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Importance of in-situ measurement techniques for Advanced Process Control of plasma processing in high volume production

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Outline

- Plasma processing
- Tool parameters - process parameters
- Application on process development and maintenance
- Demands of process control in high volume production
  - Correlation unit process parameters – product parameters
  - Data compression
- Summary

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Plasma Processing

Plasma – what´s that ?

q View from Physics: Plasma is …

… è an ionized gas …

… è containing free electrons and ions …

… è electrically driven, in non- equilibrium …

… è …

q View from Semiconductor Technology: Plasma is …

è a **difficult** tool !

- Ø **High complexity** of interactions
- Ø **Non- linearity** of interactions
  (and sometimes surprising non- linearity !)
- Ø Many **interacting** phenomena

q è Simple answers to „simple“ questions are rare !

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High complexity - Example:
Simplified equations of electron collision rate

$$\nu_{eff}(B,n,\omega) := \mathrm{Re}\left[\frac{\omega_e^2}{j\cdot\omega}\cdot\left[1+\frac{j\cdot\omega+\nu}{j\cdot\omega}\cdot\frac{\omega_{pe}(n)^2}{(j\cdot\omega+\nu)^2+\omega_c(B)^2}\right]^{-1}\right]$$

$$\omega := \left(\frac{s}{l}\right)^{\frac{1}{2}}\cdot\omega_{pe}(n)$$

s: sheath thickness,
l: plasma length,without stochasric heating

$$n = n_{Stoch} + \sqrt{\frac{8\,k_B\,T_e}{p\;m_e}}\cdot\frac{P_g}{k_B\,T_N}\cdot\sum_k\frac{p_k}{P_g}\,s_k$$

- Electron collision rate = number of elastic and inelastic collisions per second, between one electron and gas molecules in the plasma bulk

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Non- linearity – Example:
Electron collision rate vs. RF power and B- Field

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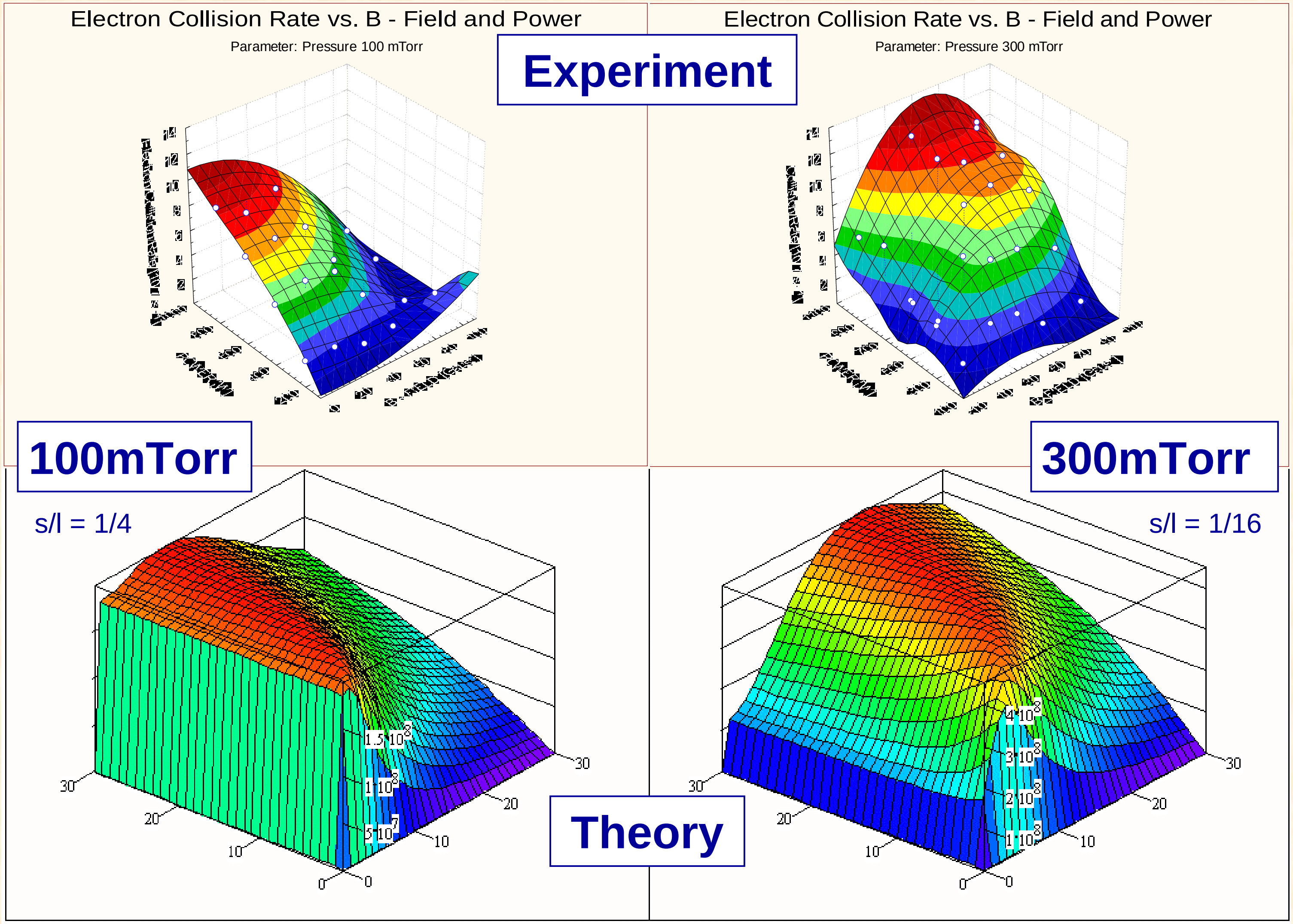

Electron Collision Rate vs. B - Field and Power

Parameter: Pressure 100 mTorr

Electron Collision Rate vs. B - Field and Power

Parameter: Pressure 300 mTorr

Experiment

100mTorr

300mTorr

s/l = 1/4

s/l = 1/16

Theory

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… and many interacting phenomena.

What do we measure ?

Tool parameters and process parameters at plasma processing

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… and many interacting phenomena: Tool parameter – process parameter

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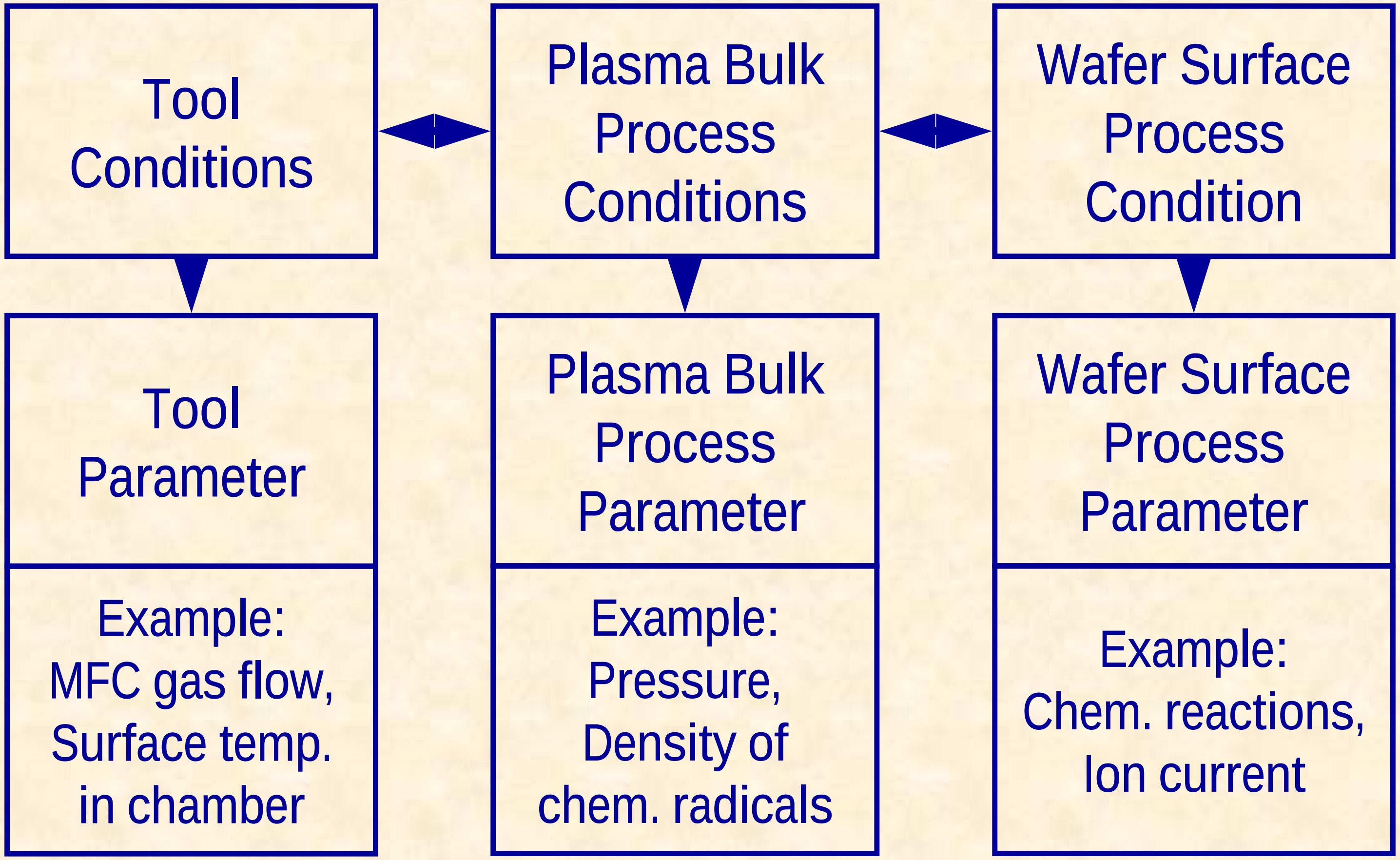

Tool Conditions

Plasma Bulk Process Conditions

Wafer Surface Process Condition

Tool Parameter

Example: MFC gas flow, Surface temp. in chamber

Plasma Bulk Process Parameter

Example: Pressure, Density of chem. radicals

Wafer Surface Process Parameter

Example: Chem. reactions, Ion current

- Process parameters on wafer surface and in plasma volume characterize process result much better than tool parameters.

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What do we measure in production tools today ?

	Tool	Plasma Bulk	Wafer Surface
Easy to measure	MFC gas flow, Chamber lid temperature	Pressure, Optical emission endpoint	Optical Interferometric Endpoint
Difficult to measure	RF power input into chamber	Neutrals density, Ion density	Wafer surface temperature
How to measure ?	Chamber surface temperature	Electron excitation, chem. reactions	Ion current density & energy, chem. reactions

- Many important process parameters and even tool parameters can not be measured directly, or even at all.
- → In-situ measurement techniques are needed.

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Example: Comparison of chamber lid temperature and electron collision rate

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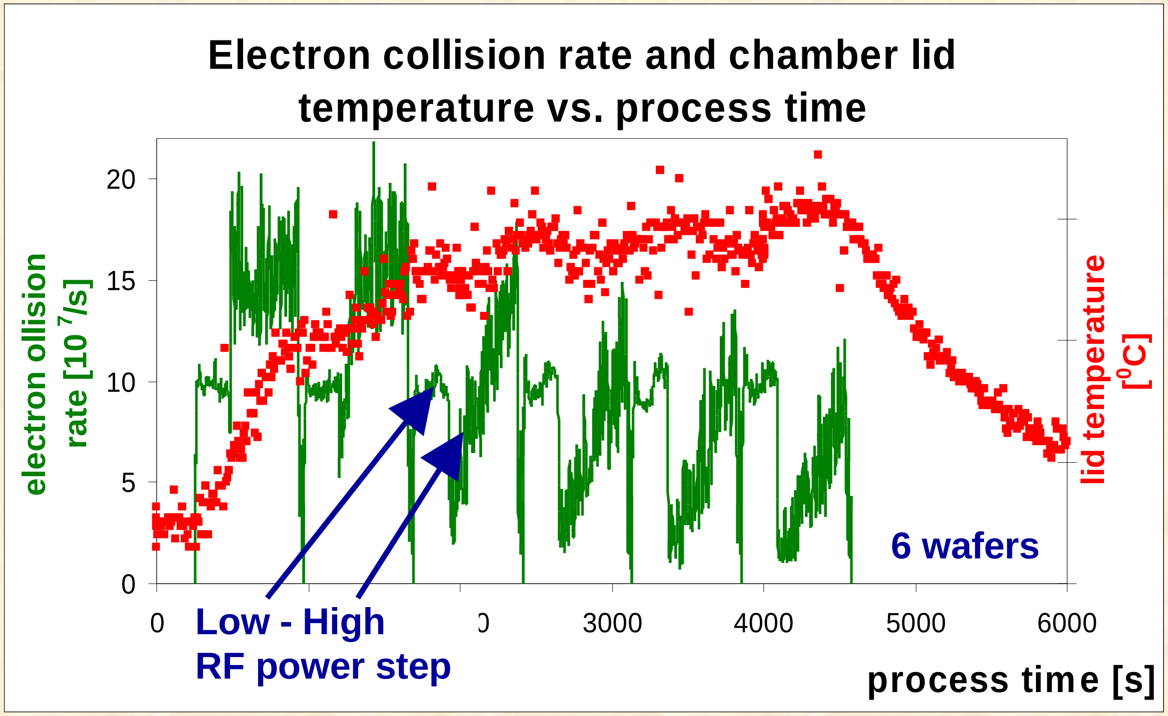

- Tool parameter: Chamber lid temperature reacts slowly

- Process parameter: Electron collision rate detects:
  - First wafer effect (gas adsorption and desorption at chamber wall)
  - Gas temperature drift, only during high RF power step
  - Gas composition drift in plasma bulk („saw tooth“), heating of chamber kit and wafer surface cause drift of chemical reactions there

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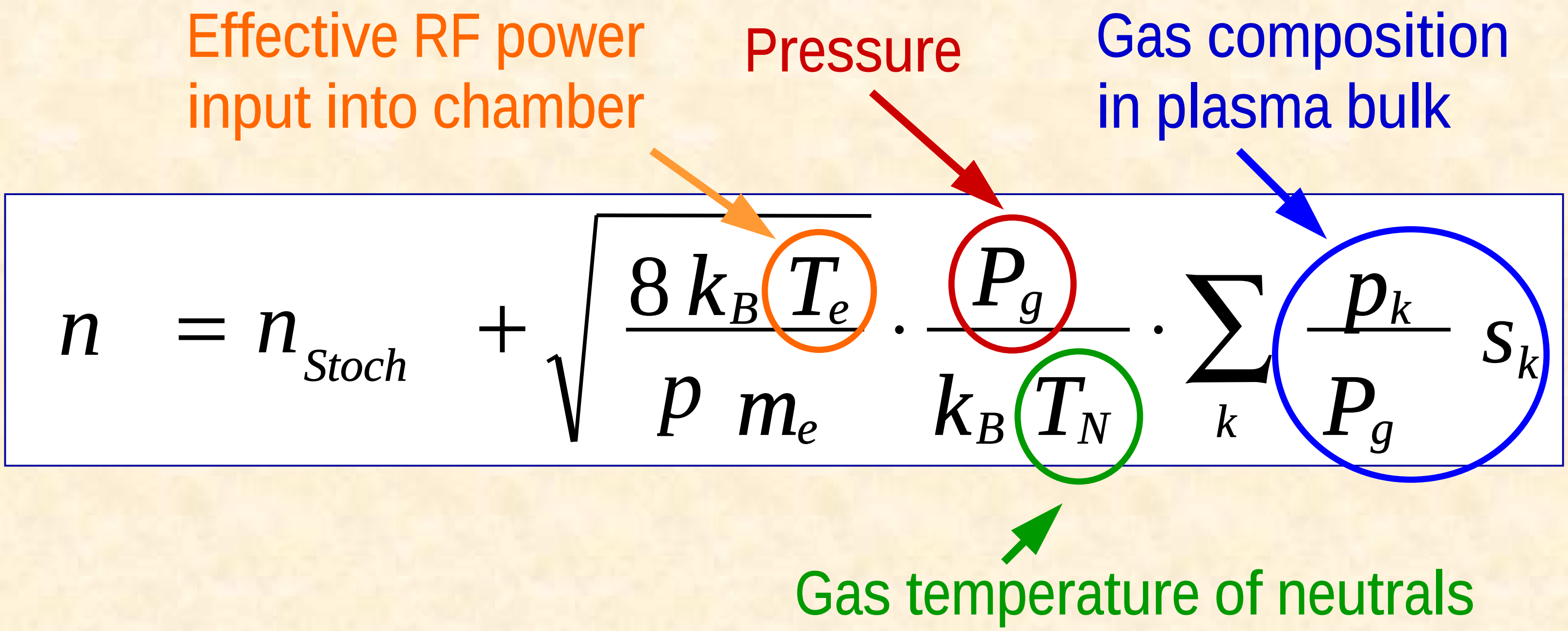
How can process parameter electron collision rate detect so many effects ?



Effective RF power input into chamber

Pressure

Gas composition in plasma bulk

$$n = n_{Stoch} + \sqrt{\frac{8\, k_B\, T_e}{p\; m_e}} \cdot \frac{P_g}{k_B\, T_N} \cdot \sum_k \frac{p_k}{P_g}\, s_k$$

Gas temperature of neutrals

- Electron collision rate **integrates** impacts of
  - Tool conditions
  - And process conditions in plasma bulk
  - And process conditions on the wafer surface

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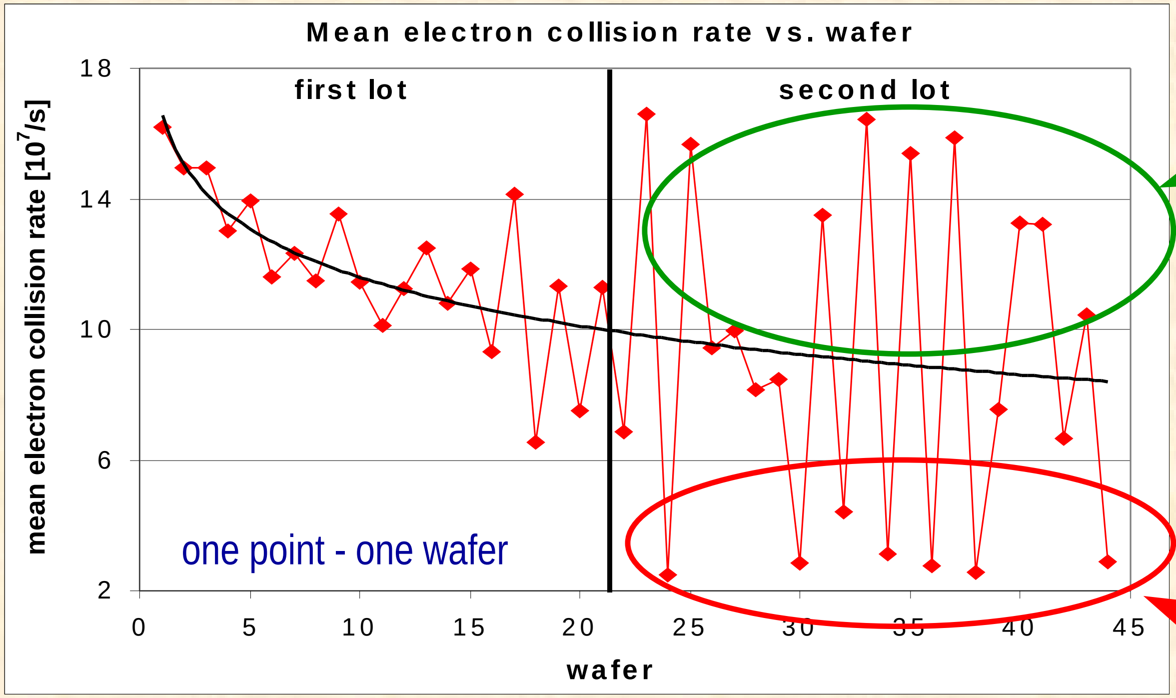
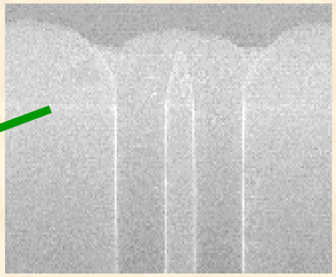
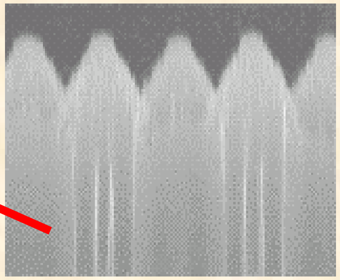
Process parameters integrate tool and wafer impacts – Example: Electron collision rate





Good etch result



Bad etch result

- Wafer to wafer signature at second lot caused by alternating mask quality, due to pre– processes (Litho, CVD)
- Drift during processing of 2 lots caused by tool impacts

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What´s the benefit of plasma
in- situ measurement techniques ?

Application at process development and maintenance

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Benefit at process development - Example: Check of process window linearity

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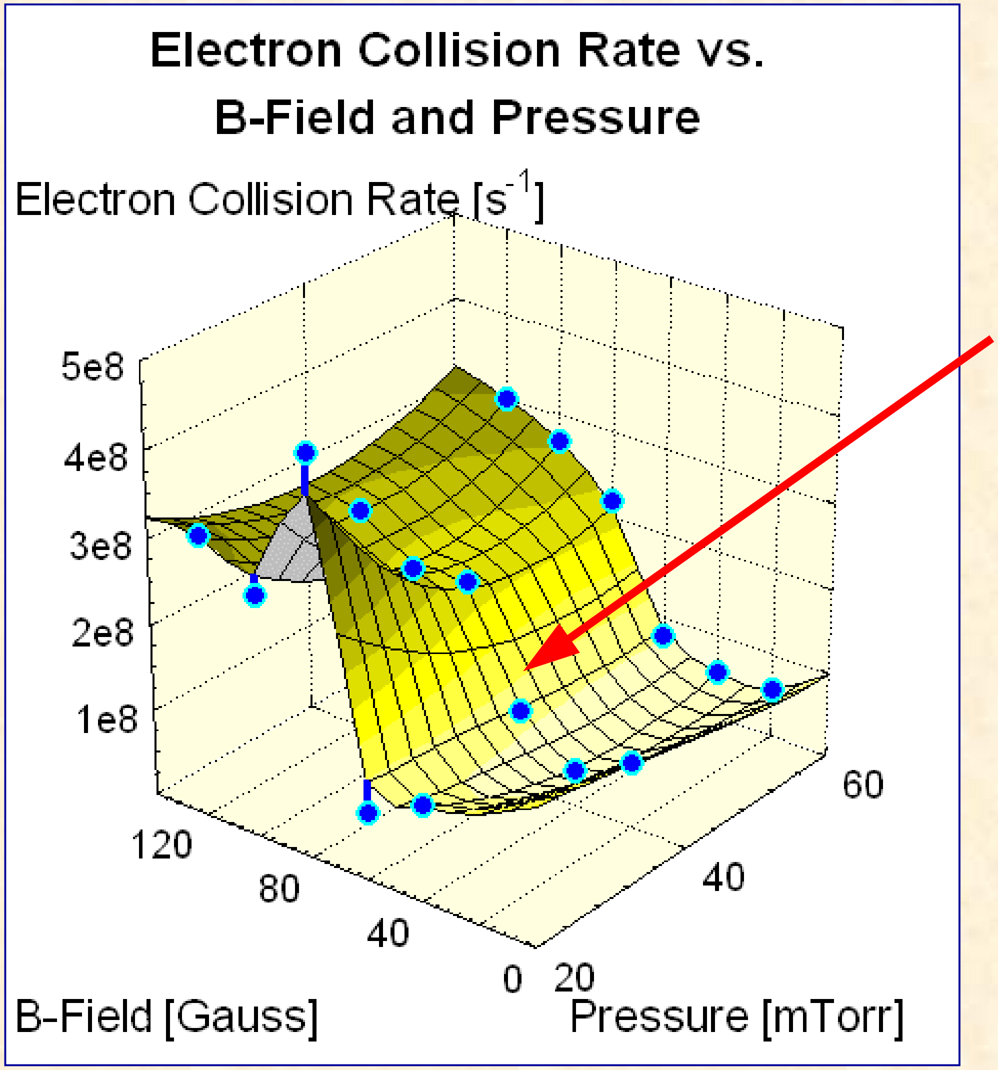

- Electron collision rate detects strong non-linearity inside process window
- Near 80 Gauss small B-field change causes large variation of process conditions
- Benefit of in-situ process parameter measurement: Reduced efforts at process development, time and nerves saved !

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Benefit at process development – Example: Check of conditioning repeatability during process development

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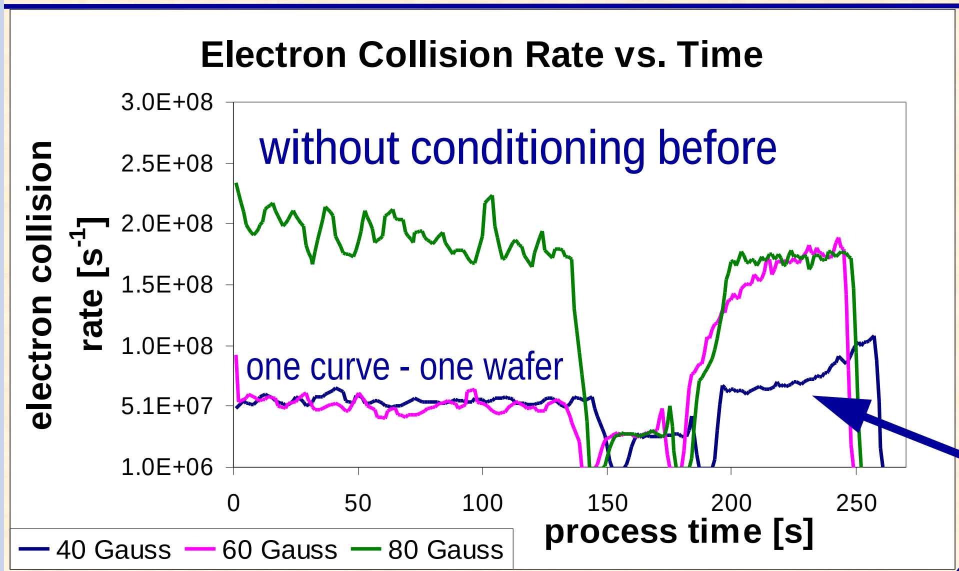
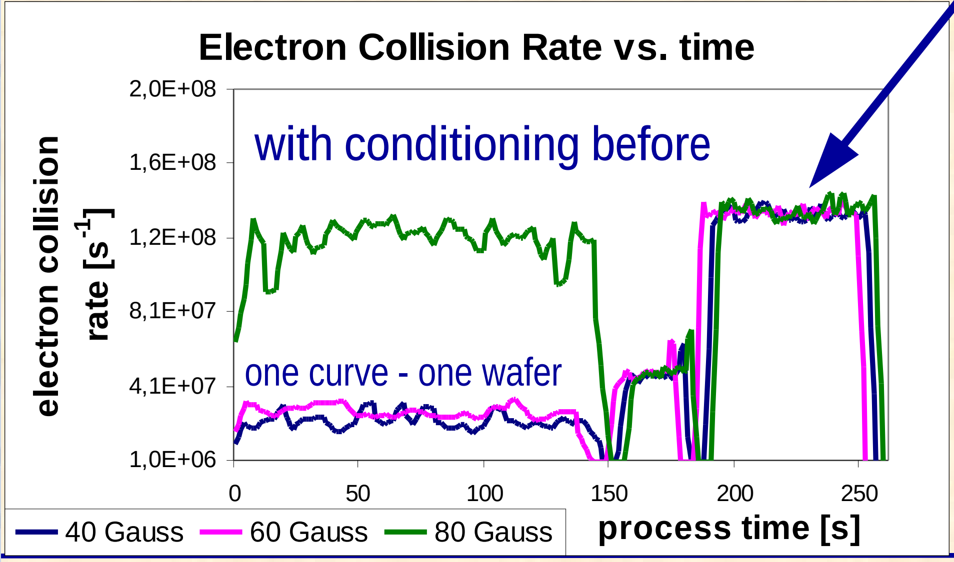

Electron Collision Rate vs. Time


Electron Collision Rate vs. time

- Electron collision rate indicates conditioning impact
  - on Nitride over etch step only
  - Depending on B- field (compare 40 Gauss and 80 Gauss)
- Two additional wafers are necessary to re-stabilize process conditions

Benefit at maintenance – Example:
Chamber matching by plasma parameter measurement

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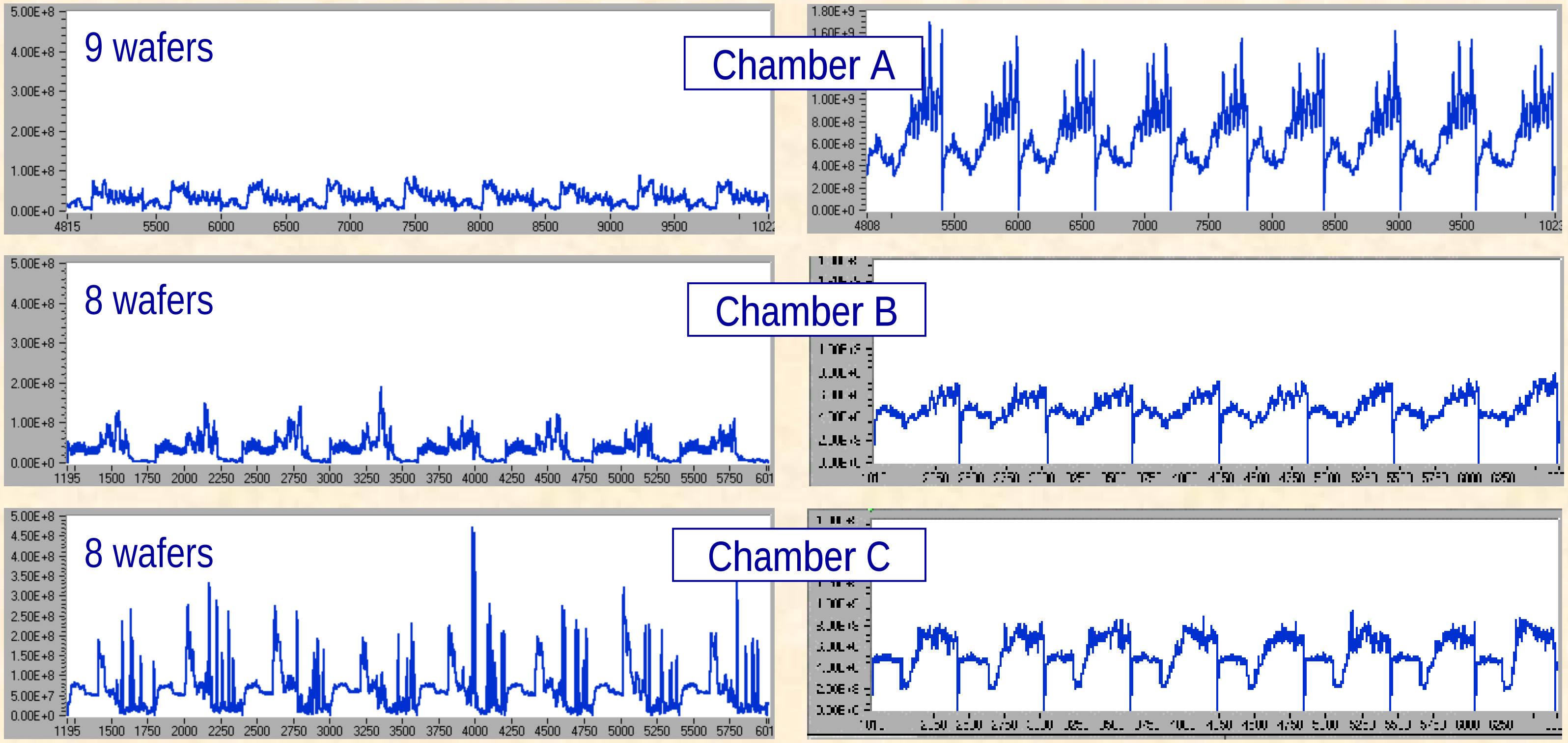
Electron collision rate   Electron density



- Split lot in chamber A, B and C: Electron collision rate and electron density detect significant process divergence immediately – chamber matching must be improved.

Abilities of in-situ measurement techniques – Example: Impulse detection in RF stray field at AMAT MxP+

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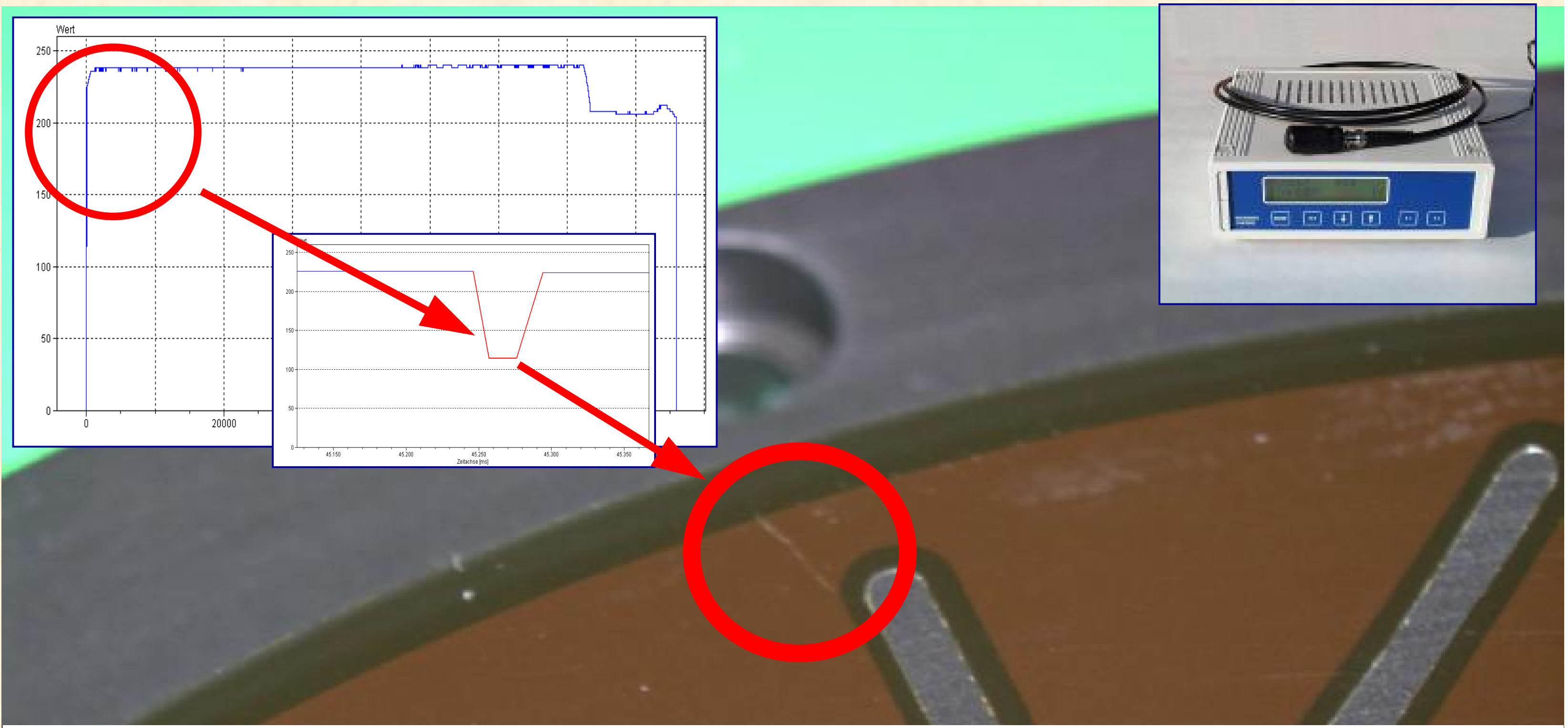

- Impulse detection in RF stray field outside of the chamber
  - RF field break down indicates break through of e- chuck isolation.
  - Tool parameters didn´t detect this tool fault at all.

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Application
on process control
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... and limits of in-situ measurement techniques - Example: Impulse detection in RF stray field

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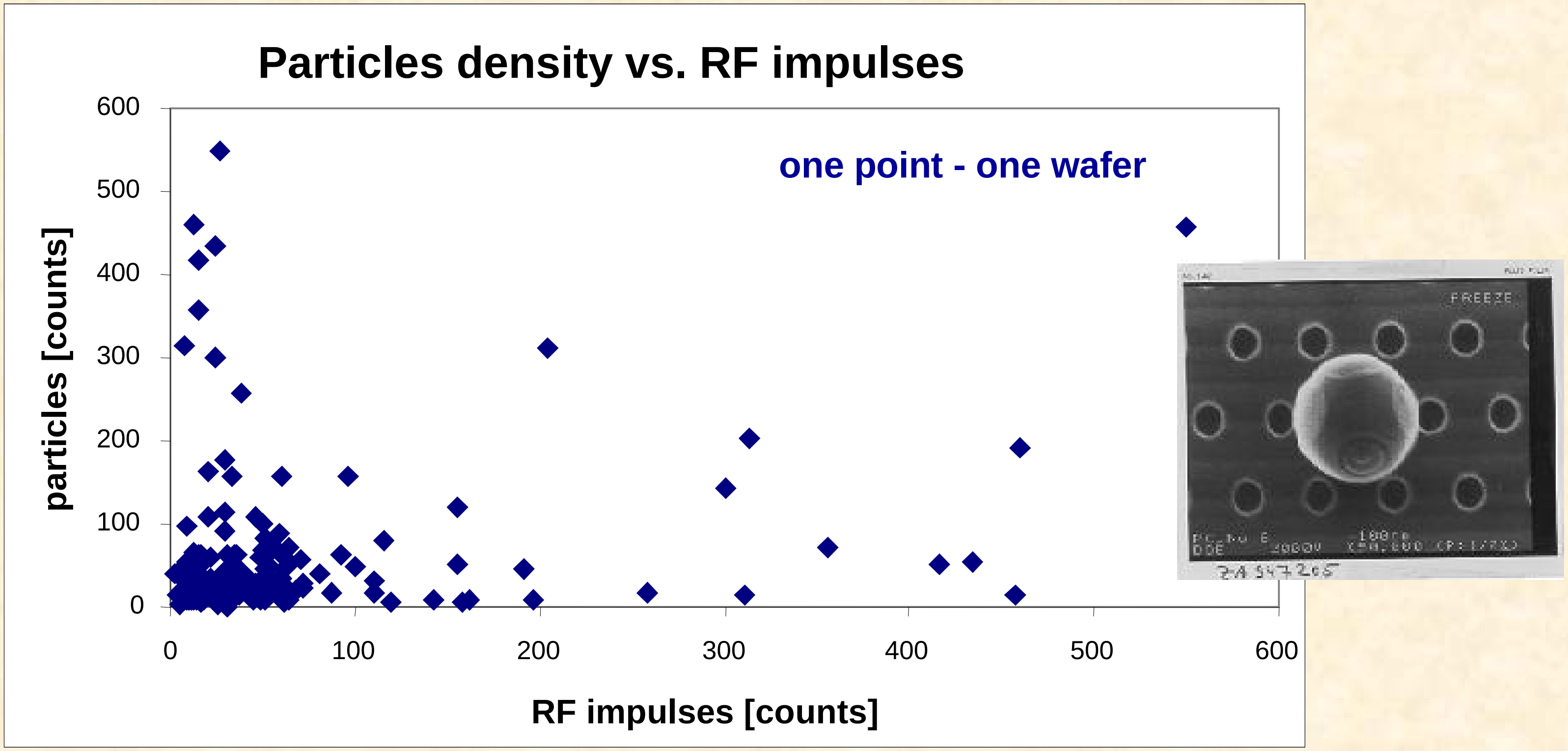

- Successful detection of some tool faults, but no correlation between particle density on wafer and RF field break downs
- Tool faults don´t always have an direct impact on wafers always of course

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Comparison of tool and process parameters – Example: GC etch in LAM TCP

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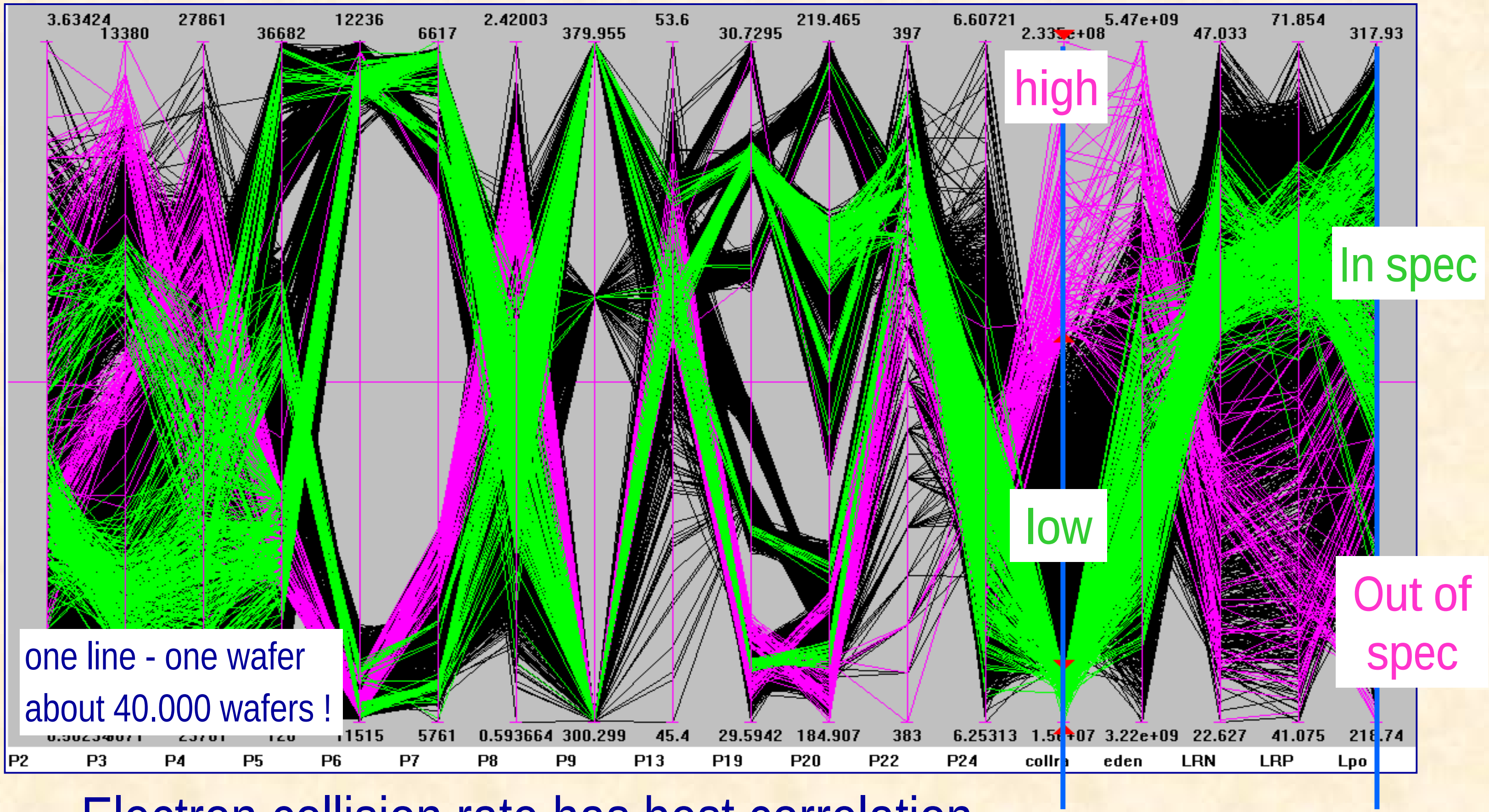

high

low

In spec

Out of spec

one line - one wafer
about 40.000 wafers !

- Electron collision rate has best correlation of all measured GC etch parameters to electrical product parameter

Electron collision rate

Electrical product parameter

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Correlation between in-situ process parameters and product parameters in high volume production

- Correlation between process parameter and product parameter
  - Product parameters (e.g. electrical results) depend on many hundreds unit processes and their interactions
  - è Simple quantitative correlations between parameters of one unit process and product parameters are rare.
  - In case this happens, this unit process would have a significant impact on electrical results, or yield (poor process engineer !)
- Benefit of in-situ process parameters:
  - **Real time** fault detection of tool failures, pre- processes, …
  - **Real time** detection of process conditions
    - Which might be critical generally
    - Without strong correlation on every single wafer

In-situ process parameter detects process impact on electrical product parameter – Example: GC etch

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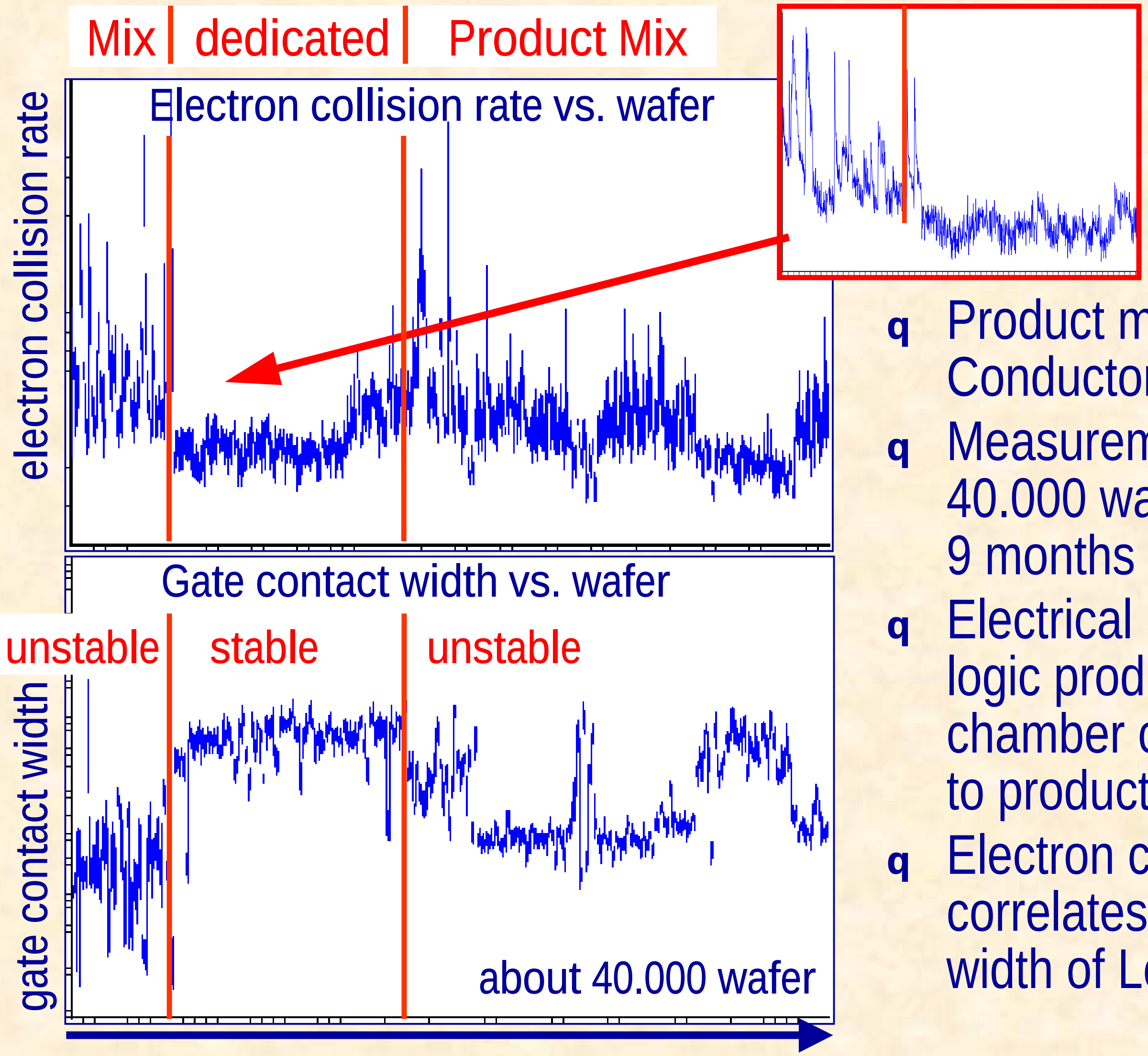

First part of results already presented last year

q Product mix at Gate Conductor etch in LAM TCP

q Measurement of about 40.000 wafers for about 9 months

q Electrical parameters of logic product depend on chamber conditioning due to product mix

q Electron collision rate correlates with gate contact width of Logic product

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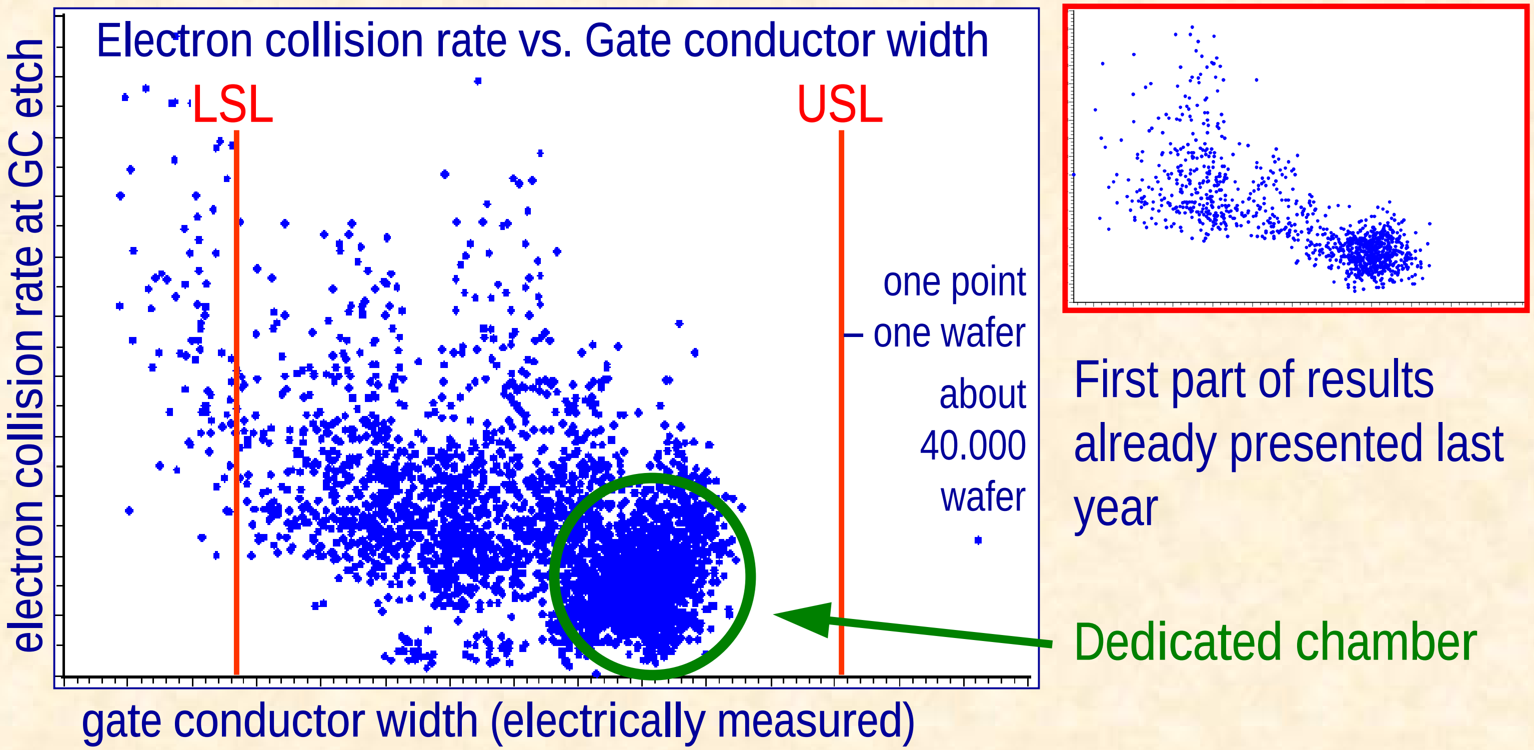
Correlation in-situ process parameter - product parameter
Example: GC etch in LAM TCP



First part of results already presented last year

- Correlation inside specification limits è significant response for rather than at serious process problems can be expected.
- From unit processing point of view the correlation is week, but from process integration view it´s fine.

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Process Control in high volume production needs data compression

q “Process Control” without data compression ?

  ø Let´s take a 4 chamber tool, 2 main products, 2- step recipe

  ø Let´s monitor of 10 parameters per chamber

  ø Let´s calculate 2 statistical key numbers per parameter (e.g., mean, standard dev.)

  ø è How many parameters would we have to check ? è 320 !!!

q Data compression by

  ø Selection of process relevant parameters

  ø Modeling

q In-situ measurement techniques provide process parameters

  ø Integrate measurable and not directly measurable impacts

  ø That´s data compression “by physics and chemistry themselves”

q è Application as real- time **indicator** of process conditions

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Summary

- So, what´s the importance of in-situ measurement techniques ?
- They provide process parameters, which **integrate** impacts of tool and wafer on plasma process conditions
  - Ø measurable impacts
  - Ø and not directly measurable impacts
- Benefit:
  - Ø Data compression “by physics and chemistry themselves”
  - Ø Application as **real- time indicator** of process condition
- „Process control“ by tool parameters mainly, without modelling
  è that´s the „poor man´s method“, sufficient yesterday
- We will need in-situ measurement techniques very soon and very strong to manage critical dimensions smaller than 100nm on 300mm wafers !

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