Application of electrical plasma measurement techniques at Advanced Process Control

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Outline

- Motivation –
  Why do we need electrical plasma measurement techniques ?
- Electrical plasma measurement techniques
  - „Classical“ electrical measurement techniques
  - Impulse detection in RF field
  - Self Excited Electron Plasma Resonance Spectroscopy
- Application of electrical plasma measurement techniques for APC
  - Data compression
  - Complex process parameters - Benefit for APC
- Summary

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Established and new measurement techniques – a historical comparison

- **Astronomy →** Optical methods
  - Widely used for some hundred years now
  - Familiar to every astronomer
  - Useful, great results
  - But they use only a small wavelength window
- New methods last century
  - Using other regions of the electromagnetic spectra
  - Offer additional information
  - Examples:
    UV- and IR-, X-Ray- and **Radio astronomy**

- **Plasma processing →** Optical methods
  - Widely used, e.g., OES and interferometry
  - Familiar to every engineer
  - Useful, e.g. endpoint
  - But they use only a small wavelength window
- New methods in recent years
  - Using other regions of the electromagnetic spectra
  - Offer additional information
  - Examples:
    Radio Frequency measurement and SEERS

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Why do we need „electrical“ plasma measurement techniques ?

- The plasma we use is:
  - A non- equilibrium plasma
  - Driven electrically by RF power
  - Excited by electron collisions with neutrals mainly
- So, if we use an „electrical“ plasma, we should use „electrical“ methods for plasma processes monitoring too !
- Well-know measurement techniques:
  - RF power, forward and reflected
  - RF peak voltage
  - Impedance
  - DC bias voltage
- New methods:
  - Impulse detection in RF field
  - Plasma parameter measurement by **S**elf **E**xcited **E**lectron **R**esonance **S**pectroscopy - SEERS

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Motivation

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„Classical“ well-known measurement techniques

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„Classical“ electrical measurement techniques

- DC bias voltage:
  - Simple principle – difficult to realize
  - Dark space voltage at cathode mainly on wafer surface ➔ DC bias plugs necessary ➔ rarely used
- RF peak voltage:
  - Simple principle, capacitive measurement at the RF matchbox output
  - Should be available in all RF matches !
- RF power, forward and reflected:
  - **Still standard:** Between RF generator output and RF matchbox input
    Power losses in RF match ! ➔ RF power input to chamber unknown
  - **Where it should be measured:** At the RF match output !
    New tools available now ➔ see exhibition
- Plasma impedance:
  - Available with new tools at the RF match output ➔ see exhibition too

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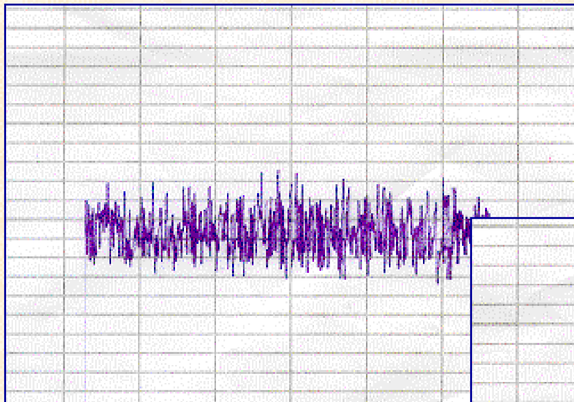
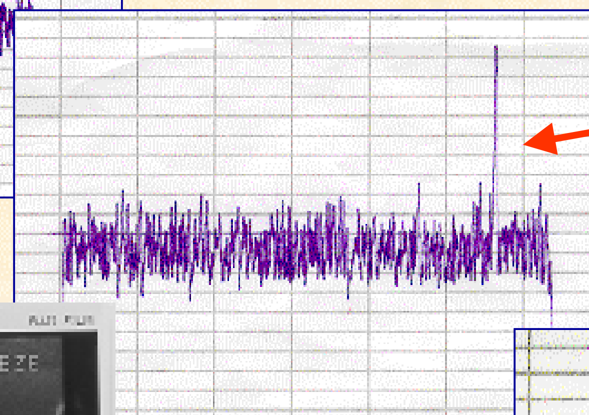
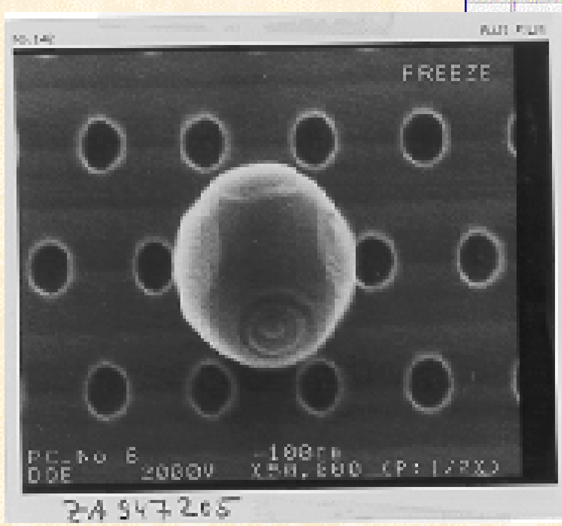
Example of DC bias voltage: Arcing detection at Via etch in AMAT MxP

- DC bias peaks indicate arcing
- Recorded with simple x,t- recorder

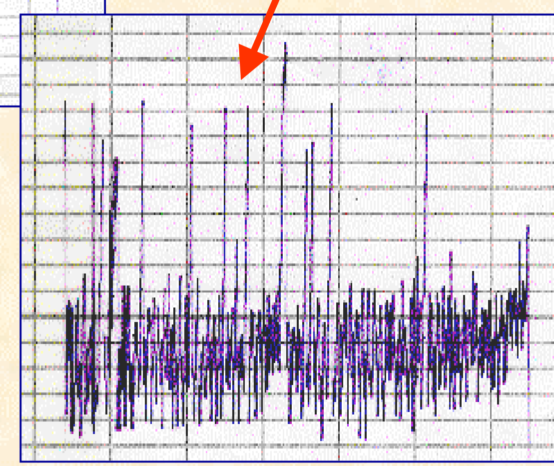




Heavy Arcing



Al particle on wafer



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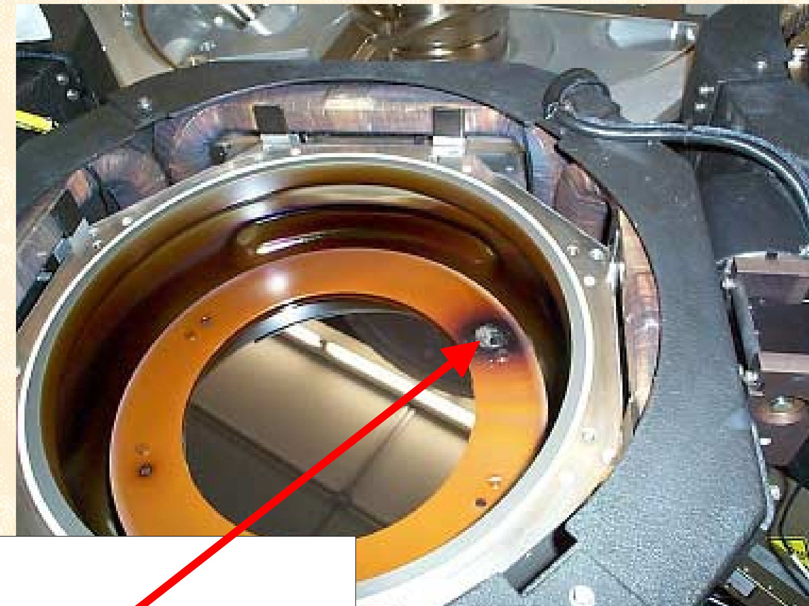
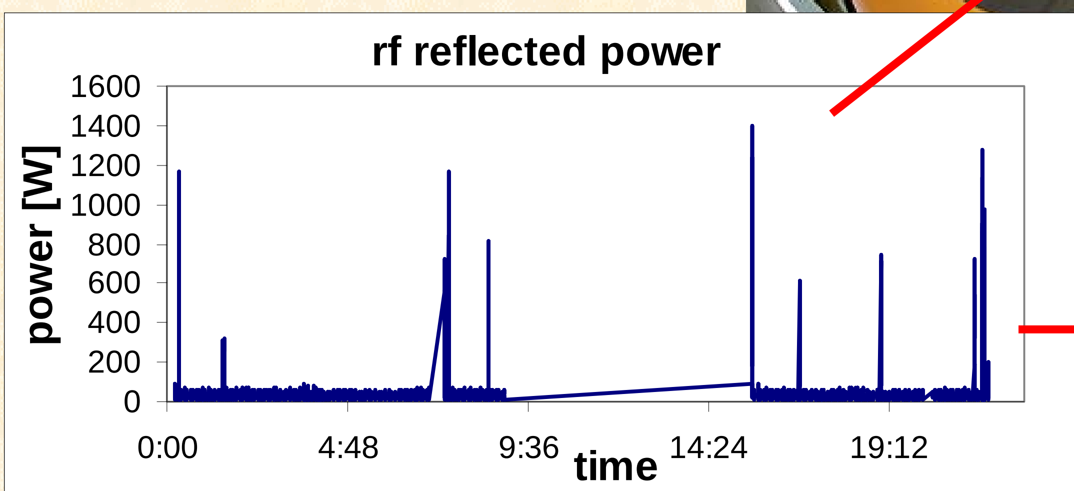
Example of RF reflected power: Ion shield burning (heavy arcing) in AMAT MxP →Poster P206

- Spikes at reflected RF power indicate upcoming heavy arcing early
- Recorded with TadiGuard Process and Equipment Enhancer
- For details see Poster P206





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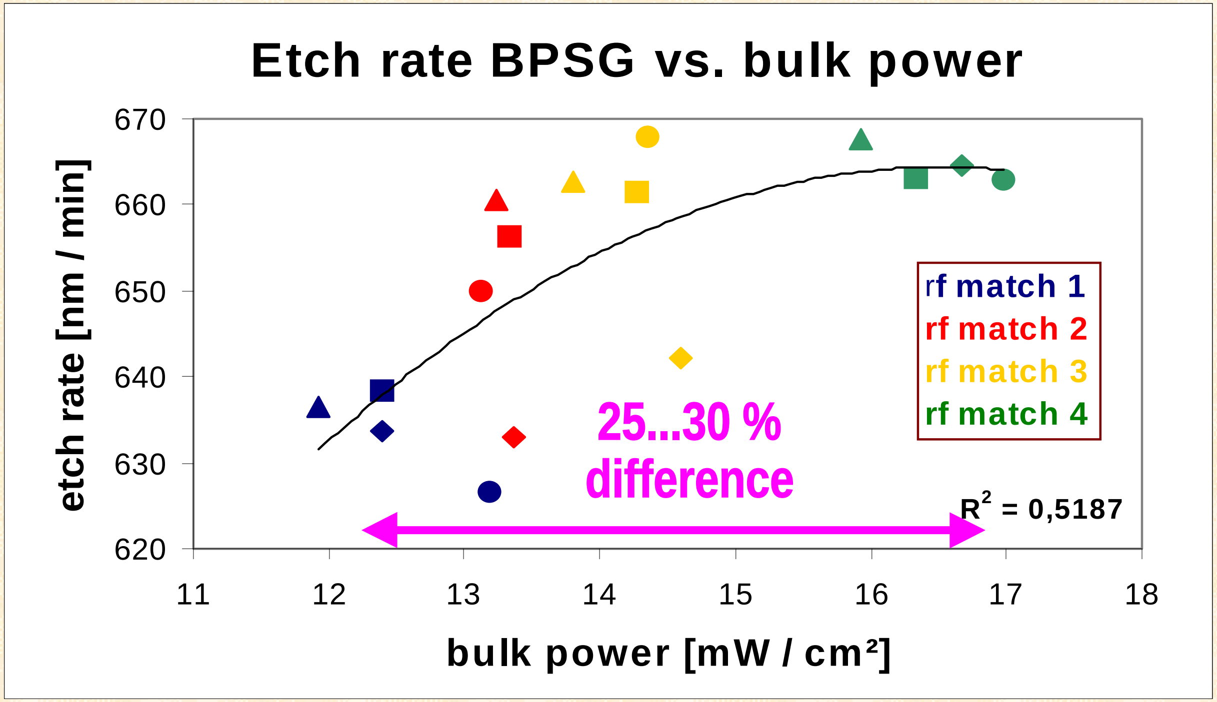
Example of RF power (at generator output): Comparison of 4 different RF matchboxes



- Recipe, e.g. RF generator power output is kept constant
- But, power dissipation in the chamber differs about 25 ... 30%, as indicated by bulk power measurement using HERCULES
- RF power measurement at RF generator output guarantees power maximum in the chamber of that configuration only, nothing else !

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Impulse detection in RF field

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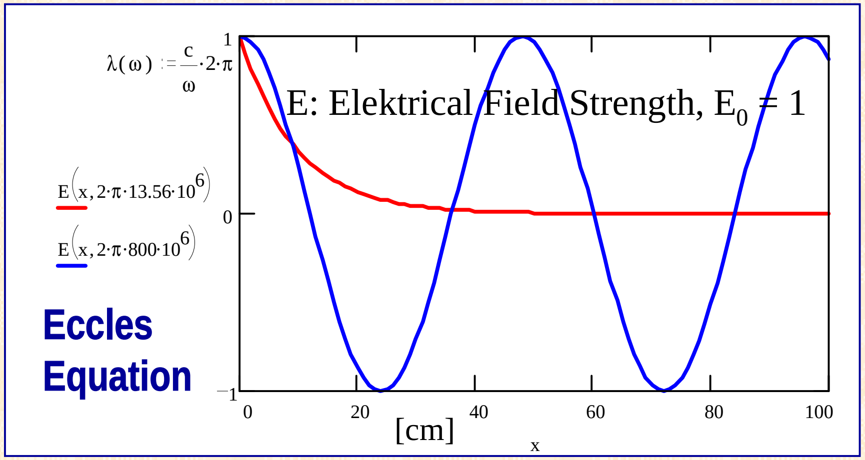
Measurement principle of RF impulse detector

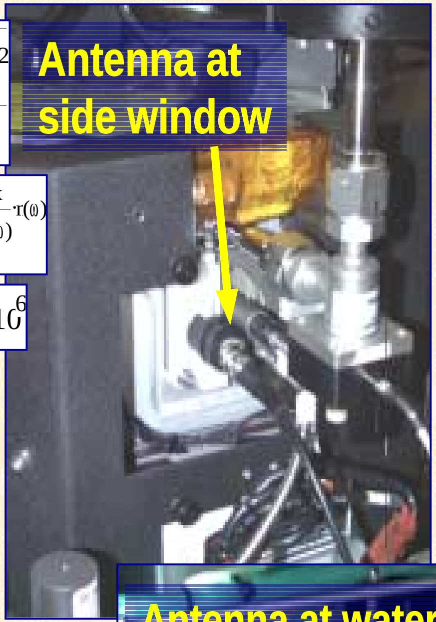


$$n(\omega) := \sqrt{1 - \frac{\omega_e^2}{\omega^2}}$$

$$E(x\omega) := E_0 e^{2\pi \cdot i \cdot \frac{x}{\lambda(\omega)} \cdot n(\omega)}$$

$$\omega_e := 2\cdot\pi\cdot 500 10^6$$

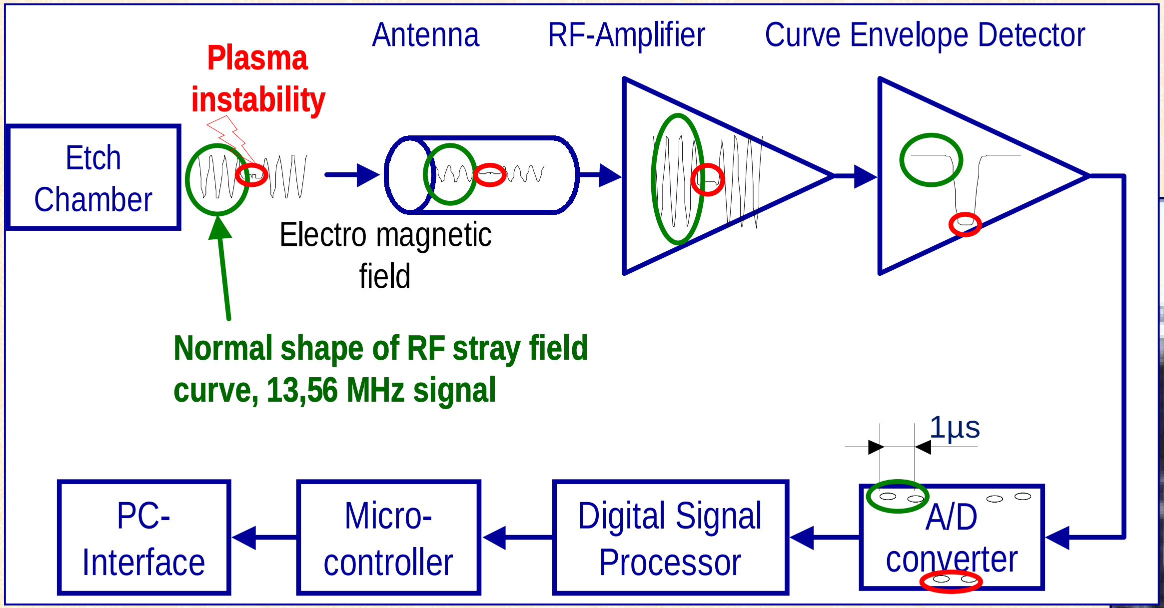
$$\lambda(\omega) := \frac{c}{\omega} \cdot 2\pi$$



- Short **local** discharge ➔
  - Variation of **global** plasma impedance
  - Mismatch of RF match
  - Insufficient power adjustment
  - Short breakdown of global RF stray field
  - Measurement of field strength breakdowns outside of the chamber, wherever electromagnetic field of plasma is detected
- No direct measurement of „arcing waves“ (see Eccles Equation)

Basic scheme of RF impulse detector

➔Poster P104



- Time resolution 1 µs
- Real-time signal compression by digital signal processor
- Individual calibration on every chamber and for every process, impulse classification
- For details see Poster P104

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RF impulse detector: Detection of scratch at chamber wall in AMAT MxP chamber

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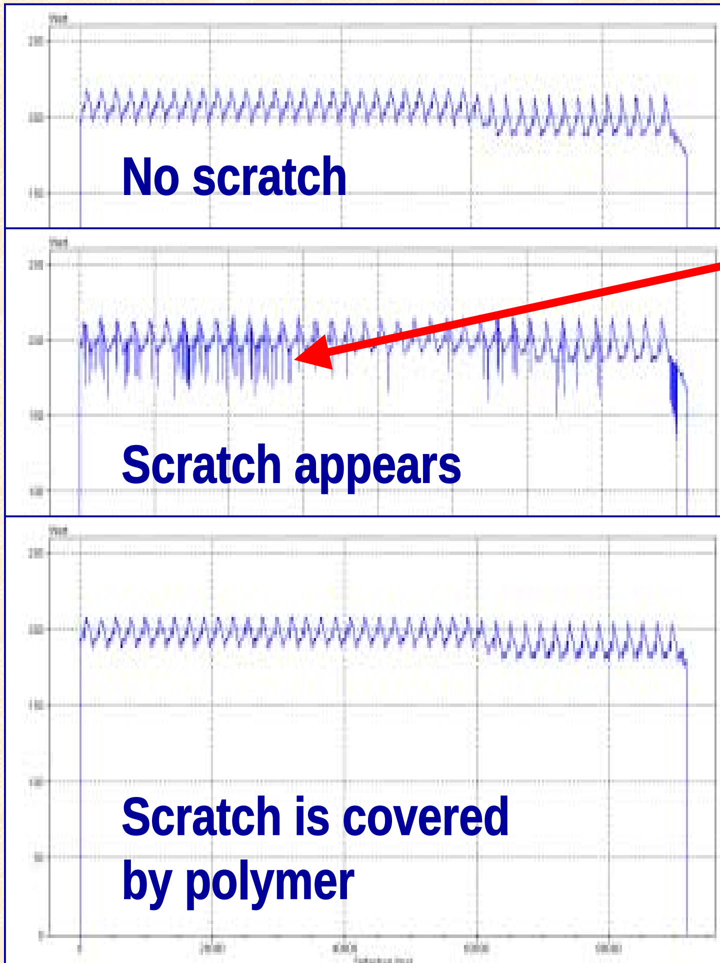
Time resolved signals



- Scratch at chamber wall detected, but no impact on particle density
- Reliable correlation to particle density on wafer (= Arcing from production point of view) not possible

RF impulse detector: Ion shield burning at Applied Materials MxP chamber

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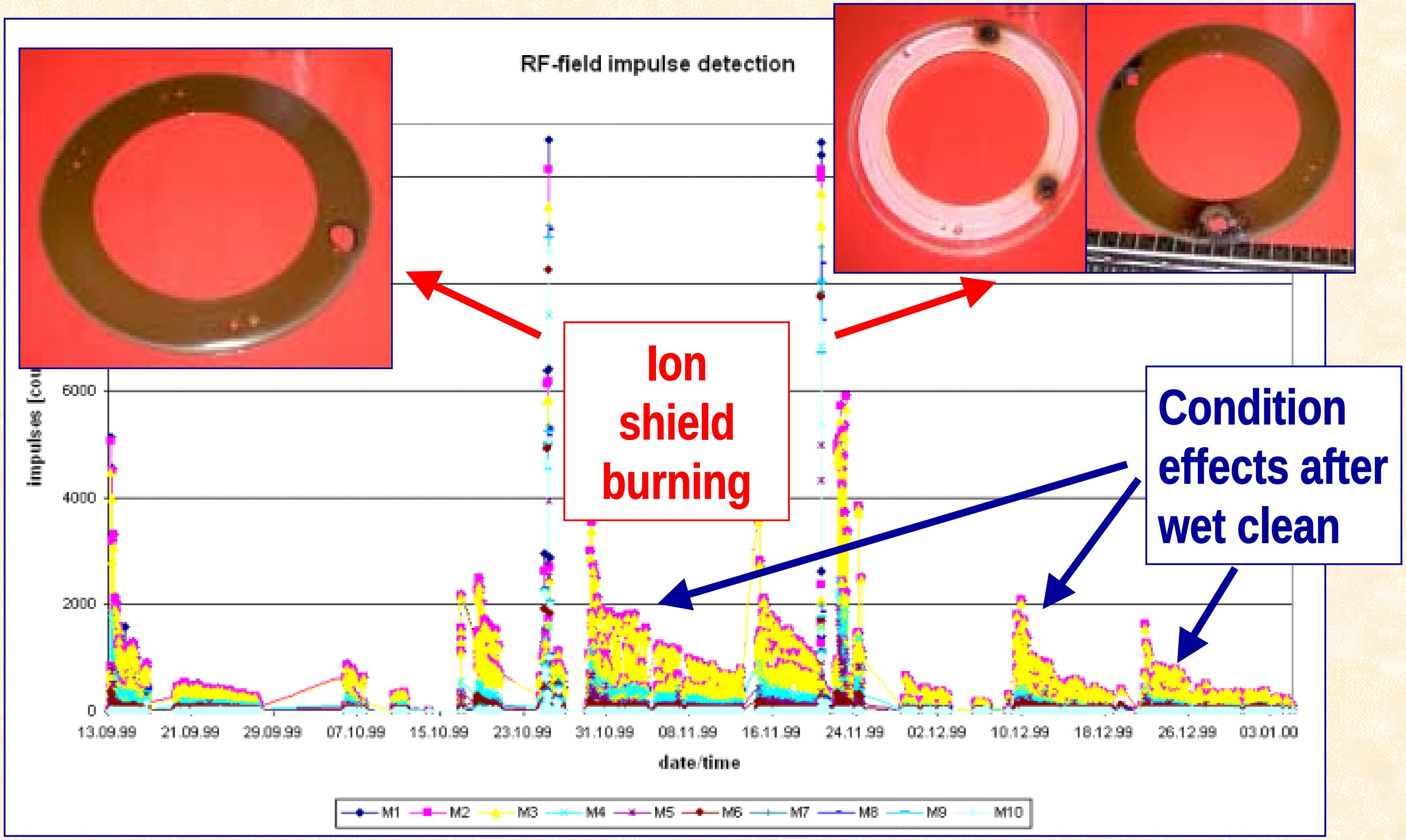

RF stray field impulses indicate ion shield burning (heavy arcing !)

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Plasma parameter measurement using **S**elf **E**xcited **E**lectron Plasma **R**esonance **S**pectroscopy

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Principle of SEERS

RF current
RF voltage

↓

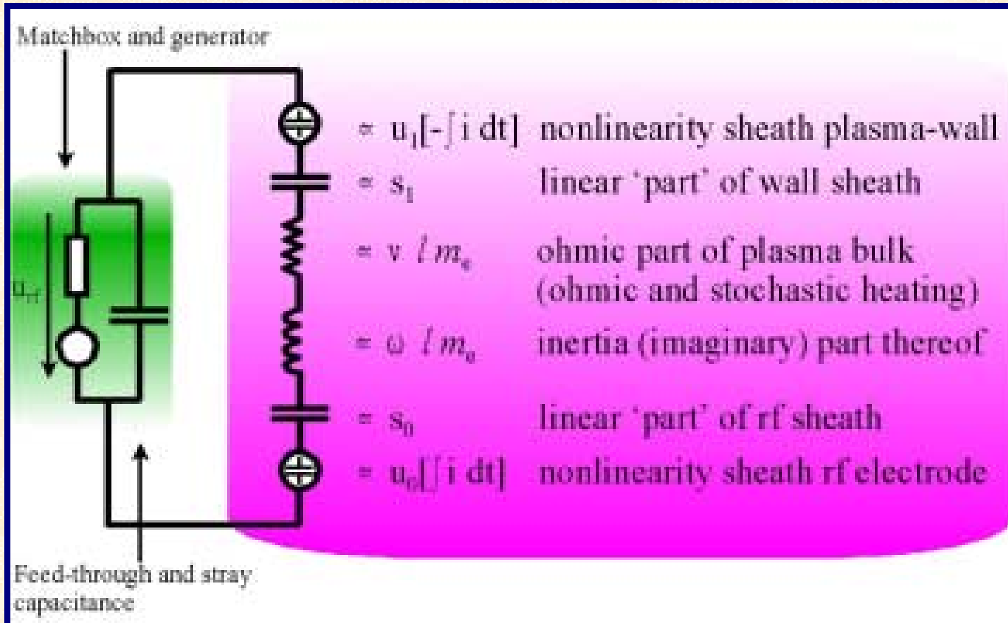
FFT

↓

Model SEERS

↓

Electron collision rate
Electron density
Bulk power
DC bias voltage



- Self Excited Electron Plasma Resonance Spectroscopy
  - Passive electrical method
  - Integral physical parameters

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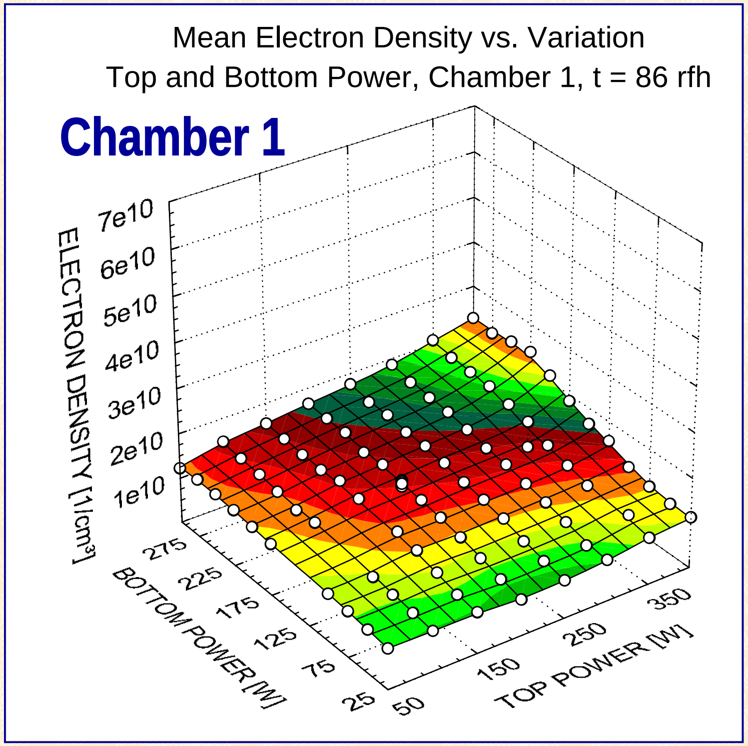
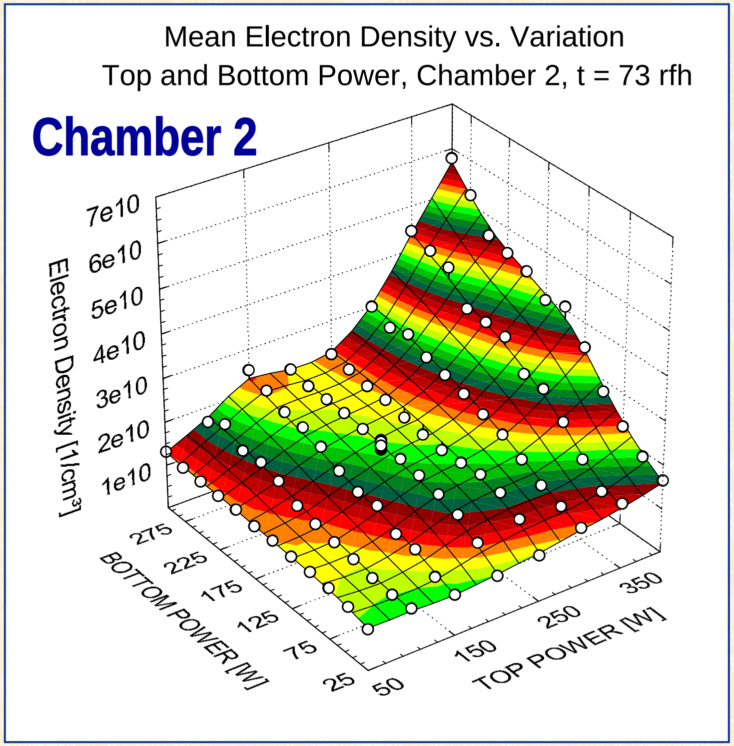
Plasma parameter: Tool comparison at GC etch in LAM TCP





- Typical problem: Nominal identical chambers and same recipe. But process result of one chamber is different to all others ! Why ?
- ➔ Reason found by electron density: Significant different power dissipation, caused by TCP top power coupling into chamber

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Plasma Parameter: Product interaction DRAM – Logic at GC etch in LAM TCP ➔Poster P204

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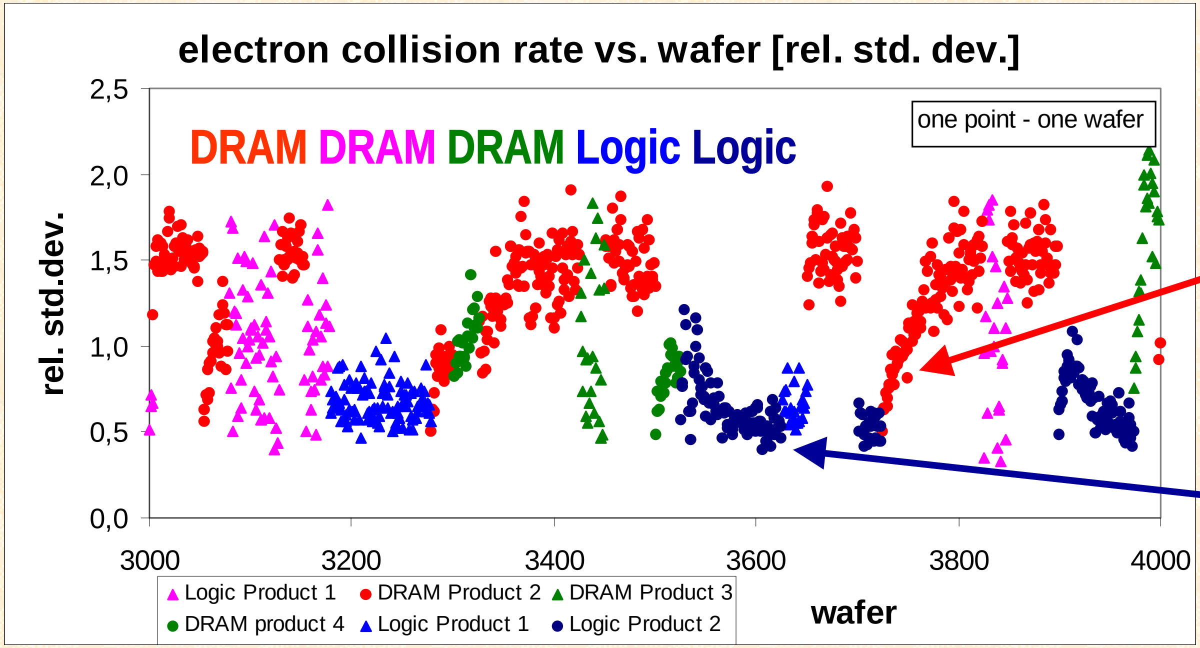

DRAM products destabilize chamber conditions

Logic Products stabilize chamber conditions

- Typical problem: Mix of many products in a chamber
  - Most products (here DRAM) show stable electrical results all the time
  - Few products (here one Logic product) show drift of electrical product parameters, e.g. depending on process mix and RF hours
- ➔ Electron collision rate indicates impact of DRAM and Logic products on chamber conditioning. For details see Poster P204

Plasma Parameter: Optimization of dry clean at STI etch in AMAT MxP ➔Poster P205

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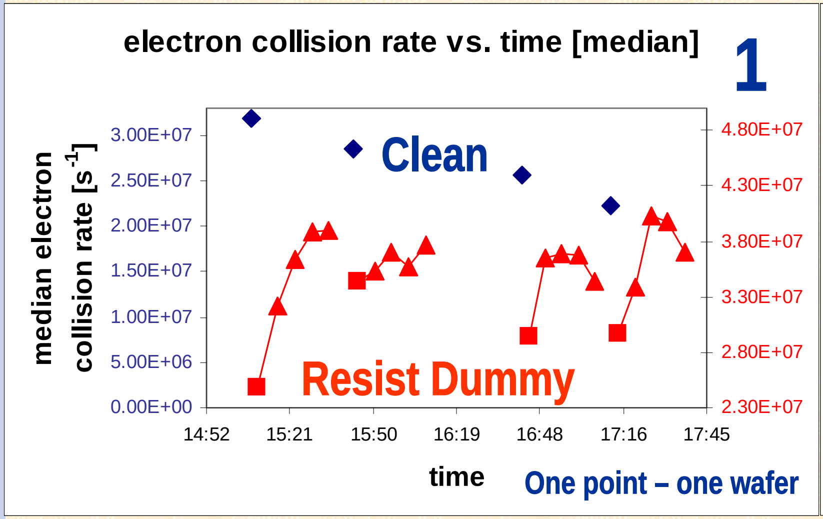

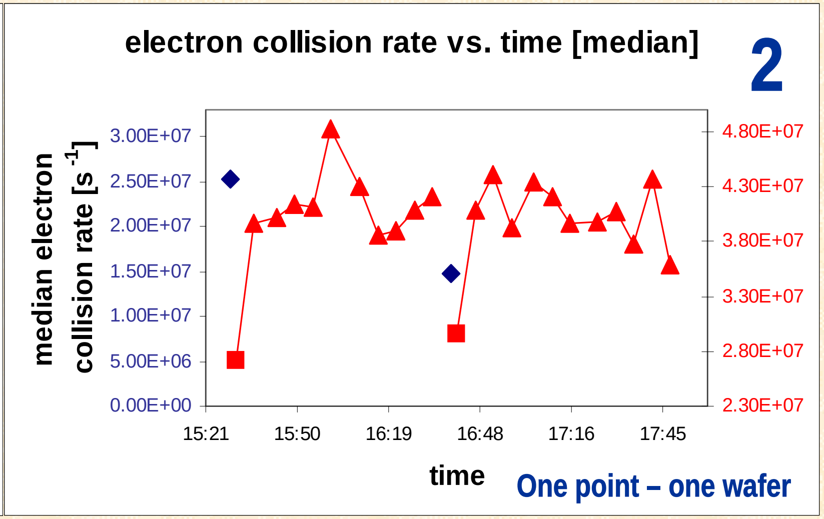

- Typical task: Optimization of conditioning or dry clean processes
  - Usually done: By experience and trial & error, efforts consuming
  - Cleverly done: By additional measurement of process parameters
- Electron collision rate measures first wafer effects, caused by clean
  - Dry clean 1: first wafer effect on 2 ... 4 following resist dummies
  - Dry clean 2: first wafer effect on 1 following resist dummy only
- For details see Poster P205

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Application of electrical plasma measurement techniques for APC

Data compression - an essential need for APC in high-volume production ➔Poster P208

- APC in high-volume production ➔ very large amounts of data
- How to compress data ? By use of
  - Smart „Intelligent“ sensors with real-time data compression
  - Calculation of statistical key numbers from raw data
  - Model-based data analysis, for details see Poster P208
  - Physical and chemical models, no blind statistics !
  - **Complex process parameters, depending on tool- and wafer impacts –**
    better to watch 2 relevant than all available parameters daily !
- Data compression for daily use by two steps:
  - 1st step:
    A complex process parameter indicates, that something might be wrong
  - 2nd step:
    Use of other tool- and process parameters to find in detail, what is wrong

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Example of complex process parameter: Electron collision rate

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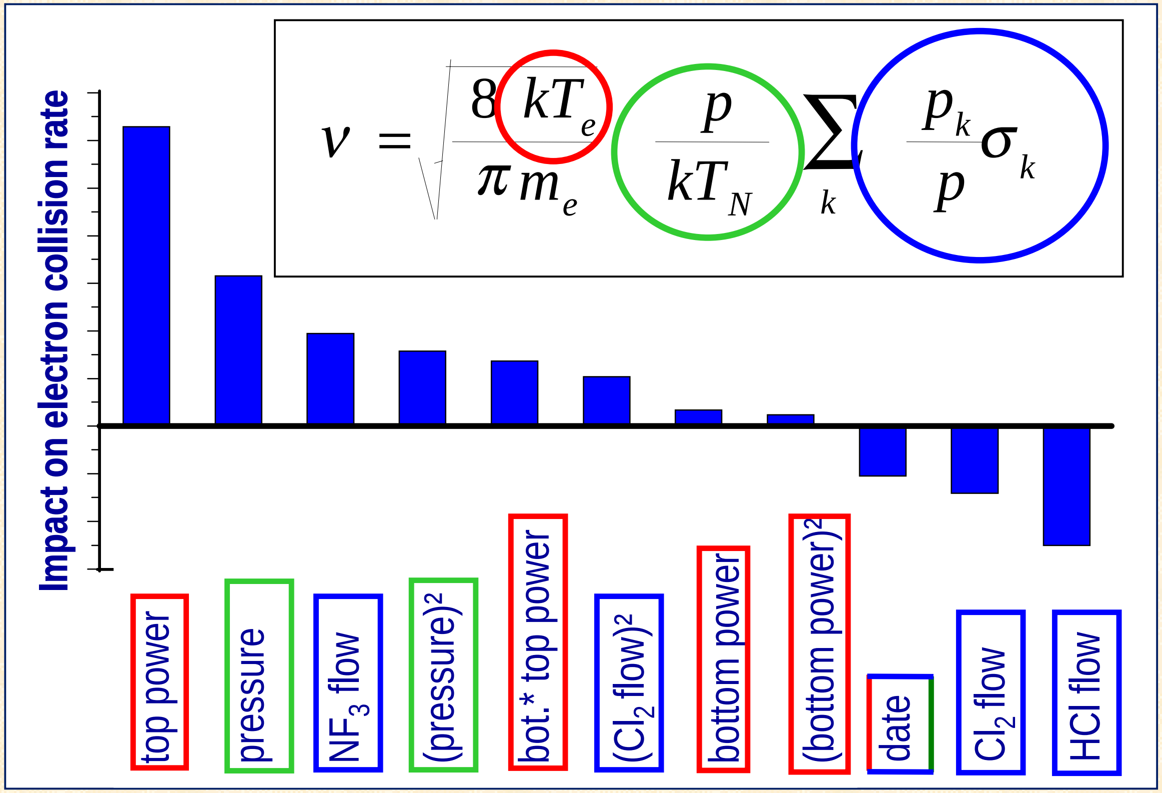
GC Stack etch at LAM TCP, main etch: Effect Pareto for electron collision rate



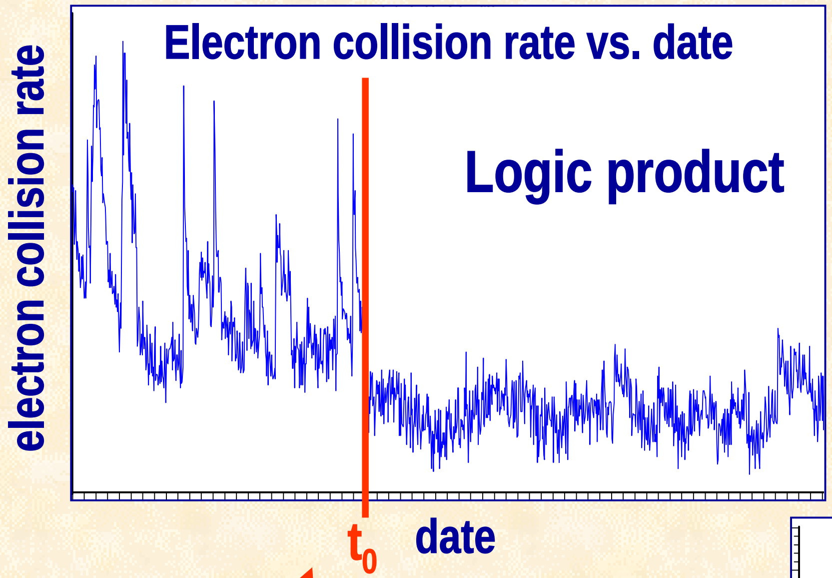
Real power dissipation in the chamber

Real particle density in plasma

Real gas mixture in chamber

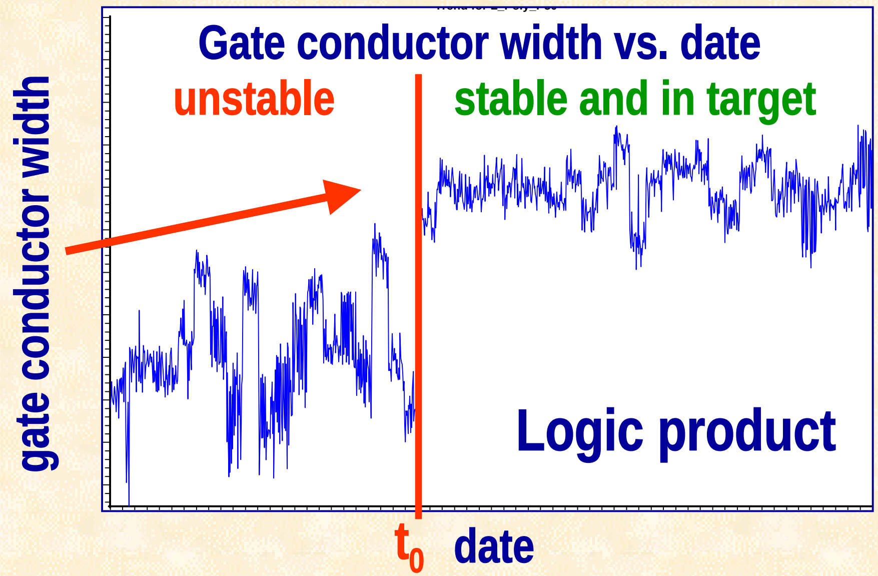
- Electron collision rate depends on parameters, which can be measured
- Electron collision rate depends also on parameters, which cannot be measured directly (chamber drift = impact of date)

Application of plasma parameters for process monitoring at GC etch at LAM TCP



- GC etch in LAM TCP
- Electron collision rate indicates stability of electrical product parameter (Example: Gate Conductor width of a logic product)

t_0 - Introduction of process mix change (chamber used for Logic mainly)



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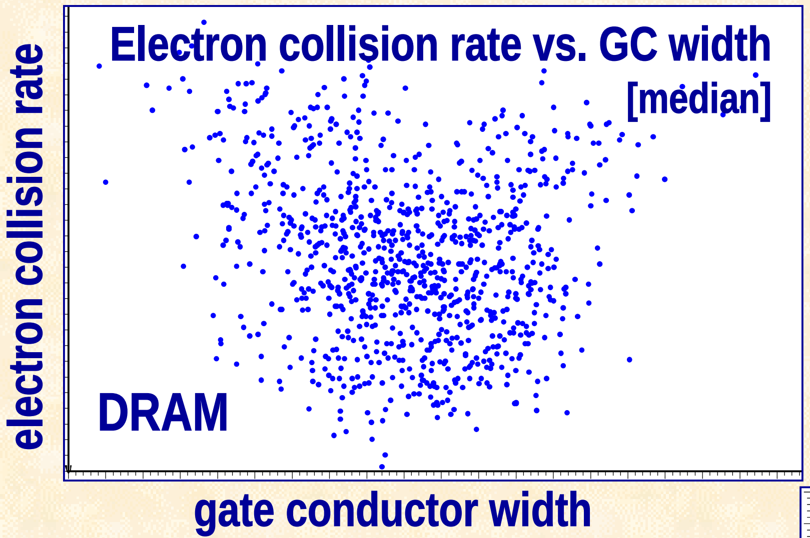
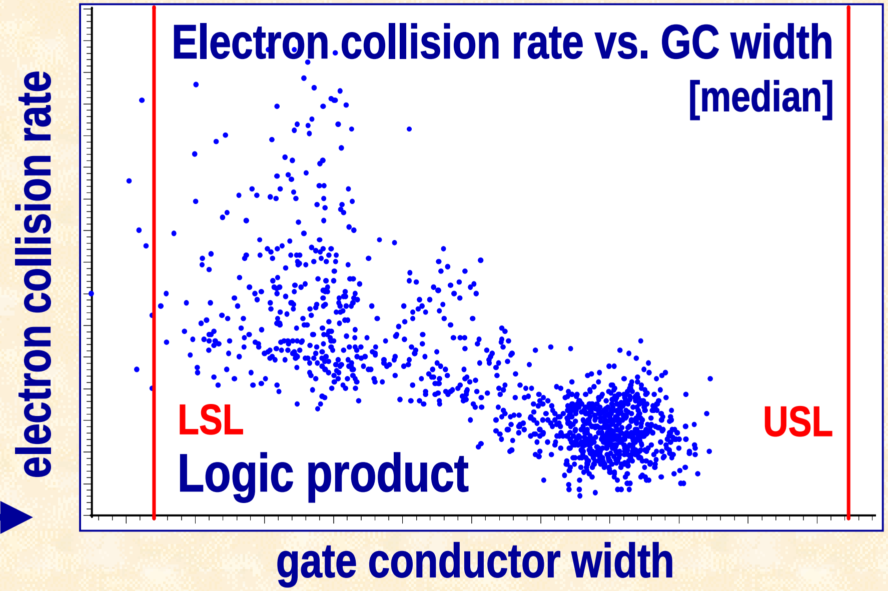
Correlation between plasma parameters and electrical product parameters ➔Poster P208



- DRAM:
  - Large process window at GC etch
  - ➔ stable electrical results on product
  - ➔ no correlation process parameter – product parameter

- Logic product::
  - Small process window at GC etch
  - ➔ unstable electrical results on product
  - ➔ correlation process parameter – product parameter



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Lessions learned: AEC and APC

- Equipment Control and Process Control
  - Are“two pairs of shoes“
  - The process can go wrong,
    while the available tool parameters are stable
- Equipment (Tool) Control
  - By process parameters, as a first indicator
  - And tool parameters, to find reasons of tool problems in detail
- Process Control
  - Demands sensitive, complex process parameters
  - Simple correlation between tool parameter and results on product ?
    ➔ use another tool !
  - Correlations between process parameters and electrical results are necessary for product-related alarm limits
  - Product engineering accepts only one or very few key numbers per process ➔ data compression

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Lessons learned: Data compression and analysis

- Data compression for APC
  - Complexity of electrical parameters, measured on plasma processes is a data compression itself ➔ data compression „by physics“.
- Correlations to product parameters have to be done separately for:
  - Wafers
  - Process steps
  - Products
- Use of reasonable statistical methods **and** technological knowledge, to reduce data amount
- You won´t find any correlation between measured parameters:
  - If the measured parameters are not really sensitive to process drift
  - In case the process is stable (see DRAM on Poster P208)
- In both cases best statistical methods won´t find any correlation.

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Summary

- Electrical plasma measurement techniques
  - Open a new window for plasma monitoring, additional information
  - Measure sensitive process parameters, tool **and** wafer impacts
  - Integral values, no local measurements usually
  - In real time
- Application for process engineering and maintenance
  - Fault detection of process and tool
  - Process development and optimization
- Application for process integration and product engineering
  - Monitoring of process drifts, product interactions **in real time**
  - Complex process parameters supplement of in-line data for product engineering
  - Bridge between process engineering and product engineering
- electrical plasma measurement techniques are an intelligent way of data compression „by physics“.

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