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# Plasma-Sensors
# for the next tool generation and chamber design

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# Motivation

- The next generation of plasma tools must be more flexible to be more effective to meet economic goals.

| | | |
|---|---|---|
| Utilization and OEE | Increase by | Dry clean (wafer less), conditioning and test wafer usage. MTTR ⇓, MTBC ⇑. |
| Maintenance and personnel effort, spare parts | Reduce recurring costs by | New coatings, service friendly. |
| Effective process time, high rate for etching / deposition | Reduce process time by | High/medium plasma density.<br>High gas flow and/or low pressure. |
| Shrinking, process flexibility, best uniformity, 'adjustable' profile, low damaging | Increase of tool applicability by | Low pressure, control of: Ion energy.<br>Peak voltage.<br>Plasma density. |
| Controllability, uniformity, tool faults | Decrease yield loss through | Process time well above time constant of tool and maximum two excitations. Robust, smart sensors. |

MTTR: Mean Time To Repair, MTBC: Mean Time Between Clean

- So dual excitation plasma tools are mostly used.
  - High (up to 100 MHz) and low capacitive excitation frequencies or
  - capacitive and inductive ones used for plasma generation.

# Contents

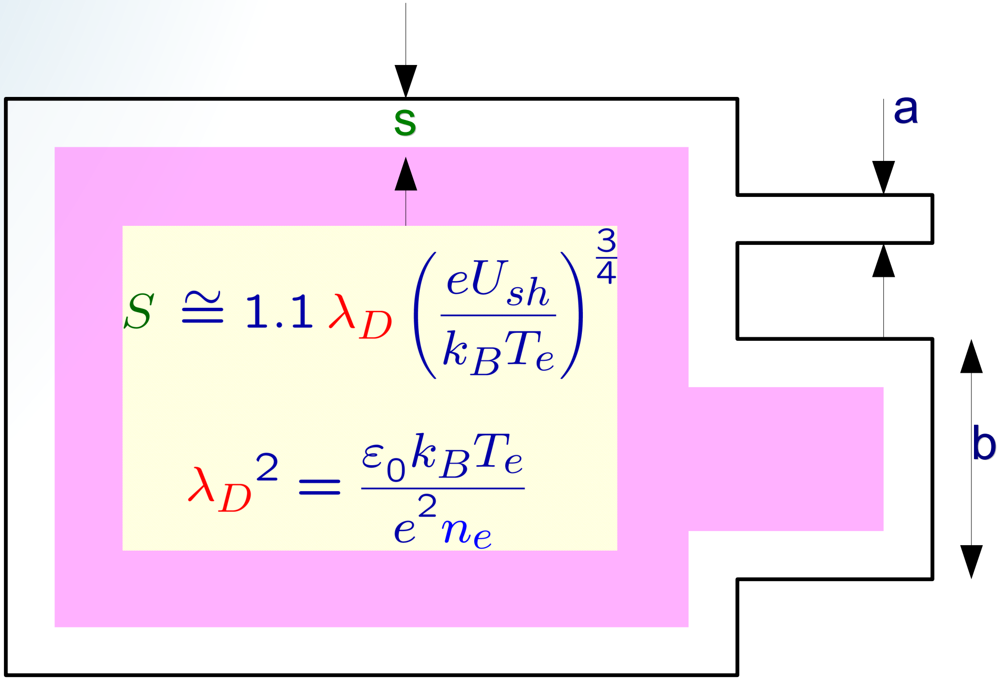
- High and medium density plasmas need
  - an optimized chamber design and
  - highly resistant chamber surface protection as $Y_2O_3$.

- New tools and processes require more control
  - Dual excitation makes control tricky but requires more control.
  - Process window is extended to lower pressure – Ion energy is more important.
  - Shorter Processes require tighter control.
  - Supervision of dedicated plasma parameters

# Plasma density and chamber design rules

- High and medium density plasma can survive in the small tube for endpoint detection due to small Debye length $\lambda_D$.

- The holes and gaps in the chamber / liner must be smaller than 1 mm for safe suppression of arcing in medium density plasmas of $10^{10}\text{cm}^{-3}$.



$$S \cong 1.1\,\lambda_D \left(\frac{eU_{sh}}{k_B T_e}\right)^{\frac{3}{4}}$$

$$\lambda_D{}^2 = \frac{\varepsilon_0 k_B T_e}{e^2 n_e}$$

# Plasma density and chamber design rules

- The higher the plasma density the smaller the Debye length and the plasma sheath, respectively!

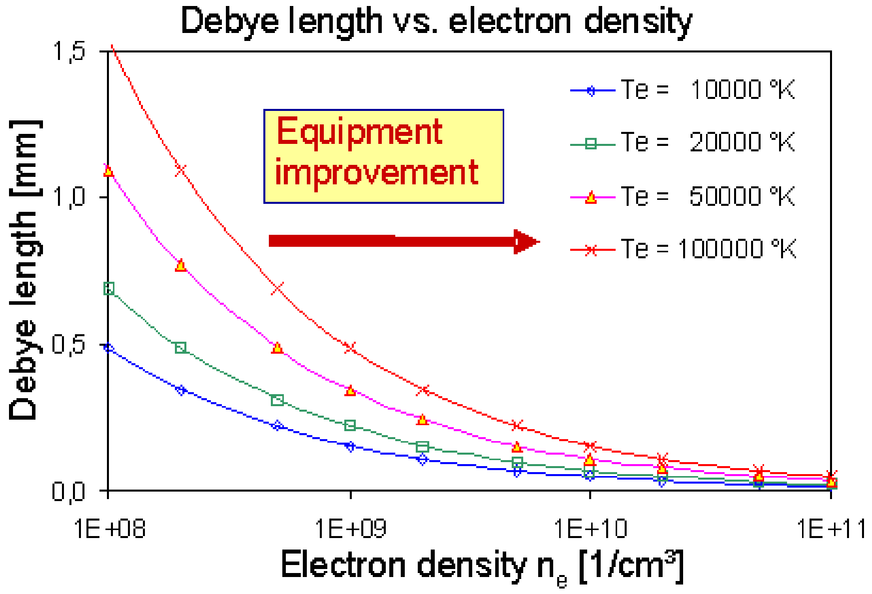
- Example:

  Plasma density → An increase of electron density $n_e$ by one order of magnitude (factor 10) leads to a decrease in the Debye length $\lambda_D$ by 30% ($10^{1/2}$).

- Sheath thickness s decreases by at least a factor of 3.

Wall sheath $s \propto \lambda_D$

- $a < 2s$ → No plasma in the gap.
- $b > 2s$ → Plasma in the gap.



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# Material

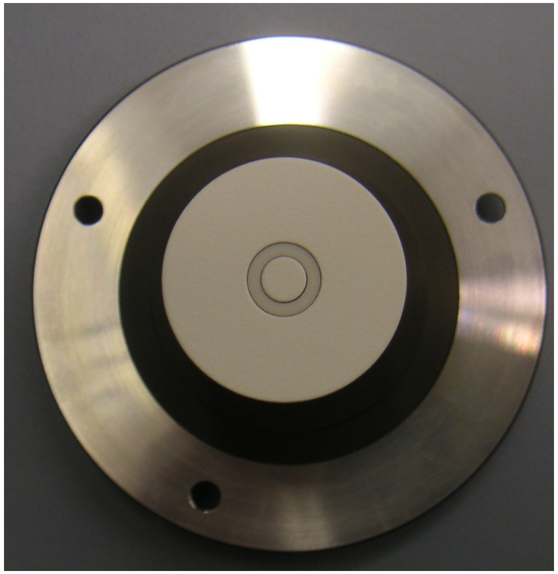
- The high density plasma tools provide high etch rates. Thus these tools tend also to faster erosion of the inner chamber and parasitic plasmas due to the very small plasma sheath thickness.
  - New materials (high resistant $Y_2O_3$ coating of the inner chamber), 10 times more resistant than aluminum anodization are needed.
  - Parasitic plasmas require new design rules as
    - as excellent grounding of chamber parts (e. g. liner),
    - very short distances between match box and RF driven electrodes,
    - minimized holes and slots in parts for plasma confinement.
- The same requirements are valid for new sensors for process characterization. New high resistance materials are necessary for sensor windows:
  - Optical windows: Sapphire for high rate oxide etch processes.
  - RF windows: Ceramics, if required with $Y_2O_3$ coating.

# New Chamber and Sensor material

- Life time increased step by step concerning process requirements:
  - Exchange of PTFE insulator by ceramic one
  - Additional coating with $Y_2O_3$.

Sensor with
PTFE insulator
(strongly eroded)

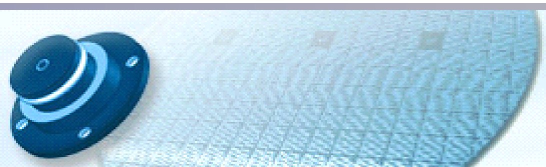
Sensor with
ceramic insulator
and anodization



Sensor with
ceramic insulator
and $Y_2O_3$ coating

# Contents

- High and medium density plasmas need
  - an optimized chamber design and
  - highly resistant chamber surface protection as $Y_2O_3$.
- **New tools and processes require more control**
  - **Design rules and consequences**
  - **RF Voltage measurement**
  - **Process window is extended to lower pressure – Ion energy is more important.**



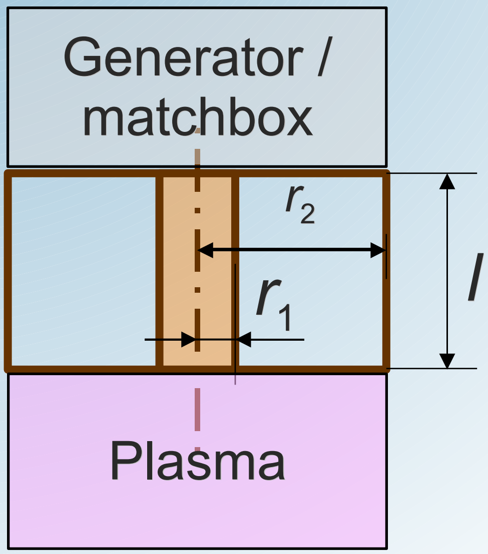
# New tools and processes require more control

- Higher frequencies
  - RF current measurement is at the edge due to inductive sensor head.
  - ***RF voltage measurement makes no sense****.*
- Two frequencies
  - Need new plasma model
  - ***Result in broadband RF current including many harmonics***
  - ➔ VI probe application very tricky.
  - *Control of ion energy distribution and thus new sensor type is needed.*

- ***More knobs – more control***

# Chamber design and inductance

- Inductance of the coaxial coil at feed through:



Example:

$l$ = 150 mm
$2{\cdot}r_1$ = 40 mm
$2{\cdot}r_2$ = 300 mm
$L$ = 60 nH

$f$ = 60 MHz

$X_L = \omega L = 22.6\ \Omega$

$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

$$\nabla \times \mathbf{H} = \mathbf{j}$$

$$\mathrm{I} = \int_A \mathbf{j}\, dA = \int_A \nabla \times \mathbf{H}\, dA = \int_L \mathbf{H}\, dl$$

$$\rightarrow \quad \mathbf{H}(r) = \frac{\mathrm{I}}{2\pi r} \quad \text{for} \quad r_1 < r < r_2$$

$$\mathbf{B}(r) = \mu_0 \mathbf{H} = \frac{\mu_0 \mathrm{I}}{2\pi r}$$

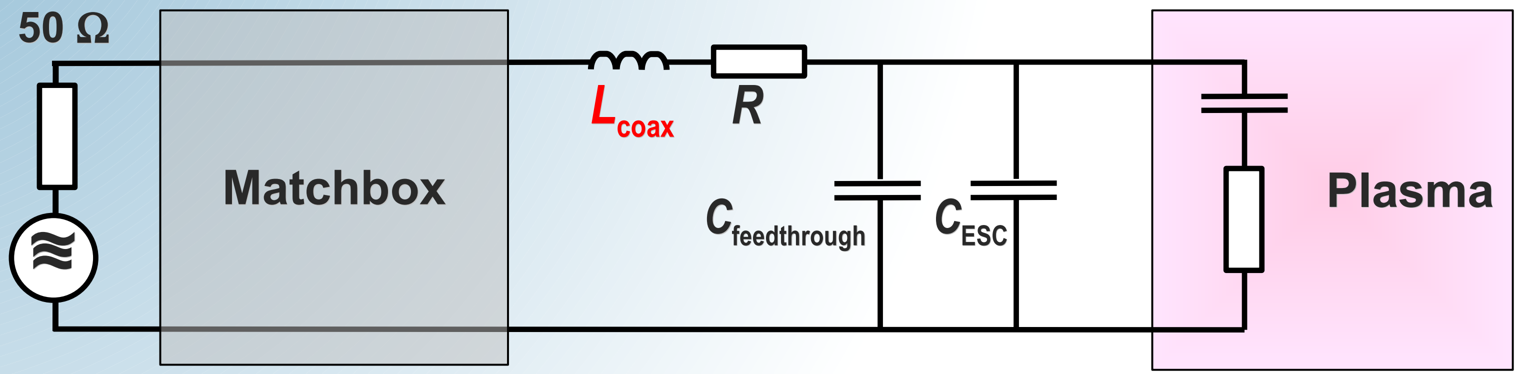
$$\mathrm{U} = -\int_L \mathbf{E}\, dl = -\int_A \nabla \times \mathbf{E}\, dA = +\int_A \frac{d\mathbf{B}}{dt}\, dA$$

$$\mathrm{U} = \frac{\mu_0\, l}{2\pi} \frac{d\mathrm{I}}{dt} \int \frac{dr}{r} = \frac{\mu_0 l}{2\pi} \frac{d\mathrm{I}}{dt} \ln \frac{r_2}{r_1}$$

$$\boxed{L = \frac{\mu_0\, l}{2\pi} \ln \frac{r_2}{r_1} = \frac{l}{10\text{cm}}\, 20\text{nH} \ln \frac{r_2}{r_1}}$$

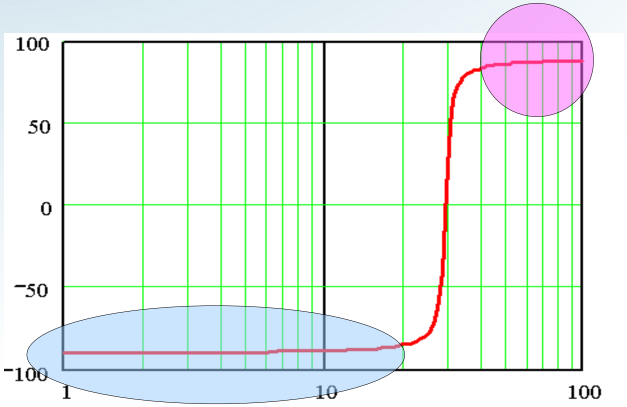
# Inductance influences RF Voltage measurement

Measured at Applied Materials® HART TS: $f_0$ = 24 MHz.



$R_{Loss} \ll \omega L$; $C_{tot} = C_{feedthrough} + C_{ESC} = 350$ pF; $L_{coax}$ = 60 nH ➔ $f_0 = \omega_0/2\pi = 30$ MHz

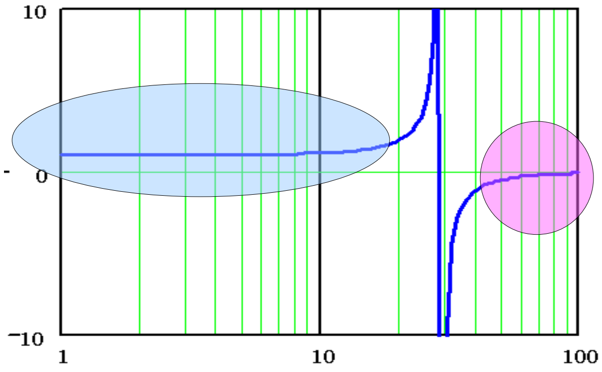
$$U_{plasma}(\omega) = \frac{U_{matchbox}}{1 - \omega^2 C_{tot} L_{coax}}$$



Phase angle vs. frequency

f < 20 MHz: Matchbox load is capacitive.

f > 30 MHz: Matchbox load is inductive.



Voltage ratio $U_{plasma}/U_{match}$ vs. frequency

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# Broadband RF current including many harmonics

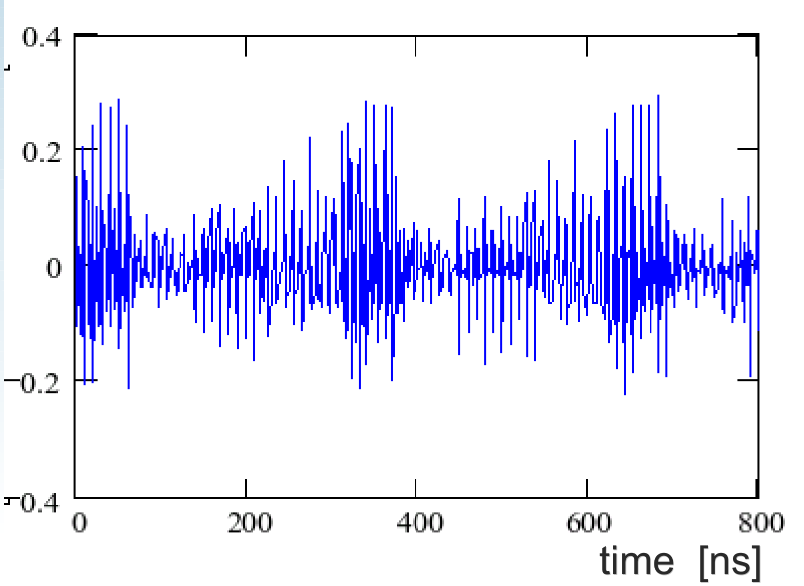
The generated mixed frequencies of the discharge current influence the process parameters sustain ably. So a new plasma model is necessary to describe the process closer to the reality.

RF current – new 300 mm tool

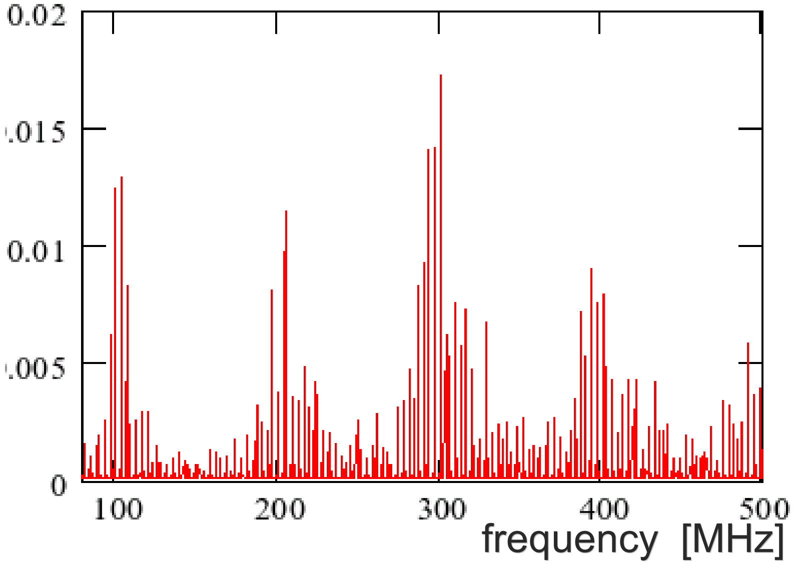
Two frequency CCP,  dielectric etch,
F / O chemistry, p ≈ 50 mTorr

$f_{top}$ = 100 MHz   $P_{top}$ ≈ 1 kW
$f_{bias}$ = 3.2 MHz   $P_{bias}$ ≈ 3 kW

RF sensor current [mA]



RF Harmonics [mA]



# More knobs require more control

High excitation frequency

High plasma density
⇨ small Debye length and plasma sheath
⇨ high frequency ➔ small capacitive resistance ➔ low ion energy
⇨ short RF cables become inductances
⇨ enables low pressure processing

Additional second 'low' excitation frequency

Necessary to get efficient ion energy
⇨ extend the plasma sheath
⇨ increase the ion energy
⇨ ion energy becomes controllable

**Results in :**

Harmonics of excitation frequency up to some 100 MHz
⇨ makes control tricky

Extent the (key) parameter set
⇨ requires more control

Generates mixed frequencies
⇨ Broad band RF discharge

Power of high and 'low' frequency determine the electron energy distribution function and so
⇨ the plasma density
⇨ the plasma chemistry
⇨ the dominant etch mechanis

# Summary

- The major scope is the new tool generation, in particular new materials and chamber design (plasma physics).
- The high density plasma tools provide high etch rates. New high resistance materials are necessary for chamber parts and sensors ($Y_2O_3$ coating).
- New tool generation with dual excitation makes control tricky and requires more process understanding and control.
- Simple RF voltage measurement makes no sense for high frequency tools.
- The load of the matchbox is inductive for capacitively coupled plasma and frequencies above 30 MHz.
- The peak voltage of the bias power is the most important key parameter, it scales the ion energy.
- New plasma models are necessary for a better process understanding.