Quality Management by Advanced Process Control in Large Area PECVD

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Quality issues in industrial Plasma Processing

- Industrial deposition of functional, e.g., optical, layers requires often large-area layers with sufficient uniformity
- Micro structuring for light trapping gets more important, e.g., in photovoltaics now for up to 6 m^2.
- Plasma Enhanced Chemical Vapor Deposition or Plasma Etching uses mostly parallel-plate RF discharges for large and flat substrates.
  - Plasma driven uniformity issues
  - Gas temperature drift affects process

Overview

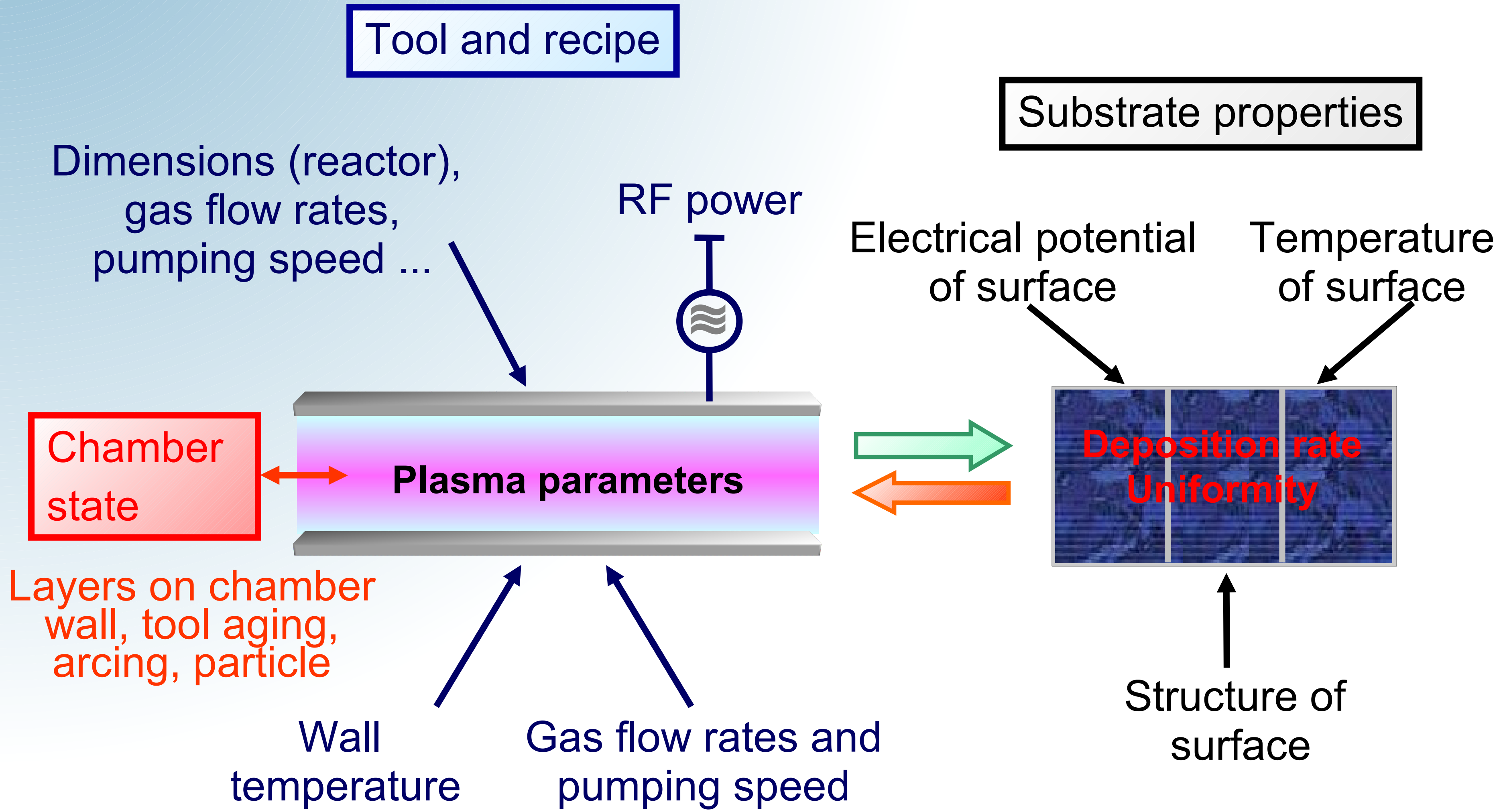
- Complexity of Plasma Processing

- Electro-dynamic model of planar, large-area RF discharges
  - RF current density distribution
  - Bulk power density distribution and layer uniformity
  - Parameter variations

- Model-based Plasma Parameter Measurement
  - Electrical measurement of plasma parameters
  - Indirect gas temperature measurement through collision rate

- Stability, Uniformity and Temperature as Quality Indicators
  - Idle time – chamber temperature
  - Substrate temperature
  - Layer uniformity, plasma parameters and gas temperature

The Complexity of Plasma Processing



Tool and recipe

Dimensions (reactor), gas flow rates, pumping speed ...

RF power

Substrate properties

Electrical potential of surface

Temperature of surface

Chamber state

Plasma parameters

Deposition rate

Uniformity

Layers on chamber wall, tool aging, arcing, particle

Wall temperature

Gas flow rates and pumping speed

Structure of surface

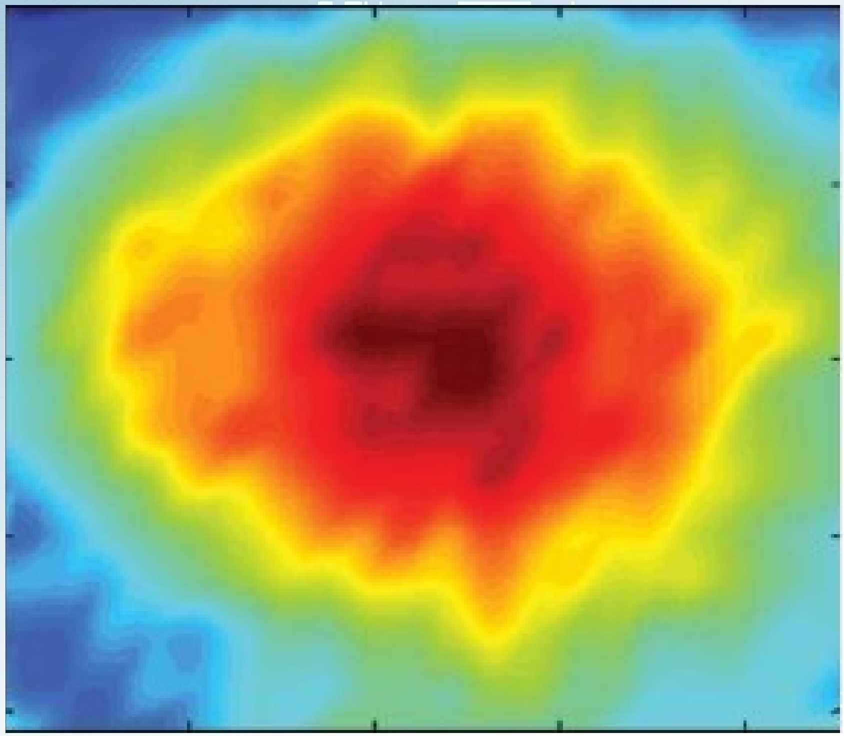
RF Current → Bulk Power → Layer Thickness

- The ion energy distribution is determined by the sheath voltage.
- Ion energy distribution seems to affect primarily the layer structure.
- RF current density determines bulk power density.
- RF bulk power provides power to plasma electrons.
    - Electrons are heated by thermalization of electric field energy.
    - More, hot electrons crack the process gas.
    - Higher crack rate provides more reactive particles

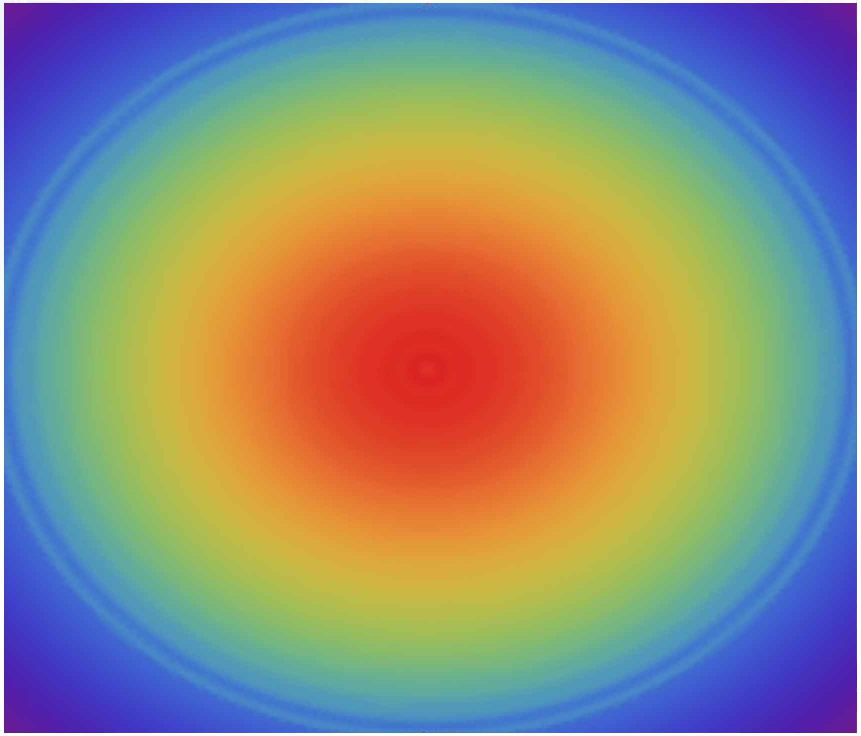
      → Higher local deposition rate

Motivation: Real a-Si Thickness on Gen 8.5 Panel

- Measured thickness distribution (left), simulated power distribution (right)



a-Si layer thickness
Ariel Ben-Porath, Benny Shoham, BrightView systems, Increasing cell efficiency and optimizing productivity using wide area metrology, Photovoltaics World, March/April 2010



RF power distribution
Simulation – Plasmetrex GmbH

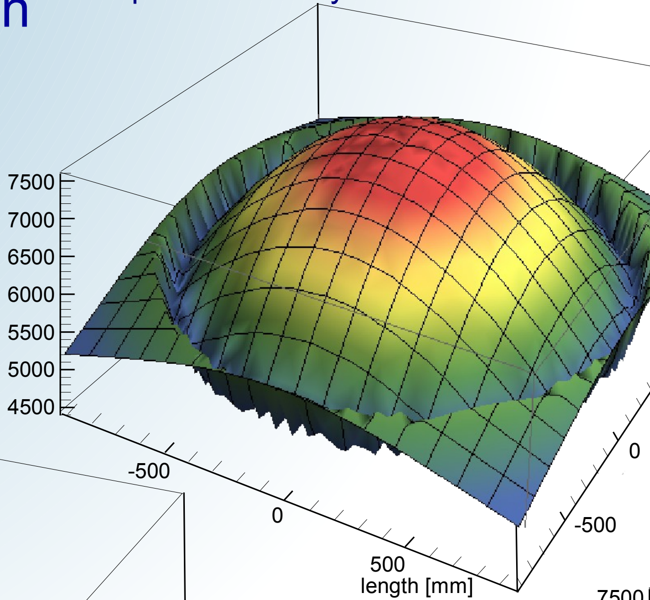
Electro-dynamic model for RF Bulk Power Uniformity from low to high Plasma Density

- The electron collision rate is constant.

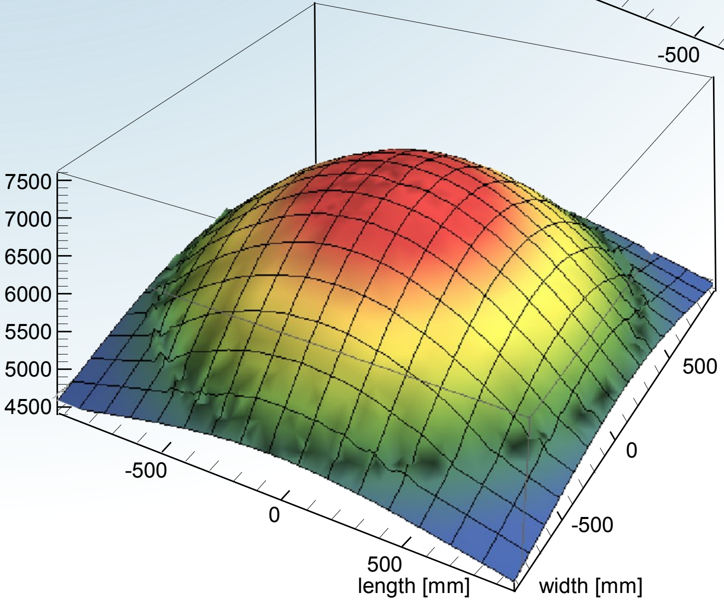
$\nu = 5.0 \times 10^{8}\ s^{-1}$

- At high plasma density the skin effect increases and the standing waves are not decreases.

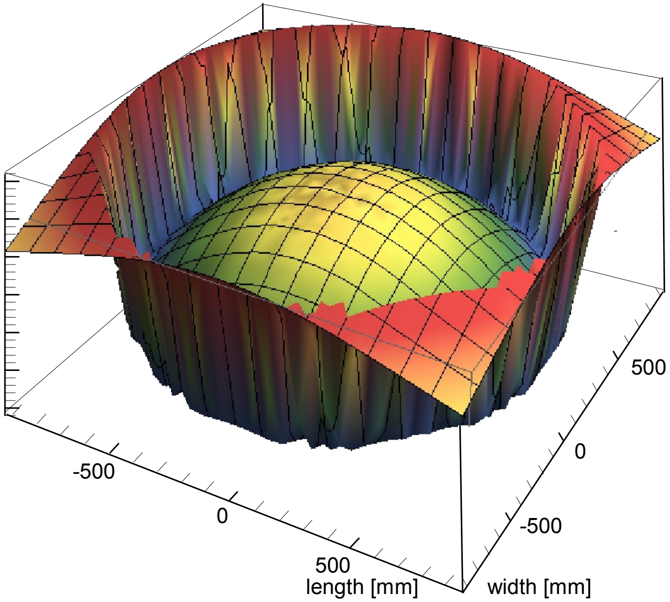
plasma density n = 1.0 x 10^9 cm^3



plasma density n = 5.0 x 10^8 cm^3



plasma density n = 2.0 x 10^9 cm^3



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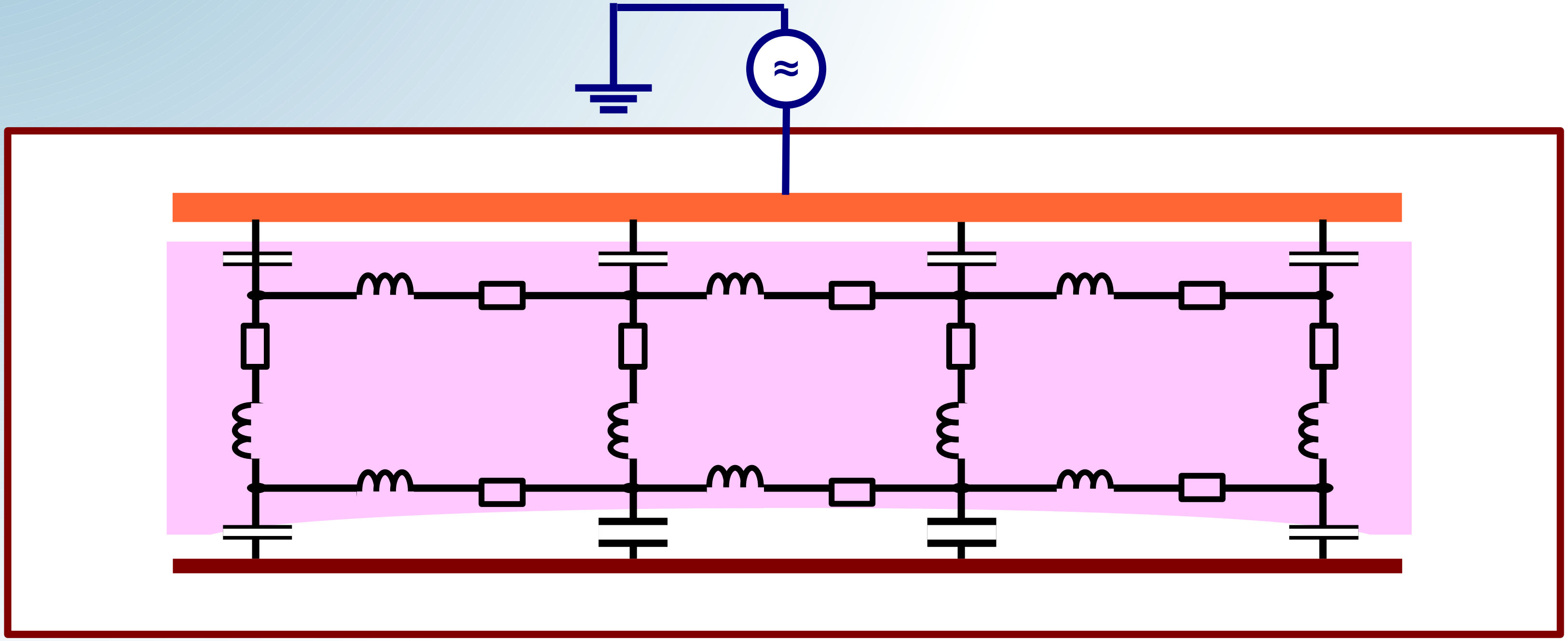
Interpretation of Standing Wave Effect

- Analog to wave propagation in open cables
  - Geometric 'compression' through smaller area.
  - Reflection in center of discharge, reflected wave dissipated additional power.

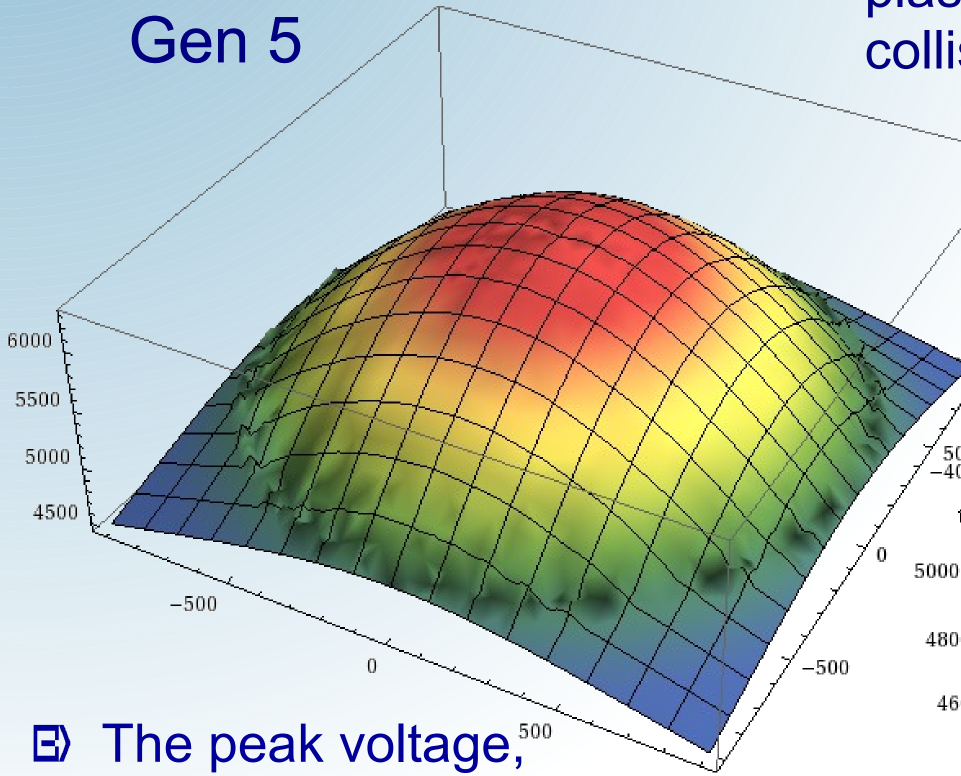


- The skin effect in plasma is like the skin effect in metal. The skin depth depends on the electron density and is higher compared to metal.

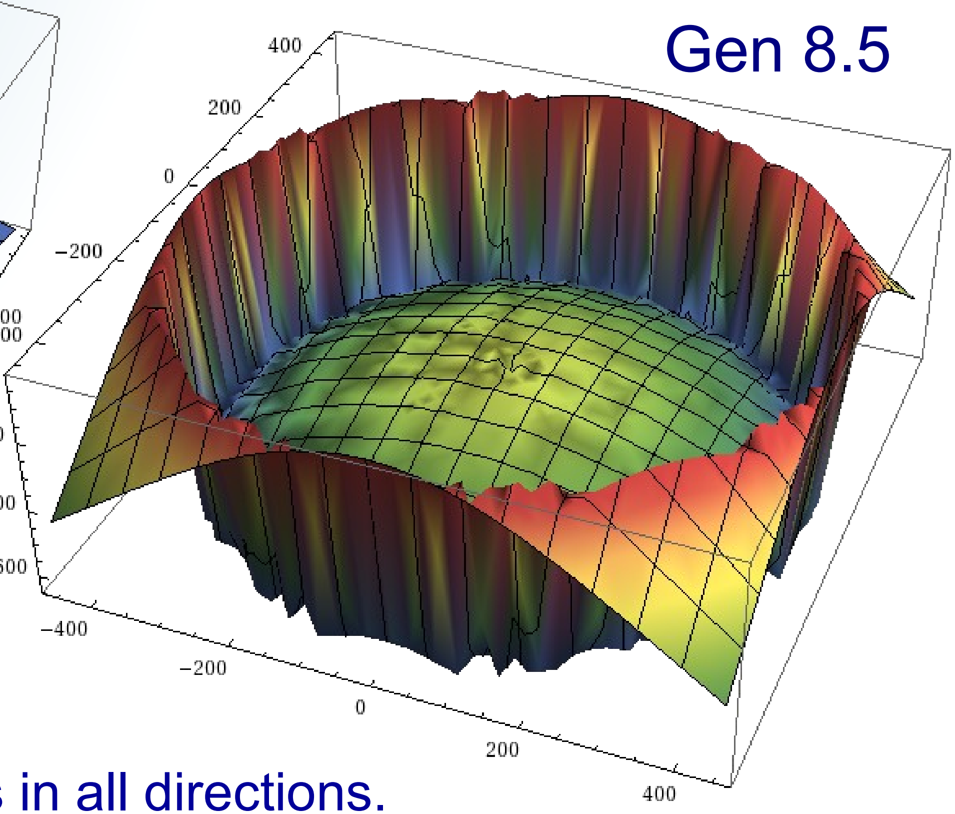
Smaller Chamber Gen 5 is more uniform compared to Gen 8.5

plasma density n = 5.0 x 10^8 cm^{-3}
collision rate ν = 5.0 x 10^8 s^{-1}

Gen 5



Gen 8.5



- The peak voltage, electron temperature, and electron density are kept constant.
- Please note the different plot ranges in all directions.

Are the model input parameters as electron collision rate and density suitable for quality management?

Gas Temperature limits Plasma Process Controllability

- The crucial plasma process parameter is the density of neutrals n_n:

$$\boxed{n_n = \frac{p}{k\,\vartheta_n}}$$

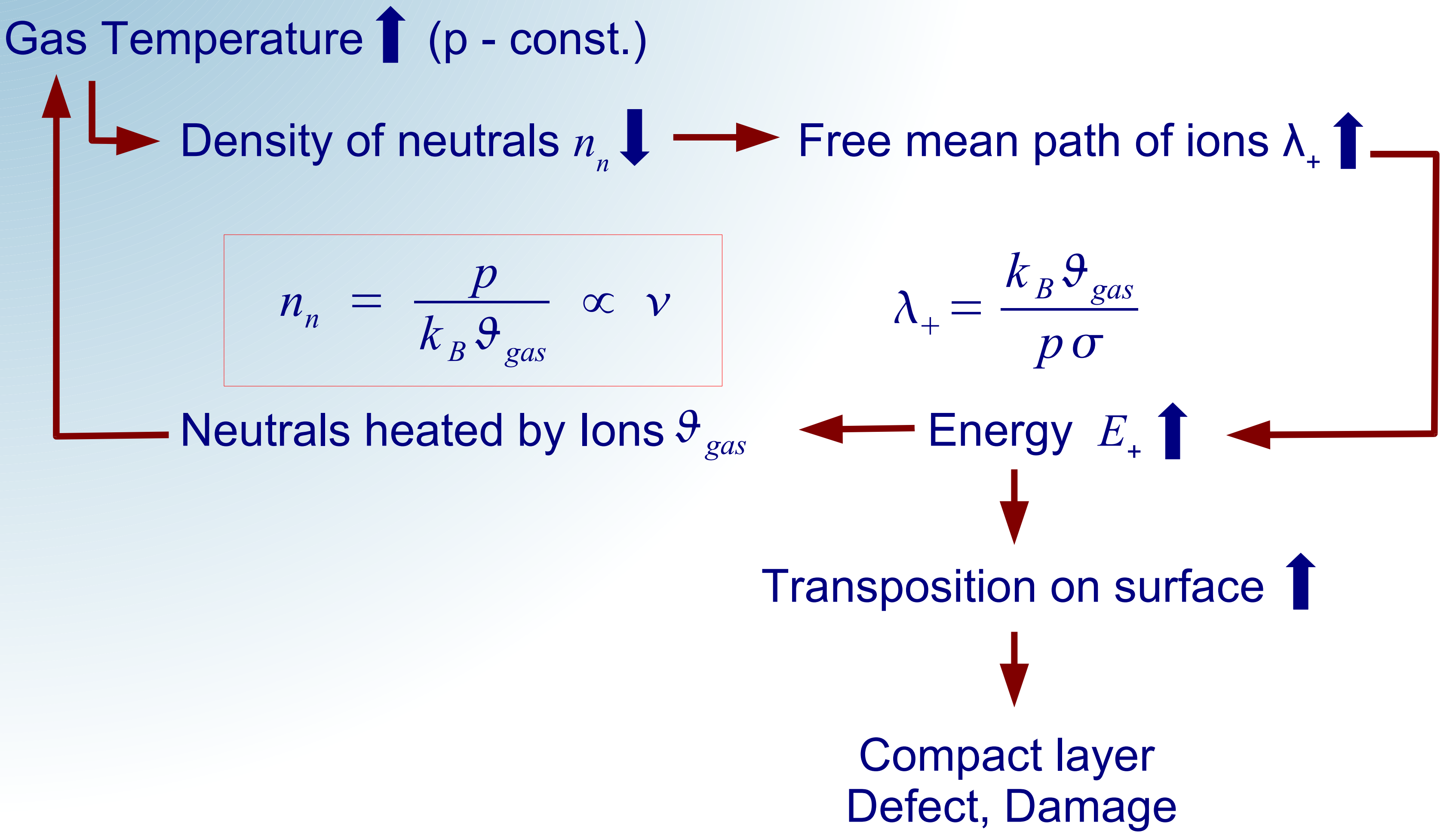
Power dissipation for chemistry by electrons (collision rate)

Energy and angle distribution of ions determines etch or deposition rate and film properties.

p	Pressure	⇨ adjustable tool parameter
ϑ_n	Gas (neutrals) temperature	⇨ unknown & depends mainly on RF power !

k: Boltzmann constant

Plasma and Surface Effects driven by Gas Heating



Gas Temperature ↑ (p - const.)

Density of neutrals n_n ↓

Free mean path of ions λ_+ ↑

$$n_n = \frac{p}{k_B \vartheta_{gas}} \propto \nu$$

$$\lambda_+ = \frac{k_B \vartheta_{gas}}{p \sigma}$$

Neutrals heated by Ions ϑ_{gas}

Energy E_+ ↑

Transposition on surface ↑

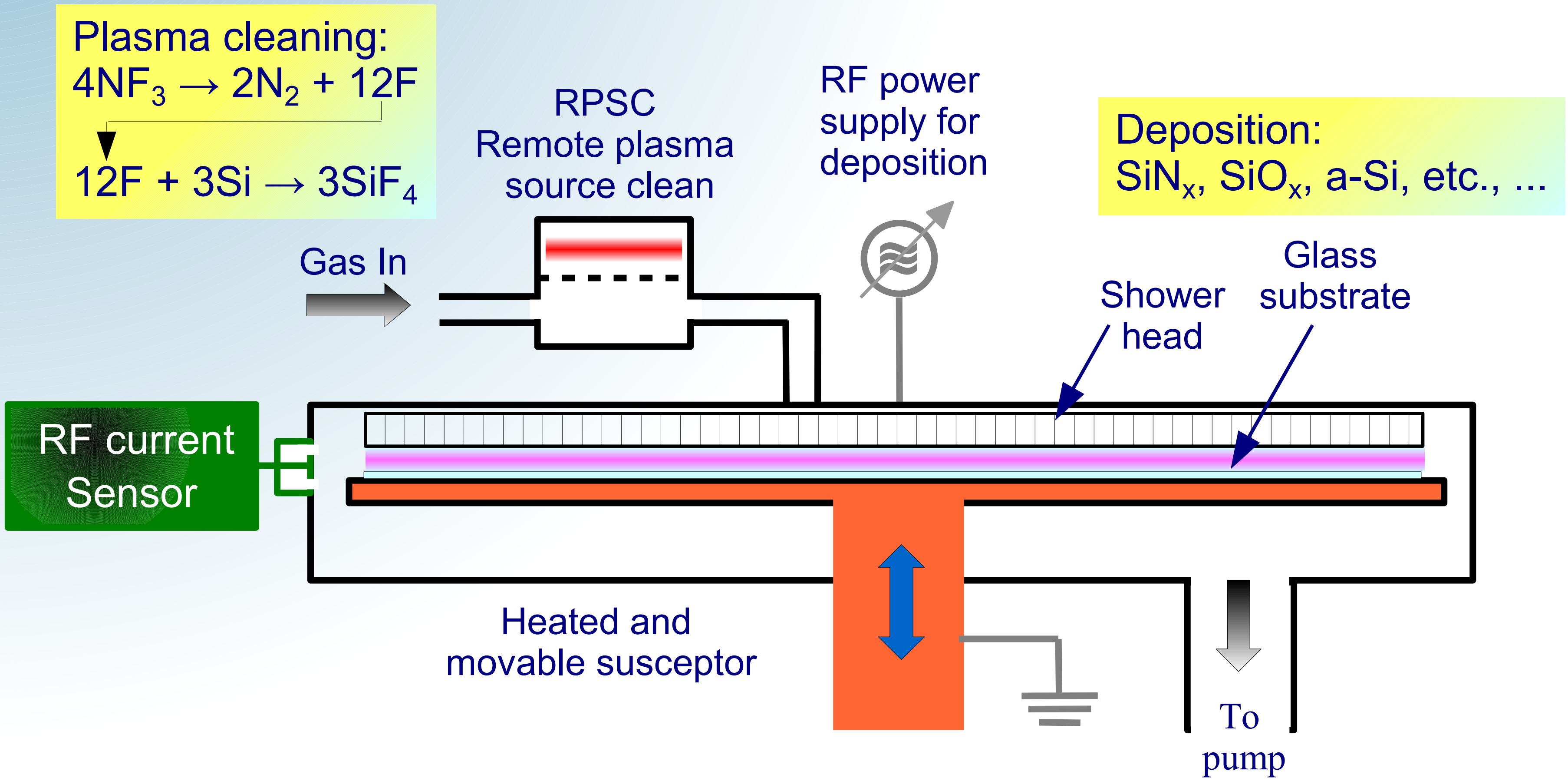
Compact layer
Defect, Damage

Applied Materials®' SunFab 5.7 (AKT60, 2.2 x 2.6 m^2)

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

Sensor Setup – Large Area PECVD

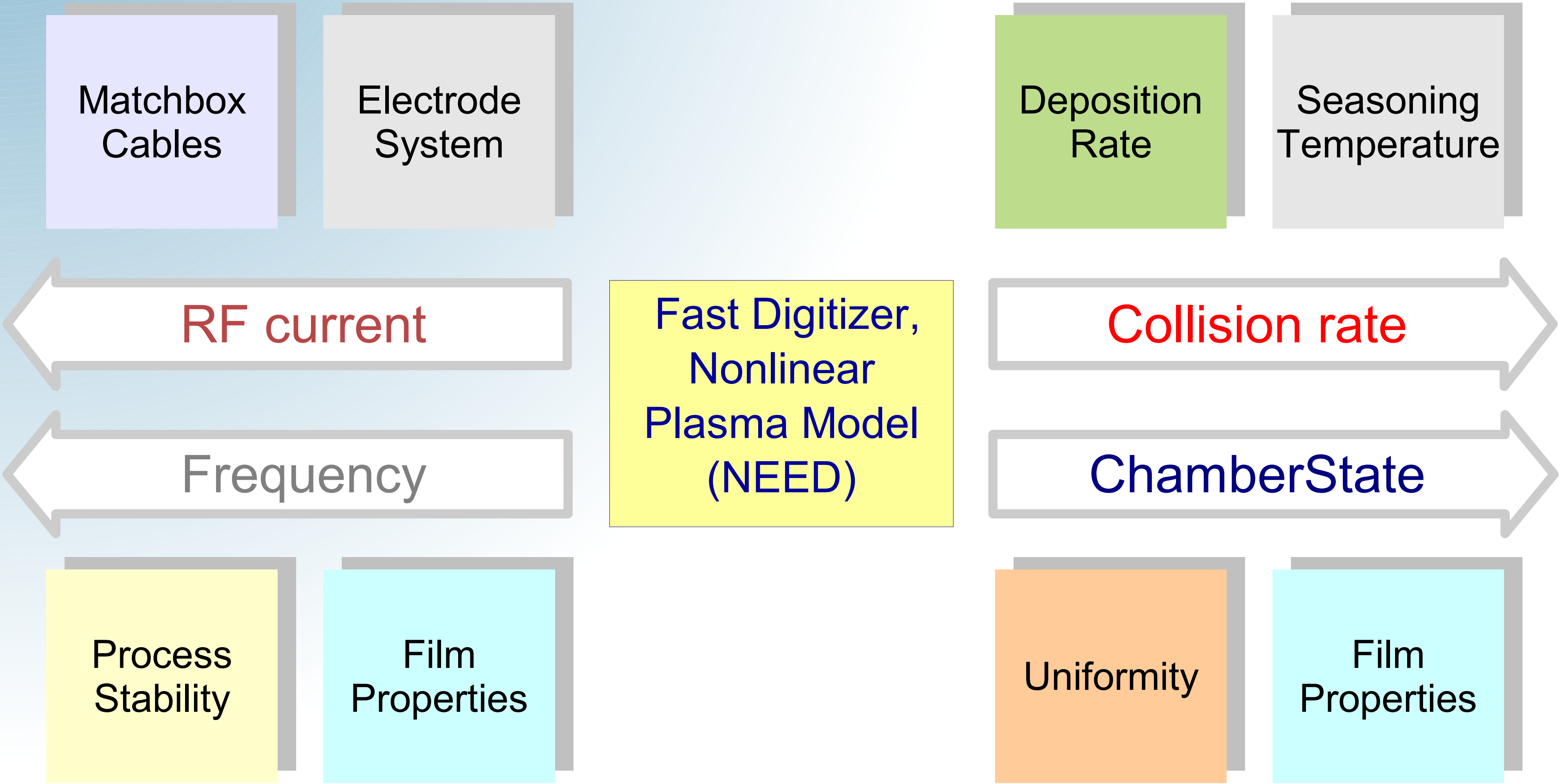
Capacitively coupled parallel plate RF plasma CVD chamber



Plasma cleaning:
$4NF_3 \rightarrow 2N_2 + 12F$
$12F + 3Si \rightarrow 3SiF_4$

Deposition:
SiN_x, SiO_x, a-Si, etc., ...

Plasma and Hardware Parameters for Process and Quality Control



Matchbox Cables

Electrode System

Deposition Rate

Seasoning Temperature

RF current

Fast Digitizer, Nonlinear Plasma Model (NEED)

Collision rate

Frequency

ChamberState

Process Stability

Film Properties

Uniformity

Film Properties

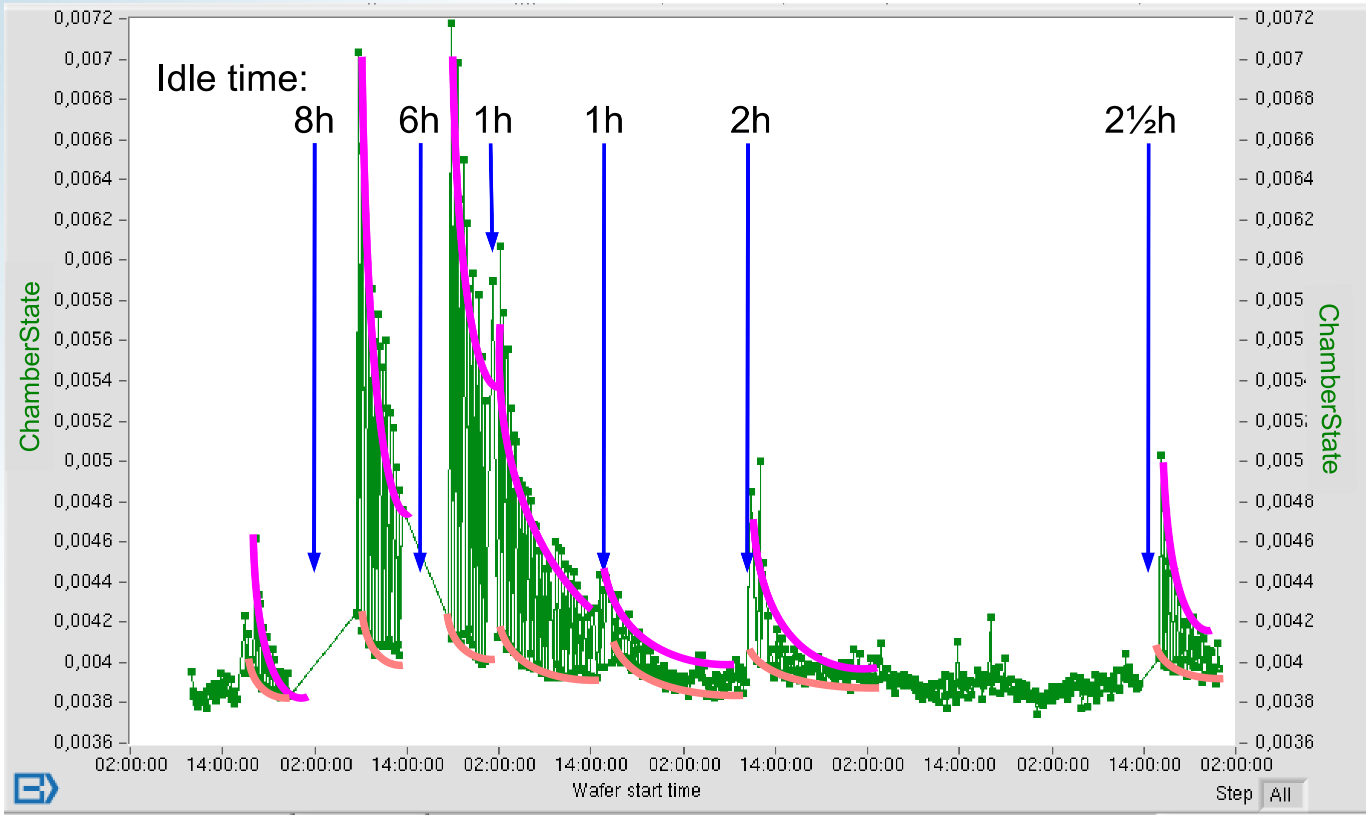
US Patents 5 705 931 and 5 861 752, European Patent EP 0 719 077 B1, Japanese Patent 2872954, other Patents pending.

Plasma Parameter:
Idle Time causes Process Deviations

- The upper curve follows means of seasoning process.
- The lower points are means of deposition process.

- Both seasoning and deposition are affected.

- High idle time cools chamber down.



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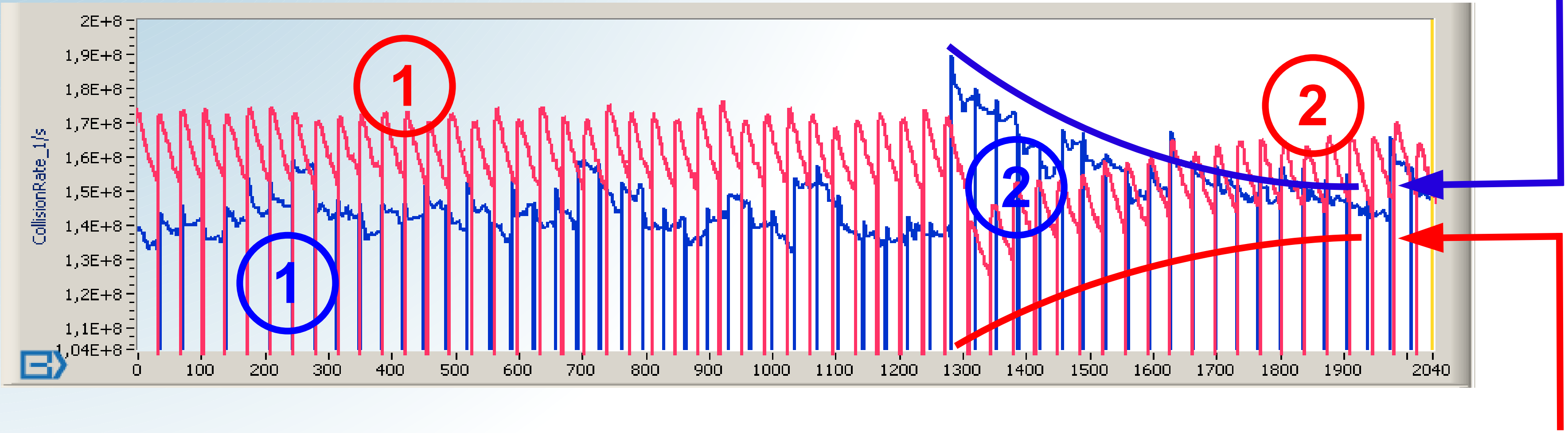
By courtesy of
signet solar

Collision rate indicator of Chemistry and Temperature

- Process variations caused by varying panel temperature ① .
- After 3h idle time, the collision rate starts at a higher level ② and is in the initial state after about 20 deposition processes when the chamber is heated up.



- Stable seasoning processing indicates thermal and chemical equilibrium ①.
- The cleaning and seasoning process depends on the final temperature of the deposition. In particular the process chemistry can only reach a balance when chamber temperature is stable ②.

Estimated Substrate Temperature Variation

- Gas temperature estimation
  - Gas is heating by plasma ions to a temperature well above the substrate.
  - Substrate temperature is about 350 °C = 650 K (Data from AKT)
  - Estimated gas temperature ≈ 700 K
  - Collision rate range +/- 7%

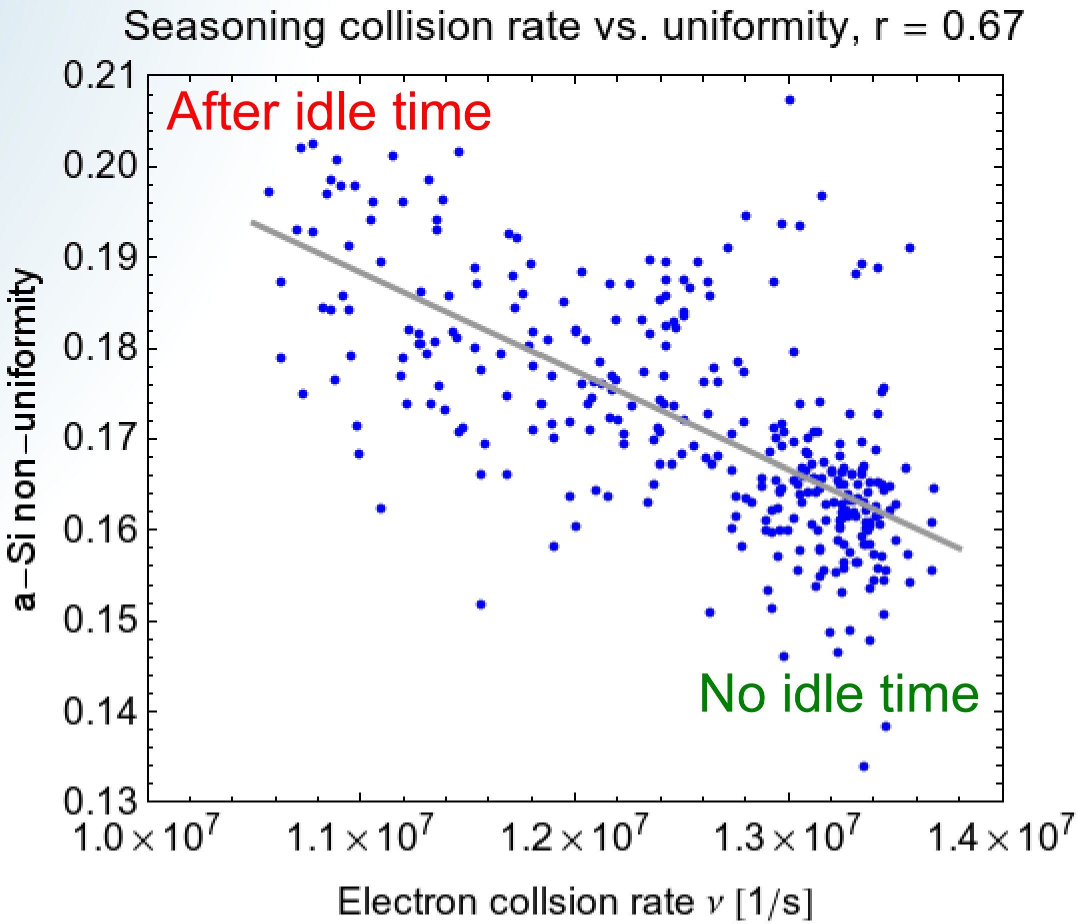
- **Estimated gas temperature variation ≈ +/- 50 K**

- Substrate temperature estimation
  - Heat capacity of panel : 1000 Ws / m^2 → 1 K
  - Radiation (dominates heath transfer) 475 K → 650 W / m^2 (Wall 445 K)

- **Substrate temperature decline within 60 s → 30 K**

How Seasoning affects Si Uniformity

- The collision rate from seasoning is both a measure of chamber temperature and wall surface chemistry.
- The variation of both parameters is caused by chamber idle time:
- Shows the importance of chamber wall seasoning after clean.



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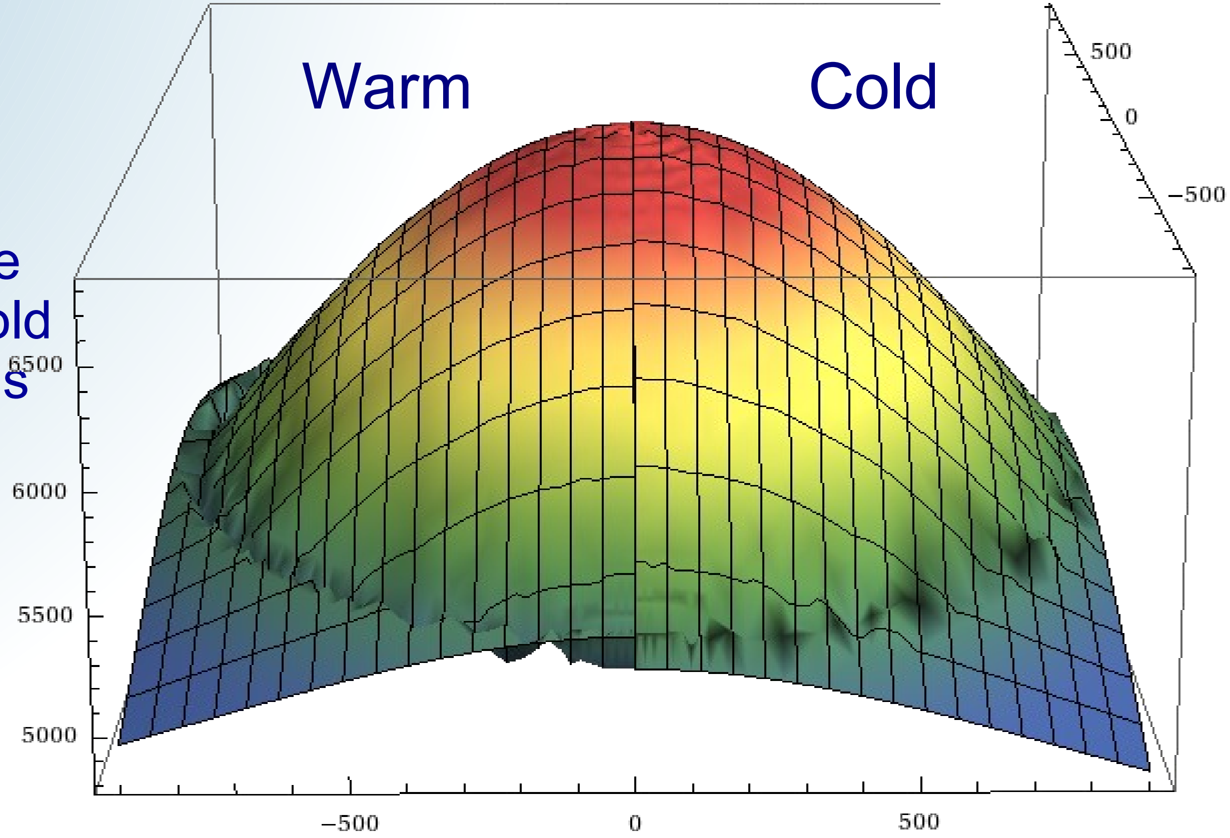
Uniformity Change with Cold Panel: Lower Pressure

- Collisions rate in 1/s
  $3\ 10^8$ vs $5\ 10^8$

- The estimated difference of uniformity between cold and warm panel confirms the measured one!



Conclusions

- A significant part of large area non-uniformity of PECVD is caused by electro-dynamic effects in the plasma. These effects influence the quality primarily.
- Gas temperature as a major reason for plasma process instability and can be indirectly measured by electron collision rate. For this reason the electron collision rate is a useful quality indicator.
- Gas temperature affect collision rate and density of electrons; this changes again the layer uniformity.
- A real quality management without plasma parameters is not sufficient.

Thank you for attention !