Plasma monitoring under industrial conditions for semiconductor technologies

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Motivation

Why should we measure plasma parameters?

The important process parameter is the density of the neutrals n_n

$$n_n = \frac{p}{kT_n}$$

- **power dissipation for chemistry by electrons (collision rate)**
- **energy and angle distribution of ions determines etch profile**

depending on both pressure p and gas (neutrals) temperature T_n.

n_n: density of the neutrals ⇒ crucial process parameter

p: pressure ⇒ adjustable tool parameter

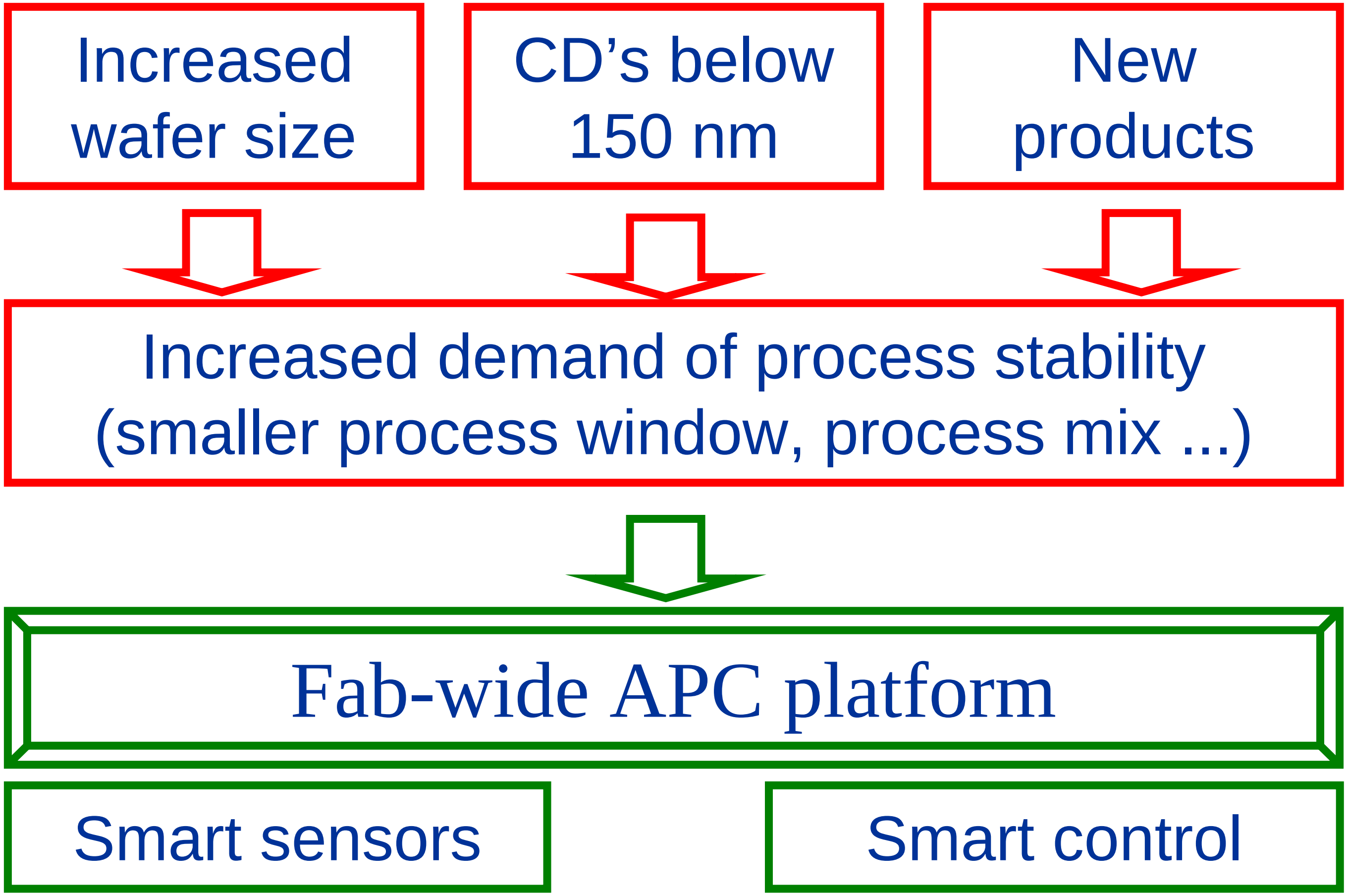
T_n: gas (neutrals) temperature ⇒ hardware parameter (chamber... electrode temperature)

k: Boltzmann constant

In a non-thermal, low pressure plasma – the neutral's density is the core parameter!

Contents

The up-coming challenges



Increased wafer size

CD's below 150 nm

New products

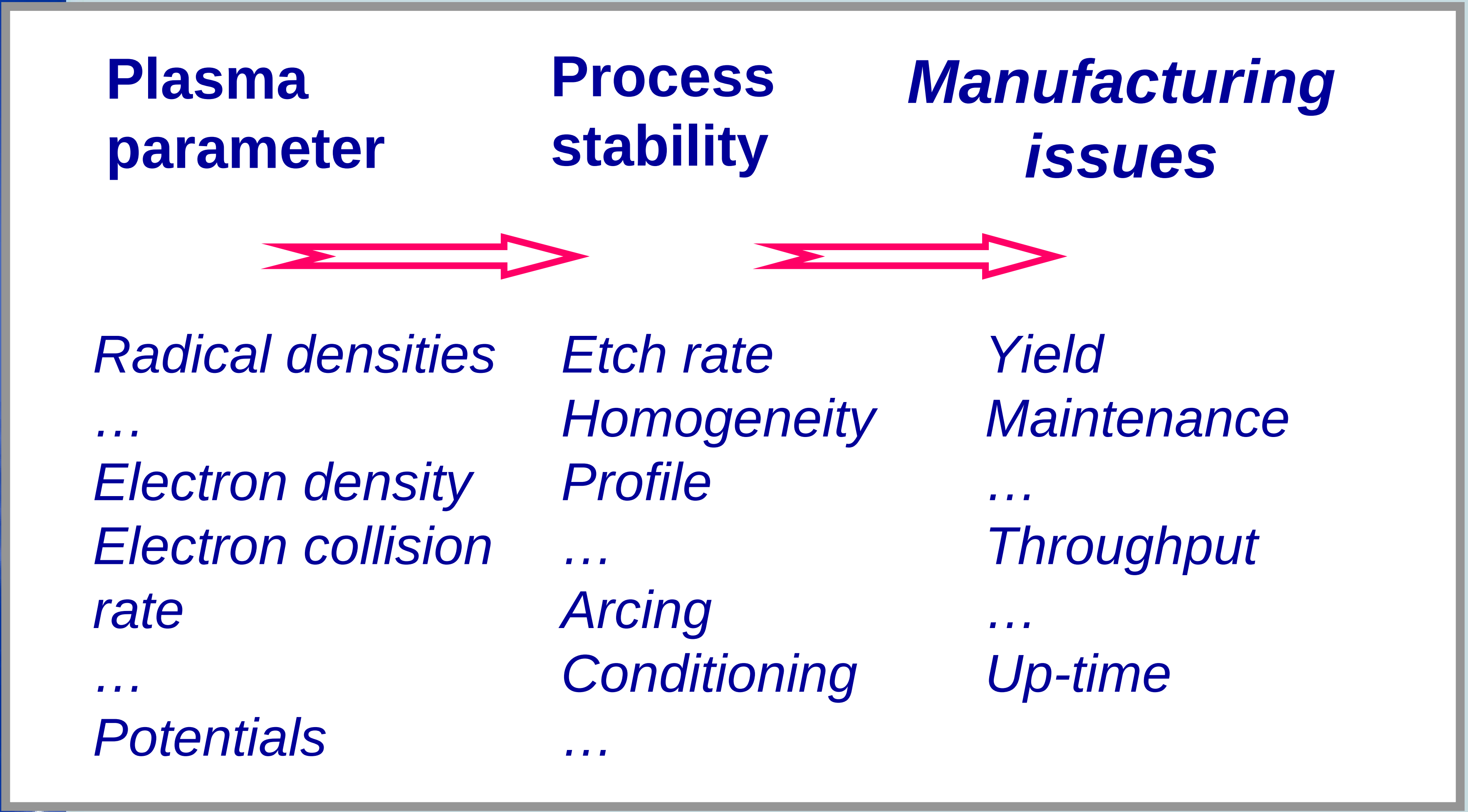
Increased demand of process stability (smaller process window, process mix ...)

Fab-wide APC platform

Smart sensors

Smart control

Process knowledge and economic benefit



Plasma parameter

Radical densities
…
Electron density
Electron collision rate
…
Potentials

Process stability

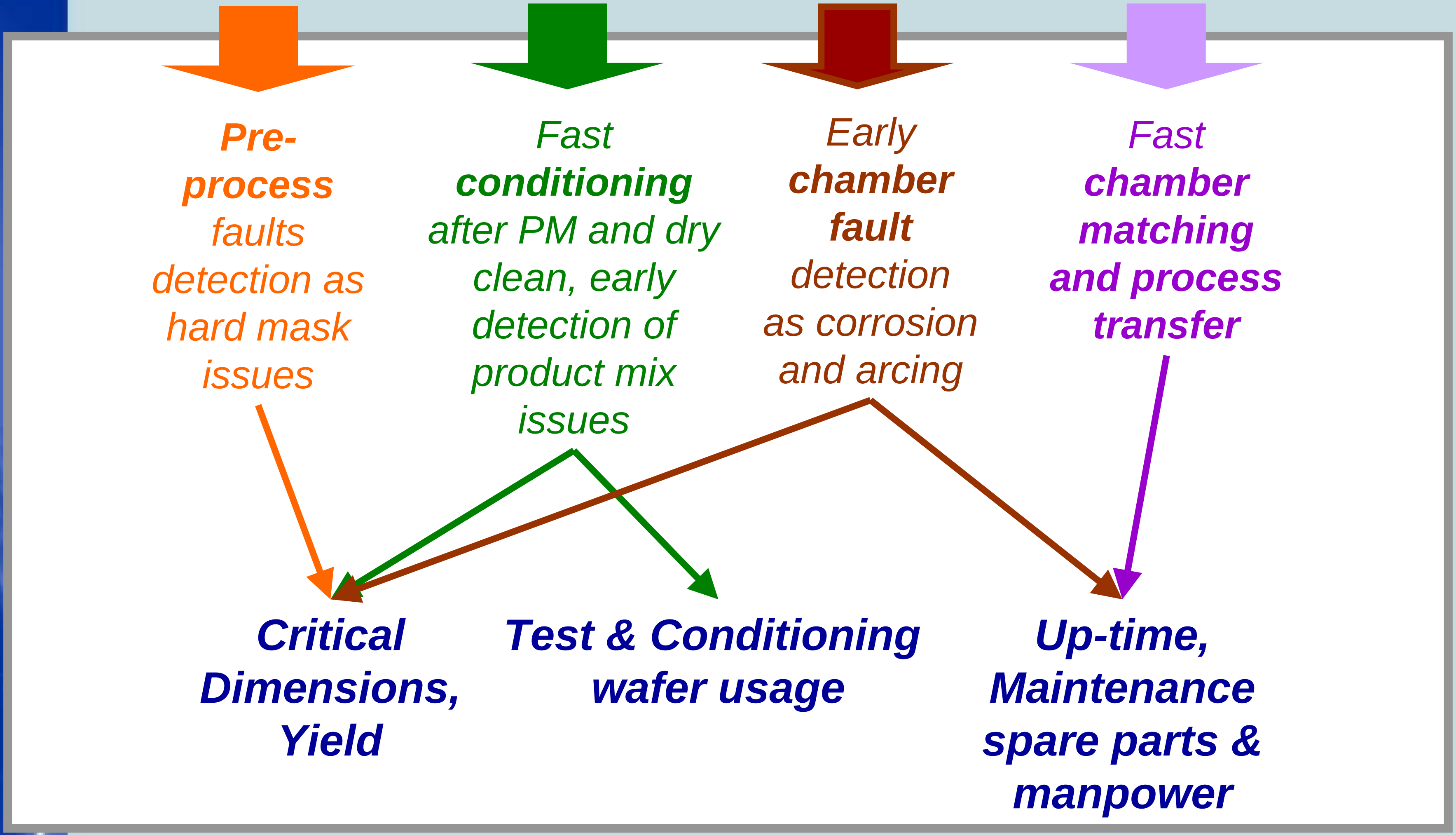
Etch rate
Homogeneity
Profile
…
Arcing
Conditioning
…

Manufacturing issues

Yield
Maintenance
…
Throughput
…
Up-time

ADVANCED SEMICONDUCTOR INSTRUMENTS

Plasma parameter and process state



Pre-process faults detection as hard mask issues

Fast conditioning after PM and dry clean, early detection of product mix issues

Early chamber fault detection as corrosion and arcing

Fast chamber matching and process transfer

Critical Dimensions, Yield

Test & Conditioning wafer usage

Up-time, Maintenance spare parts & manpower

Plasma parameter and process state

In-situ measurement techniques are needed

	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 plasma	Parameters of electron, ions and neutrals	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 cannot be measured directly, or even not at all.

Source: A. Steinbach (Infineon), 2nd AEC/APC Europe, Dresden, Germany, 2002.

Which parameters should be measured

- ❑ RF power input into plasma?
  - VI probe delivers RF power into chamber including feed-through, cooling system and e-chuck.
- ❑ Electron parameters are the key parameters of the bulk plasma (ionization, dissociation, fragmentation, excitation...).
  - Optical Emission Spectroscopy (OES) reflects electronic excitation for different species.
  - Self Excited Electron Resonance Spectroscopy (SEERS) provides global electron parameters directly.

Contents

- Introduction
  - Plasma monitoring for low pressure application, mainly plasma etching
  - The IC manufactures application conditions and requirements
- ***Comparison of applicable monitoring methods***
  - ***OES***
  - ***VI Probe***
  - ***SEERS***
- Application examples and conclusions
  - Plasma physical effects in production chambers
  - Fault detection and conditioning
  - Plasma and product parameter

Applicable methods under industrial conditions

VI probe

- RF voltage and current as well as phase angle at matchbox
- Main application: RF Maintenance
- Disadvantage
  - Strictly speaking no plasma parameter, RF current 90% ’chamber current’ and 10% ‘plasma current’. Measures mainly the chamber’s impedance
  - ‘New game’ in case of new chamber hardware (see above)
  - Provides only the fundamental or some harmonics
- Advantage
  - Easy to understand
  - Supports chamber development and analysis

ADVANCED SEMICONDUCTOR INSTRUMENTS

Applicable methods under industrial conditions

Optical emission spectroscopy (OES)

- ☐ Relative intensities of excited species
- ☐ Main and pure application: Endpoint detection
- ☐ Disadvantage
  - Interpretation needs high level of knowledge
  - Requires data compression due to large amount of data via Principal Component Analysis (PCA) or ...
- ☐ Advantage
  - Easy access via sight window
  - Different species can be identified
  - Supports process development and analysis

Applicable methods under industrial conditions

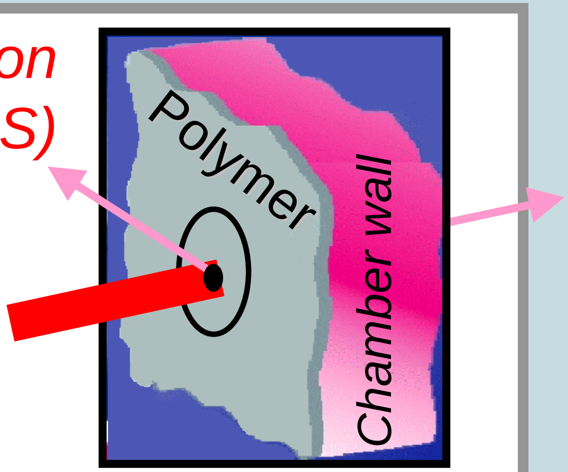
Self Excited Electron Resonance Spectroscopy (SEERS)

- ☐ Based on a broad-band RF current measurement
- ☐ Approximately volume averaged density and collision rate of electrons and the electronic bulk power
- ☐ Main application: Process monitoring
- ☐ Disadvantage
  - Needs access to chamber via passive sensor on ground potential
  - Not available for all chamber types
- ☐ Advantage
  - Provides real plasma parameters (inside measurement)
  - Easy handling for process monitoring
  - Supports process and chamber development

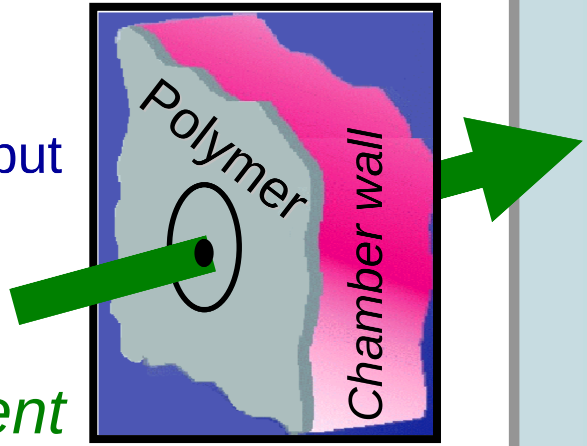
Robustness under industrial conditions

Does an insulating layer disturb ?

- ☐ Classical, optical approach
  - Optical sight window access
  - New intensity level after PM
  - Damping by polymers/by products
  - No absolute values and chamber matching



- ☐ SEERS and VI probe
  - Based on passive RF current sensor flat in chamber wall (SEERS) or at matchbox output
  - No impact of chamber wall polymer
  - Absolute values
  - Chamber matching



SEERS Theory

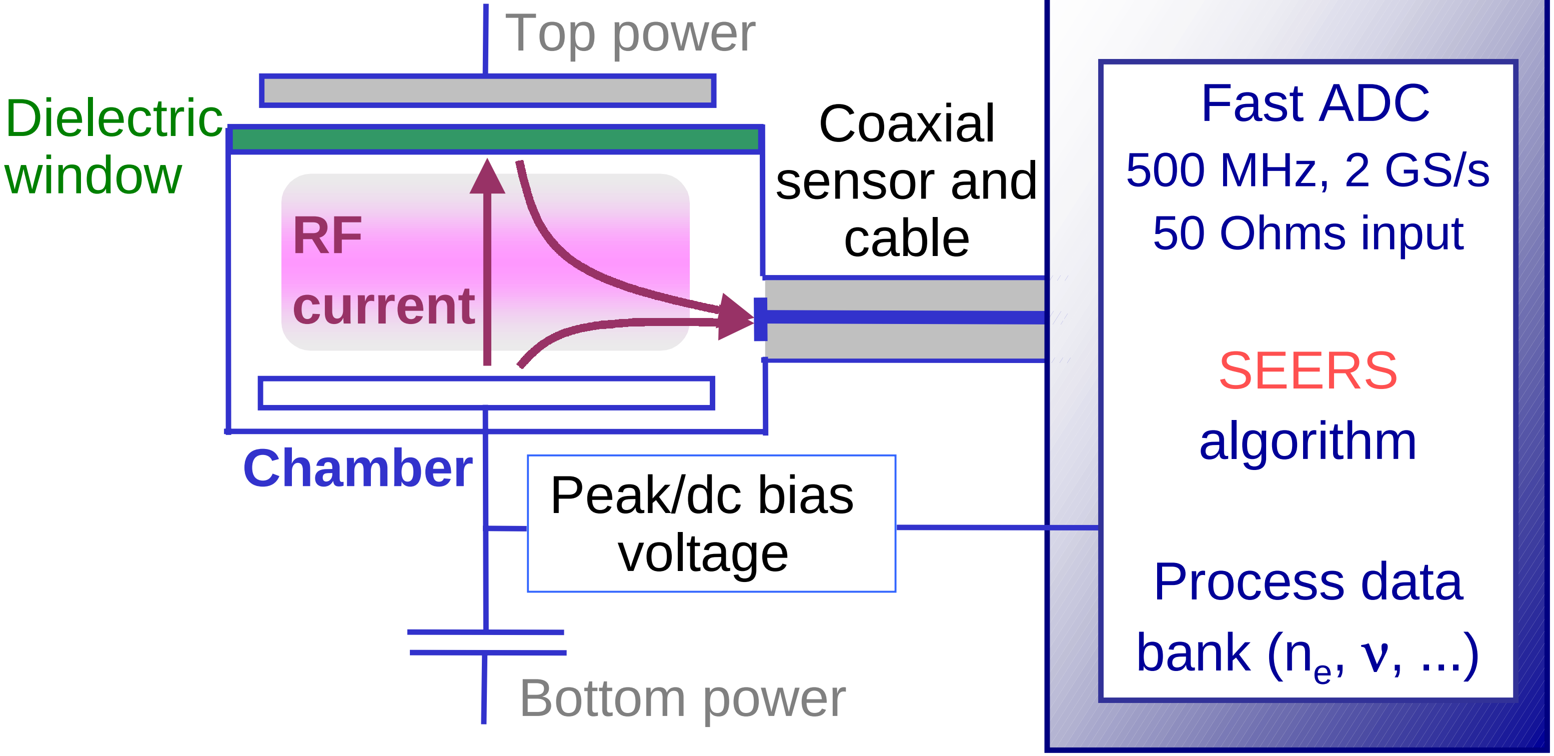
SEERS - model-based measurement of plasma parameters

- ❑ SEERS Fundamentals:
  - Non-linearity between voltage and displacement current in space charge sheath
  - The resonance capability of the plasma (damped series resonance circuit)
  - Geometric resonance frequency depending on electrode gap
  - Treatment of full Fourier spectrum in model with free parameters
  - Parameter estimation provides electron density and collision rate as core parameters
- ❑ SEERS Assumptions
  - Electron plasma frequency >> RF frequency >> ion plasma frequency
  - Plasma sheath assumed as one dimensional
  - Plasma bulk as cylindrical

SEERS Theory

Experimental setup of SEERS

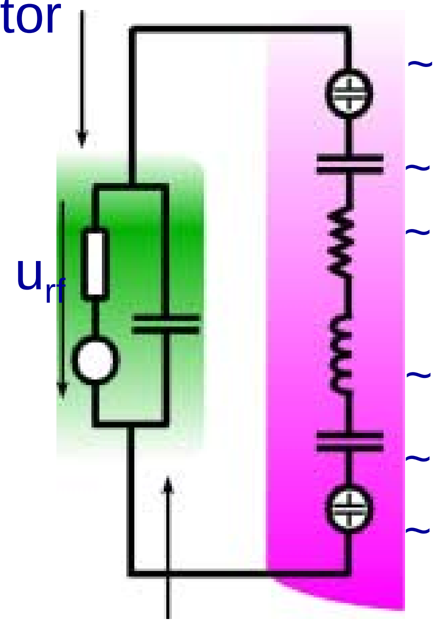
Example: TCP®



- ☐ The current pitch ratio is determined dynamically.

SEERS Theory

SEERS equivalent circuit



matchbox and generator

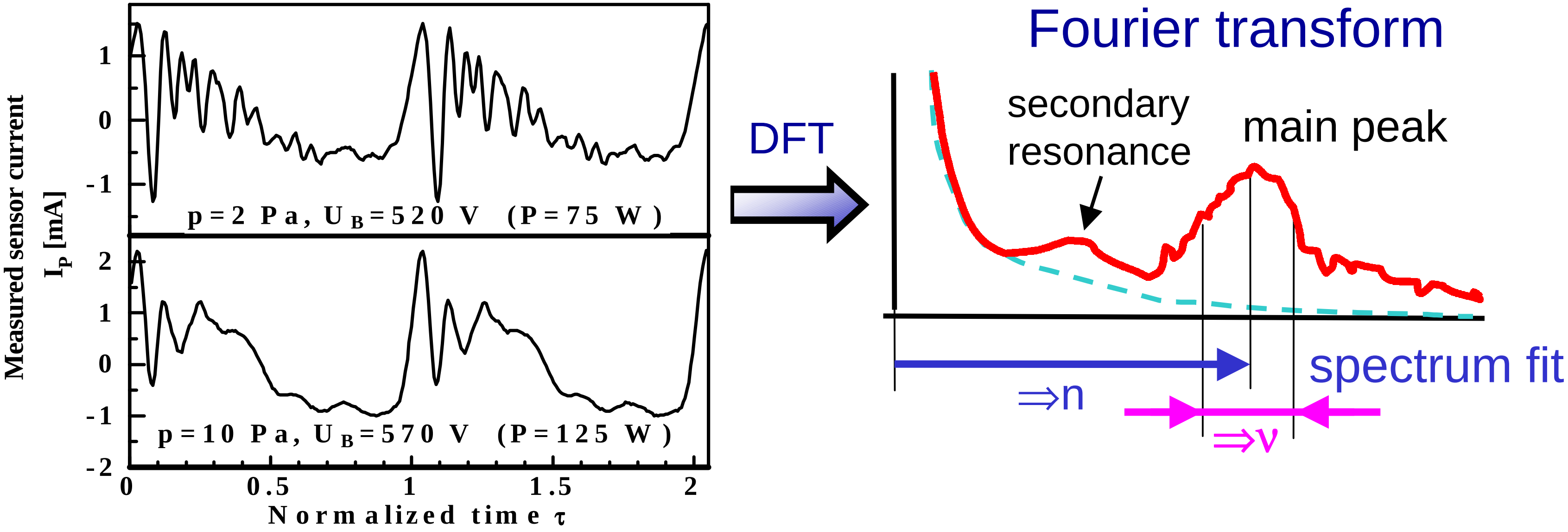
$\sim u_1\,[\int -\,i\,dt]$	nonlinearity sheath plasma-wall
$\sim s_1$	linear „part“ of wall sheath
$\sim n\,l\,m_e$	ohmic part of plasma bulk (ohmic and stochastic heating)
$\sim \omega\,l\,m_e$	inertia (imaginary) part thereof
$\sim s_0$	linear „part“ of RF sheath
$\sim u_0\,[\int i\,dt]$	nonlinearity sheath RF electrode

feed-through and stray capacitance

☞ The plasma can be regarded as a damped resonance circuit.

SEERS Theory

An easy explanation of SEERS



- Shape of the FOURIER-transform provides the information
  - amplitude is not important!

- Needs non-iterative and robust algorithm due to nonlinearity, fluctuation or model violations

One signal - one parameter set

SEERS Theory

Reciprocally and spatially averaged plasma parameters

☐ SEERS determines reciprocally volume averaged:

- electron density:

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

- electron collision rate:

$$\tilde{\nu} \approx \frac{\tilde{n}}{V} \int_V \frac{\nu}{n}\, dV$$

- (electronic) bulk power:

$$P_B \propto \frac{\tilde{\nu}}{\tilde{n}} \sum \left[\; I^{(k)} \right]^2$$

Due to 1/n averaging, ranges of lower density get a higher weight!

SEERS sensors

Standard sensor types for etch tools and unaxis

DN16CF

DN25KF

DN40KF
customer modified

unaxis (PlasmaTherm)

SEERS sensors

Sensors for 300 mm etch tools

APPLIED MATERIALS® DPS™
- ⇨ peak voltage
- ⇨ inductively coupled
- ⇨ capacitive ≠ inductive coupled frequency

LAM® 2300™
- ⇨ peak voltage
- ⇨ inductively coupled
- ⇨ PnP data interface

APPLIED MATERIALS® eMxP+™
- ⇨ peak voltage
- ⇨ rotating B-field
- ⇨ optical access for OES

Source: V. Tegeder, AEC/APC-Symposium XII, Lake Tahoe, USA, 2000.

by courtesy of Infineon technologies

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  - VI Probes
  - SEERS
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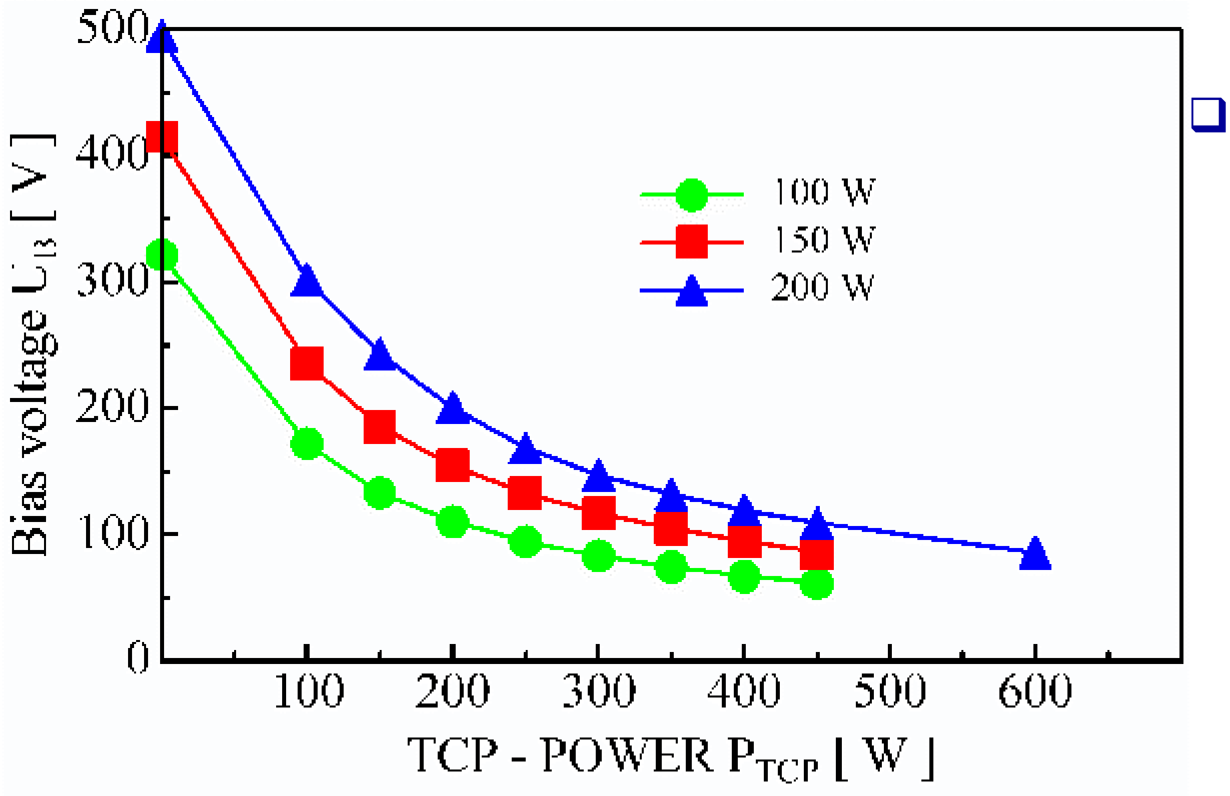
  - ***Fault detection and conditioning***
  - ***Plasma and product parameter***

ADVANCED SEMICONDUCTOR INSTRUMENTS

LAM® TCP® 9600 (Al etch, Cl chemistry)

Decreasing dc bias for increasing TCP® power



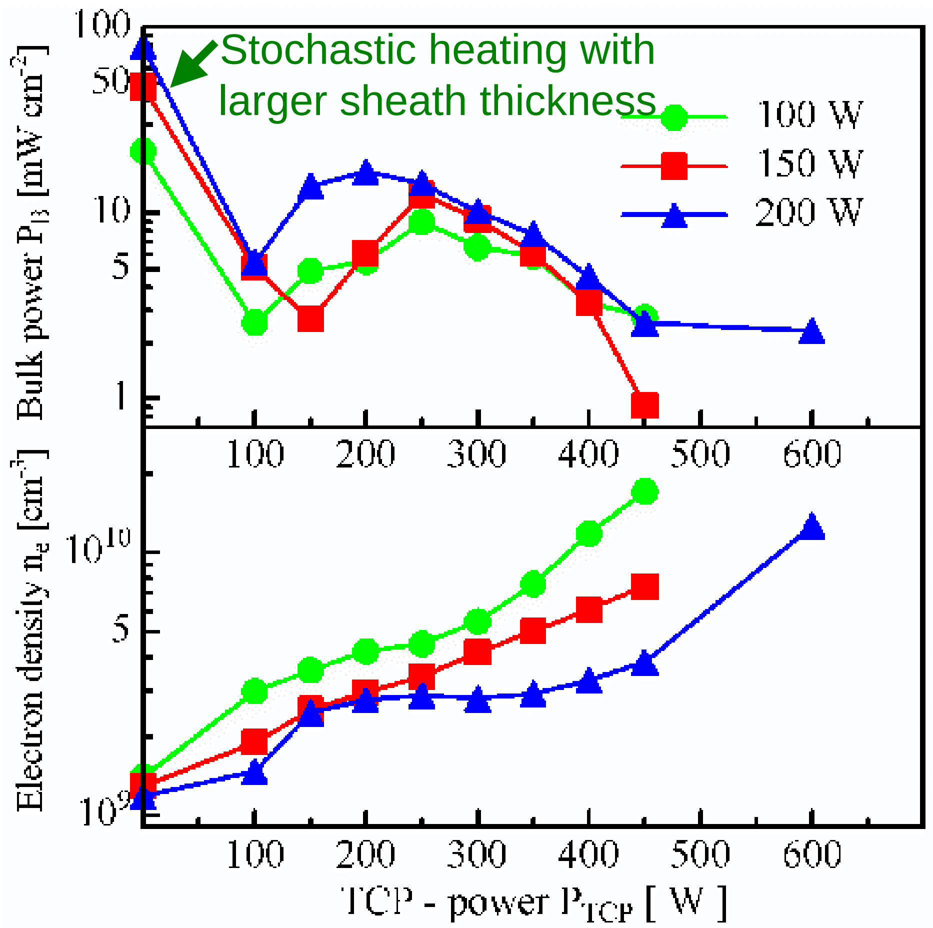
❑ TCP® power effects the electron density, thus the bias voltage and therefore the plasma impedance and the power dissipation of the bottom power (capacitive).

Source: S. Wurm, Lam Research Corp., 10th Ann. European Techn. Symp., Geneva, Switzerland, 1998.

by courtesy of Infineon technologies

LAM® TCP® 9600 (Al etch)

Bulk power and electron density for increasing TCP® power


Stochastic heating with larger sheath thickness

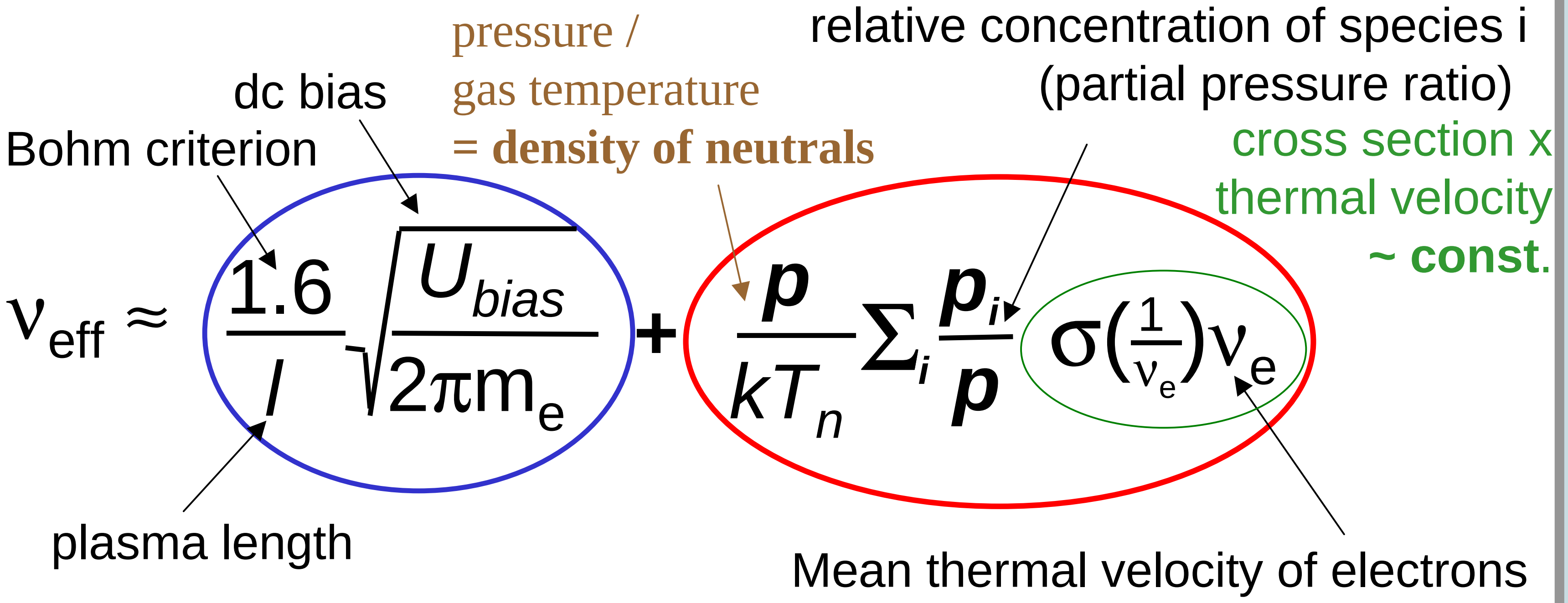
- ☐ TCP® power effects the density and collision rate of electrons and therefore the plasma impedance and the power dissipation of the bottom power (capacitive).
- ☐ **Mainly dependent on collision rate, the bulk power** (top) decreases for increasing TCP® power (>259 W). This is the reason for the plateau in the electron density.

Source: S. Wurm, Lam Research Corp., 10th Ann. European Techn. Symp., Geneva, Switzerland, 1998.

by courtesy of Infineon technologies

SEERS Theory

Physical background of the electron collision rate



$$\nu_{eff} \approx \frac{1.6}{l}\sqrt{\frac{U_{bias}}{2\pi m_e}} + \frac{p}{kT_n}\sum_i \frac{p_i}{p}\,\sigma\left(\frac{1}{\nu_e}\right)\nu_e$$

Bohm criterion

dc bias

plasma length

pressure / gas temperature **= density of neutrals**

relative concentration of species i (partial pressure ratio)

cross section x thermal velocity **~ const.**

Mean thermal velocity of electrons

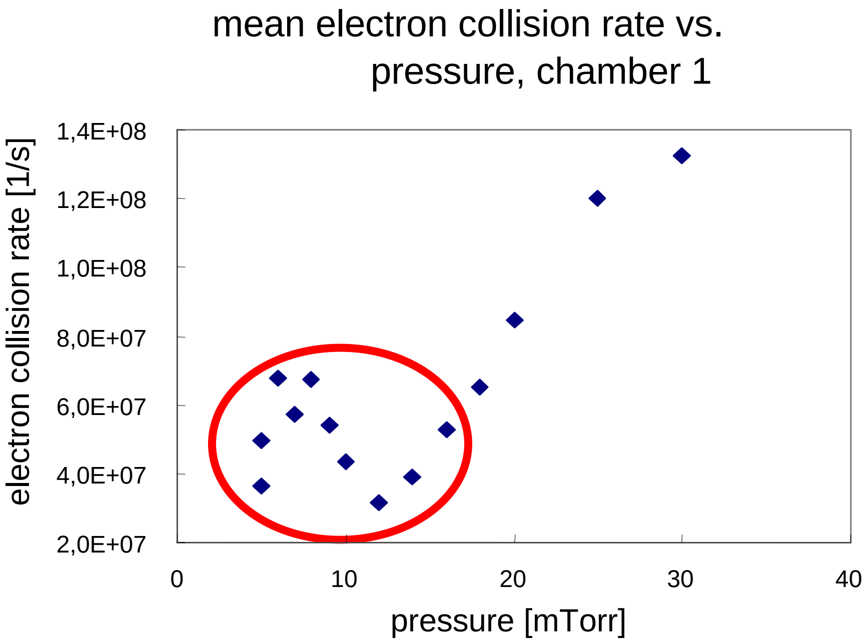
Stochastic heating,
dominating for low pressure,
< 10 Pa = 75 mTorr

Momentum transfer,
dependent on gas mixture, pressure,
and gas temperature directly

No magnetic field (B = 0) and capacitive coupling

LAM® TCP® 9400 (poly-Si etch)

Collision rate depending on pressure



- ❑ Pressure variation: collision rate shows nonlinear behavior
- ❑ Distinction of domination by ohmic heating / stochastic heating possible (= different modi of power conversion into plasma)
- ❑ Saturation / maximum at even higher pressures estimated

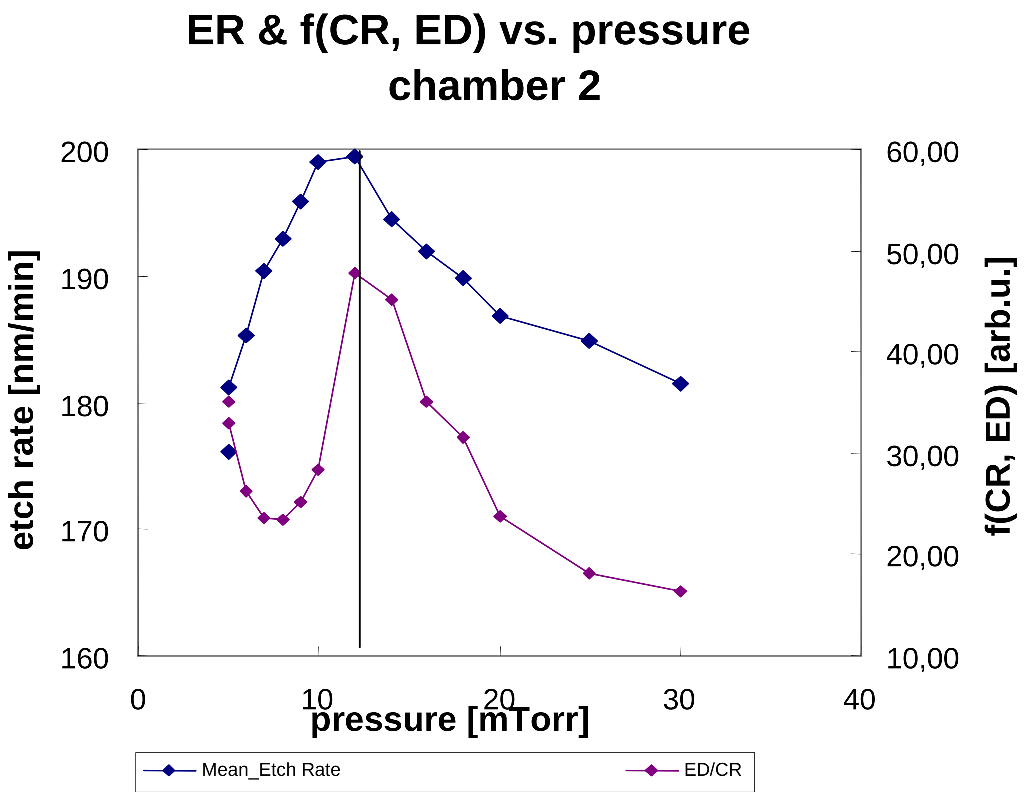
- ❑ **Potential process instability, basic understanding is needed for process development!**

Source: C. Steuer (TU Dresden), 2nd Workshop of SEERS, Dresden, Germany, 2000.

by courtesy of Infineon technologies

LAM® TCP® 9400 (poly-Si etch)

Etch rate and plasma parameters depending on pressure



- ☐ Plasma parameter: electron density / collision rate (ED/CR)
- ☐ Correlation between in-situ and in-line measurements mean etch rate, (blue) and quotient electron density / electron collision rate (purple) for pressure variation.

Source: C. Steuer (TU Dresden), 2nd Workshop of SEERS, Dresden, Germany, 2000.

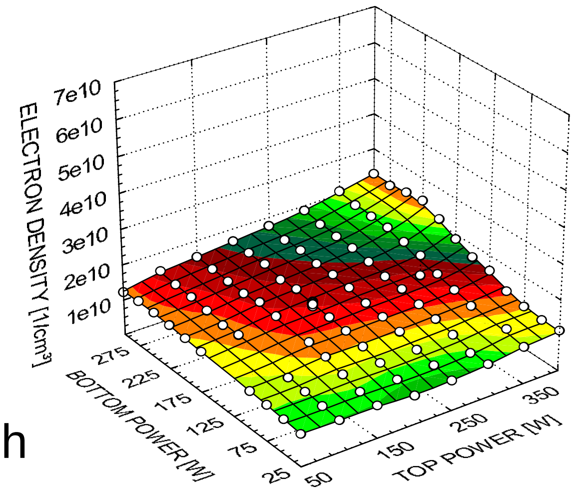
by courtesy of Infineon technologies

Chamber Comparison, LAM® TCP® 9400/SE

Electron density depending on top power and bottom power

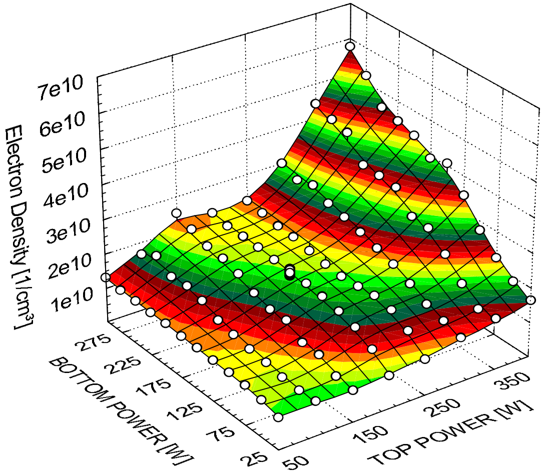
GC etch

Mean Electron Density vs. Variation
Top and Bottom Power, Chamber 1, t = 86 rfh



reference chamber

Mean Electron Density vs. Variation
Top and Bottom Power, Chamber 2, t = 73 rfh



striking chamber

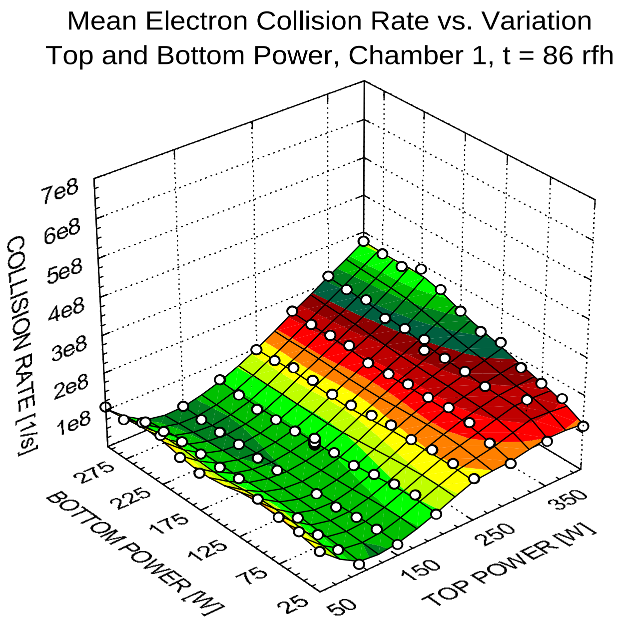
- bad selectivity between poly-Si and gate oxide in striking chamber
  ➔ lower electron density for the same TCP® power
- RF power dissipation in plasma!
- easy tool fault detection ➔ TCP® Matchbox

Source: C. Steuer (TU Dresden), 2nd Workshop of SEERS, Dresden, Germany, 2000.

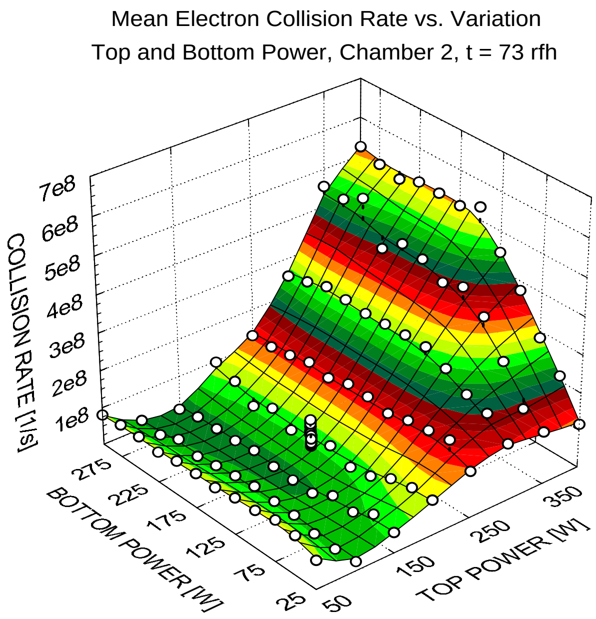
by courtesy of

Chamber Comparison, LAM® TCP® 9400/SE

Collision rate depending on top power and bottom power


Mean Electron Collision Rate vs. Variation
Top and Bottom Power, Chamber 1, t = 86 rfh

reference chamber


Mean Electron Collision Rate vs. Variation
Top and Bottom Power, Chamber 2, t = 73 rfh

striking chamber

Quantitative difference in collision rate,

local minimum along increasing bottom power

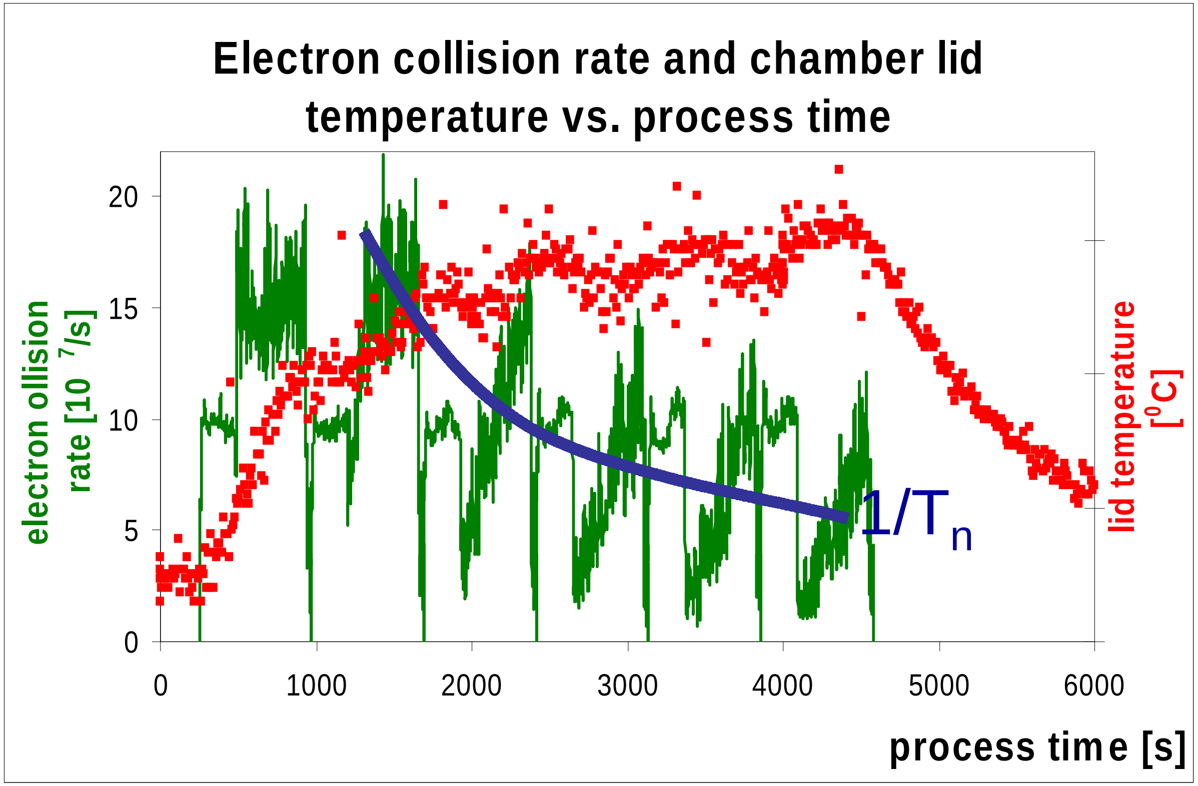
➔ separating ohmic + stochastic heating

Source: C. Steuer (TU Dresden), 2nd Workshop of SEERS, Dresden, Germany, 2000.

by courtesy of Infineon technologies

Chamber lid temperature and electron collision rate

Si etch in APPLIED MATERIALS® HART chamber, oxide wafers


Electron collision rate and chamber lid temperature vs. process time

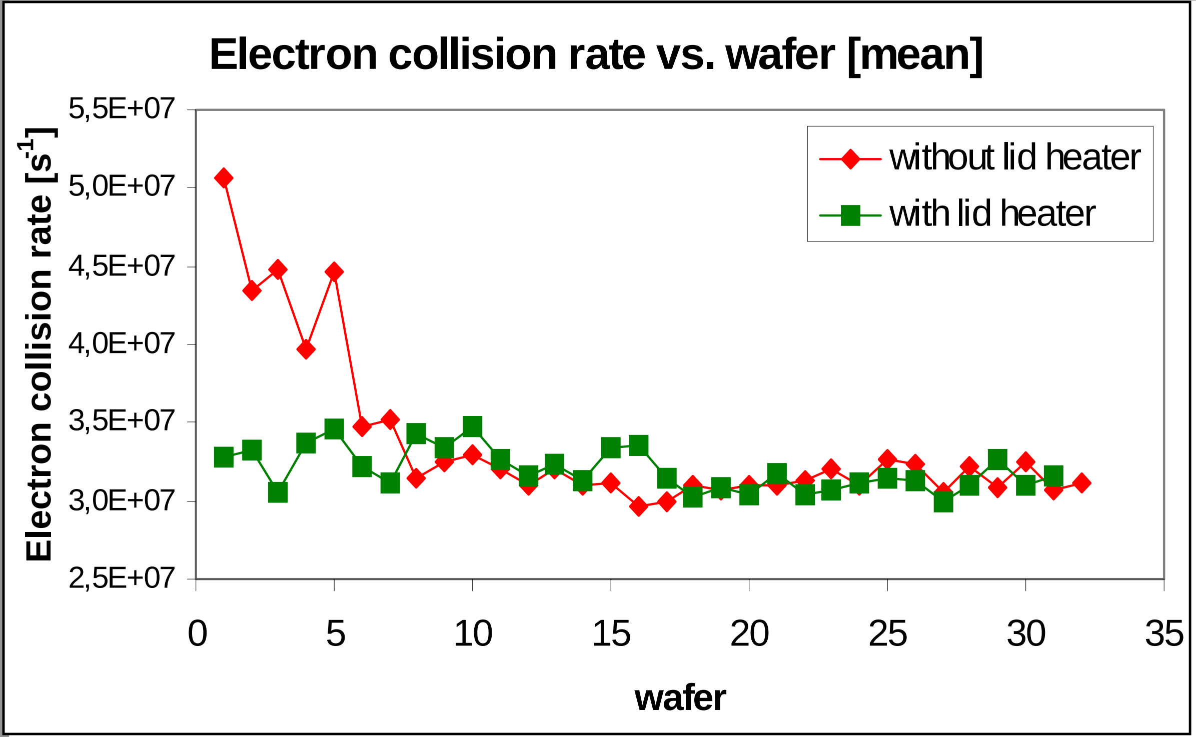
- First wafer effect (gas adsorption and desorption at chamber wall)
- Gas composition drift in plasma bulk („saw tooth“), heating of chamber kit and wafer surface cause drift of chemical reactions there.

Gas temperature drift only during high RF power step

by courtesy of Infineon technologies

Chamber lid temperature and electron collision rate

Si etch in APPLIED MATERIALS® HART chamber, product wafers



- ☐ Verifies again the temperature dependence of the electron collision rate ($1/T_n$).
- ☐ Temperature control of lid heater leads to stable conditions.

Electron collision rate versus magnetic field

Chamber: MxP™, B-field parallel to wafer

- Simple ansatz using the dielectric tensor leads to an one-dimensional approximation.

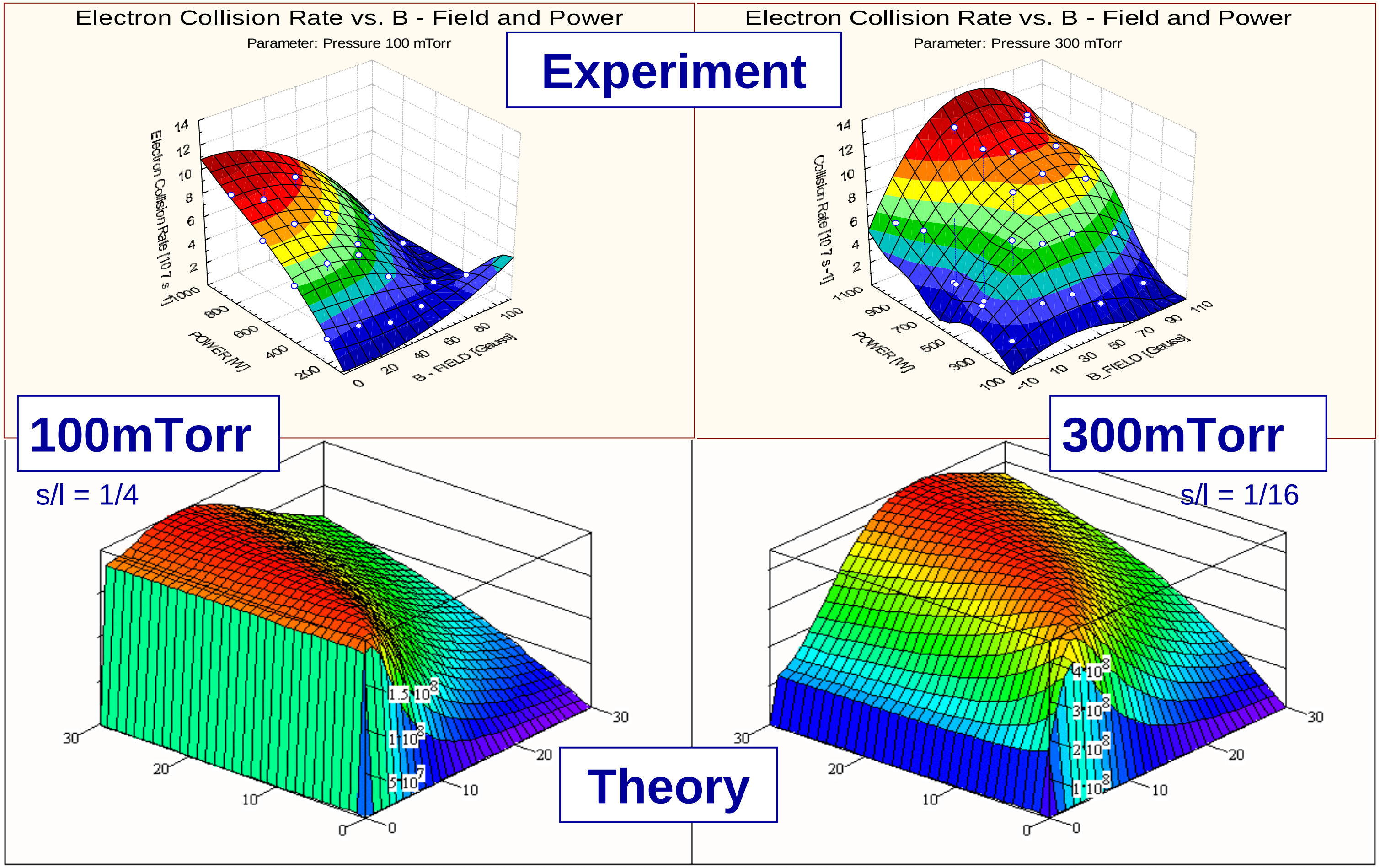
s: sheath thickness,
l: plasma length, without stochastic heating for B > 0

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

$$\omega := \left(\frac{s}{l}\right)^{\frac{1}{2}}\cdot\omega_{pe}(n) \qquad \nu = \nu_{Stoch} + \sqrt{\frac{8\,k_B\,T_e}{\pi\,m_e}}\cdot\frac{P_g}{k_B\,T_N}\cdot\sum_k\frac{p_k}{P_g}\,\sigma_k$$

Electron collision rate versus magnetic field

Chamber: MxP™, B-field parallel to wafer



Electron Collision Rate vs. B - Field and Power

Parameter: Pressure 100 mTorr

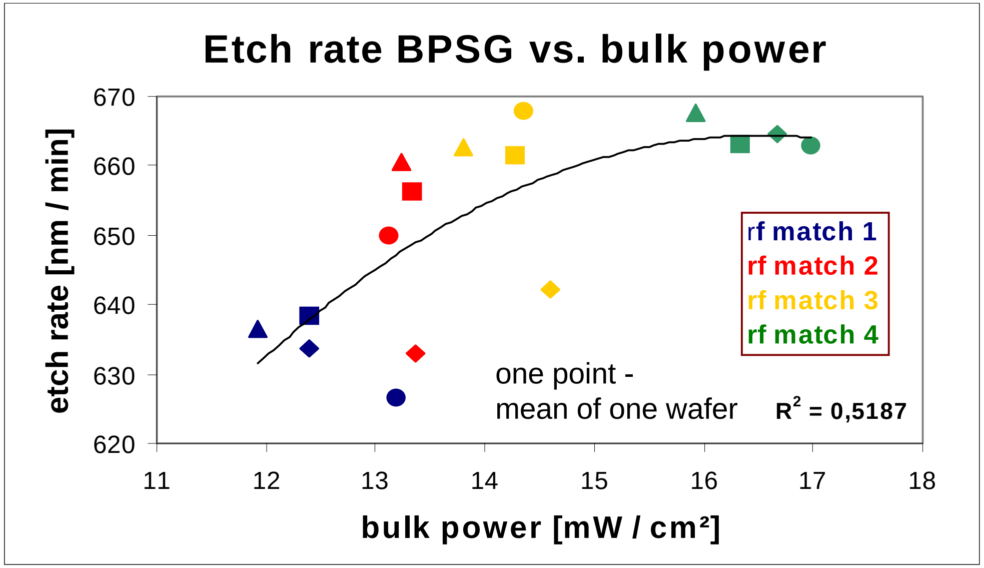
Electron Collision Rate vs. B - Field and Power

Parameter: Pressure 300 mTorr

by courtesy of Infineon technologies

APPLIED MATERIALS® MxP+™ (CT etch)

RF matchbox comparison by power density measurement



Contact etch at APPLIED MATERIALS® MxP+™

Comparison of power dissipation inside the chamber, while nominal rf power kept constant.

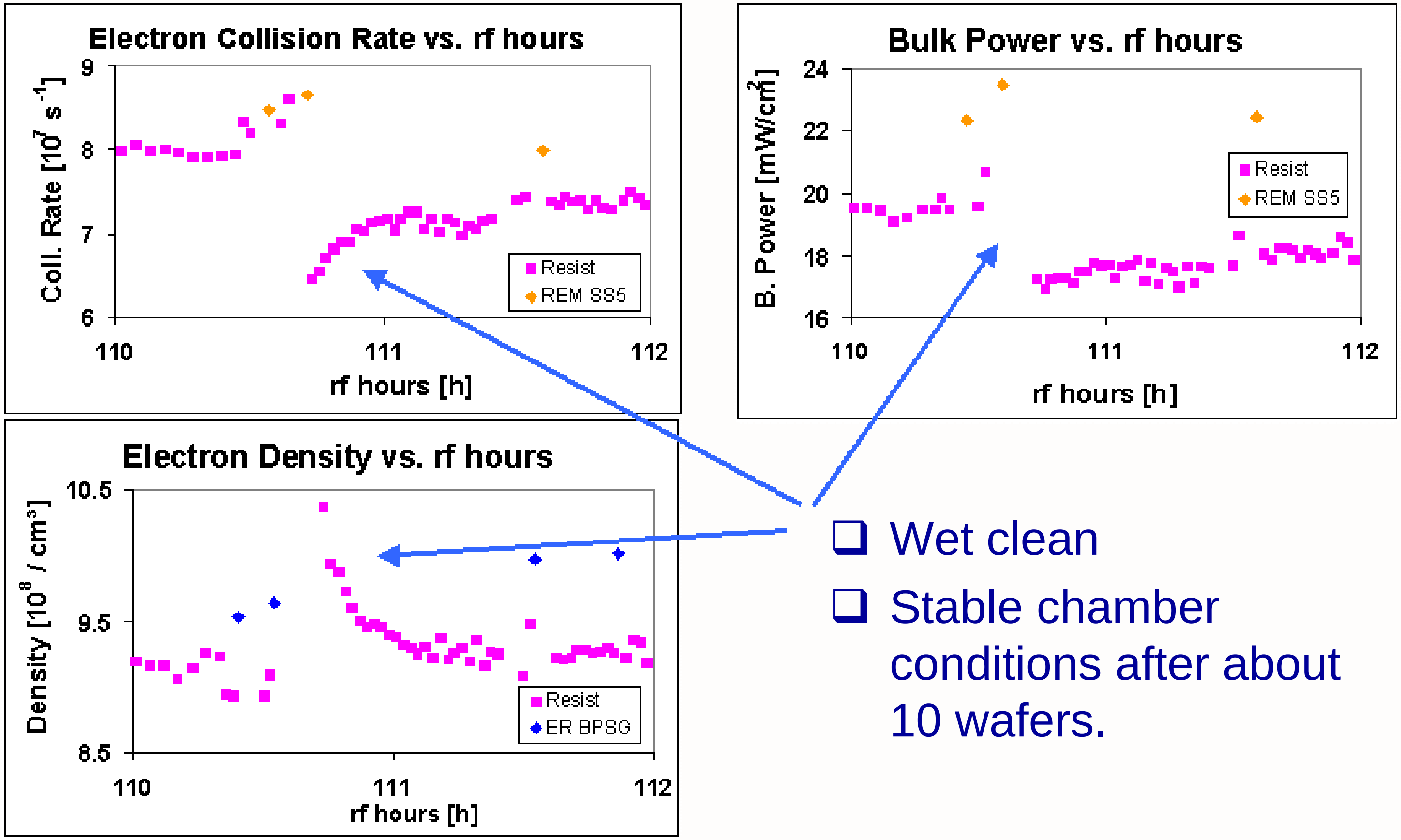
- ☐ RF match box comparison by bulk power measurement.
- ☐ Power coupling into the chamber differs about 30% as indicated by bulk power.
- ☐ Impact of chamber conditions.
- ☐ Oxide etch rate saturation at high power dissipation (rf match 4) possibly caused by transport processes or surface reactions.

Source: A. Steinbach, et. al. SEMATECH AEC/APC Symposium XI, Vail, USA, 1999.

by courtesy of Infineon technologies

Conditioning after wet clean

Chamber: MxP+™, B-field parallel to wafer



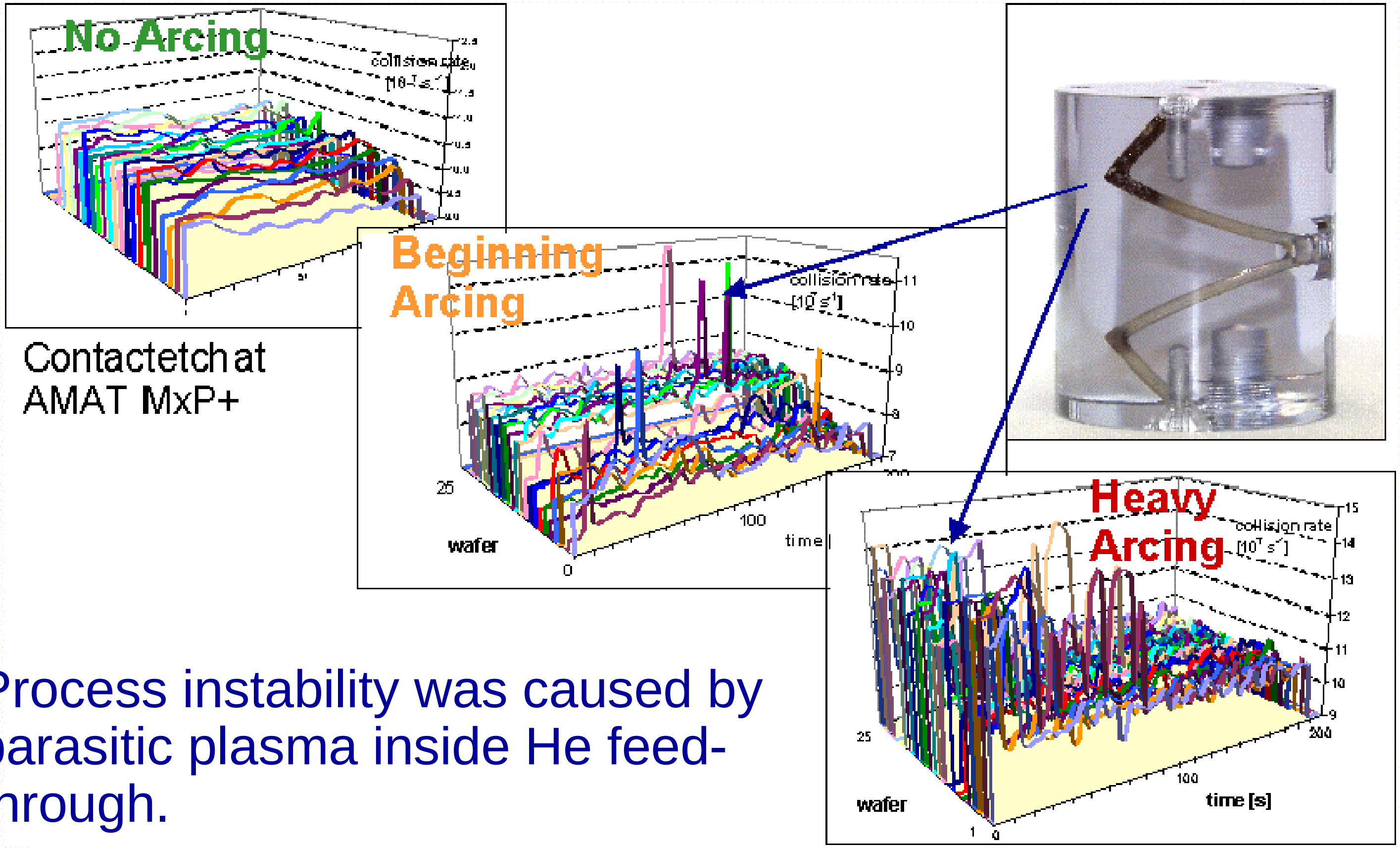
- ☐ Wet clean
- ☐ Stable chamber conditions after about 10 wafers.

Source: A. Steinbach et al. (SIEMENS Dresden), AEC/APC X, Vail, USA, 1998.

by courtesy of Infineon technologies

Plasma in helium feed-through

Real time detection for contact etch etch at MxP+™



Contactetch at AMAT MxP+

Process instability was caused by parasitic plasma inside He feed-through.

Source: A. Steinbach, et. al. SEMATECH AEC/APC Symposium XI, Vail, USA, 1999.

by courtesy of Infineon

Arcing

Introduction

- Arcing is basically a breakthrough in an insulating layer at the chamber wall, wherever potential grown-up.
  Reasons for arcing are:
  - inhomogeneous polymer build-up at chamber wall
  - incorrect grounding of parts of chamber

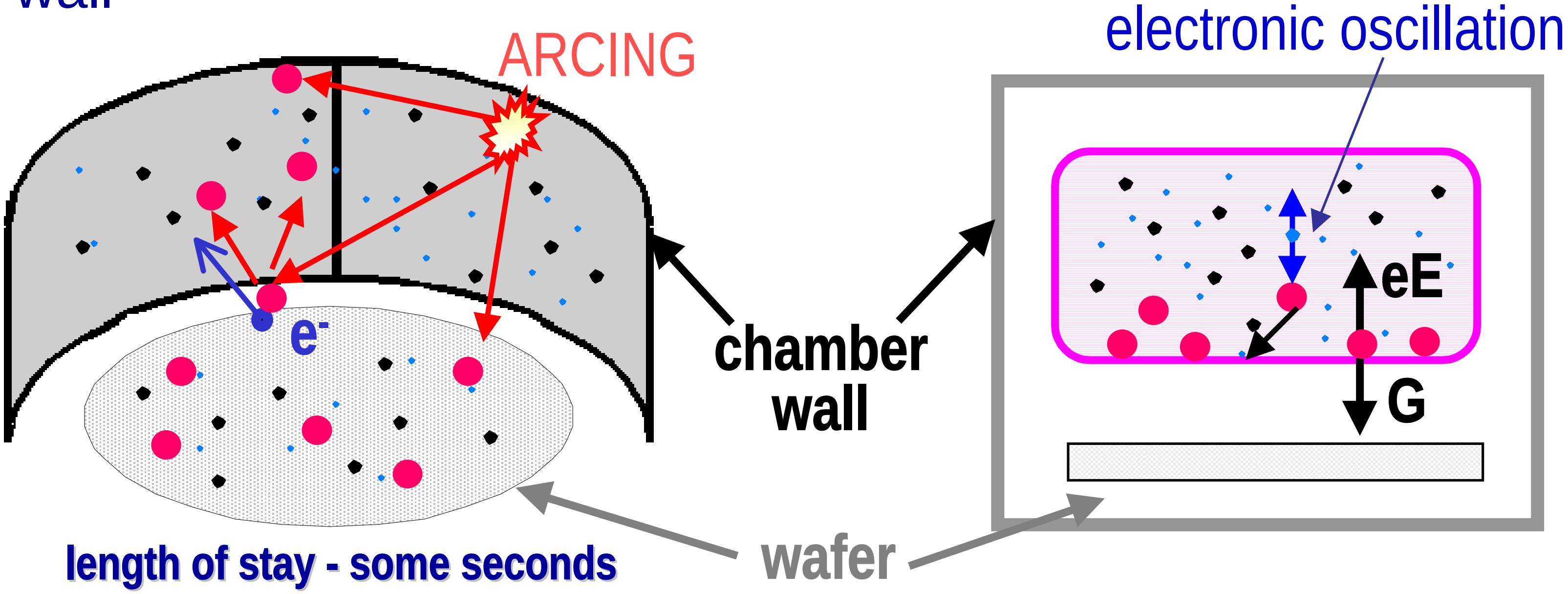
- Arcing leads to a reaction in collision rate:
  - increase ➔ large polymer molecules
  - decrease ➔ relative small metal ions

- SEERS enables the detection the process relevant chemical ‘drag-mark’ of arcing.

Arcing

Generation and behavior of particles

- ☐ in case of arcing - increase of collision rate at least for some seconds due to additional polymer particles from chamber wall

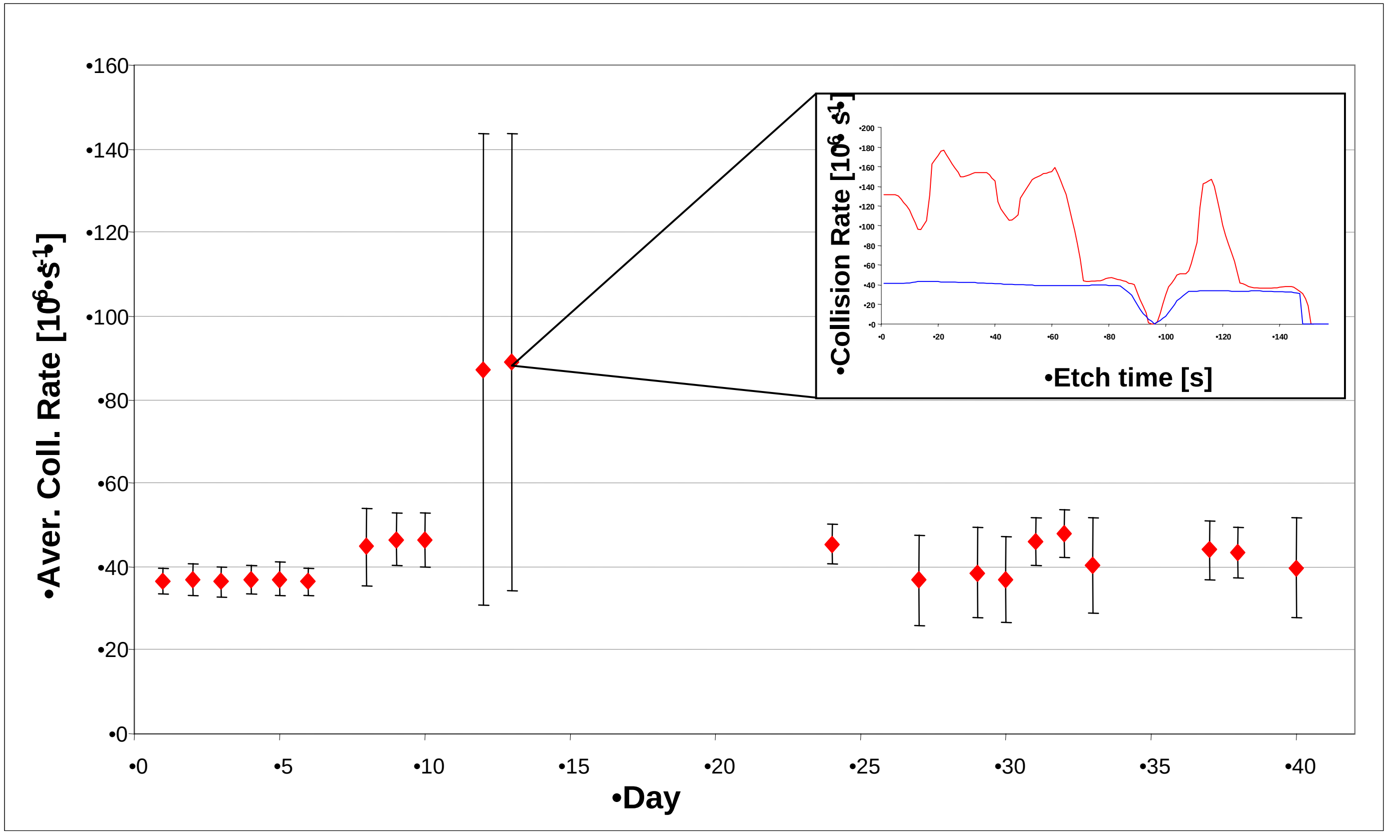


length of stay - some seconds

Process gas and polymer

Arcing

Fault detection at eMxP+™ (300 mm, F chemistry)



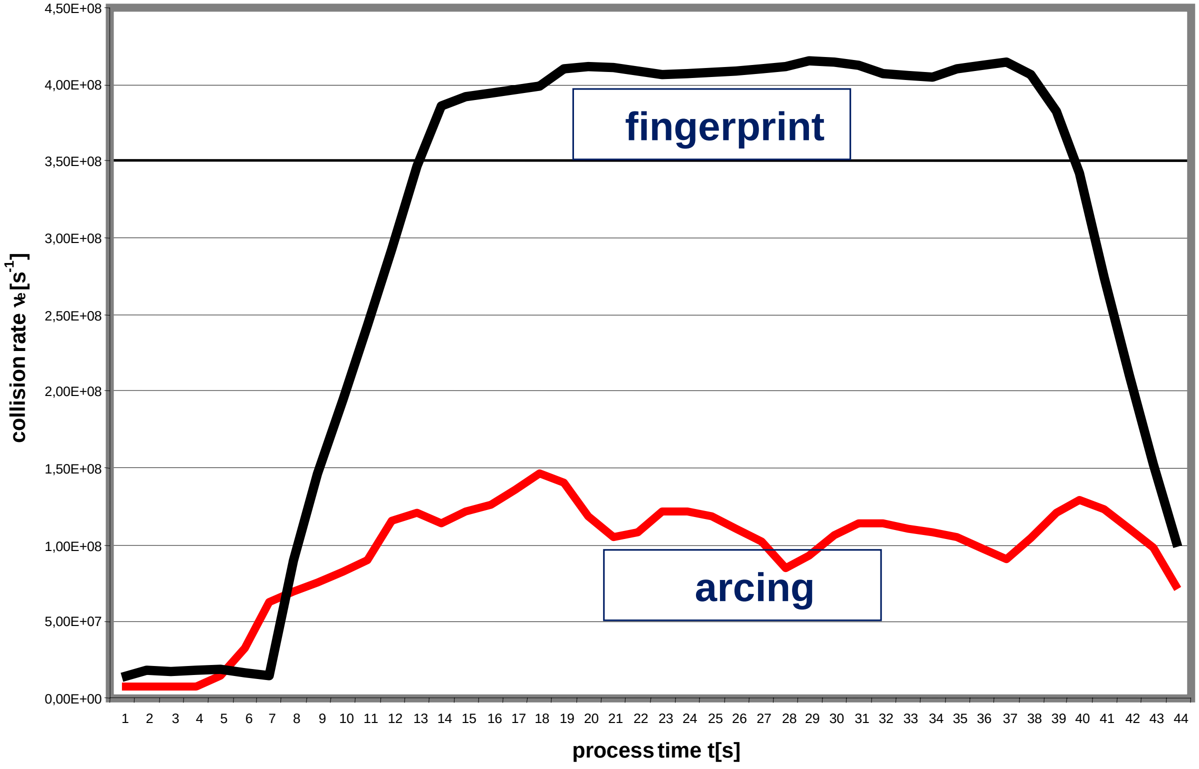
Arcing Traces in Chamber ➔ Exchange of E-Chuck and Ion Shield

Source: V. Tegeder, AEC/APC-Symposium XII, Lake Tahoe, USA, 2000.

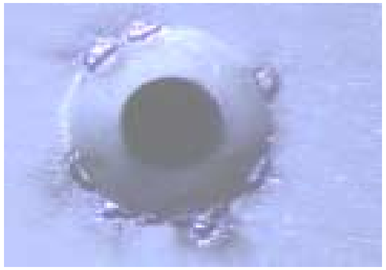
by courtesy of Infineon technologies

Arcing

Arcing at gas distribution, APPLIED MATERIALS® eMxP+™



Arcing detected at new tool



Arcing traces at gas distribution

Recipe

Step 1

25mtorr / 215W / 30G/ 50 sccm O2

Step 2

25mtorr / 215W / 0G/ 50 sccm O2

Source: V. Tegeder, AEC/APC-Symposium XII, Lake Tahoe, USA, 2000.

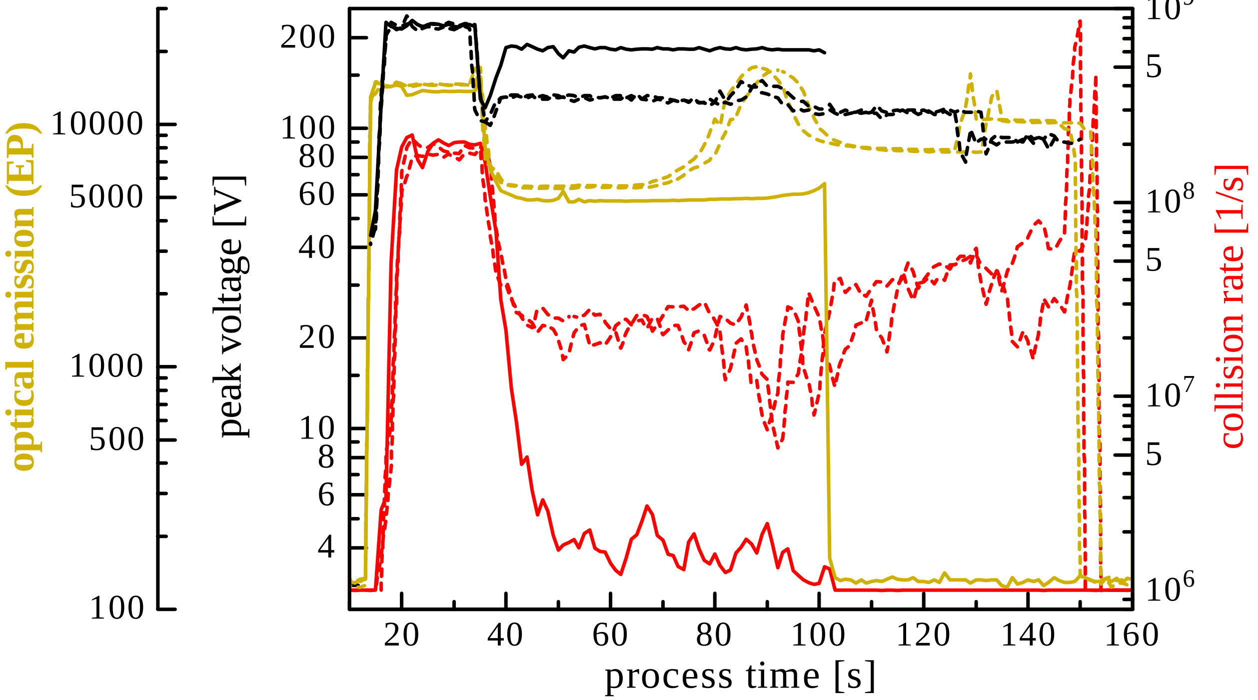
by courtesy of AMD

The impact of polymers onto the plasma

Wafer Fault Analysis: no resist, faultless dashed at LAM® TCP®

LAM® TCP® 9600SE

Fault: no resist, faultless dashed (reference wafer)



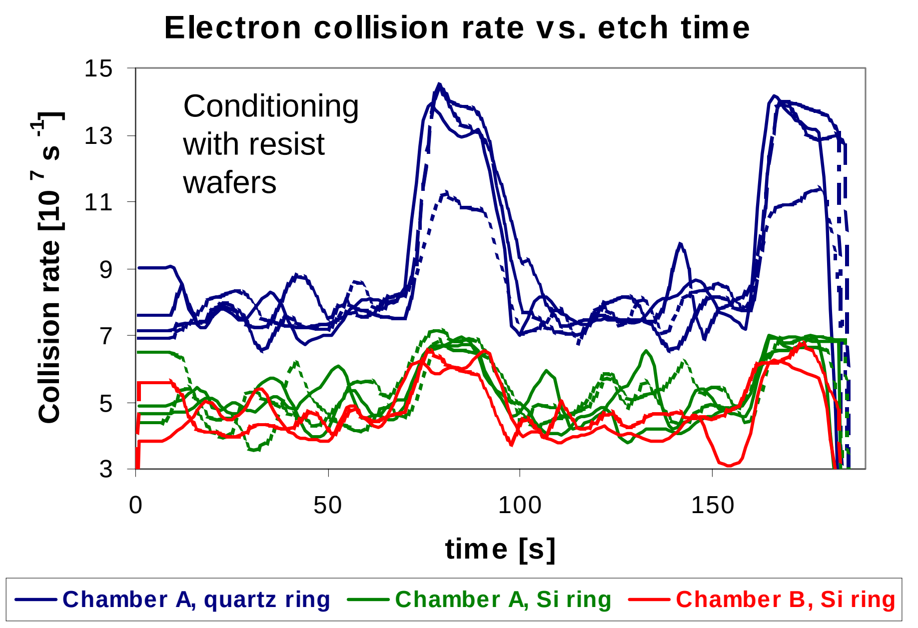
- ☐ The break-through is not influenced (here separate step).
- ☐ In case of the main etch the collision rate decreases by one order of magnitude due to no polymer on the wafer.
- ☐ Chemistry: Cl_2/BCl_3

Source: S. Wurm, Lam Research Technical Symposium, Geneva, Switzerland, 1998.

by courtesy of Infineon

Evaluation of shadow rings at MxP™

Increase of virtual electrode size by Si shadow ring



Parameter	Ratio Si ring / Quartz ring
Nitride etch rate	0.66
Wafer temp.	0.71
Inverse ring temp.	0.78
El. collision rate	0.69
Electron density	0.55
Sqrt. Bulk Power	0.59
Inverse ratio of the cathode areas	0.59

Comparison at chamber A:

- Quartz ring ➔ isolating
- Si ring ➔ rf conducting

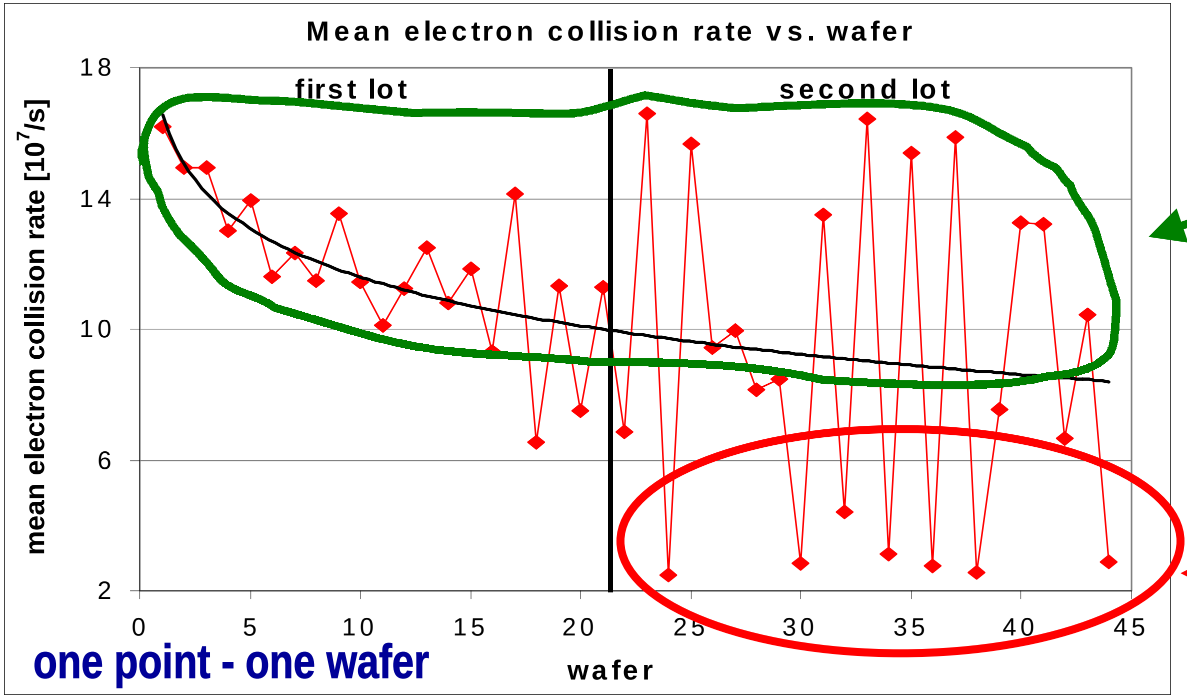
increase of effective cathode area ➔ decrease of power density

Source: A. Steinbach, et. al. SemiPAC´99, San Antonio, USA, 1999.

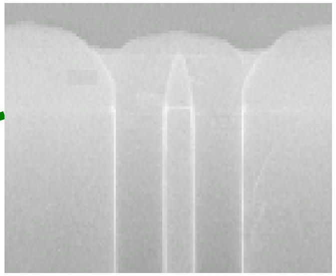
by courtesy of Infineon technologies

Deep trench etch (Si etch using Cl and F chemistry)

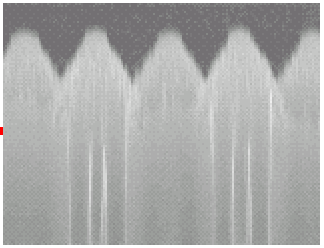
Trench etch, wafer history - impact from Litho on Etch



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 both lots is caused by tool impacts.

Source: S. Bernhard, A. Steinbach, 3th AEC/APC Europe, Dresden, Germany, 2002.

by courtesy of Infineon technologies

Deep trench etch (Si etch using Cl and F chemistry)

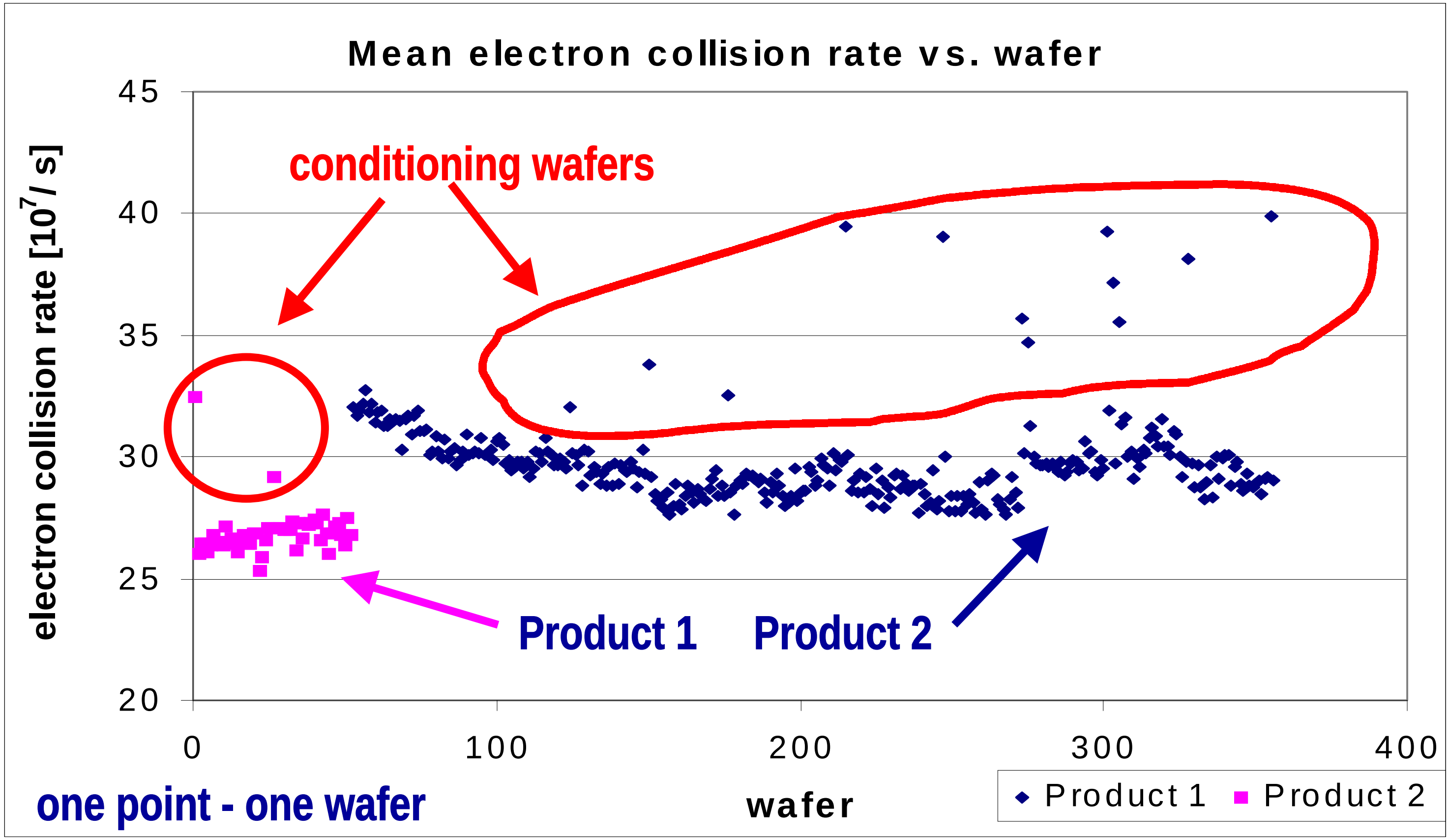
Monitoring of product mix impact on process stability

- ☐ Product mix impact of two different Si etch processes on process stability was monitored by
  - Plasma parameter measurement using Self Excited Electron Resonance Spectroscopy (SEERS)
  - Multichannel Optical Emission Spectroscopy (MPCA) at wavelengths from 200nm to 480nm during main etch step
- ☐ Analysis of measurements
  - Plasma parameters are calculated by plasma monitoring system Hercules® internally in real time, no further calculation necessary
  - Analysis of optical emission spectra offline by Multiway Principal Component Analysis

Source: S. Bernhard, A. Steinbach, 3th AEC/APC Europe, Dresden, Germany, 2002.

Deep trench etch (Si etch using Cl and F chemistry)

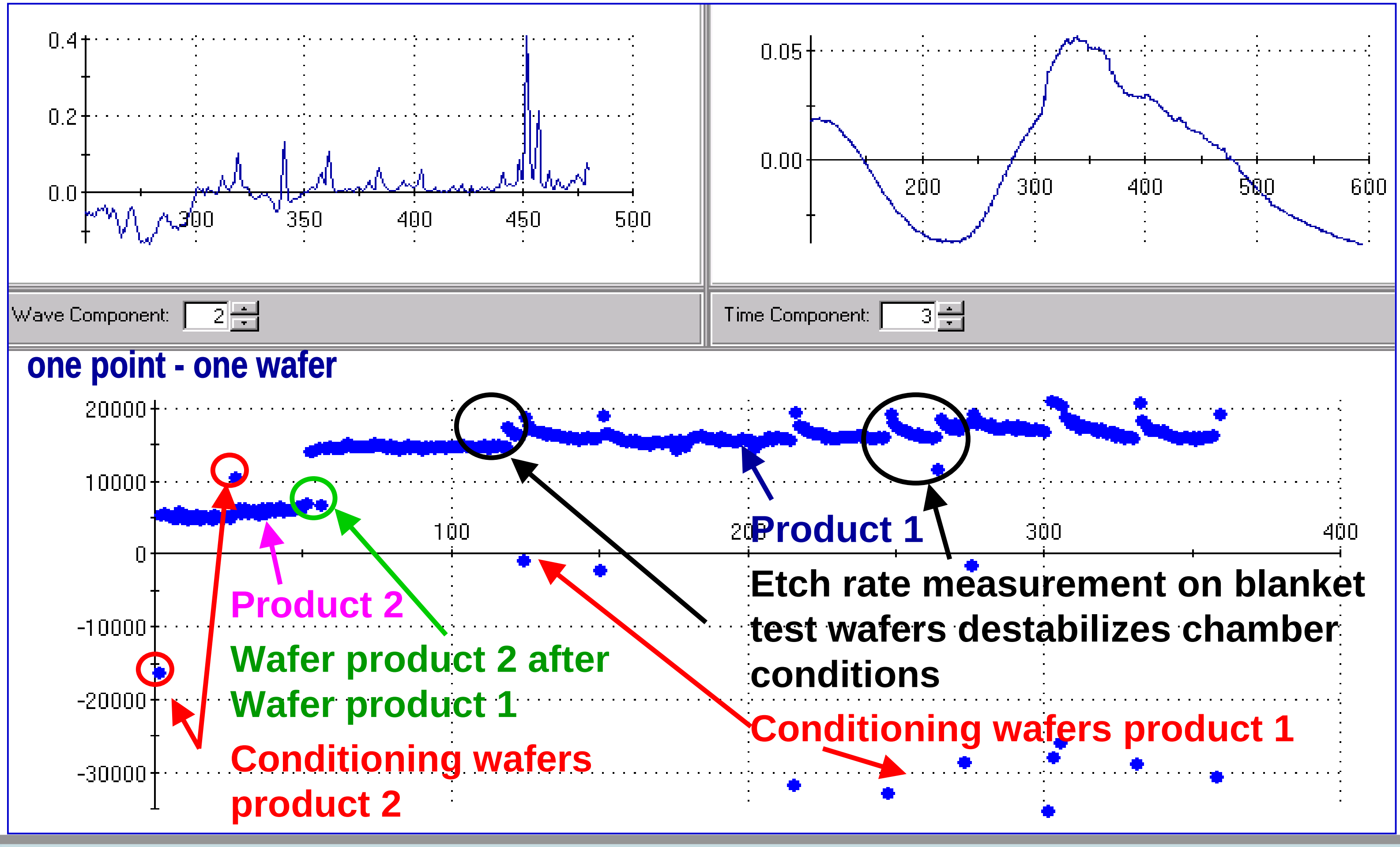
Impact on process stability by electron collision rate



Source: S. Bernhard, A. Steinbach, 3th AEC/APC Europe, Dresden, Germany, 2002.

Deep trench etch (Si etch using Cl and F chemistry)

Off-line analysis of product mix impact on process stability by MPCA



one point - one wafer

Product 2

Wafer product 2 after Wafer product 1

Conditioning wafers product 2

Product 1

Etch rate measurement on blanket test wafers destabilizes chamber conditions

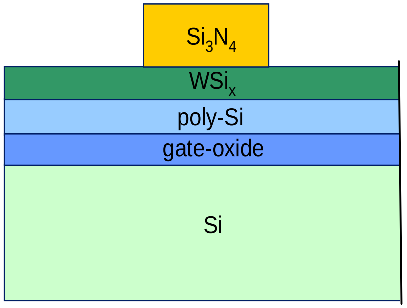
Conditioning wafers product 1

Source: S. Bernhard, A. Steinbach, 3th AEC/APC Europe, Dresden, Germany, 2002.

Gate contact etch (GC)

Cross section of GC Stack

DRAM



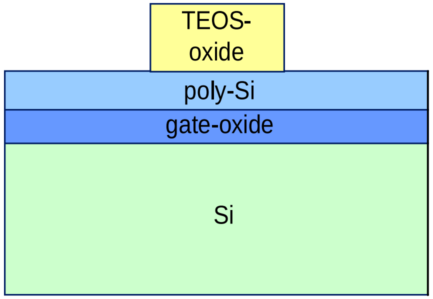
- Si_3N_4- hard mask

  WSix- metal layer etched with fluorine chemistry

  Poly-Silicon-Layer etched with Chloride/Bromide chemistry

  - Main-Etch etches main part of Poly-Si
  - Over-Etch etches only a fraction of Poly-Si

LOGIC



- TEOS- oxide hard mask

  No metal layer → no fluorine chemistry

  Poly-Silicon-Layer etched with chlorine/bromide chemistry

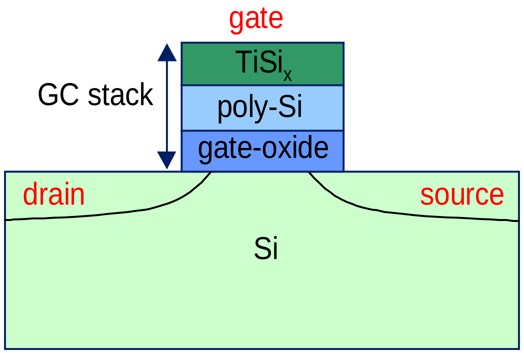
Source: T. Dittkrist, A. Steinbach (Infineon), AEC/APC Europe, Dresden, Germany, 2001.

by courtesy of

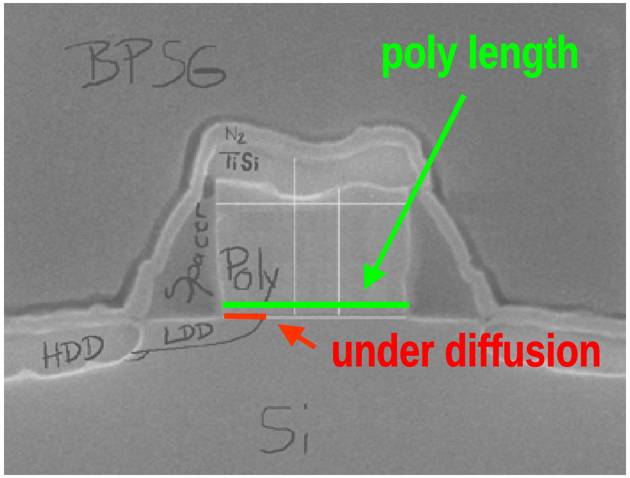
Gate contact etch (GC)

Geometry definitions of GC Stack

GC Stack cross section



GC Stack SEM



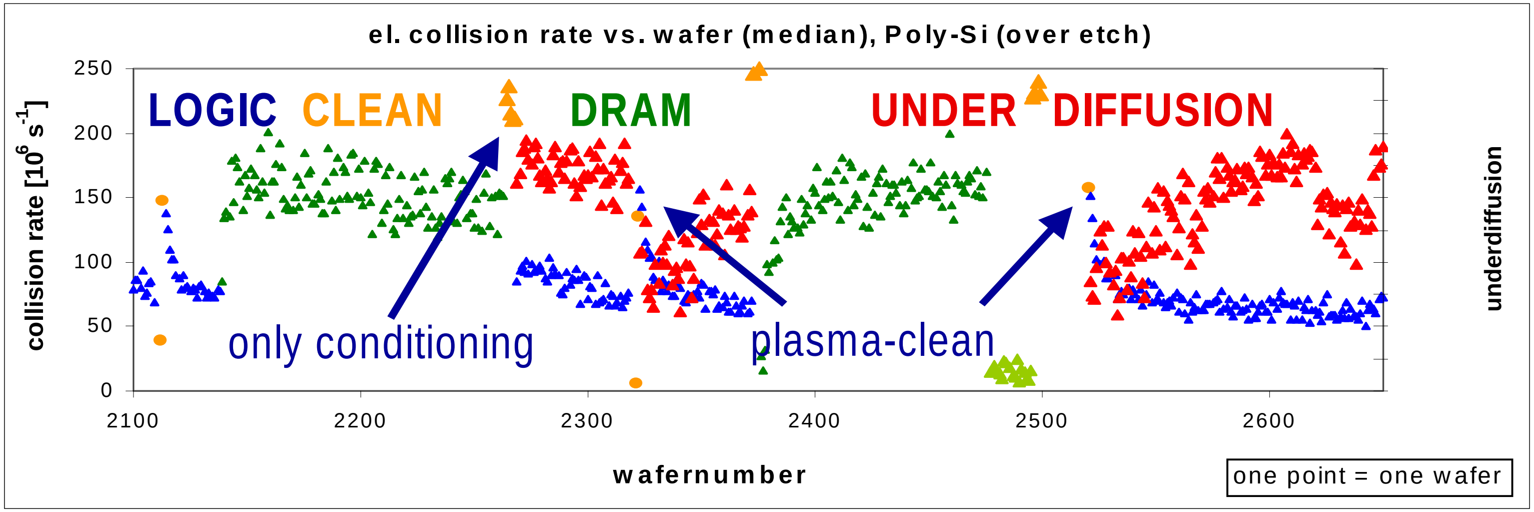
- ☐ GC Stack cross section of logic product
- ☐ Problem: under diffusion length and poly length to small

Source: T. Dittkrist, A. Steinbach (Infineon), AEC/APC Europe, Dresden, Germany, 2001.

by courtesy of Infineon technologies

Gate contact (GC)

Product Mix observed by electron collision rate



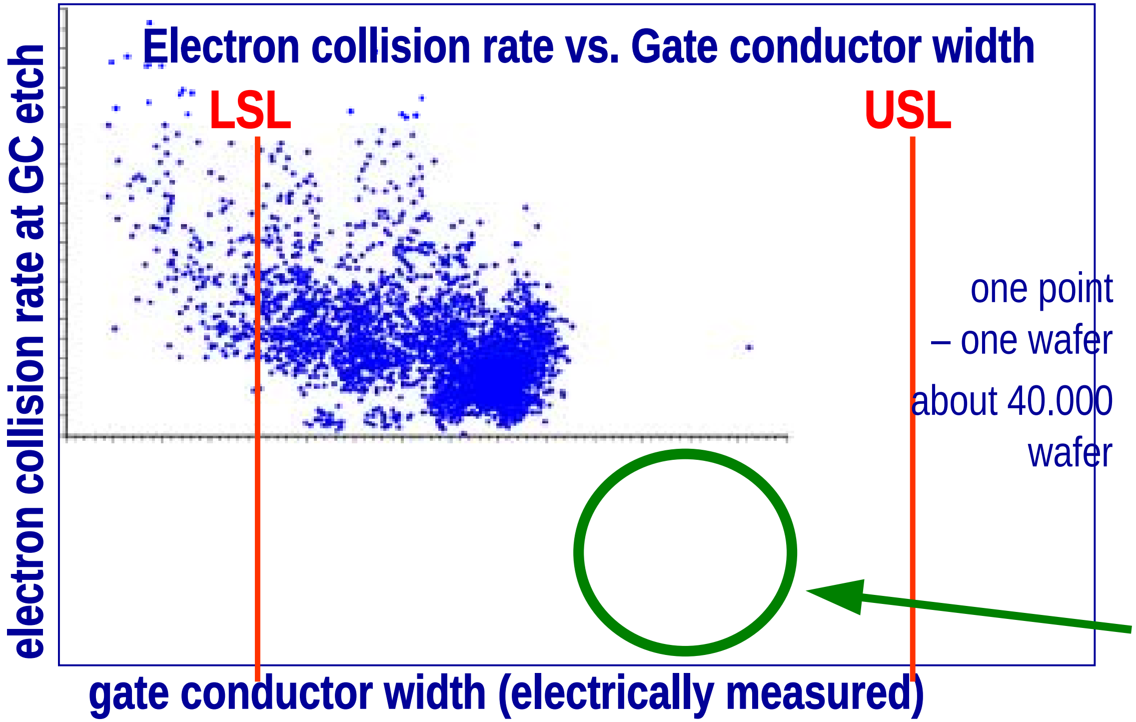
- ❑ First wafer effect for electron collision rate and under diffusion length for LOGIC processes after plasma clean and conditioning no first wafer effect if only conditioning without plasma clean
  - – Processes are influenced by plasma clean.
  - – Etching of chamber wall with fluorine is possible reason for bad etch results after plasma clean.

Source: T. Dittkrist, A. Steinbach (Infineon), AEC/APC Europe, Dresden, Germany, 2001.

by courtesy of Infineon

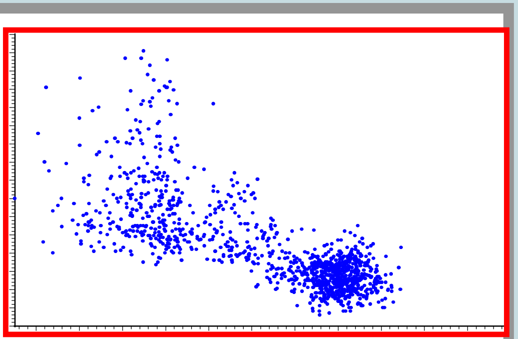
Gate contact (GC)

Electron collision rate vs. poly length



one point – one wafer about 40.000 wafer

Dedicated chamber



First part of results already presented last year

- Correlation inside specification limits ➔ 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.

Source: A. Steinbach, 3rd AECAPC, Dresden, Germany, 2002.

by courtesy of Infineon technologies

Conclusions

- Plasma parameter measurement in IC manufacturing requires robust methods and basic understanding of the plasma.
- The usage of plasma parameters is just at the beginning and requires more experience and knowledge in
  - Handling and extraction of core parameters,
  - Automatic model building to predict product parameters.
- The best method depends on
  - Final goal (fault detection, process development…),
  - Chamber type and process,
  - Knowledge available.
- Electron parameters are most sensitive (OES, SEERS).