SEERS under industrial conditions

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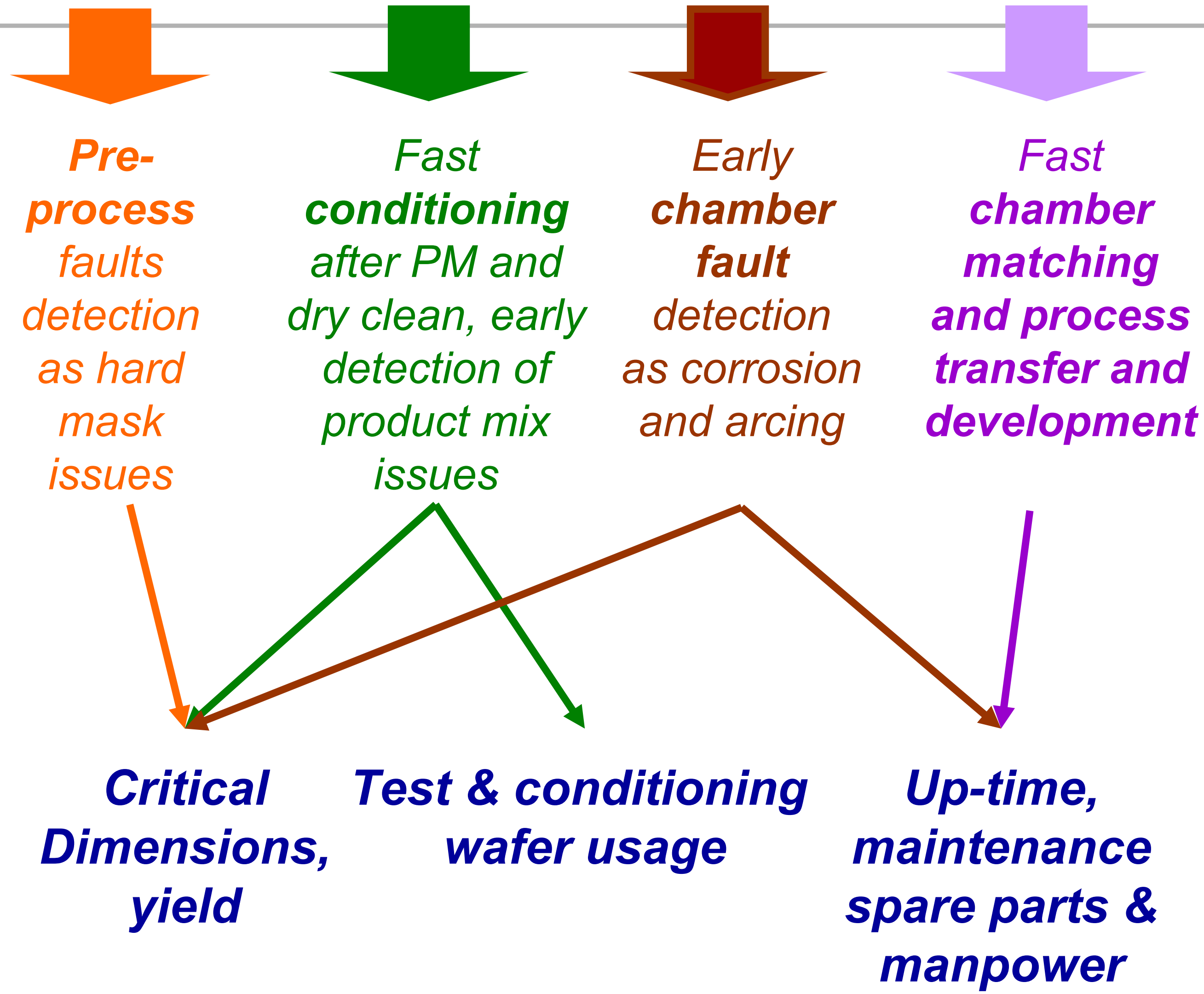
The need of process control under industrial conditions



The requirements from the semiconductor production on plasma monitoring

- Passive (non-intrusive)
- No calibration necessary
- Endpoint detection
- Absolute to enable chamber comparison and matching
- Spatial resolution
- Exactly as sensitive as the most tricky product
- Easy to understand
- Allows to identify hardware faults
- …

→ **There is no all-in-one solution!**

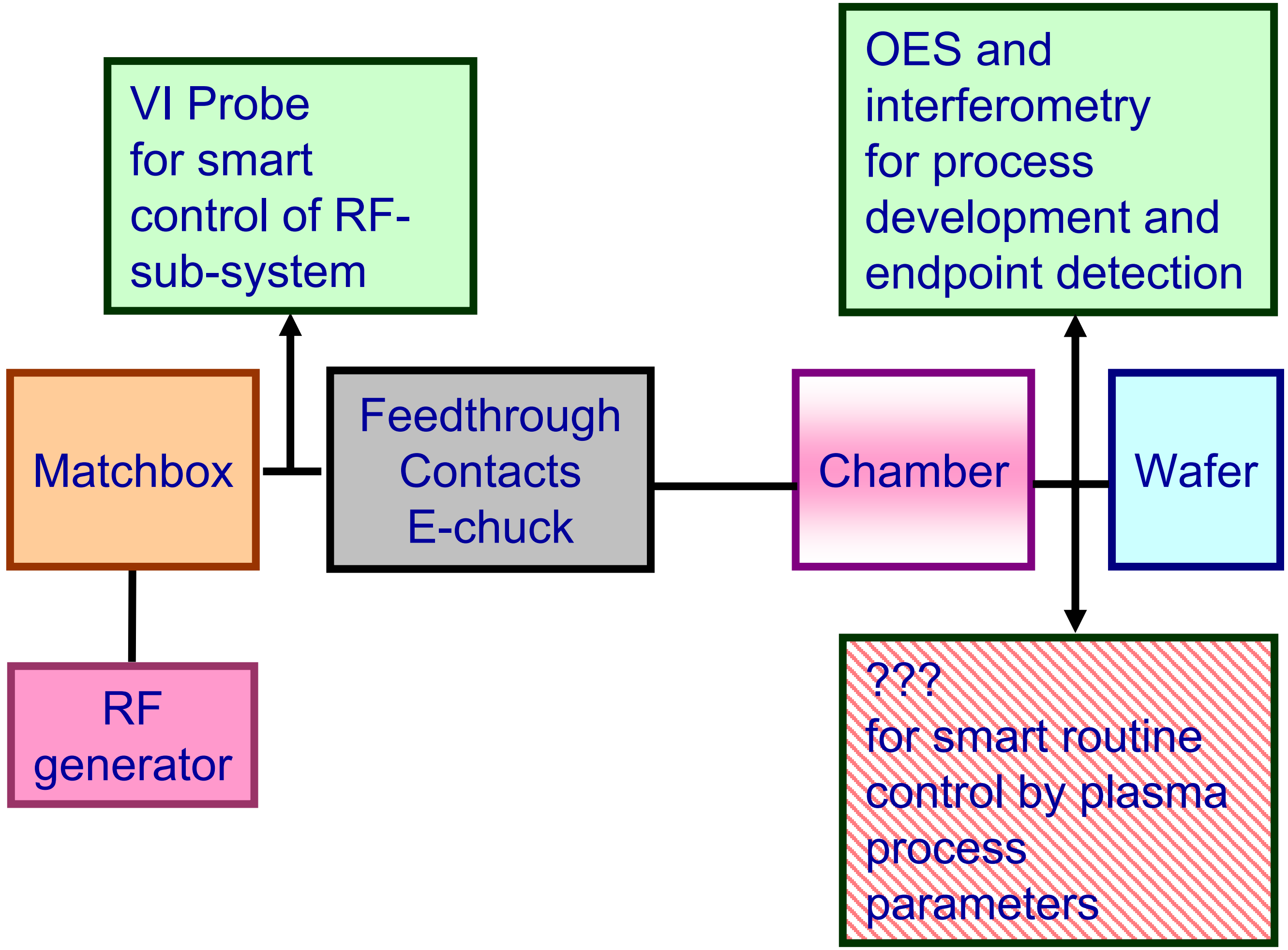
Which parameters should and are measured under industrial conditions?

- Do not try to use LIF, Microwave interferometry and reflectrometry, Langmuir probes … under industrial conditions.
- Due to the e-chuck the DC Bias cannot be measured.
- RF power input into plasma?
  - VI probe provides RF power into chamber including feed-through, cooling system, and e-chuck.
  - Owing to additional power losses by contacts, e-chuck including pin lift and He-backside cooling, the ‘plasma power’ is usually significantly lower than the ‘chamber power’!
  - The main target: (Very important!) RF hardware control but cannot usually be process control (except CVD clean).
- Electron parameters are the key parameters of the bulk plasma (Ionization, dissociation, fragmentation, excitation,...).
  - Optical Emission Spectroscopy (OES) reflects electronic excitation for different species but no absolute values.

→ **Lack of absolute plasma parameters!**

→ **Should be electron and/or ion parameters!**

Plasma monitoring under industrial conditions: A first overview

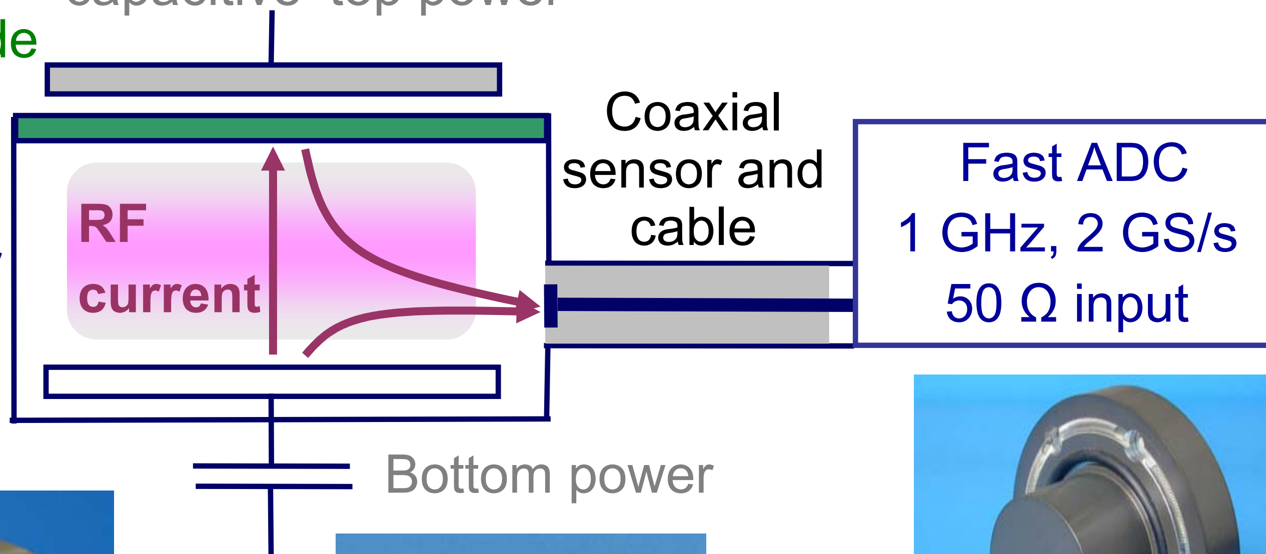


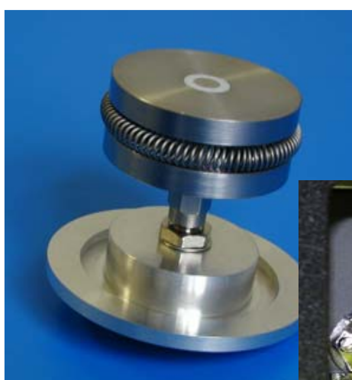
How to get absolute electron parameters under industrial conditions?

- The method used must be passive (non-intrusive) and robust.
- Absolute parameters are required for chamber comparison and matching - cannot be provided by classical methods as OES, LIF, and Langmuir probe… under industrial conditions.
- Solution: Use internal properties of the discharge.

→ **Measure the RF current inside the chamber at the chamber wall.**

The RF current - the experimental setup





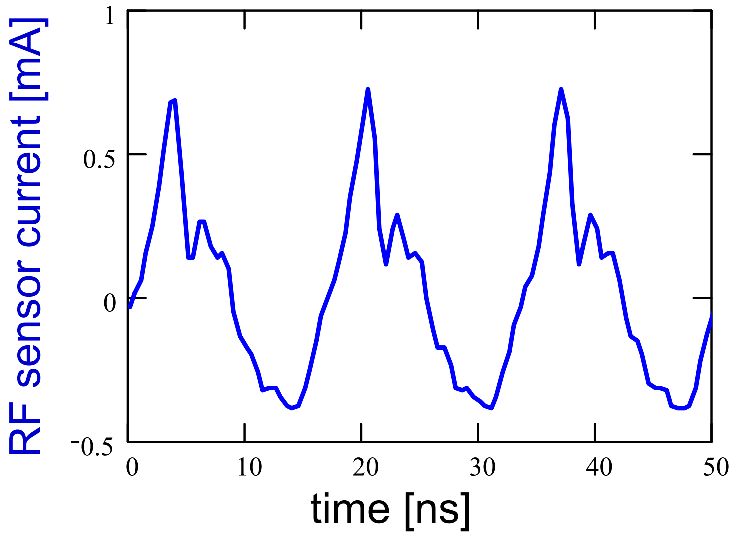
DN40KF

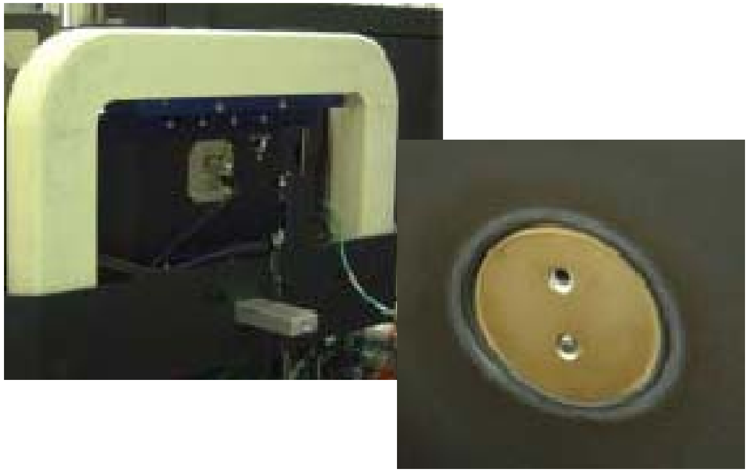
AMAT® eMxP+™

LAM® 2300™

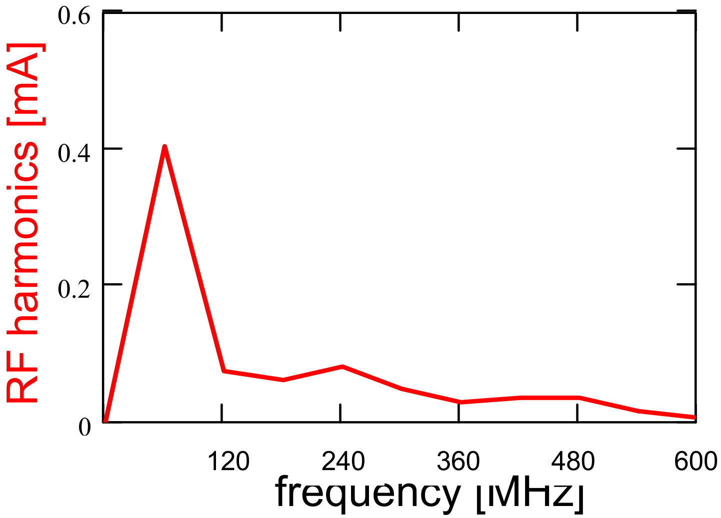
US Patents 5 705 931 and 5 861 752, European Patent EP 0 719 077 B1, Japanese Patent 2872954

RF current - Applied Materials® HART TS™



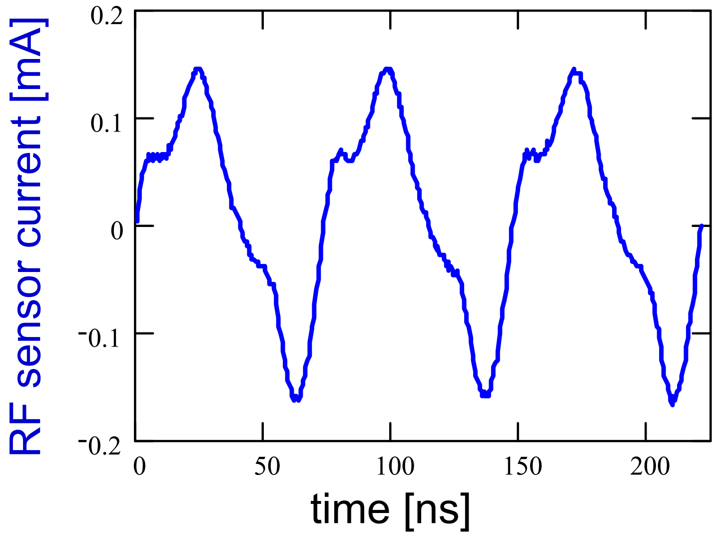


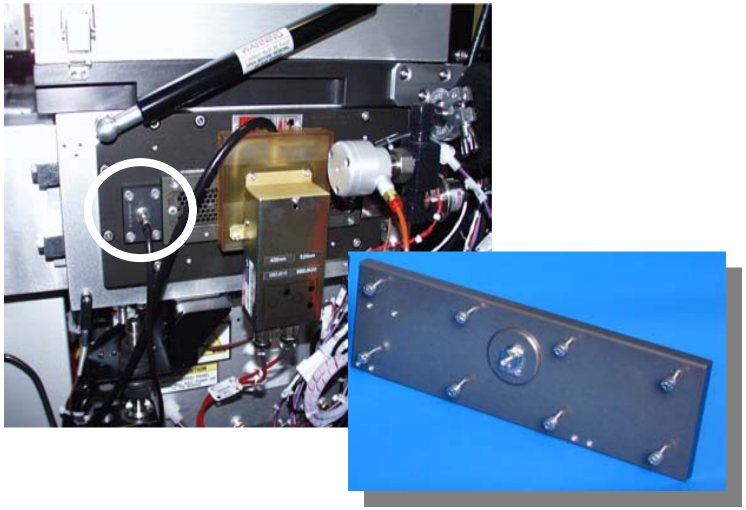
Silicon etch
HBr / F / O chemistry
MERIE
p ≈ 250 mTorr
f_{top} = 60 MHz
f_{bias} = 2 MHz
P_{top} ≈ 2.5 kW
P_{bias} ≈ 2 kW
Wafer diameter: 200 mm



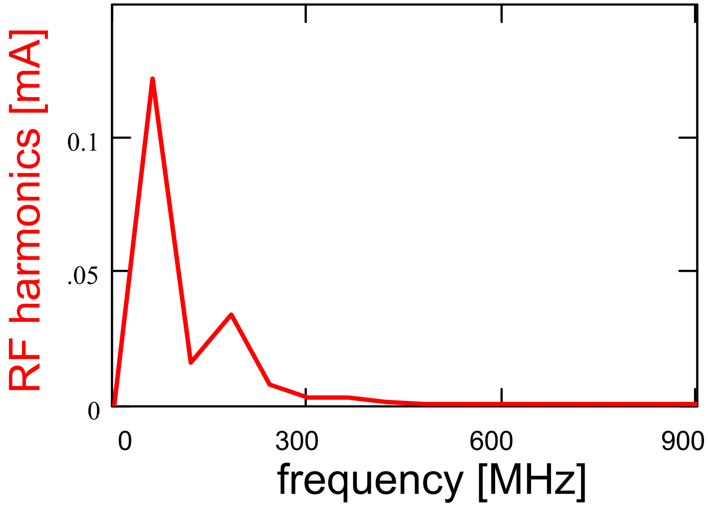
Data from full running production!

RF current - Lam® TCP® 9400 PTX



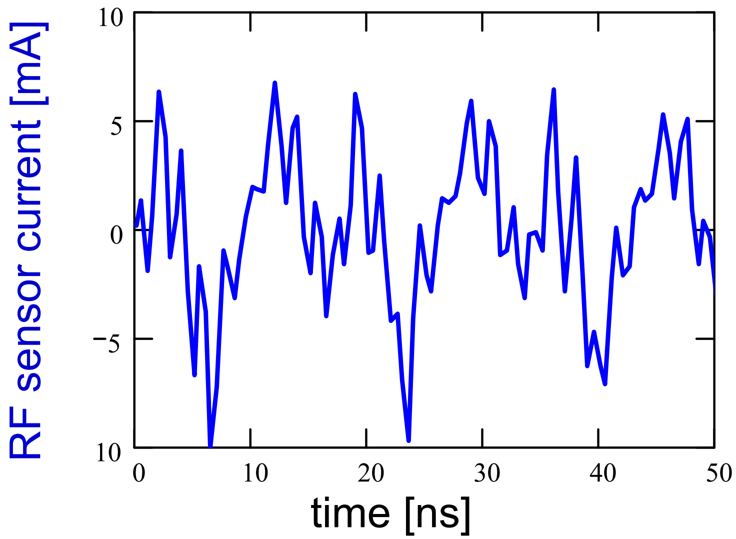


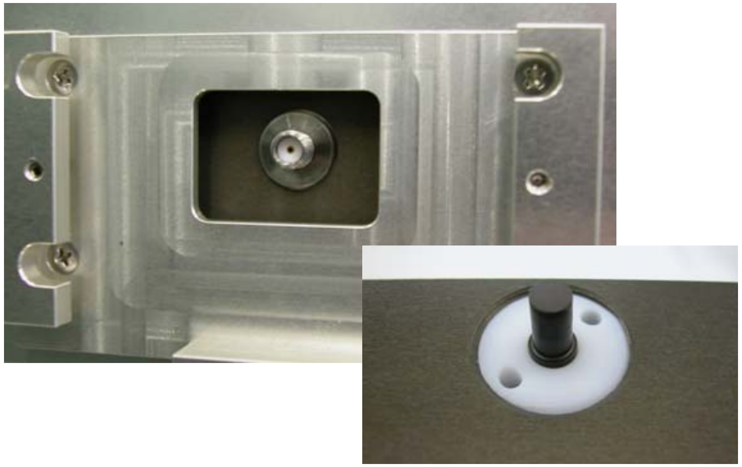
Gate Conductor Stack (GC Stack)
Cl/F/O – chemistry
p ≈ 10 mTorr
f_{TCP} = 13.56 MHz
f_{Bias} = 13.56 MHz
P_{TCP} ≈ 400 W
P_{bias} ≈ 100 W
Wafer diameter: 300 mm



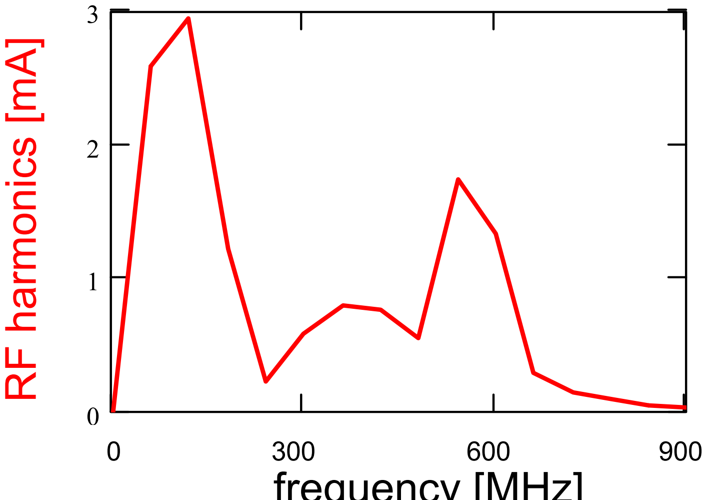
Data from full running production!

RF current - TEL SCCM™ 300 mm



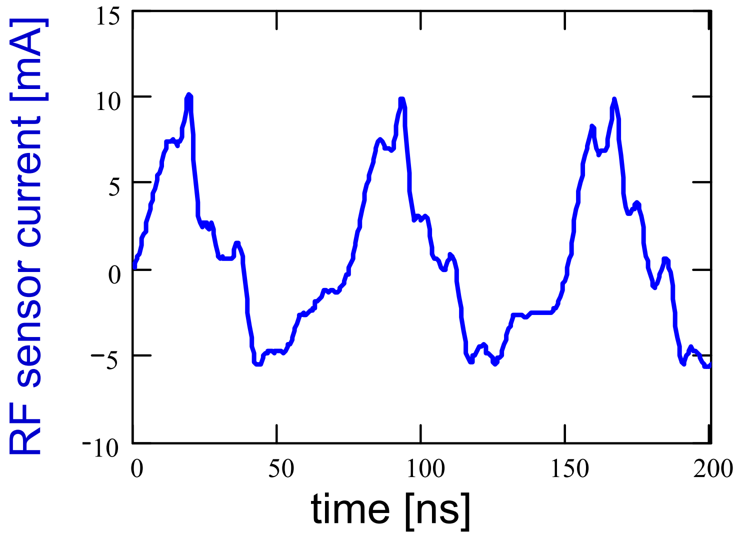


Dielectric etch
F / O chemistry
p ≈ 50 mTorr
f_{top} = 60 MHz
f_{bias} = 2 MHz
P_{top} ≈ 3 kW
P_{bias} ≈ 4 kW
Wafer diameter: 300 mm



Data from full running production!

RF current - Applied Materials® HDP CVD Ultima



Intermetal Dielectric (IMD)

$SiH_4/O_2/Ar$ – chemistry

p ≈ 10 mTorr

$f_{Inductive}$ = 800 kHz

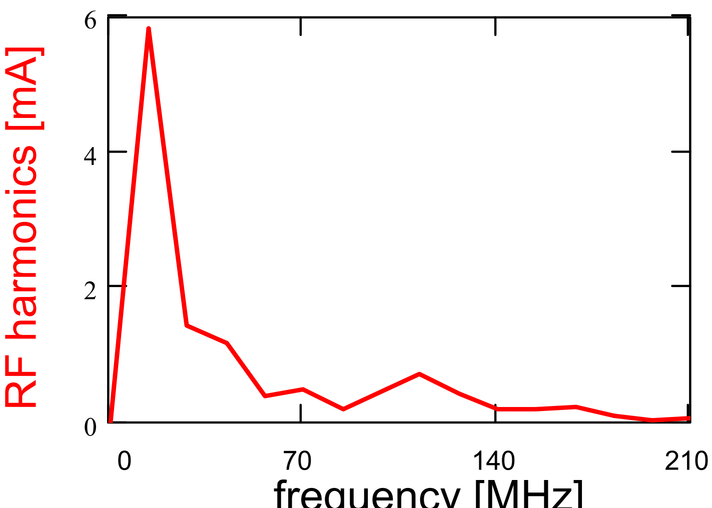
$f_{Capacitive}$ = 13.56 MHz

$P_{Inductive}$ ≈ 8000 W

$P_{Capacitive}$ ≈ 8000 W

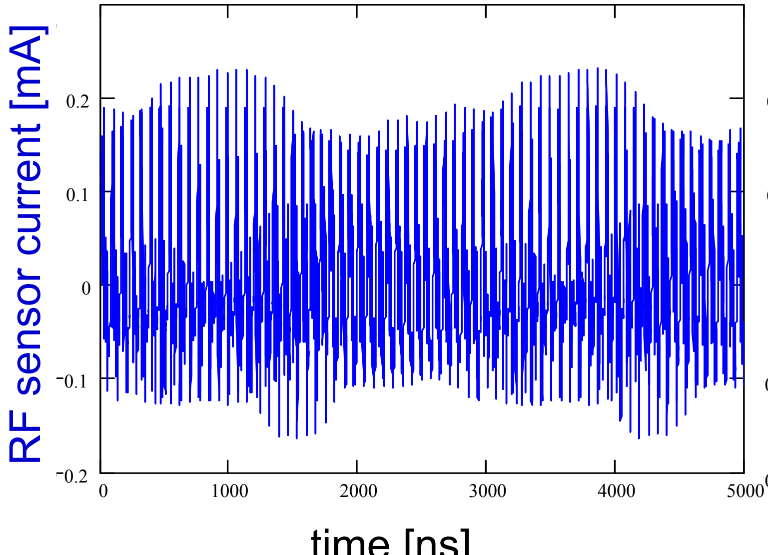
T ≈ 320 °C (600 K)

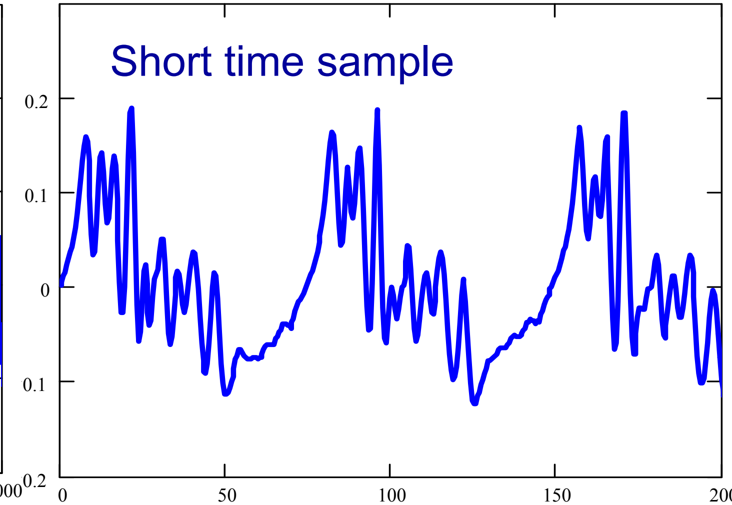
Wafer diameter: 300 mm



Data from full running production!

RF current - Novellus® HDP CVD Speed: Two frequencies lead to side bands





Oxide Trench Fill

$SiH_4/O_2/He$ – chemistry

p ≈ 3.5 mTorr

$f_{Inductive}$ = 400 kHz

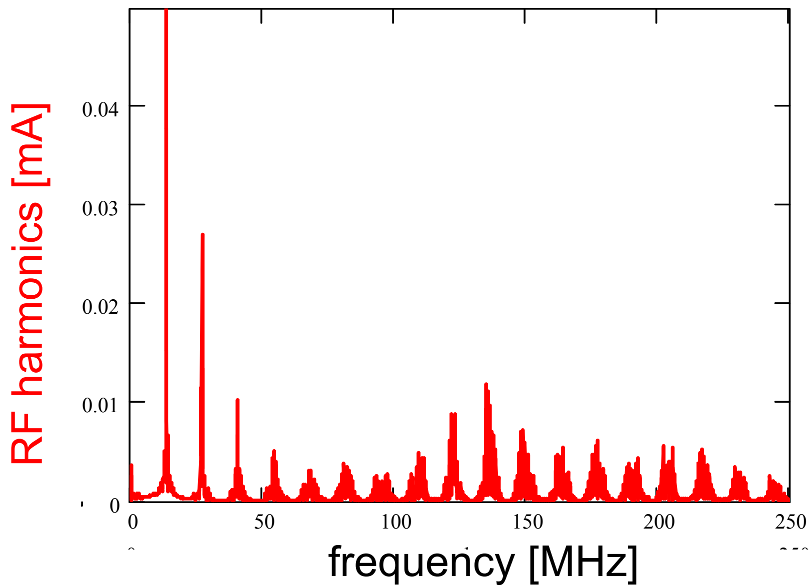
$f_{Capacitive}$ = 13.56 MHz

$P_{Inductive}$ ≈ 4500 W

$P_{Capacitive}$ ≈ 4500 W

T ≈ 700 °C (1000 K)

Wafer diameter: 300 mm



Data from full running production!

How to handle the nonlinear and resonance effects in the plasma?

- Almost all discharge models assume a sinusoidal RF current (Makes the calculation simple)!
- **This assumption is wrong.**
  - **The reality is much more difficult that the models.**
  - **We need an extended model.**

Contents

- Process control for industrial plasmas
- Understanding the real world - SEERS theory
- Parameter studies
- Fault detection and classification
- Conclusions

The fundamental RF sheath equation

- Normalized current Γ, voltage η and sheath thickness δ:

$$\Gamma = \frac{j}{e\, n\, (T/m)^{1/2}} \;, \quad \eta = \frac{eV}{T} \;, \quad \delta = \frac{s}{\lambda_D}$$

- Displacement current of the rf sheath ($\varphi = \omega_{rf}\, t$)

$$\Gamma_d = \frac{\Omega}{\delta(\eta_s)} \frac{d\,\eta_s}{d\,\varphi}$$

- The relation between the displacement current and the sheath voltage is highly nonlinear and provides for a sinusoidal voltage a saw-tooth shaped current.
- The product in the time domain provides a convolution in the Fourier transform $\eta_s = \Omega^{-1}\, \delta * \Gamma$.

→ Provides harmonics in RF current !

M. Klick, J. Appl. Phys. 79, 3445 (1996)

The plasma bulk impedance

- Fourier transform → Plasma body impedance (R_E .. Electrode radius):

$$Z = \frac{m\, l}{\tilde{n}\, e^2\, \pi\, R_E^2} \left(i\omega + \nu \right)$$

- Extension to cylindrical plasmas (mathematically non-trivial) was added,
  - results owing to the additional radial RF current in an effective length *l* of the plasma bulk usually smaller than electrode gap.
- Further extensions:
  - Cylindrical and inhomogeneous plasma bulk.
  - Skin effect which leads to an increase of the effective length – depending on the electron density. (See also recent publications of R. P. Brinkmann, Ruhr-University Bochum, Germany)

The normalized plasma bulk voltage

- Normalized inductive (Λ) and resistive (ρ) part of impedance:

$$\Lambda = \frac{n_0}{\tilde{n}} \frac{l}{\lambda_D} \frac{\omega}{\omega_e}, \quad \rho = \frac{n_0}{\tilde{n}} \frac{l}{\lambda_D} \frac{\nu_e}{\omega_e}, \quad \Omega = \frac{\omega_{rf}}{\omega_e}, \quad \mu = \frac{\omega}{\omega_{rf}}$$

- Plasma bulk voltage in frequency domain:

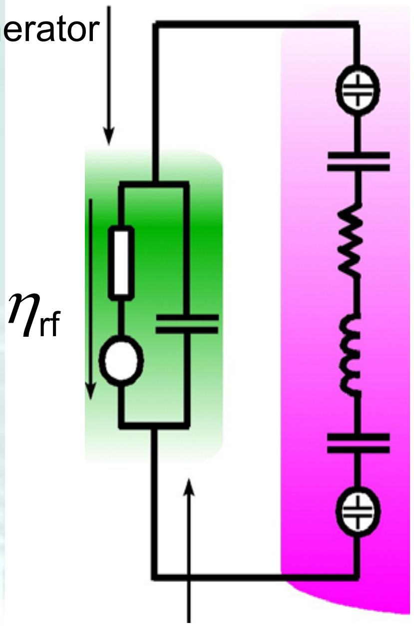
$$\eta_{bulk} = \rho\Gamma + i\,\mu\,\Lambda\,\Gamma$$

The fundamental equation in the frequency domain

Sheathes — Ohmic / damping term

$$i\mu\;\eta_{rf} = \Omega^{-1}\,\delta * \Gamma + i\mu\,\rho\,\Gamma - \mu^2\,\Lambda\,\Gamma$$

External RF excitation — Inertia (electron mass)



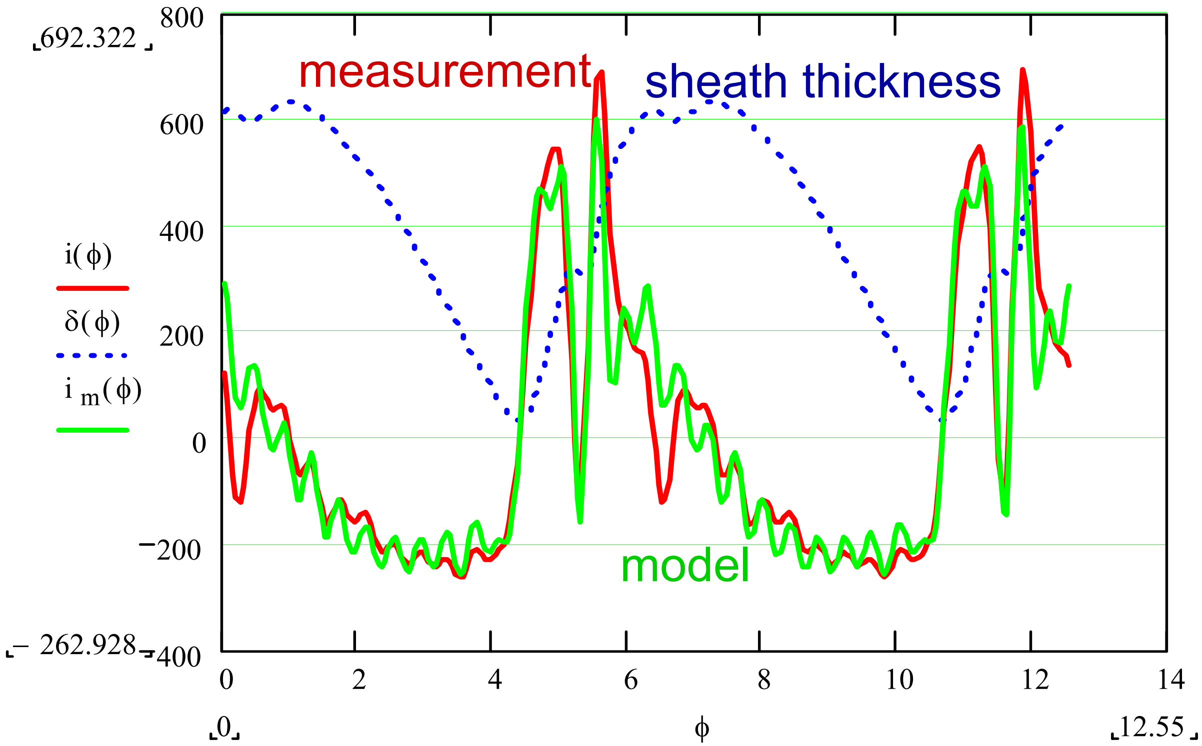
$(\delta_1 - \bar{\delta}_1) * \Gamma$	nonlinearity sheath plasma-wall
$\bar{\delta}_1\,\Gamma$	linear „part“ of wall sheath
$i\mu\,\rho\,\Gamma$	ohmic part of plasma bulk (ohmic and stochastic heating)
$\mu^2\,\Lambda\,\Gamma$	inertia part thereof (e^- mass)
$\bar{\delta}_0\,\Gamma$	linear „part“ of wall sheath
$(\delta_0 - \bar{\delta}_0) * \Gamma$	nonlinearity sheath RF electrode

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

$\delta = \delta_0 + \delta_1$, $*$ denotes convolution

M. Klick, et. al., Jap. J. Appl. Phys. 36, (1997) 4625.

Plasma parameter estimation: An application example



→ Basic issue: Fitting the model onto the real signal by minimum three parameters. Example:

- Ar discharge, 10 Pa, 500 $V_{p,}$ 13.56 MHz.
- 'Geometric' resonance (eigen) frequency: 145 MHz.
- Electron density: 1.8 10^9 cm^{-3} and Collision rate: 2.6 10^8 $s^{-1.}$

The SEERS output: 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:

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

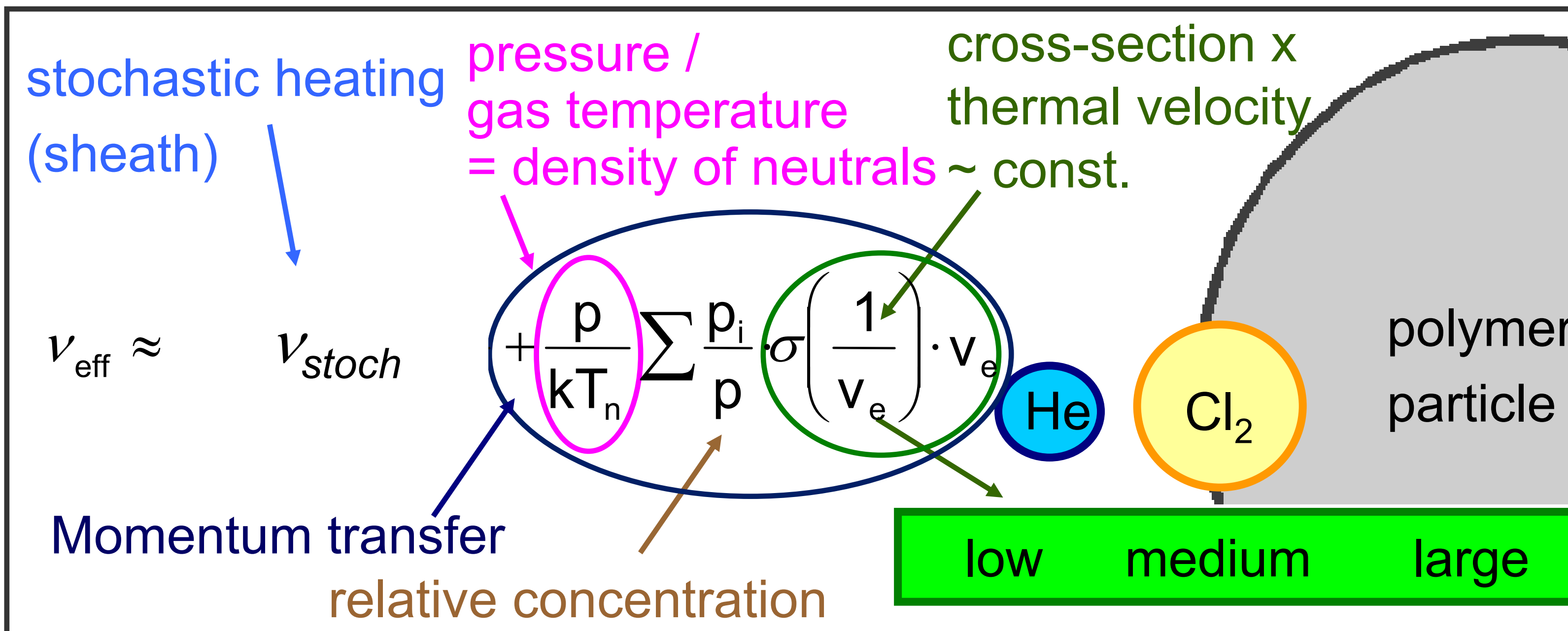
  - (electronic) Bulk power:

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

- The relations are exact for the one-dimensional case.
- Due to 1/n averaging, ranges of lower density get a higher weight!

The electron collision rate - a smart solution for the initial problem

- Depends directly on the neutral's density = pressure / gas temperature.
- Depends on power and gas mixture.
- Impact of electrons on chemistry via heating.
- Feedback from chemistry via cross sections and relative concentration of species.

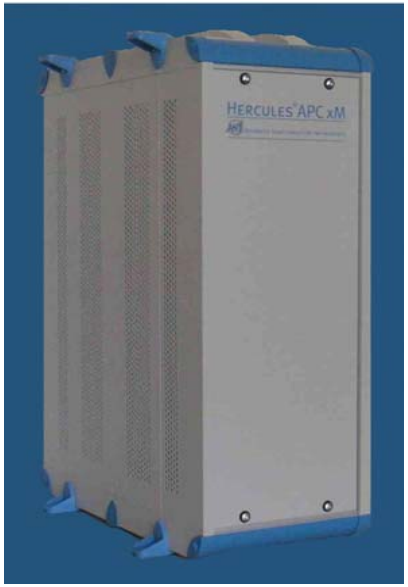


$$\nu_{eff} \approx \nu_{stoch} + \frac{p}{kT_n} \sum \frac{p_i}{p} \sigma\left(\frac{1}{v_e}\right) \cdot v_e$$

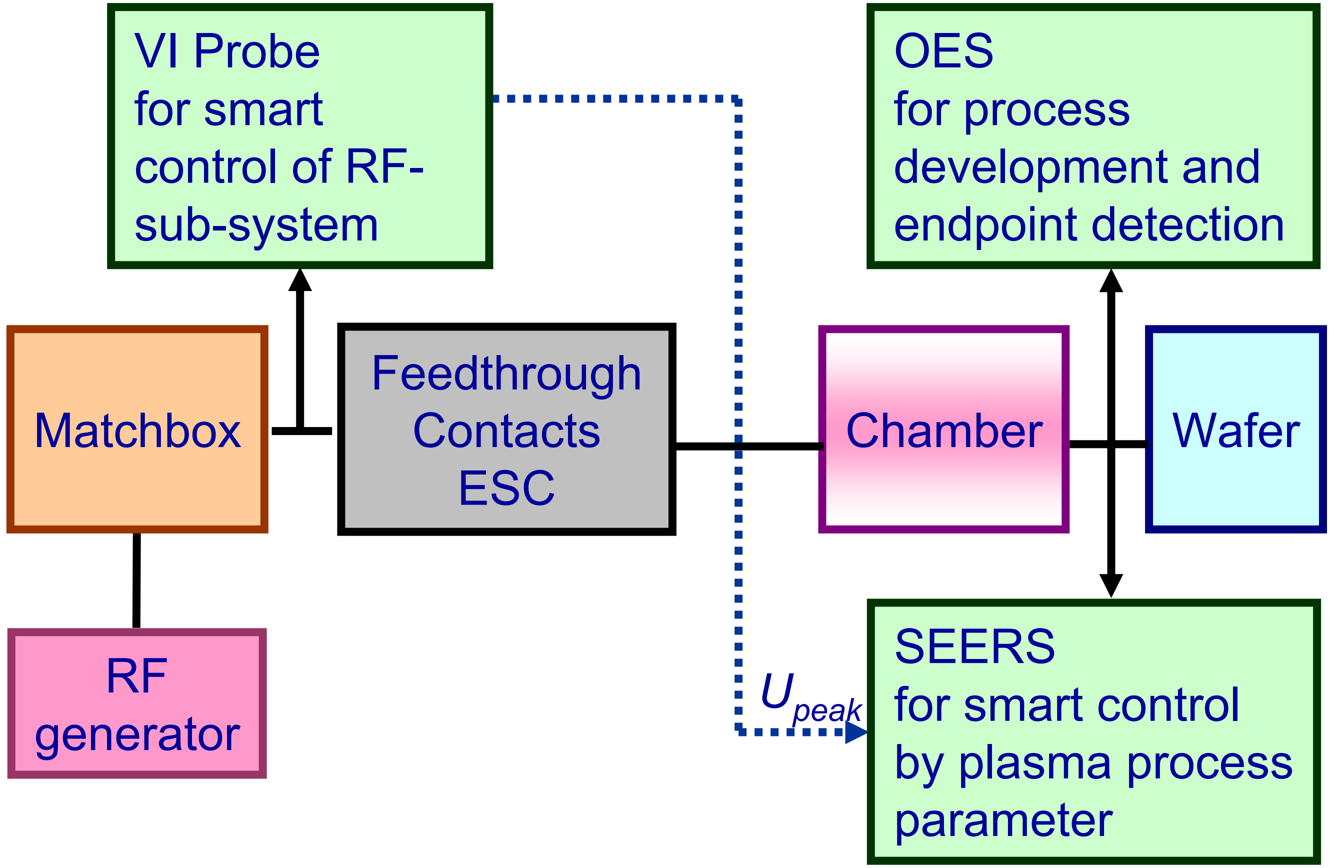
Some more preconditions to get success

- Software implementation of the 'reverse' model.
- Parallel handling of up to four chambers.
- Automatic data acquisition.
- Connection to logistical data,
  - e.g., through Lam® Plug and Play interface at the Lam® 2300 (Domino platform).
- Software for data analysis.
- Commercially available.

Hercules® APC xM



Plasma monitoring under industrial conditions: A combination of complementary systems



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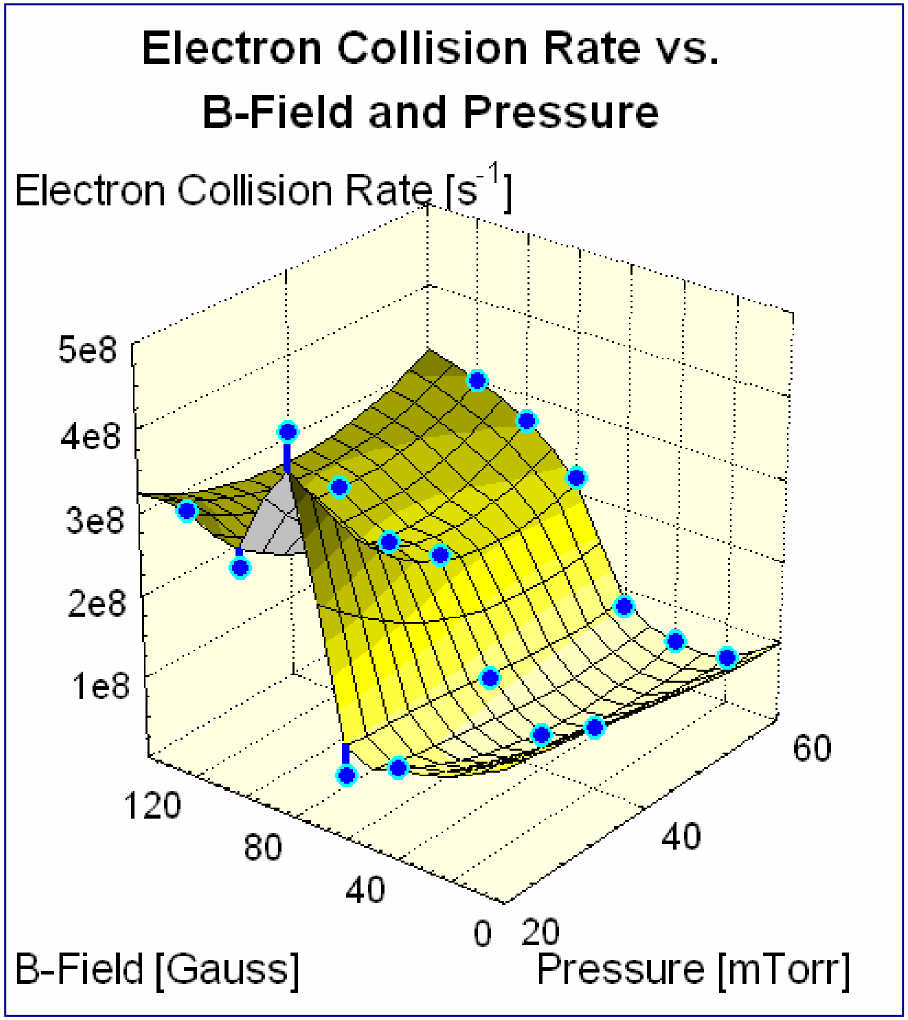
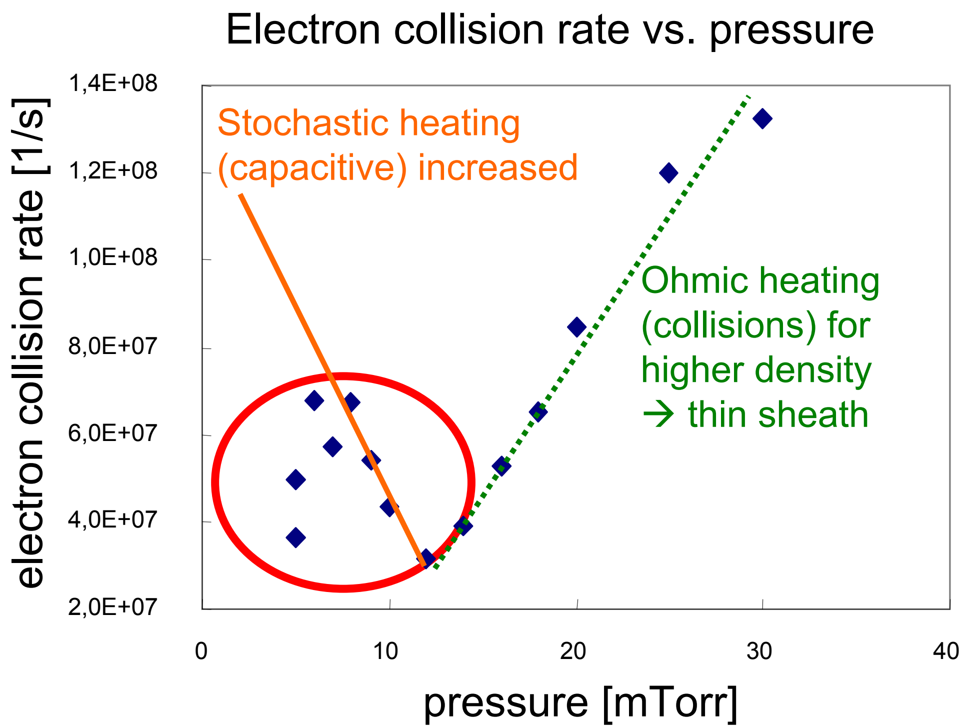
Process development: Monitoring of process window linearity



- Electron collision rate shows nonlinearity inside process window.
- In particular a maximum of the collision rate at higher magnetic field.
- Reduced efforts at process development.

A. Steinbach, ISSM 2002, Tokyo, Japan, 2002.

Lam® TCP® 9400 (poly-Si etch): Collision rate depending on pressure



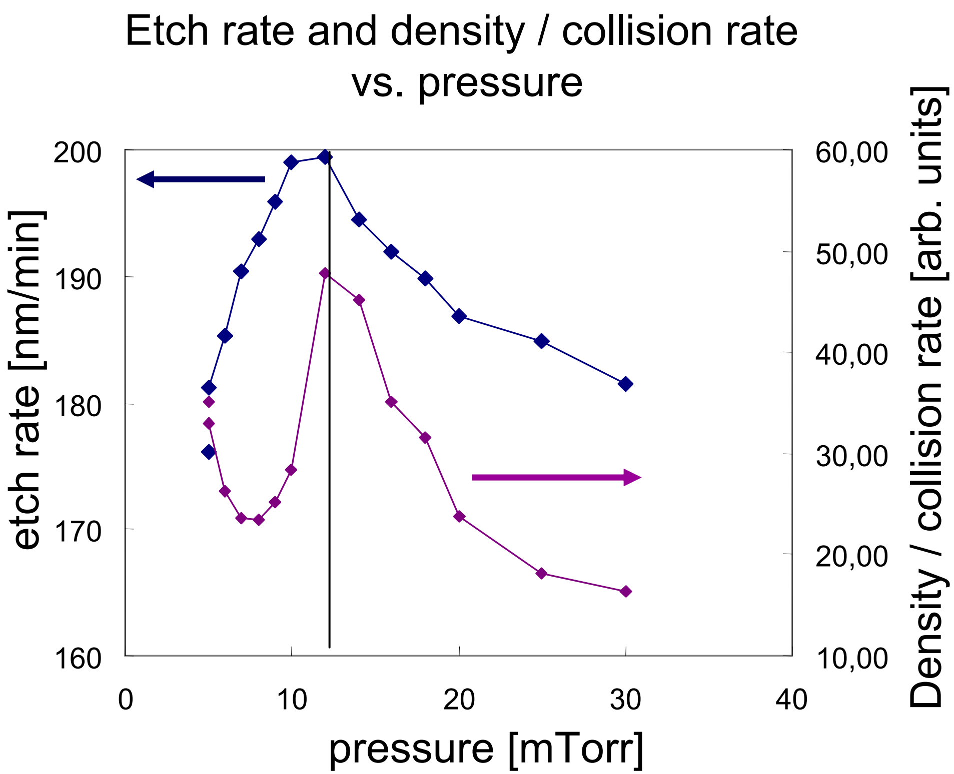
- TCP power = 300 W.
- Pressure variation: collision rate shows nonlinear behavior.
- Distinction of domination by ohmic heating / stochastic heating possible (= different modi of power conversion into plasma).

Potential process instability, basic understanding is needed for process development!

by courtesy of Infineon technologies

C. Steuer, 2nd SEERS Workshop, Dresden, Germany, 2000.

Lam® TCP® 9400 (poly-Si etch): Etch rate and plasma parameters depending on pressure



- Plasma parameter: electron density / collision rate.
- Correlation between in-situ and in-line measurements
  - **etch rate (blue)**
  - **quotient electron collision rate over density (purple)**

Electron density / Collision rate ⇔ Generation of reactive species / Transport limitation to wafer by lower diffusion constant (reactive species, e^-, and ions) ⇒ Etch rate

by courtesy of Infineon technologies

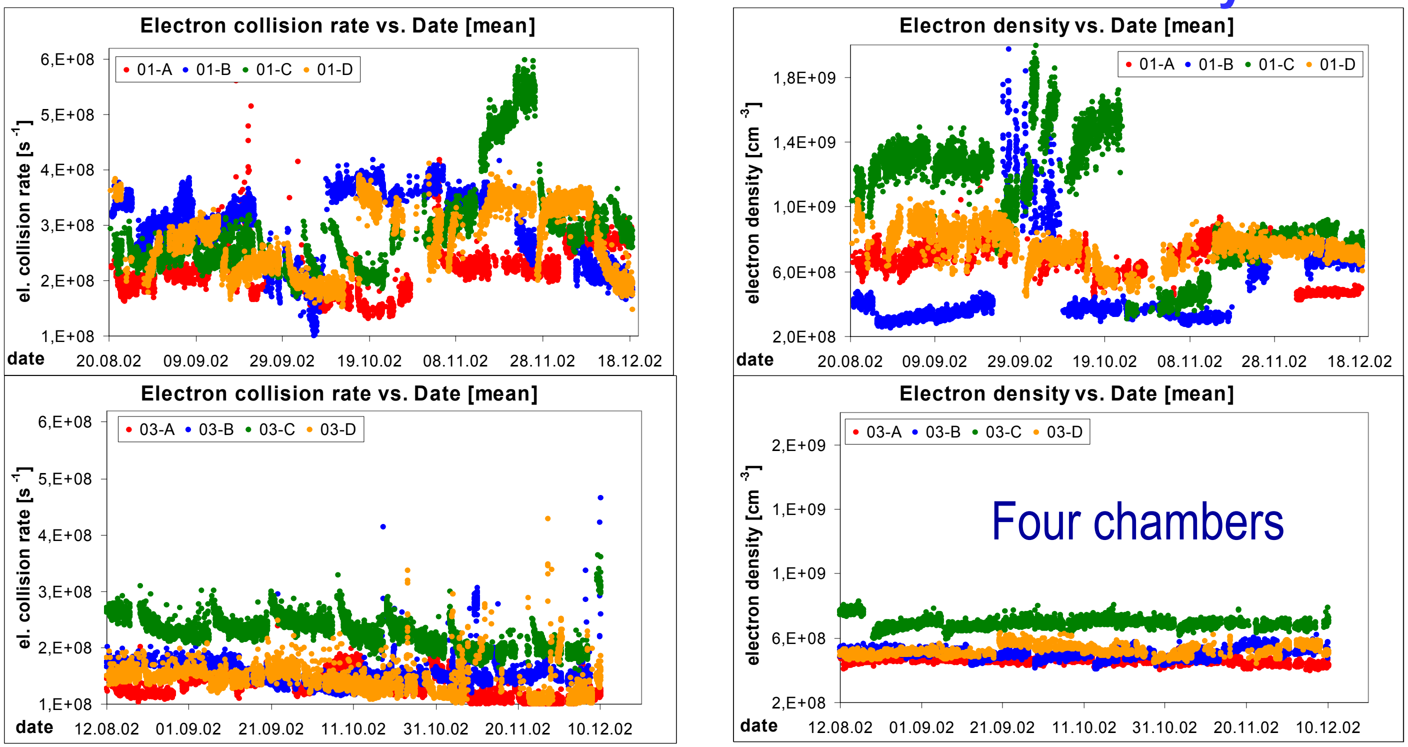
C. Steuer, 2nd SEERS Workshop, Dresden, Germany, 2000.

Parameter studies

Contents

Process stability & chamber matching of an etch process

Electron Collision Rate | **Electron Density**



Tool A

Tool B

- About 70.000 wafer within four month monitored.
- Indicated by plasma parameter electron collision rate and plasma density, Tool 2 shows a very good process stability and chamber matching in contrary to Tool 1.

by courtesy of

A. Steinbach, et. al., 4th European AEC/APC Conference, Dresden, Germany, 2003.

The gas temperature – the unknown parameter

- The important process parameter is the density of 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 pressure p **and** gas (neutrals) temperature T_n.

n_n: density of the neutrals ⇒ crucial process parameter

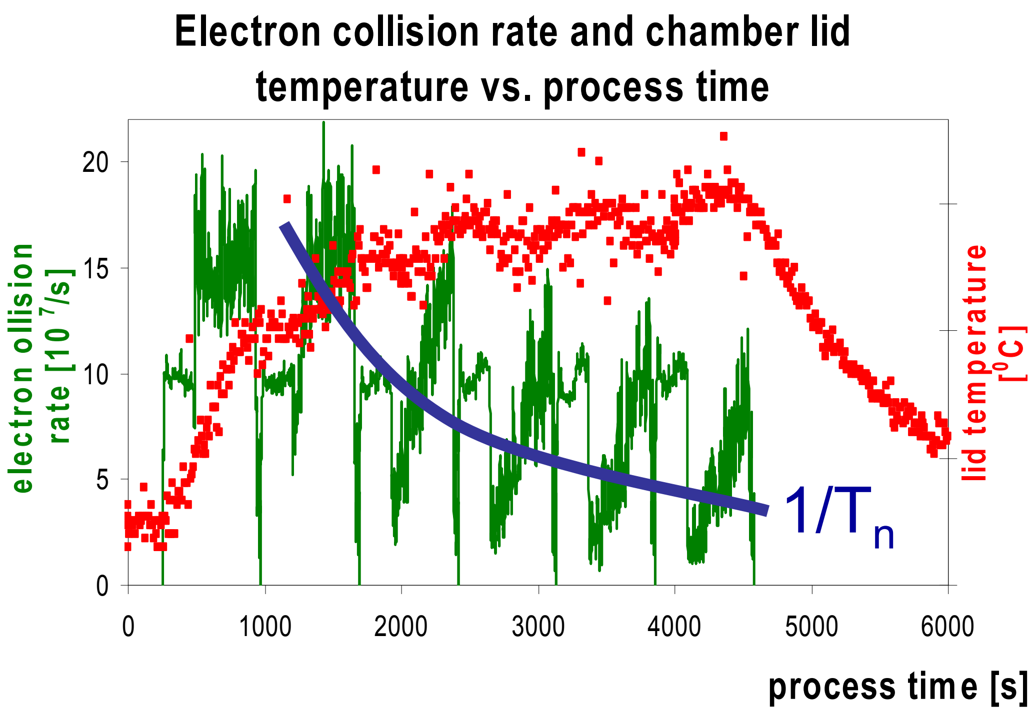
p: pressure ⇒ adjustable tool parameter

T_n: gas (neutrals) temperature ⇒ hardware parameter (chamber temperature …)

k: Boltzmann constant

- Control of crucial parameter by plasma monitoring !
- In a non-thermal, low pressure plasma – the neutral's density is the core parameter !

Chamber lid temperature and electron collision rate: Si etch in narrow gap chamber



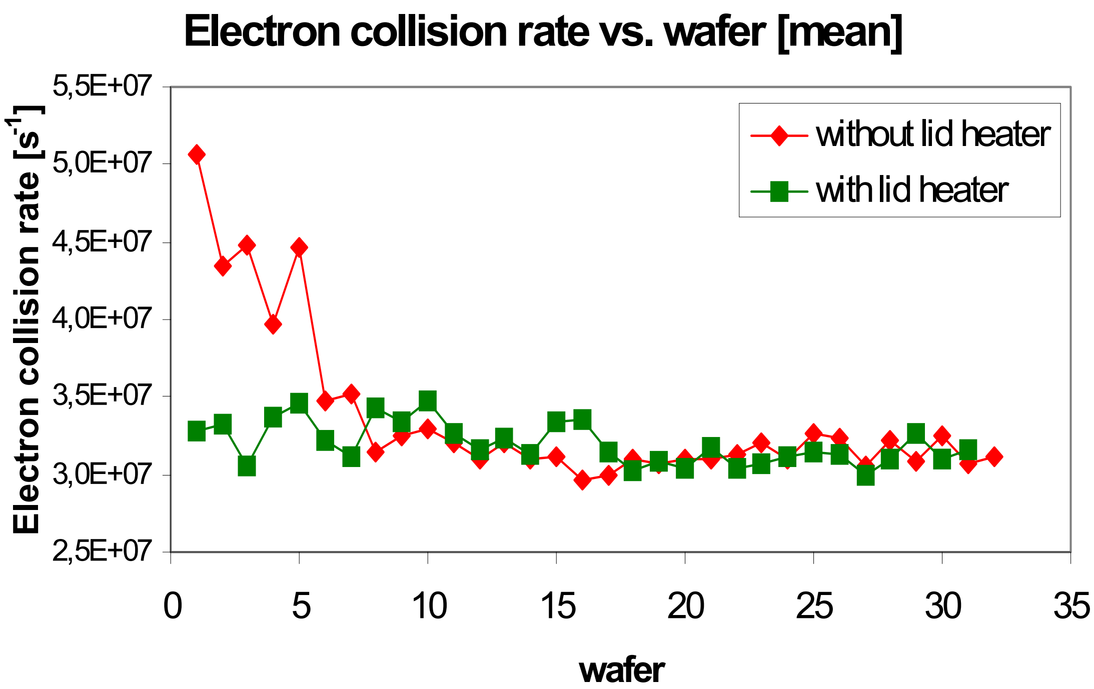
- First wafer effect (gas adsorption and desorption at chamber wall).
- Gas composition drift in plasma bulk ('saw tooth'), heating of chamber kit and wafer surface cause drift of chemical reactions there.

- 300 mm oxide (test) wafers.
- Gas temperature drift only during 2nd high RF power step.

by courtesy of Infineon technologies

S. Bernhard, et. al., 3th European AEC/APC Conference, Dresden, Germany, 2002.

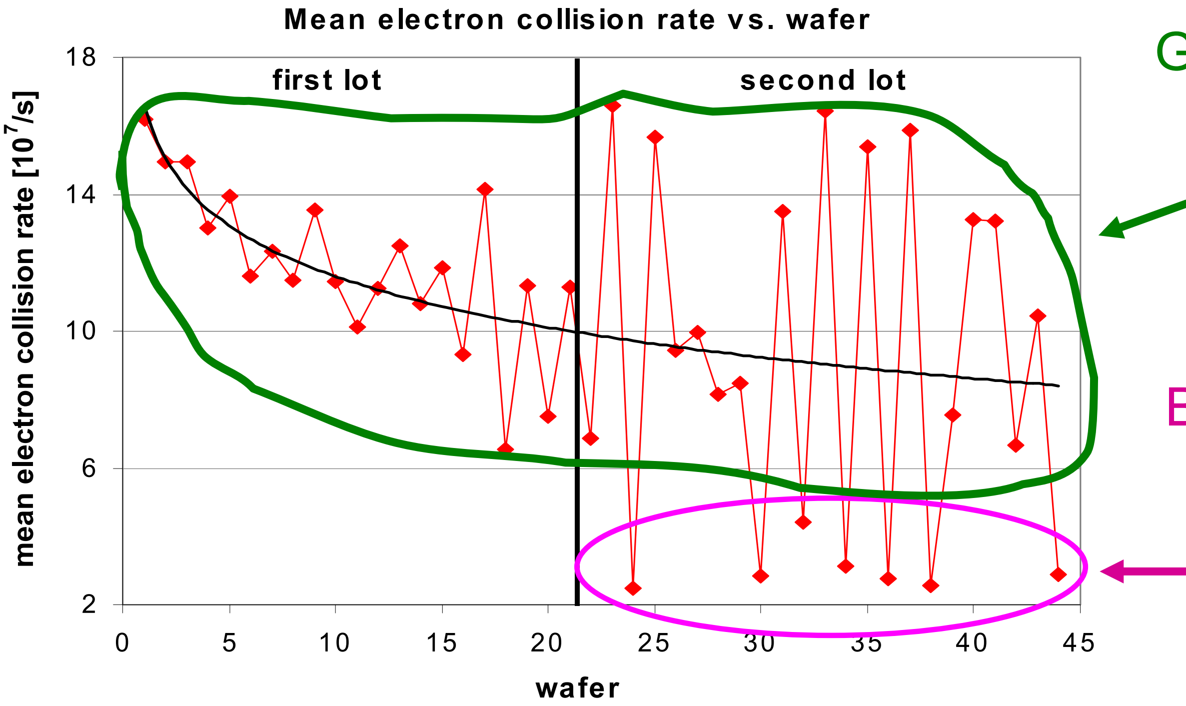
Chamber lid temperature and electron collision rate: Si etch in narrow gap chamber



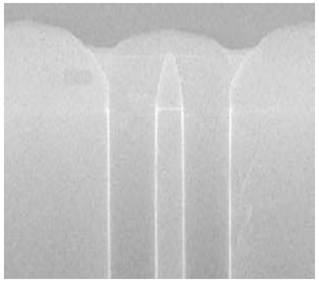
- 300 mm product wafers.
- Verifies the gas temperature dependence of the electron collision rate ($1/T_n$) → density of neutrals.
- Temperature control by the lid heater leads to stable conditions.

by courtesy of Infineon technologies

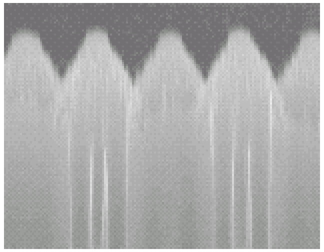
Pre-process fault - Impact from Litho on Etch



Good etch result



Bad etch result

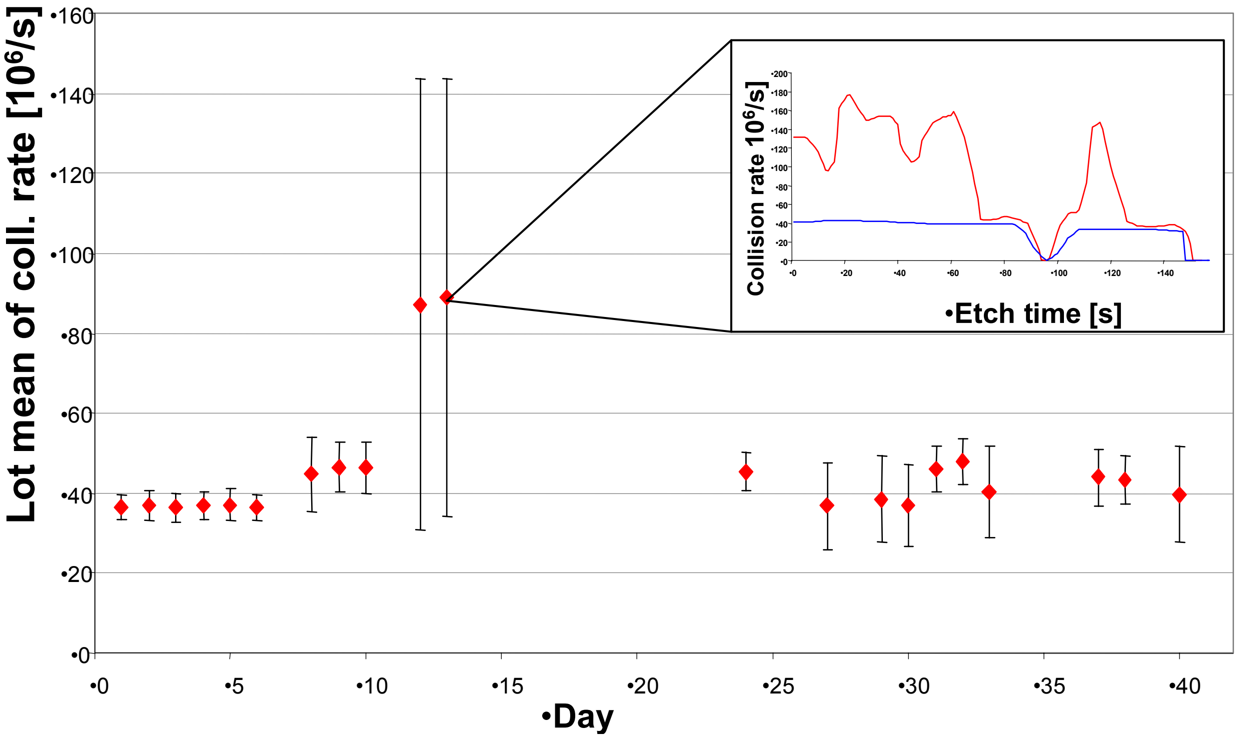


- Deep trench etch (Si etch using Br and F chemistry).
- Wafer to wafer signature at second lot caused by alternating mask quality, due to pre–processes (Litho, CVD, ...).
- Drift during processing of both lots is caused by tool impacts.

by courtesy of Infineon technologies

S. Bernhard, et. al., 3th European AEC/APC Conference, Dresden, Germany, 2002.

Arcing in AMAT eMxP+™



- Arcing Traces in 300 mm chamber detected:
  - Product was damaged.
  - Polymer particles are generated and negatively charged.

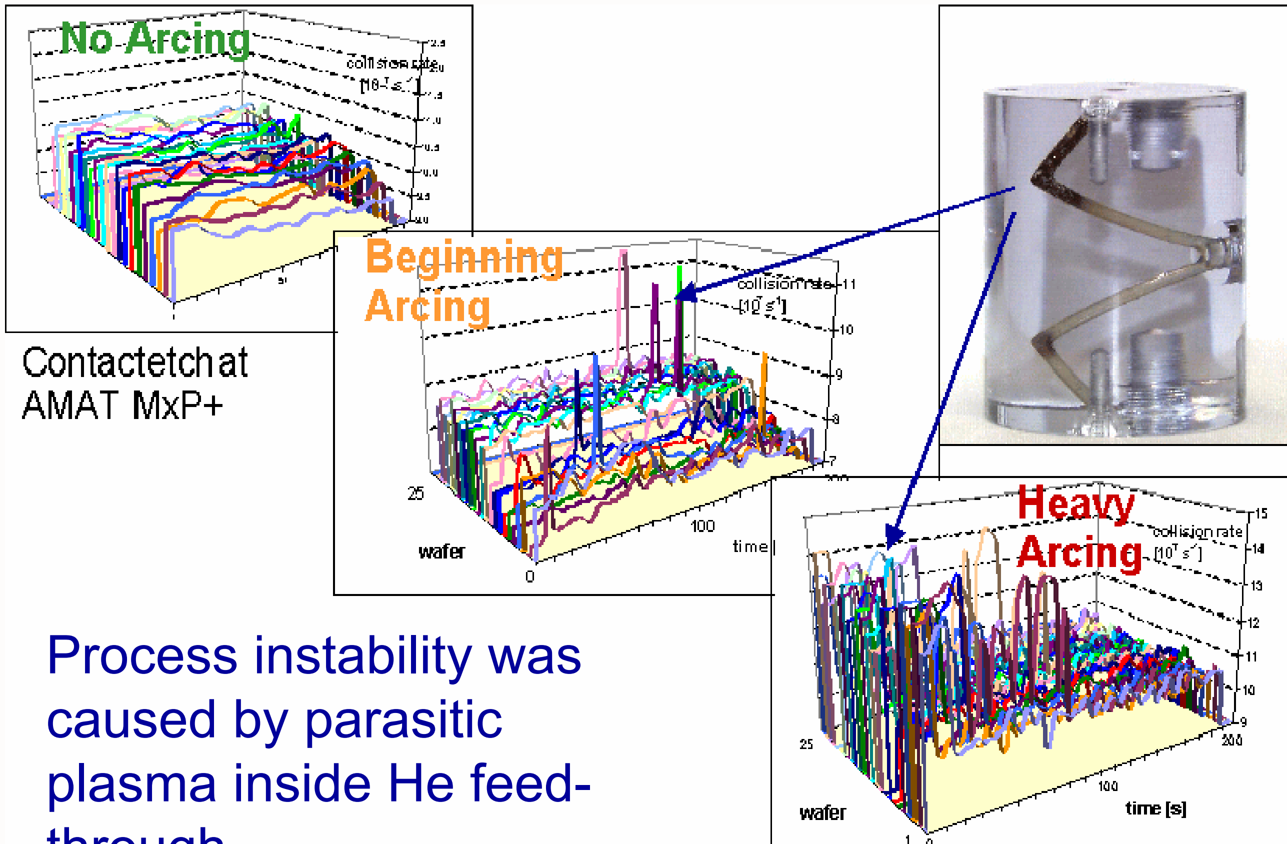
→ Increase of electron collision rate.

→ Exchange of E-Chuck and Ion shield.

by courtesy of Infineon technologies

V. Tegeder, SEMATECH AEC/APC Symposium XII, Lake Tahoe, USA, 2000.

Parasitic Plasma in helium feed-through: Real time detection for contact etch at MxP+™

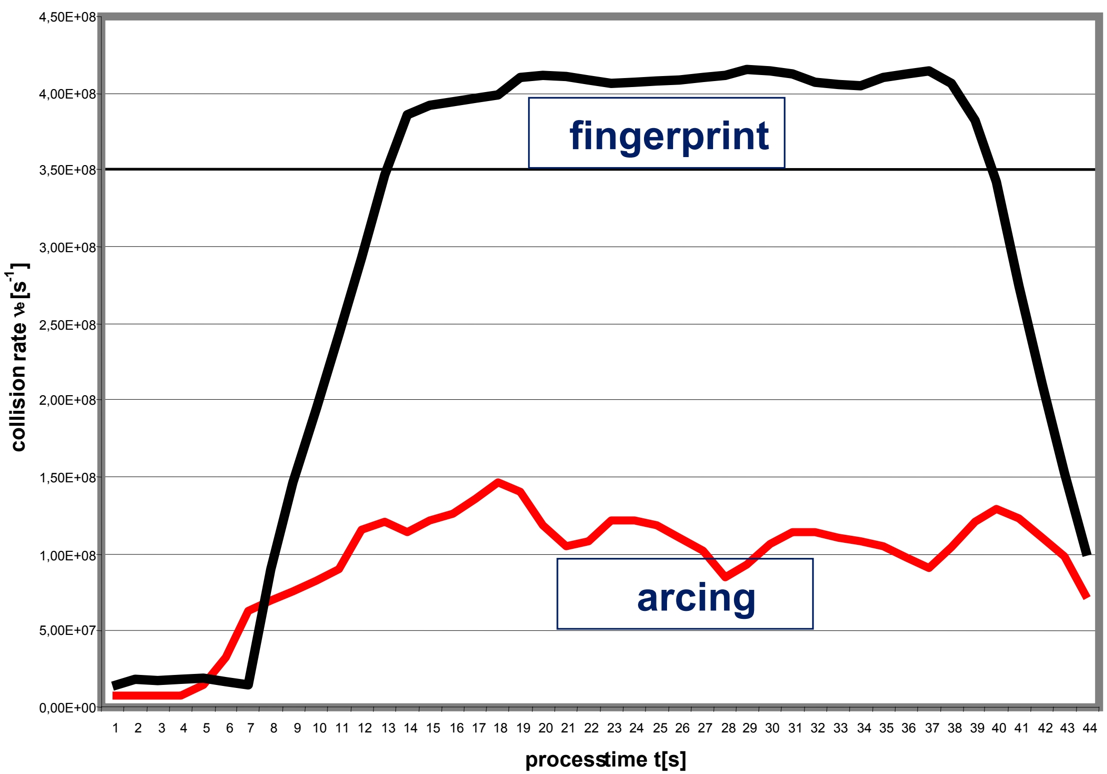


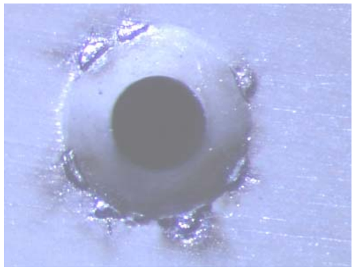
Process instability was caused by parasitic plasma inside He feed-through.

by courtesy of Infineon technologies

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

Arcing at gas distribution in AMAT eMxP+™





Arcing traces at gas distribution

- Recipe:
  Step 1
  25mtorr / 215W / 30G/ 50 sccm O_2
  Step 2
  25mtorr / 215W / 0G/ 50 sccm O_2

Arcing at the GDP (shower head) detected at brand new tool. Detected first at one chamber, the other ones were saved.

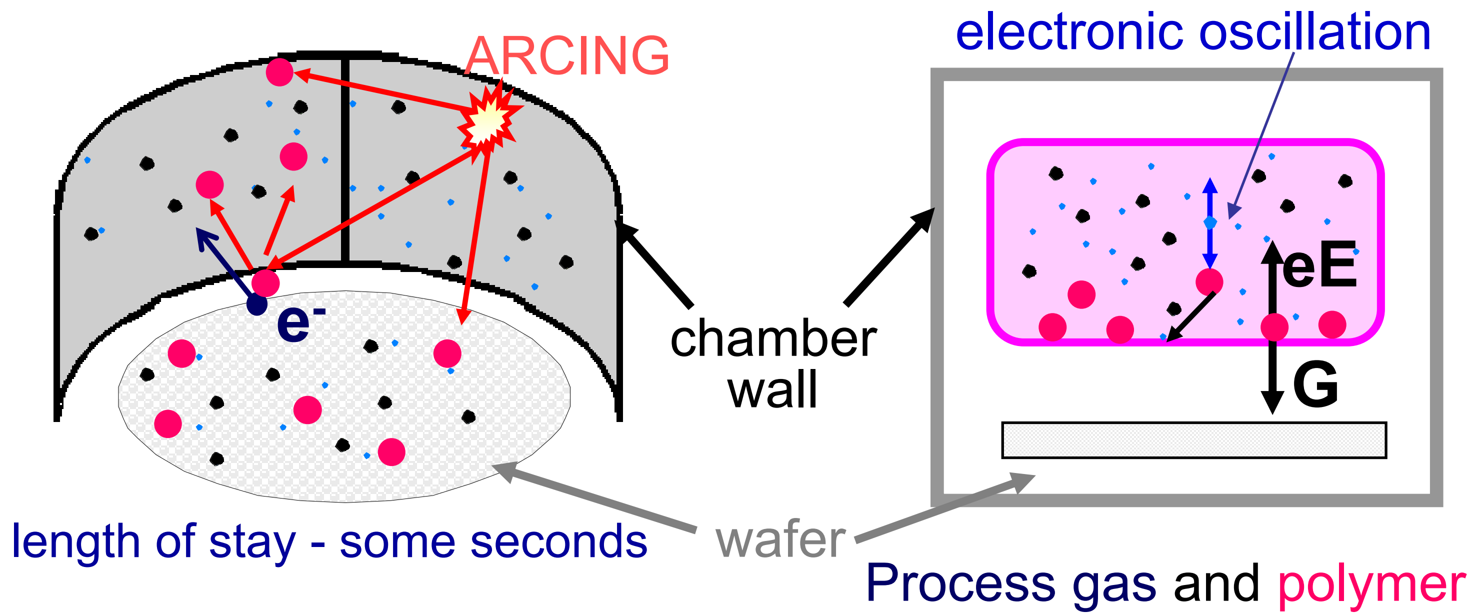
Only Maintenance costs saving about 100 k$!

by courtesy of AMD

V. Tegeder, SEMATECH AEC/APC Symposium XII, Lake Tahoe, USA, 2000.

Arcing

- Arcing is observed as an electrical breakthrough of an insulating layer deposit on the chamber wall where a sufficient electrical potential has developed.
- The insulator breakthrough is a stochastic process!



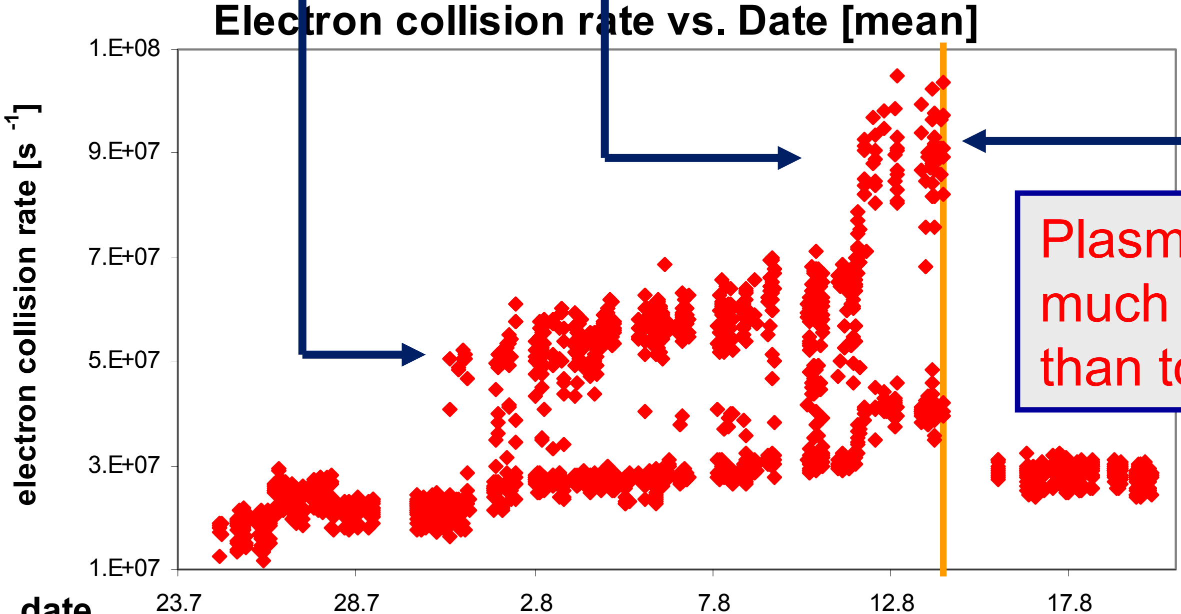
Large polymer molecules → increase collision rate.
Relative small metal ions → decrease collision rate.

Conditioning monitoring and leak detection of CVD process

- Increased electron collision rate detects tool excursion after dry clean. Leak and particle in spec.

Leak detection by tool after 38 processed lots.

Particle out of spec detected after 4 further processed lots – tool down.



Plasma parameters much more sensitive than tool parameters!

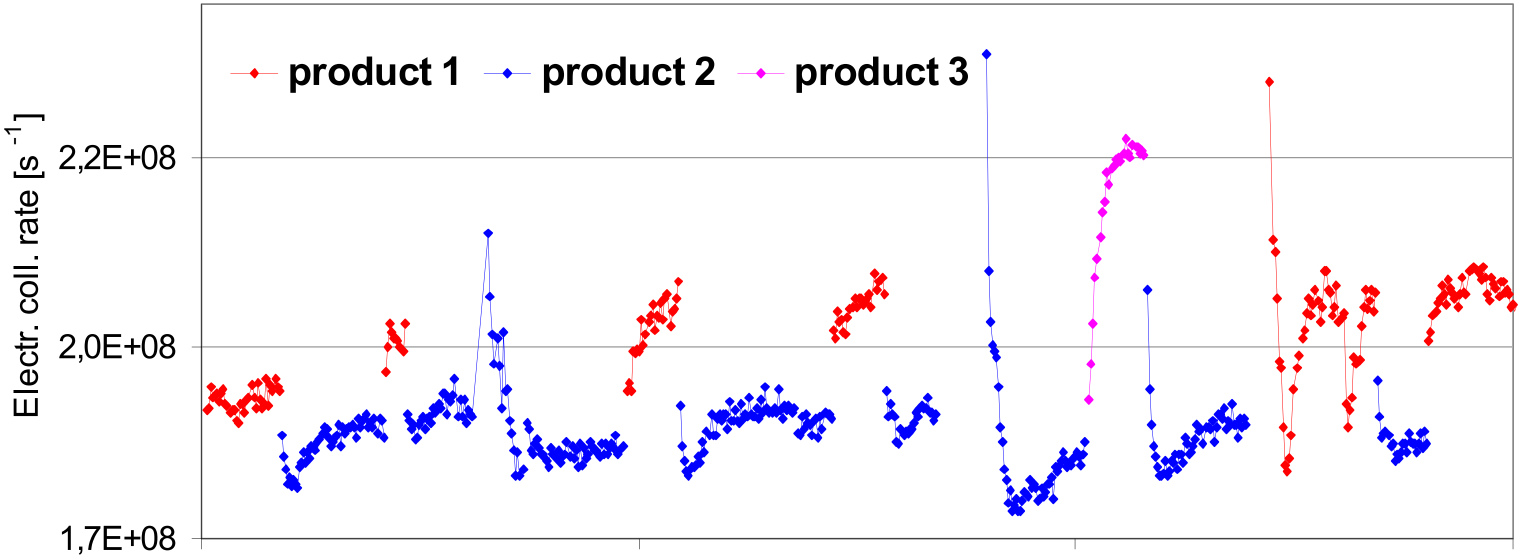
One point – one wafer

by courtesy of Infineon technologies

A. Steinbach, et. al., 4th European AEC/APC Conference, Dresden, Germany, 2003.

Product mix - Oxide etch at TEL SCCM

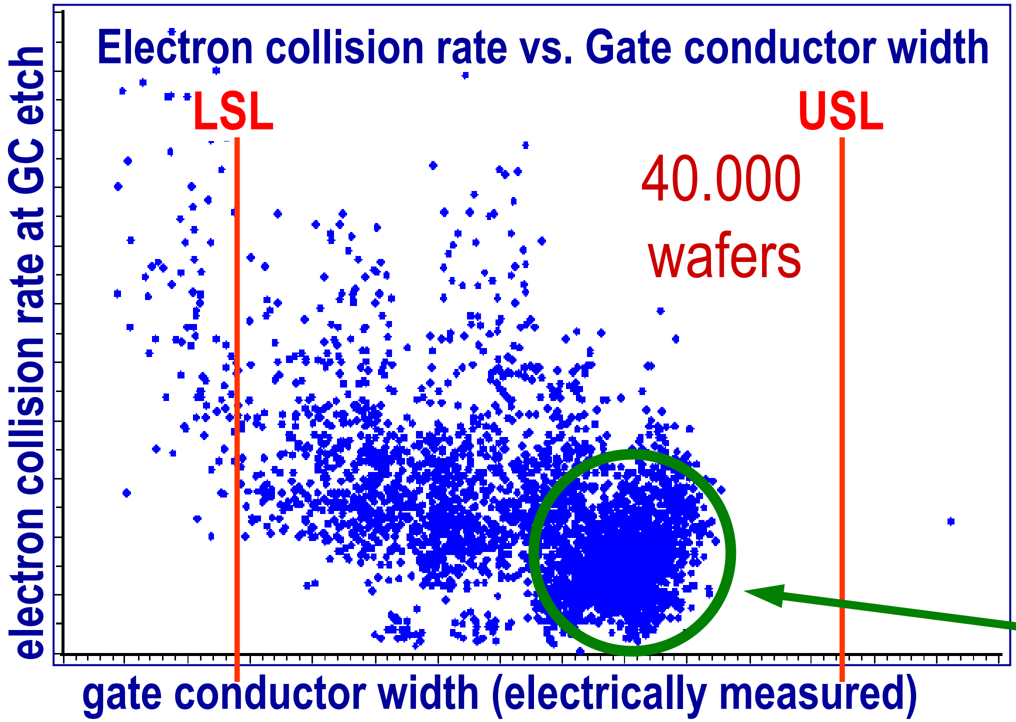
- Different products requests to chamber dedication or needs a sufficient process control - to avoid process drift by product mix.

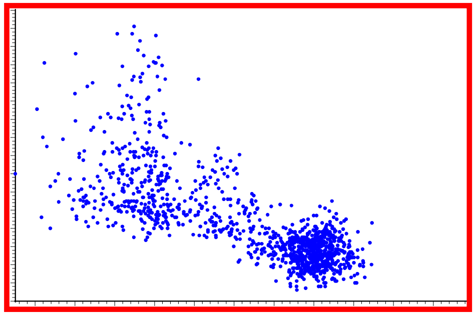


- The electron collision rate (one point – one wafer mean) shows the process variation caused by product switching and can be used as real-time process stability indicator – to maintain save conditions and provide acceptable process results for all wafers and products.

L. Eichhorn et. al, 5th European AEC/APC Conference, Dresden, Germany, 2004.

Gate contact etch (GC): Electron collision rate vs. poly length





First part of results (one year earlier).

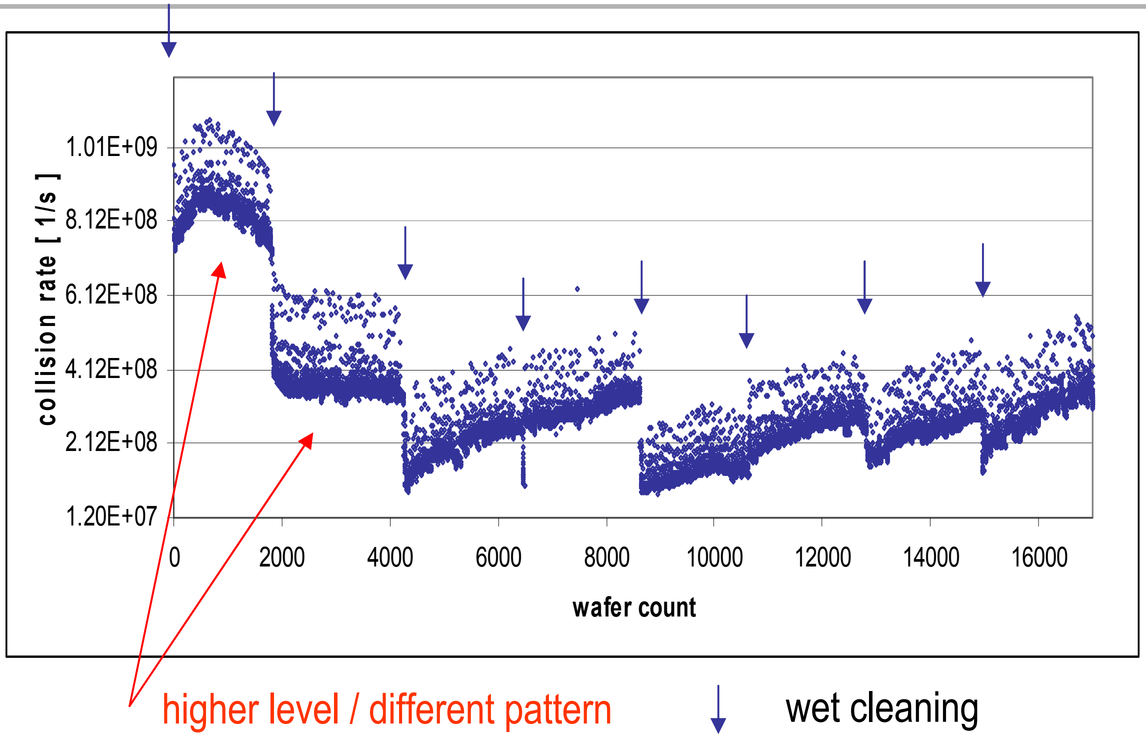
Dedicated chamber

- ± 50% variation of collision rate due to product mix impact.
- 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 this is fine.

by courtesy of Infineon technologies

A. Steinbach, 3th European AEC/APC Conference, Dresden, Germany, 2001.

Sensitivity of the collision rate to equipment parts and process chemistry change



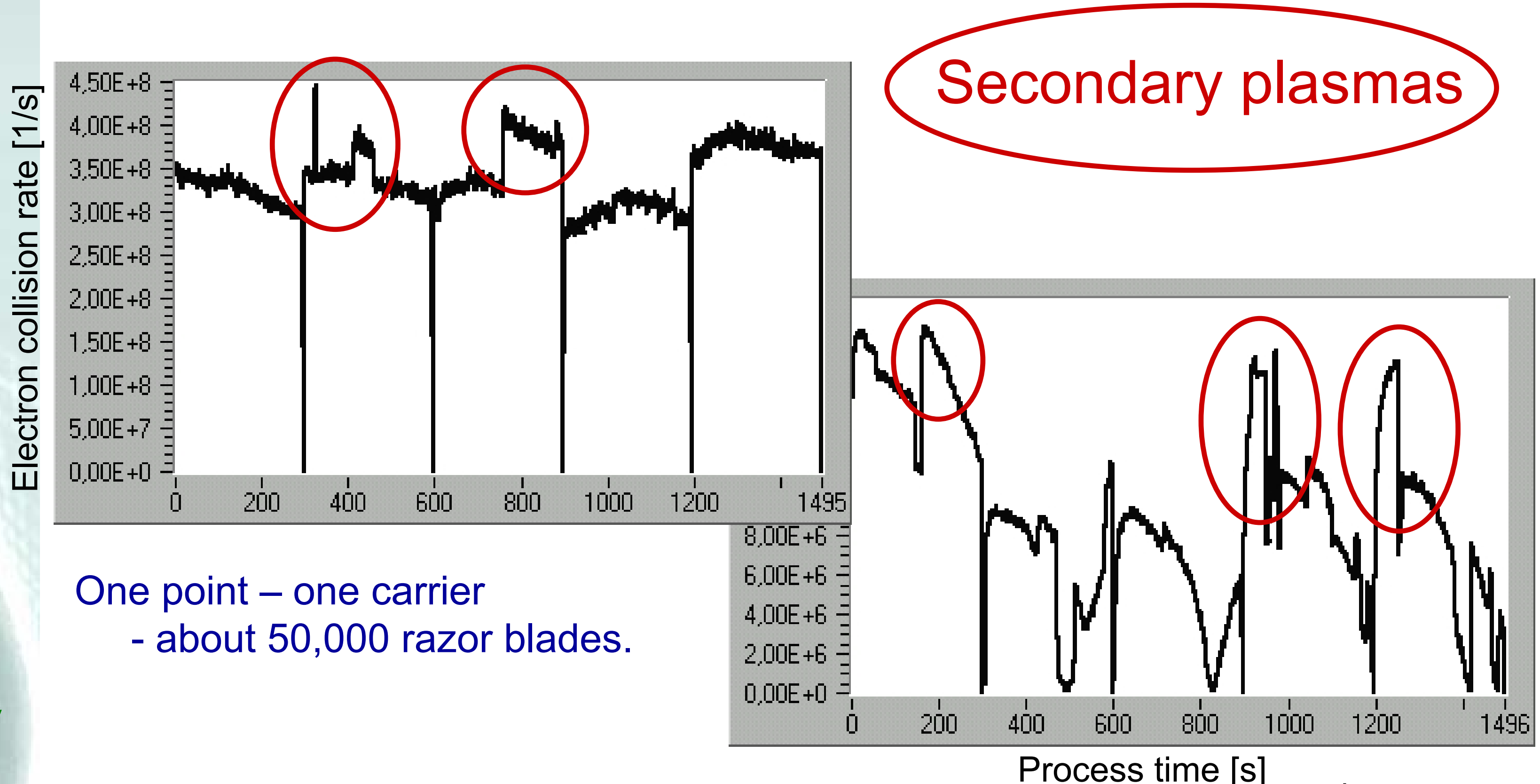
- Before the sensor was installed, the chamber was used for a different gas chemistry ($Ar/C_5F_8/O_2$ instead of $Ar/C_4F_8/O_2$).
- It took two wet cleaning cycles or about 4000 wafers completely „forget“ the former chemistry.
- Steps after wet clean are related to changed consumables.

by courtesy of RENESAS Everywhere you imagine.

C. Schmidt, et. al., SEMATECH AEC/APC Symposium XV, Colorado Springs, USA, 2003.

Secondary plasma in sputter clean process for PVD

- Inert gas used for cleaning process leads to layers at chamber wall and RF feedthrough → **Secondary plasmas**
- Electron collision rate used as indicator for secondary plasmas



One point – one carrier
- about 50,000 razor blades.

by courtesy of The Gillette Company

P. Krenzlin, 1th European AEC/APC Conference, Dresden, Germany, 2000.

Conclusions

- Plasma parameter measurement in IC manufacturing requires robust and passive 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 process model building to predict product parameters.
- The best method depends on:
  - Final goal (fault detection, process development,…).
  - Chamber type and process.
  - Knowledge available.
- VI probes will be a must for the control of the RF sub-system but not sufficient at all.
- Electron parameters are most sensitive
  - OES for endpoint detection and process development
  - SEERS for routine control – the electron collision rate is the most sensitive parameter.

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