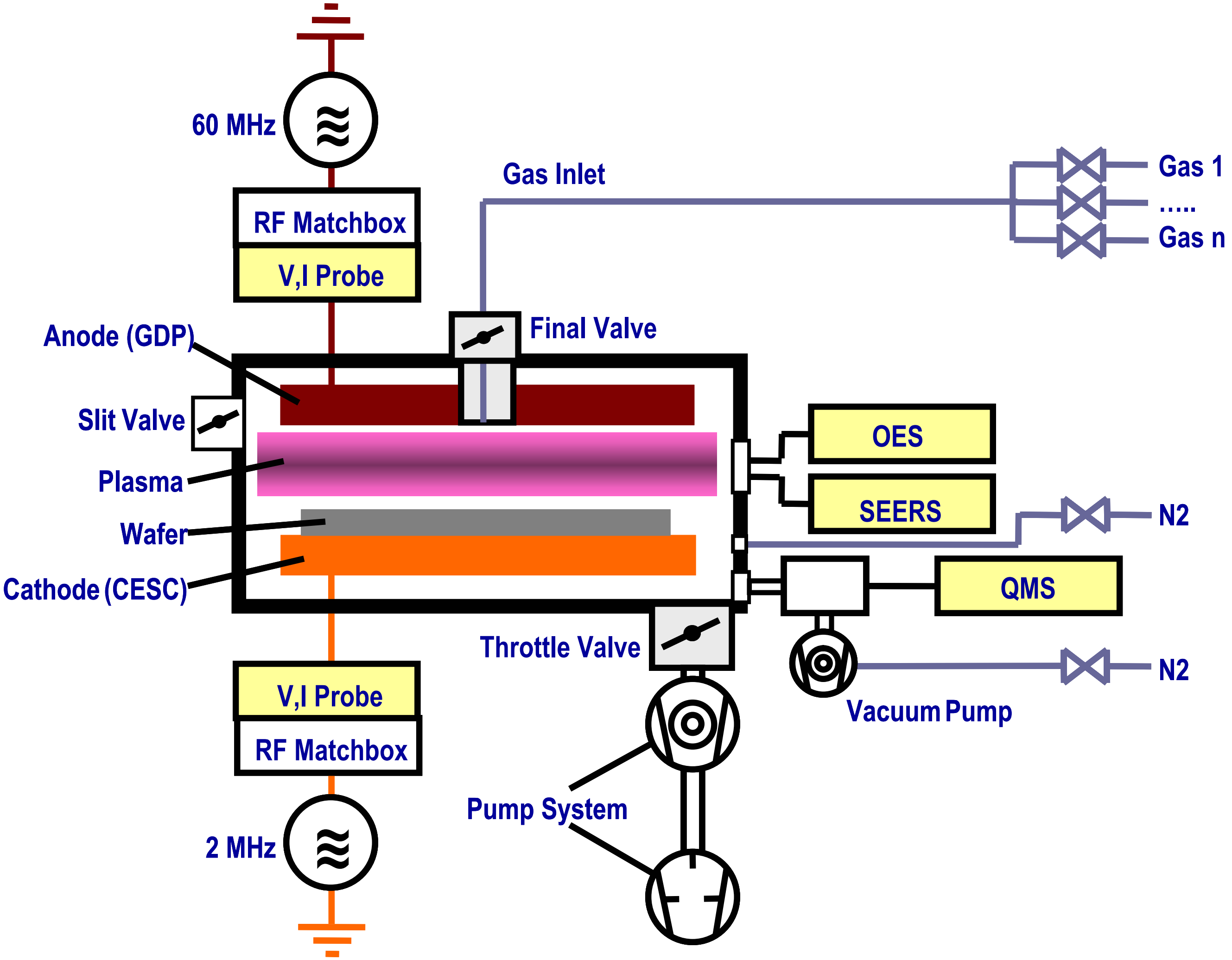
Measurement Equipment Setup for Chamber Hardware and Process Development at 300mm Etch Chamber



- All experiments performed in production environment

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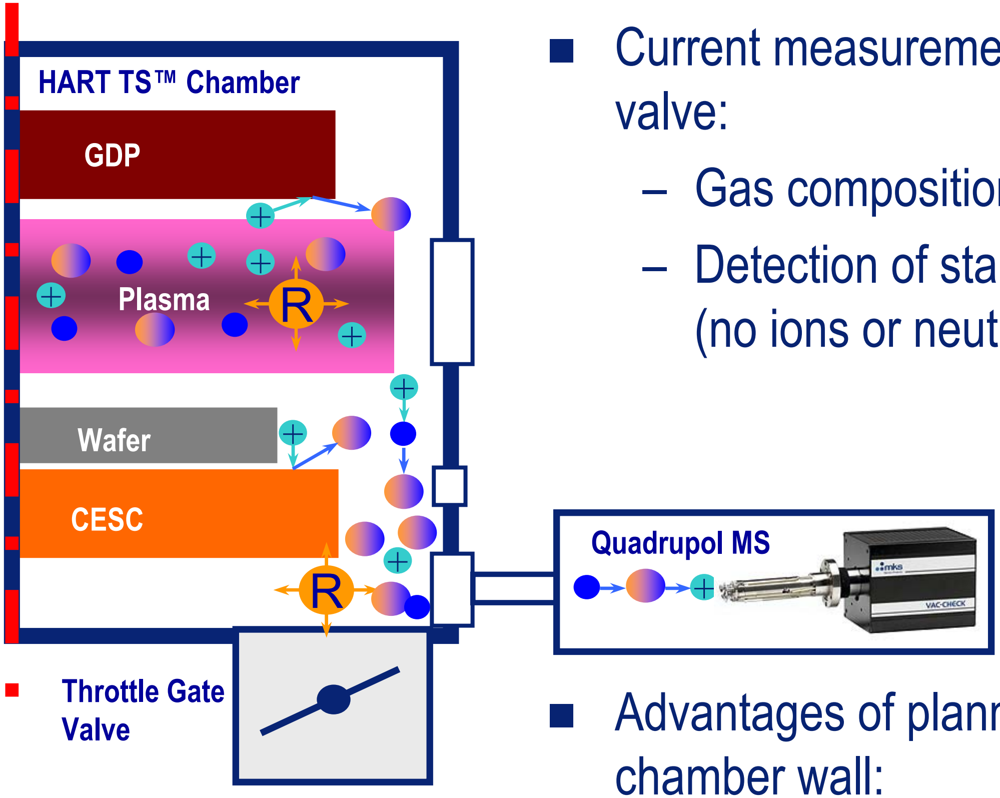
Quadrupol Mass Spectroscopy (QMS)



- Current measurement position above throttle valve:
  - Gas composition analysis
  - Detection of stable gas components (no ions or neutrals)
- Advantages of planned QMS installation at chamber wall:
  - Detection of ions and neutrals
  - Measurement of plasma potential
  - Ion energy analysis at chamber wall

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Optical Emission Spectroscopy (OES)

Low resolution OES	**High resolution OES**
	
Hamamatsu Optical Multichannel Analyzer (OMA)	Acton Research Spectrometer Focal length: 500 mm
■ Spectral range: 200nm – 950nm ■ Resolution: **> 1nm** ■ Sampling rate: min. **20ms** per full spectrum	■ Spectral range: 300nm – 900nm ■ Spectral Resolution: app. **0.2nm** ■ Sampling rate: app. **90s** per full spectrum
➔ Focus on complex DoE parameter scans	**➔ Focus on detailed analysis of molecular species**

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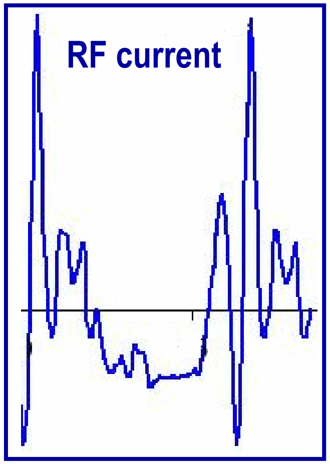
Self Excited Electron Resonance Spectroscopy (SEERS)



$$\nu_{\text{eff}} \approx \nu_{\text{stoch}} + \frac{p}{kT_n}\sum\frac{p_i}{p}\cdot\sigma\left(v_e^{-1}\right)\cdot v_e$$

$$\tilde{n}_e \approx \left(\frac{1}{V}\int_V n^{-1}\,dV\right)^{-1}$$

- Electrons are key in electrically excited plasma
- Electron collision rate ν_{eff} reflects:
  - Excitation
  - Ionization rates
- Electron density n_e is:
  - Plasma density
  - total number of positive - negative ions

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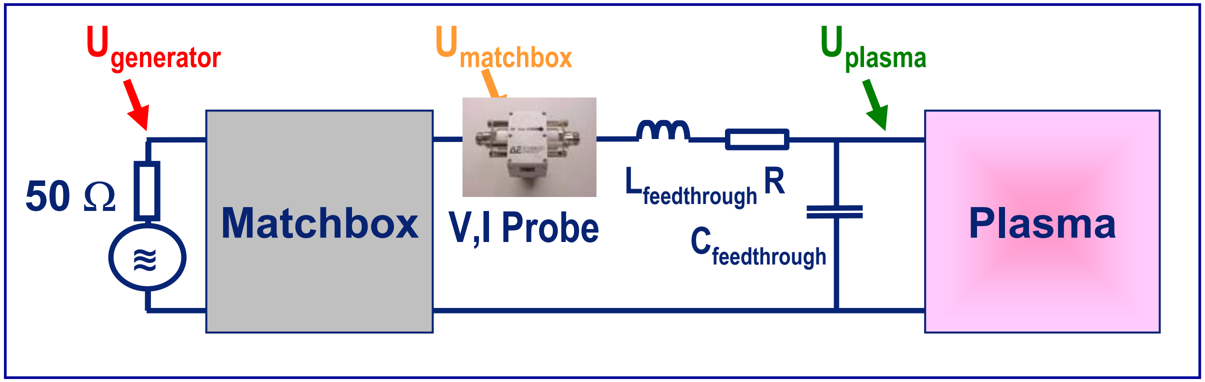
RF Voltage and Power Measurement by V,I Probe



- Measurement of RF voltage, current and phase at RF matchbox output
  - RF power dissipation in feedthrough and plasma can not be separated
  - Above chamber resonance frequency feedthrough impedance dominates load impedance → significant voltage difference between RF matchbox output and plasma

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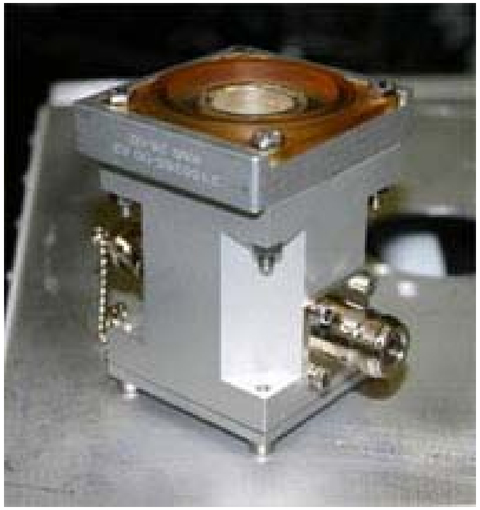
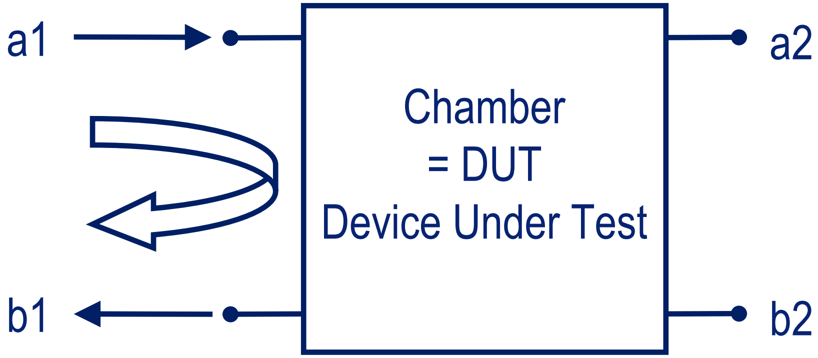
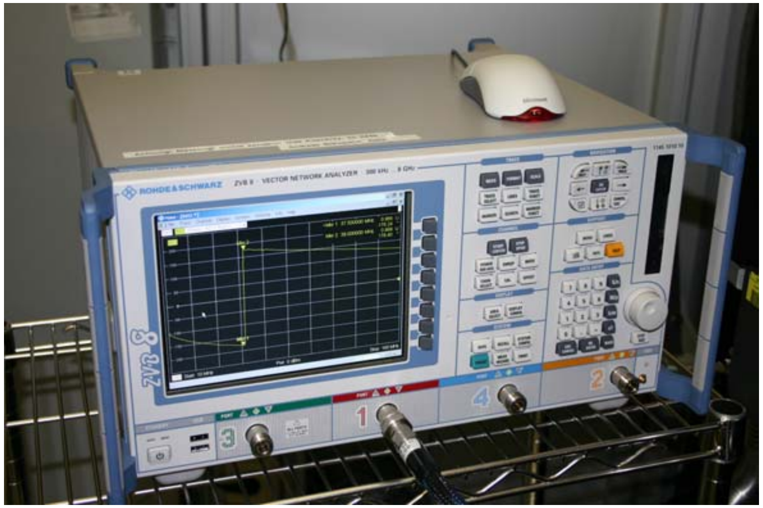
Chamber Impedance Measurement by Network Analyzer





- Measurement of chamber and feedthrough impedance without plasma by Network Analyzer

$$S_{11} = \frac{b_1}{a_1}\bigg|_{a_2 = 0}$$



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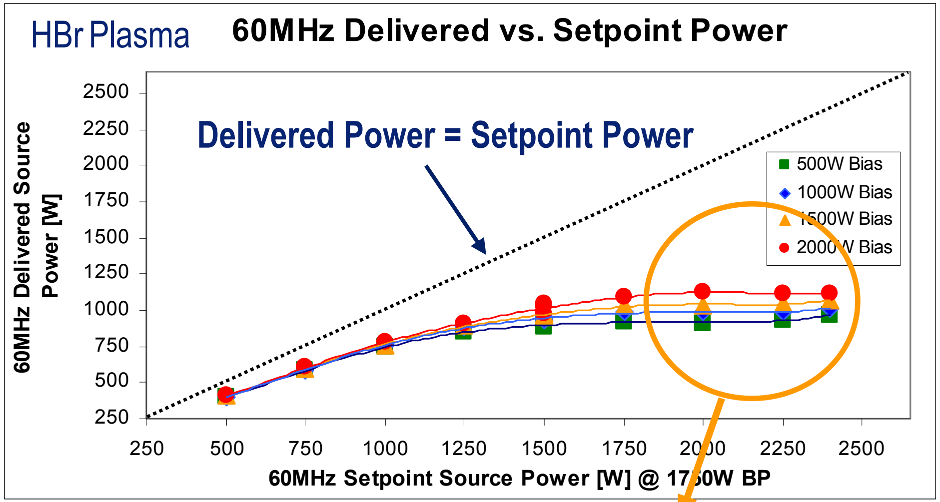
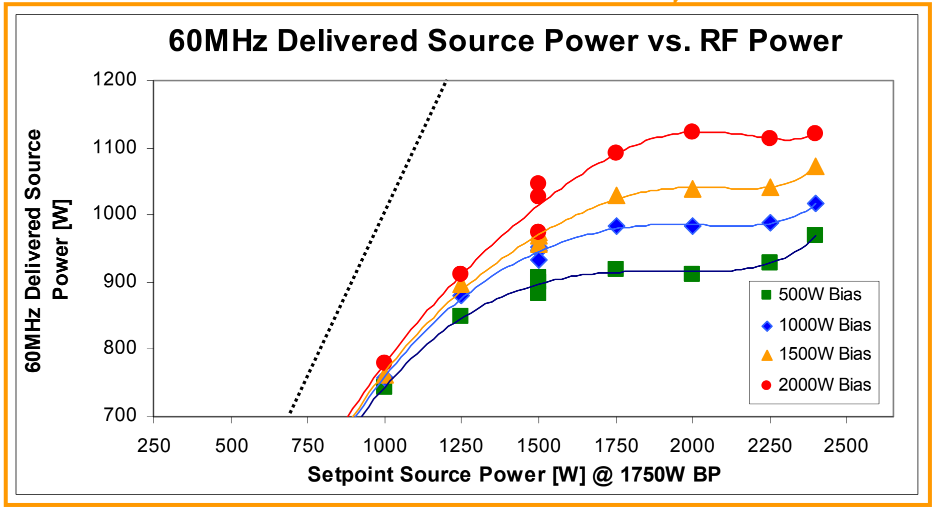
Power Dissipation and RF Frequencies: 2MHz Bias Power Impact on 60MHz Source Power





- Interaction of 2MHz and 60MHz RF power sources was detected by V,I probe measurements
- 60MHz source power loss increases with:
  - Higher nominal source power
  - Decreasing 2MHz Bias Power
- Possible root causes: RF matching limits, temperature drift effects

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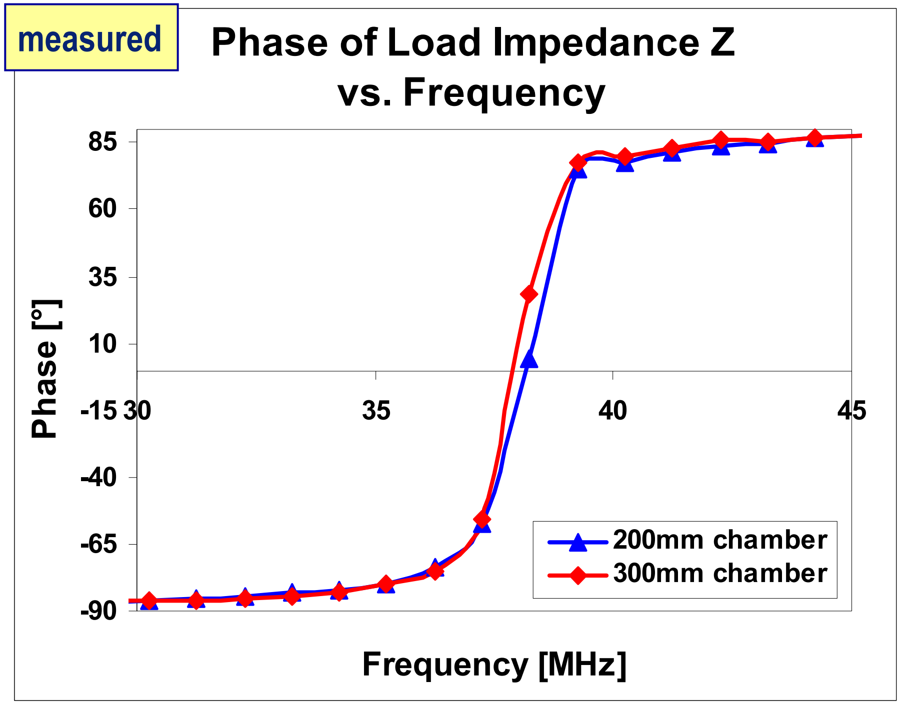
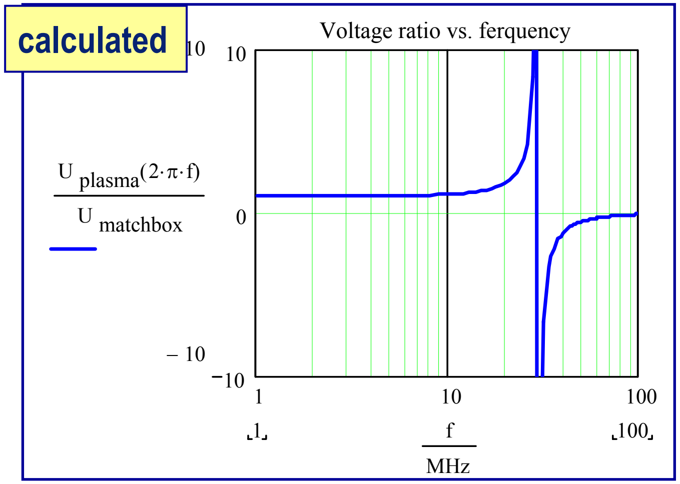
Power Dissipation and RF Frequencies: Chamber Resonance Frequency Analysis





$$U_{plasma}(\omega) := U_{matchbox} \frac{1}{1 - \omega^{2} \cdot C_{feedthrough} \cdot L_{feedthrough}}$$

See Presentation 1.3 at 5th European AEC&APC Conference, Dresden, 2004

- Resonance frequency at about 37 …38 MHz
- Resonance frequency depends mainly on RF feedthrough
  → Nearly no impact of chamber geometry (200 mm or 300 mm)
- 60MHz excitation is above chamber resonance
  → considerable RF voltage loss at feedthrough

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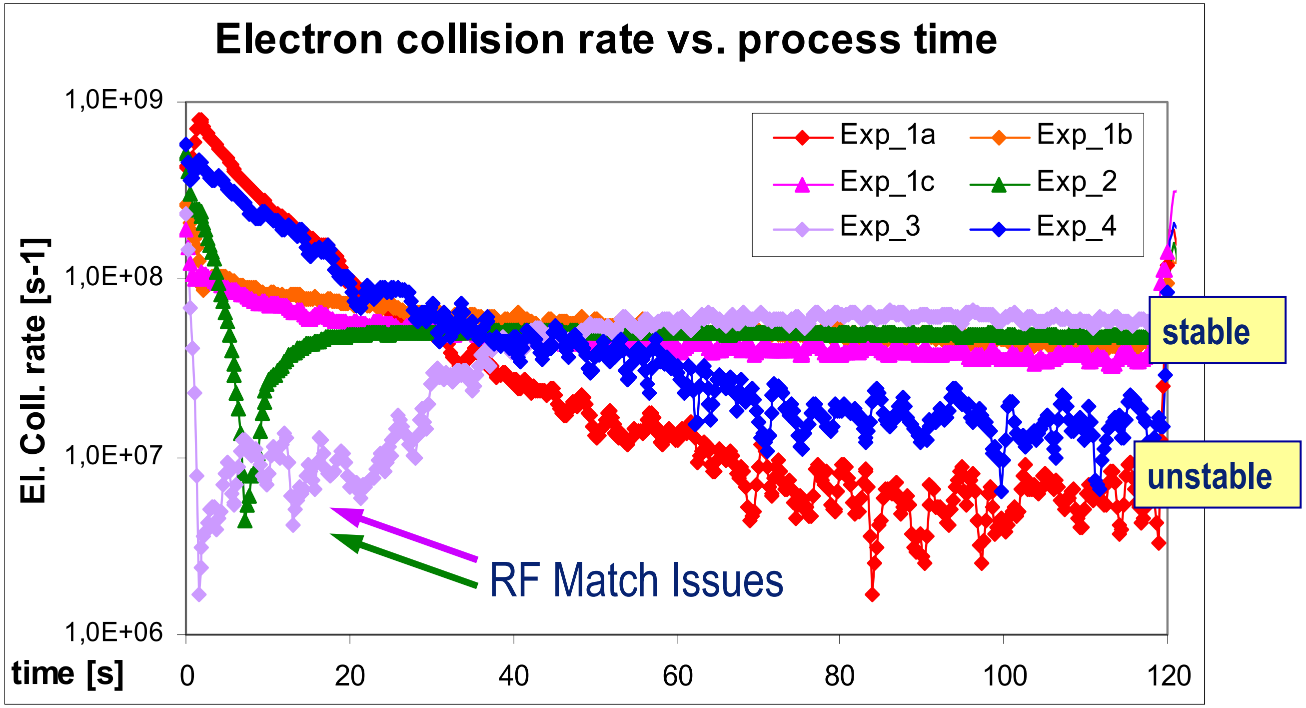
Chamber Conditioning: Monitoring and Baseline by Electron Collision Rate



stable

unstable

RF Match Issues

- Chamber conditioning was instable due to many different productive lots running in parallel !
- Electron collision rate directly indicates:
  - Chamber hardware issues
  - Stability and reproducibility of chamber conditioning

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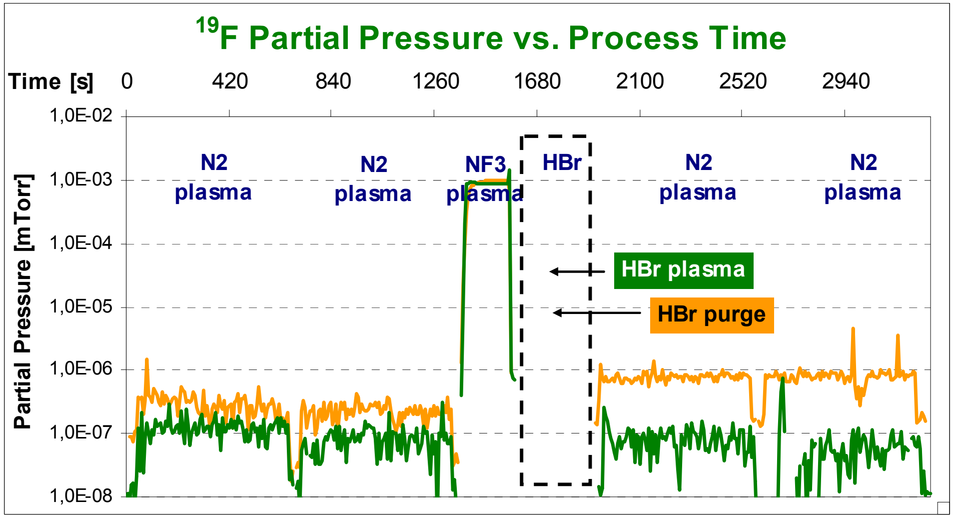
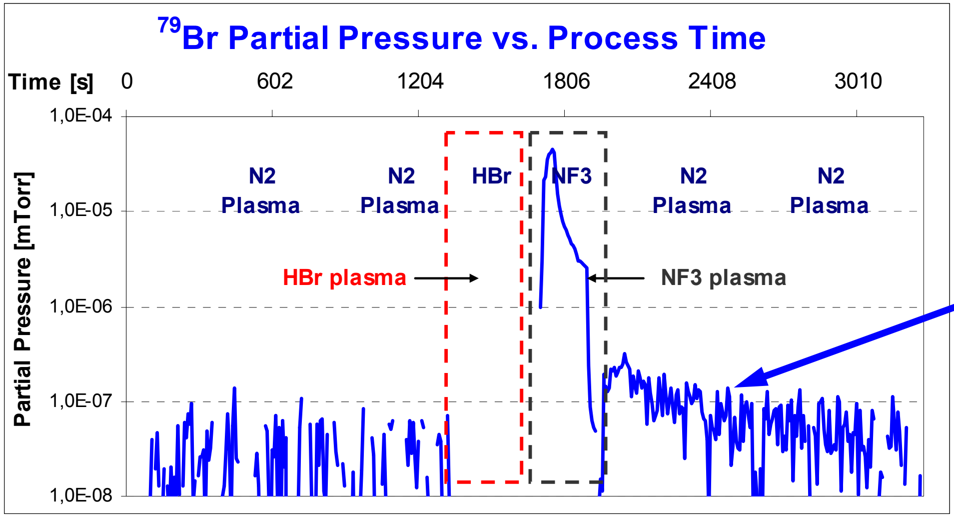
Chamber Conditioning:
Chemical Impact of Fluorine Clean and HBr Plasma


^{19}F Partial Pressure vs. Process Time


^{79}Br Partial Pressure vs. Process Time

- QMS application to optimize chamber clean procedure:
  - Goal: Stable and reproducible conditioning
  - Effectively decrease fluorine (bromine) contamination inside chamber by HBr (NF3) plasma or purge

    $F + HBr \longrightarrow HF + Br$
  - Mass spectrometer useful to monitor behavior of Br/HF species

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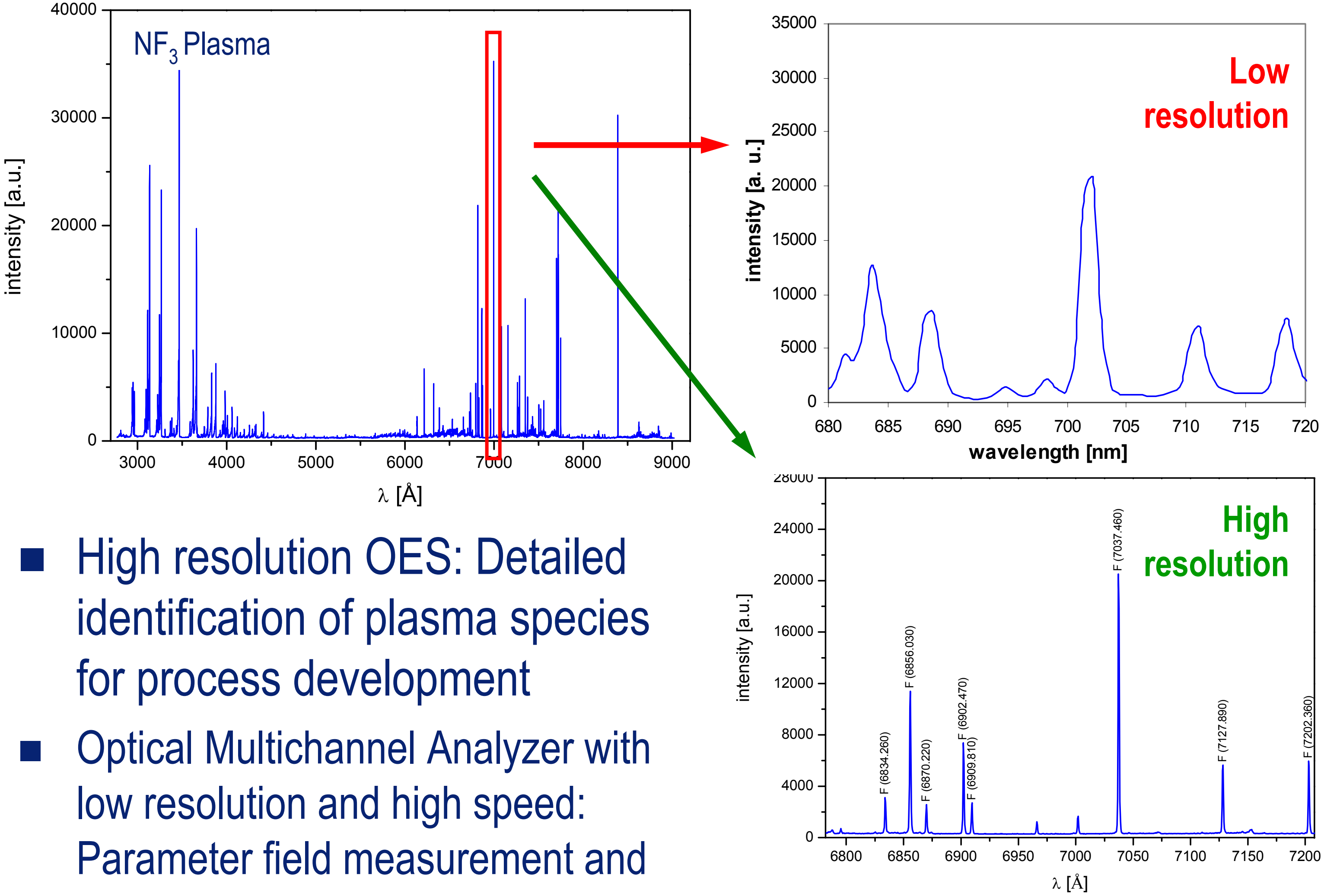
Process Development:
Why Application of High and Low Resolution OES ?



- High resolution OES: Detailed identification of plasma species for process development
- Optical Multichannel Analyzer with low resolution and high speed: Parameter field measurement and DoE experiments, see next page

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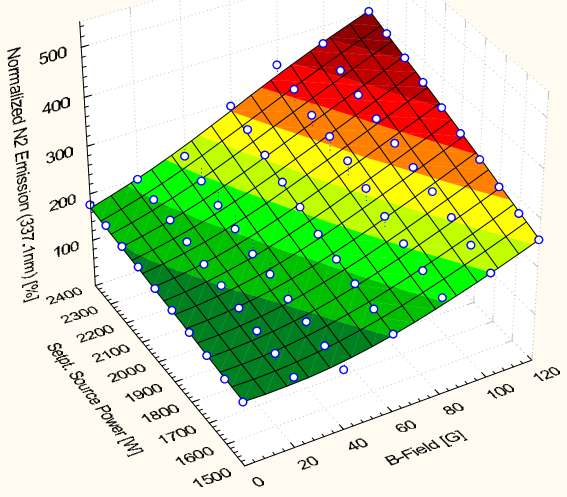
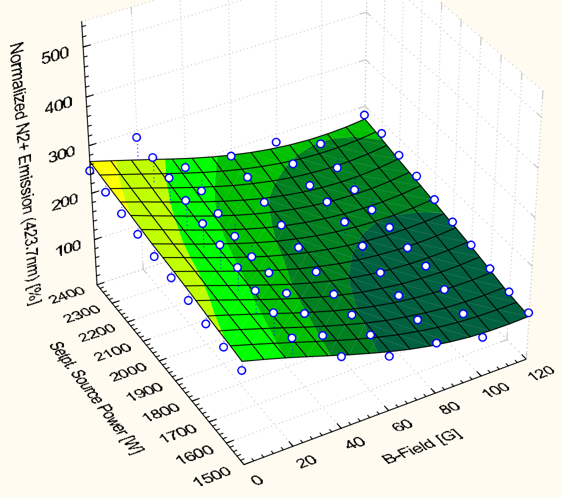
Process Development:
B- Field and RF Power Impact on Plasma Excitation

- Simple model gas used: N_2
- Electron collision rate indicates nonlinear energy transfer from RF power to gas by electrons
- Optical emission indicates ionic and neutral species in excited states

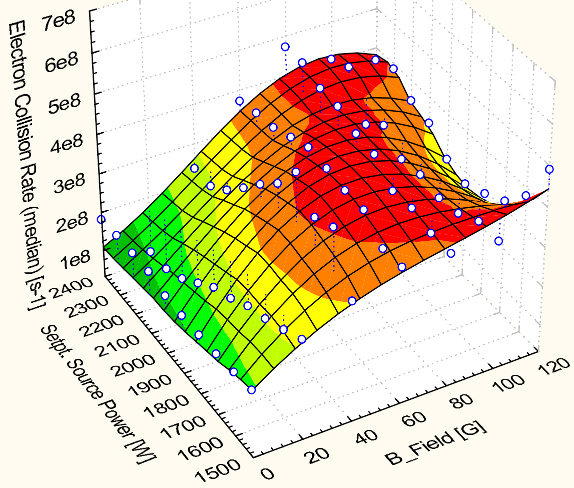
N_2 Emission 337.1nm



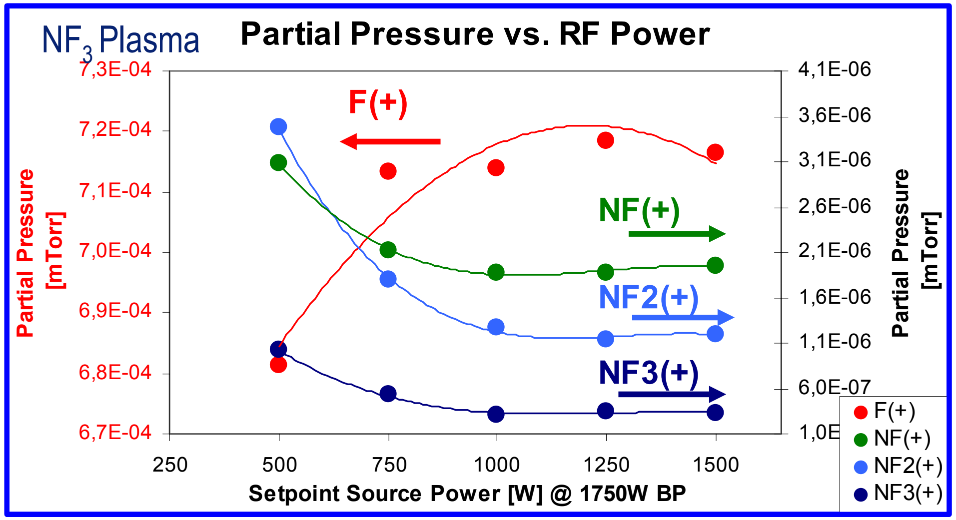
N_2^+ Emission 423.7nm



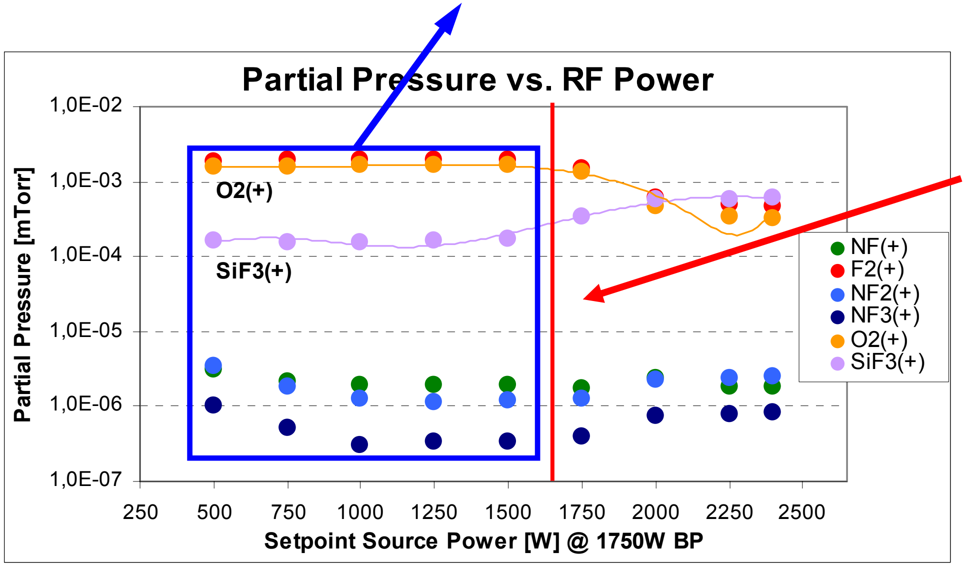
Electron Collision Rate



Process Development: Source Power Impact on NF_3 Etch Gas Fragmentation



- NF_3 fragmentation increases with higher source power



- Attention: Decrease of O_2 and increase of SiF_3 indicate complete removal of SiO_2 hardmask only

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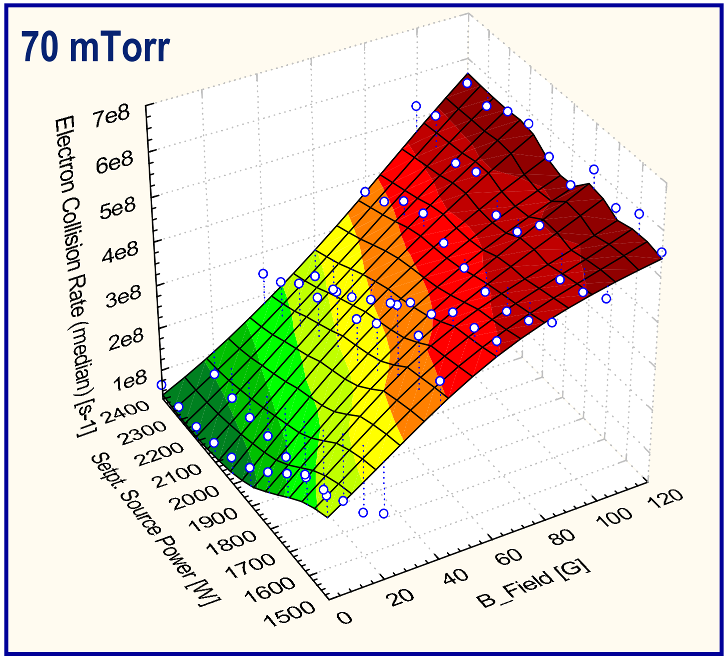
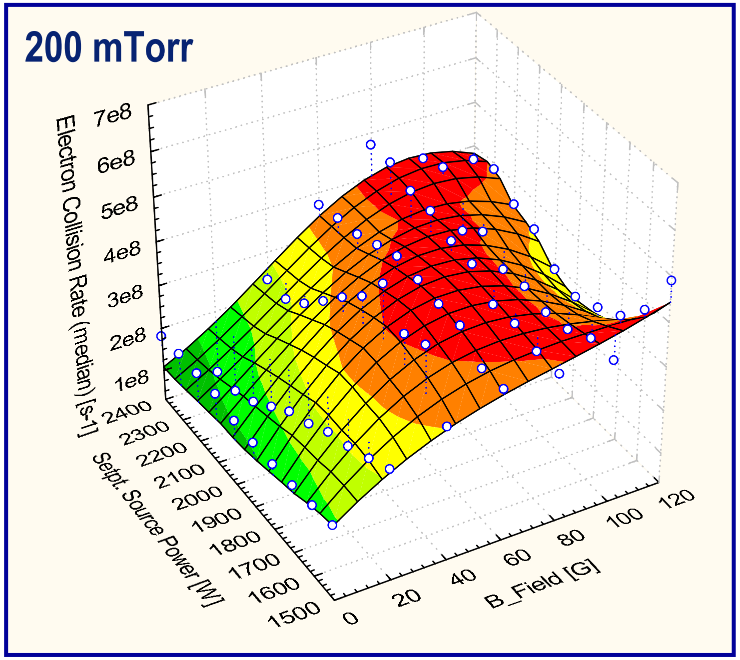
Process Development:
B-Field and RF Power Impact on Electron Collision Rate


70 mTorr


200 mTorr

- Electron collision rate depends on relation between mean free path of gas molecules and electron Larmor Radius.
- Larmor Radius is an nonlinear function of 60MHz Source Power, 2MHz Bias Power and B- Field !

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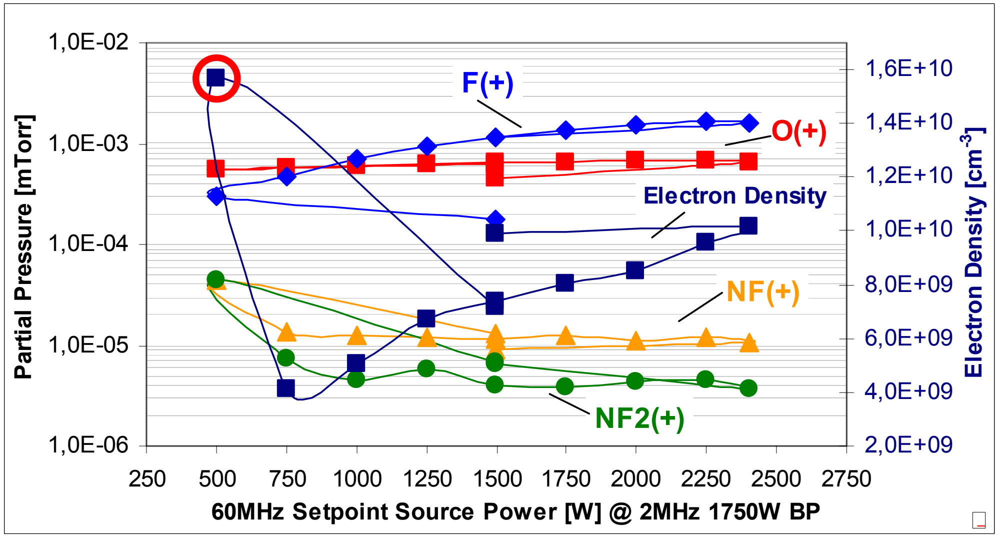
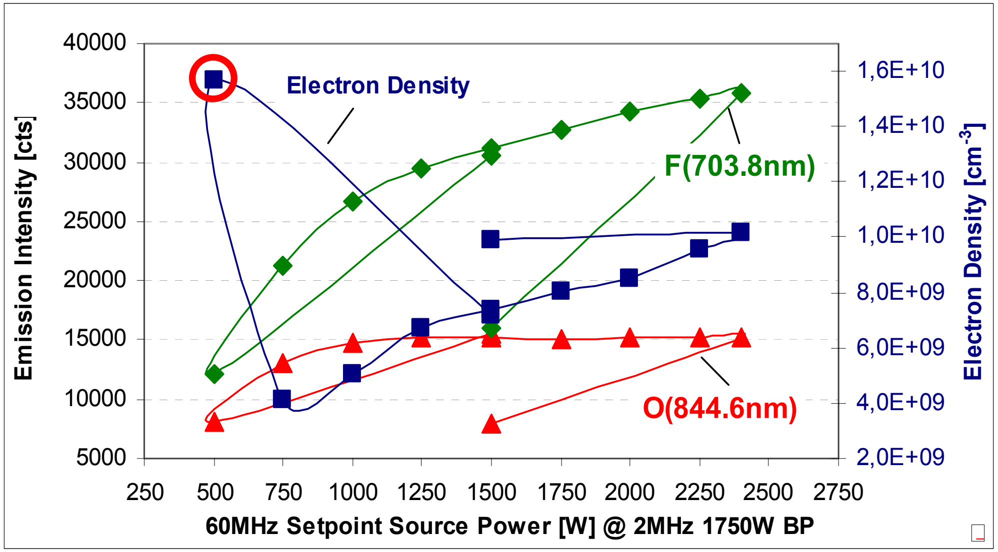
Process Development: RF Source and Bias Power Impact on Plasma Density and Gas Excitation in NF_3

Outlier indicates dominance of 2MHz Bias Power in range of 60MHz Source Power (SEERS model range)





- Electron density increases with source power and changes gas excitation and fragmentation
- Outlier indicates bias power dominance at low source power
- All measured parameters demonstrate drift of process conditions during the measurements.

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Summary:
The Paradigm Change in Plasma Process Development

- Joint development work by tool vendors and customers
- Joint application of *insitu* and *exsitu* measurement methods

Enable to

- Improve knowledge of tool characteristics and plasma process conditions significantly
- Accelerate plasma etch tool and process development
- Develop reliable tools and processes as a basic precondition of AEC/APC in production

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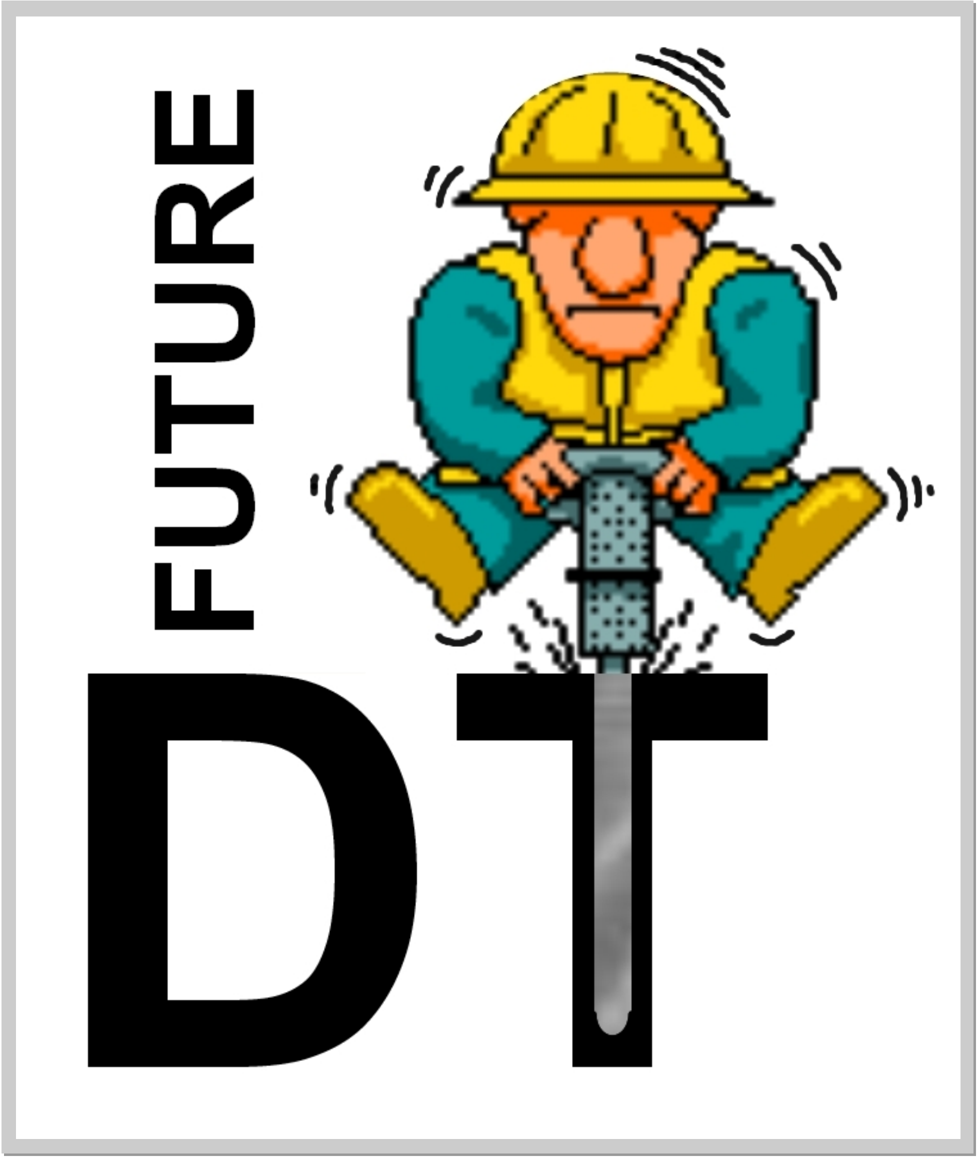
… Finally a possible Back Up Solution, if the Paradigm Shift should not work …



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