E-H Mode Detection and Chamber Comparison in Lam Versus 2300

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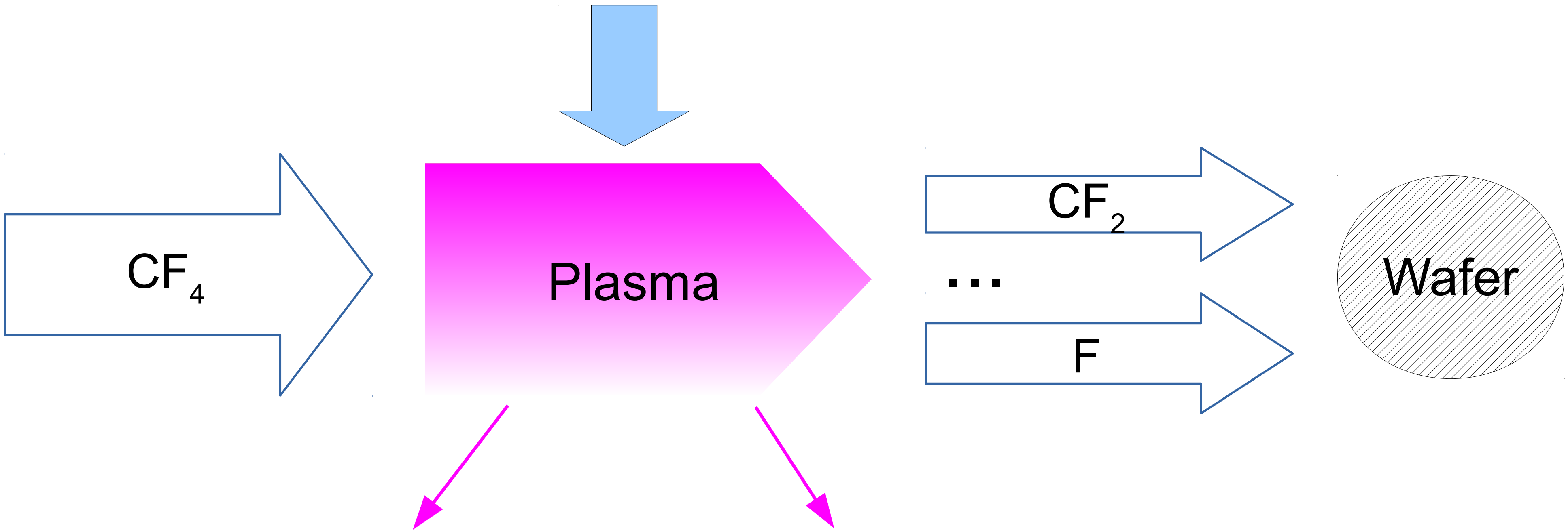
Content

- Plasma processing and heating of electrons
- Nature and detection E-H mode transition
- New plasma sheath model provides new, sensitive parameters
- Conclusions

How Does Plasma Processing Work ?

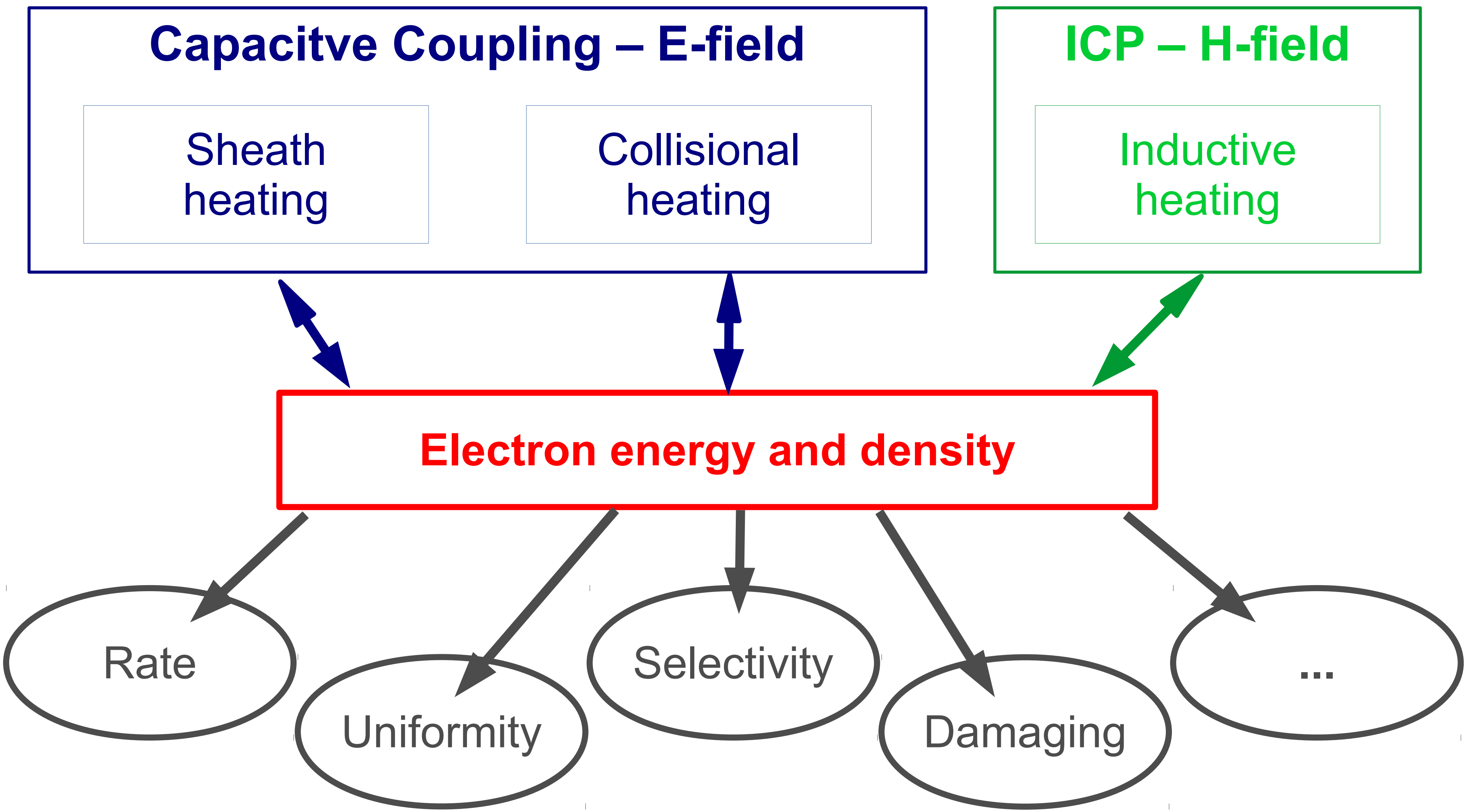
Hot electrons with
20 000 … 50 000 K
control the plasma
chemistry



- Etch rate
- Profile (sidewall angle)
- Uniformity

- Selectivity
- Damage

Heating of Electrons is the Key of Plasma Chemistry



How Does it Work in an ICP Etcher ?

Low ICP power → E-Mode (CCP)

Sheath heating of electrons

→ Low electron density & high temperature
→ More physical etching
→ Deep fragmentation of process gas

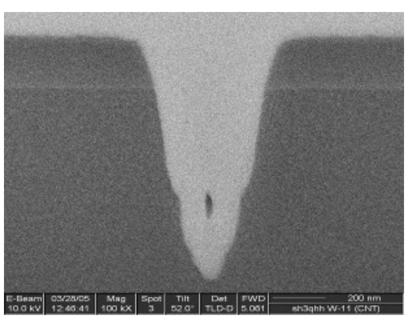
→ Many F radicals destroy sidewall passivation for F chemistry

High TCP power → H-Mode (ICP)

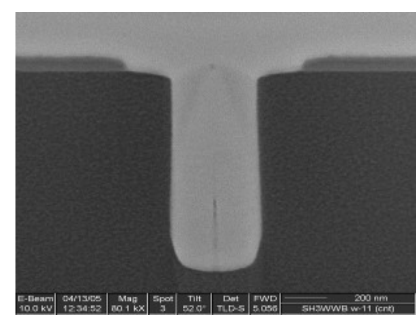
Inductive heating of electrons

→ High electron density & low temperature
→ More chemical etching
→ but only medium fragmentation of process gas

→ Almost no F radicals, good sidewall passivation



Example:
Si trench etching
using HBr / SF_6 / O_2



F. Session et al., Process Development and Control for Silicon Trench Etch, AEC/APC Europe, Aix-en-Provence, 2006.

Questions on the H-Mode

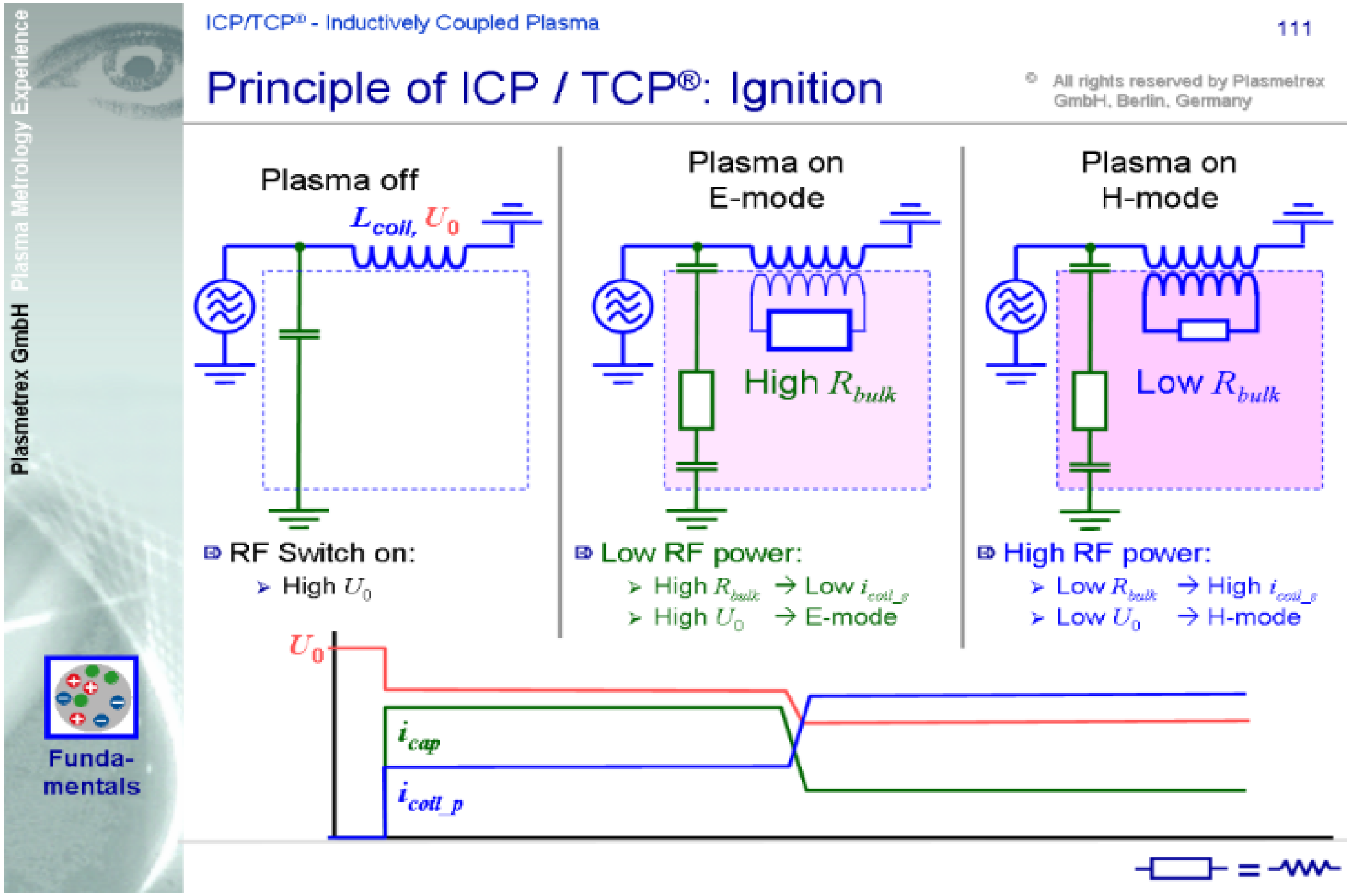
- How to get in the desired H-mode ?
- How to detect the desired H-mode ?
- What can the plasma drive back in the E-Mode ?

Ignition of an ICP/TCP® Plasma

- During ignition and at lower power the plasma in a TCP chamber is in the E-mode. With increasing RF power the electron density increases, the inductive heating becomes more efficient.

- Thus, the transition changes the electron heating, the resulting Electron Energy Distribution Function (EEDF) so the overall chemistry in the process chamber.

- Heating mode of electrons in sheath will change dramatically.



Ref: Plasmetrex Plasma School for Semiconductor Manufacturing, Module I: Plasma Physics Fundamentals, (c) Plasmetrex GmbH.

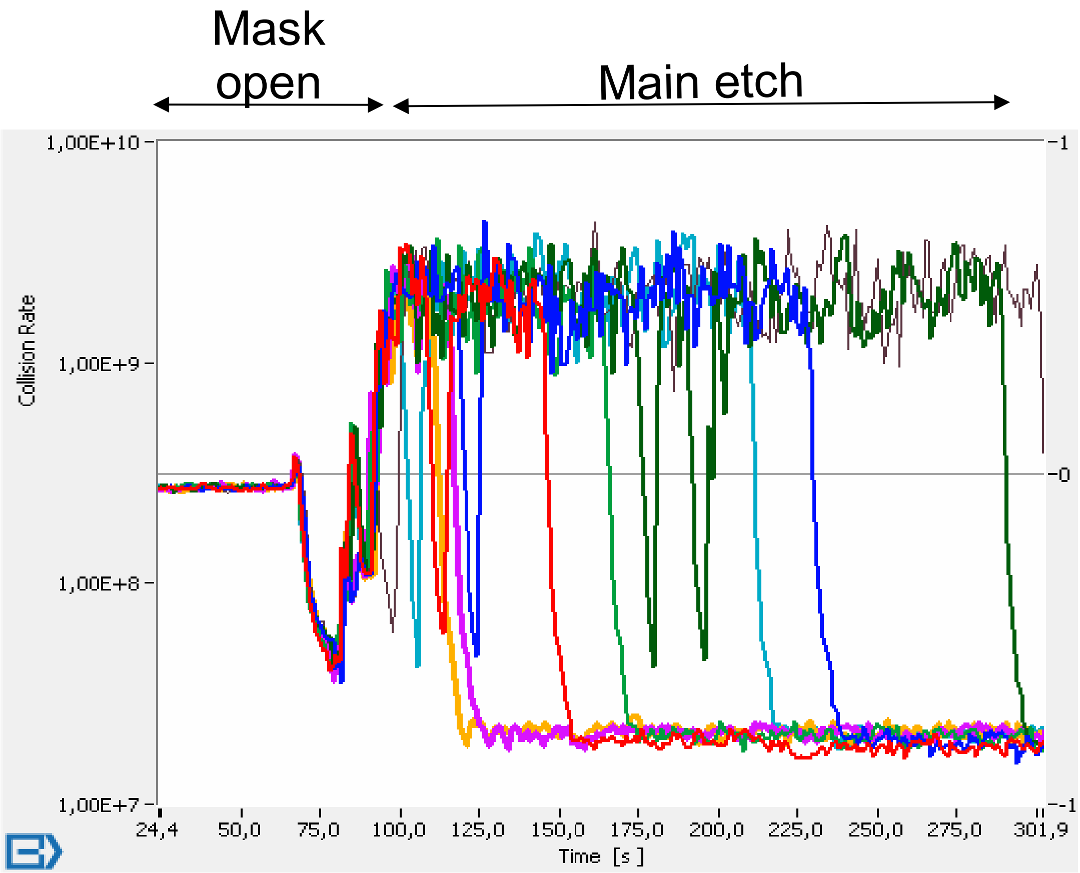
How to Detect the Desired H-mode ?

- Measurement of density and/or temperature of electrons
  - Langmuire probe → cannot be done in process plasmas
- Optical emission
  - needs light from hot zone near the coil
  - message not unique, needs full spectrum and right process-related model
    $n_e \uparrow \; T_e \downarrow$
- Effective electron collision rate using SEERS

What Can the Plasma Drive Back in the E-Mode ?

- Real RF power in the chamber, can be much less than generator power ! Increasing power losses in older tools can drive the plasma in the E-Mode.
- Interaction with other power coupling as RF biasing.
- Density of neutrals → Pressure and (unknown) gas temperature
- Chemistry and chamber wall state (secondary electron emission)
- Negative Ions reduce the electron density:
  - → E-Mode also over 1 kW in 200 mm chamber
  - → Sometimes E-H-Mode oscillations (frequency in kHz-range), not detectable by tool parameters

Example: Switch from E to H Mode in SF_6 / HBr / O_2



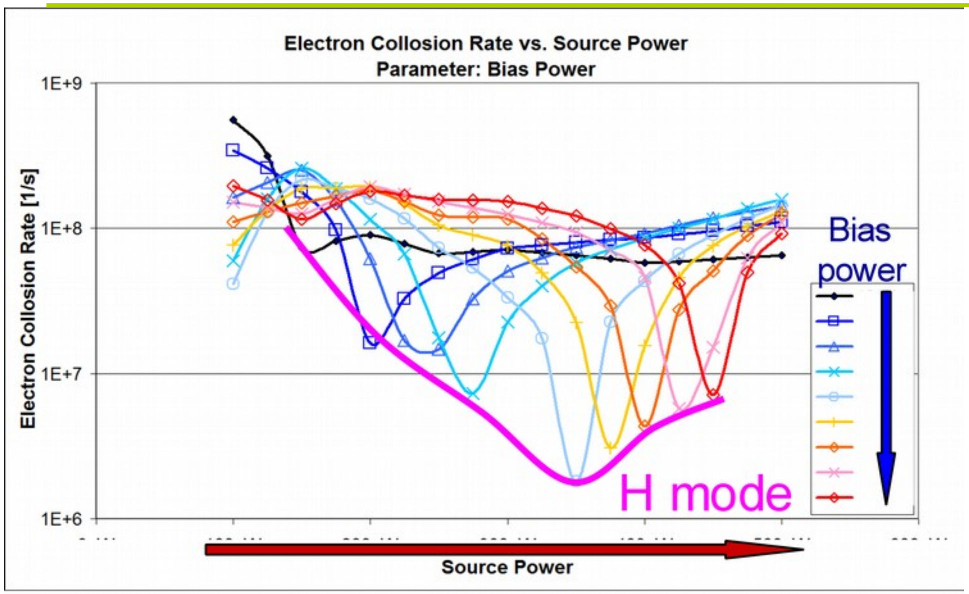
Plasma etcher, ICP/CCP, Coil at ceramic dome

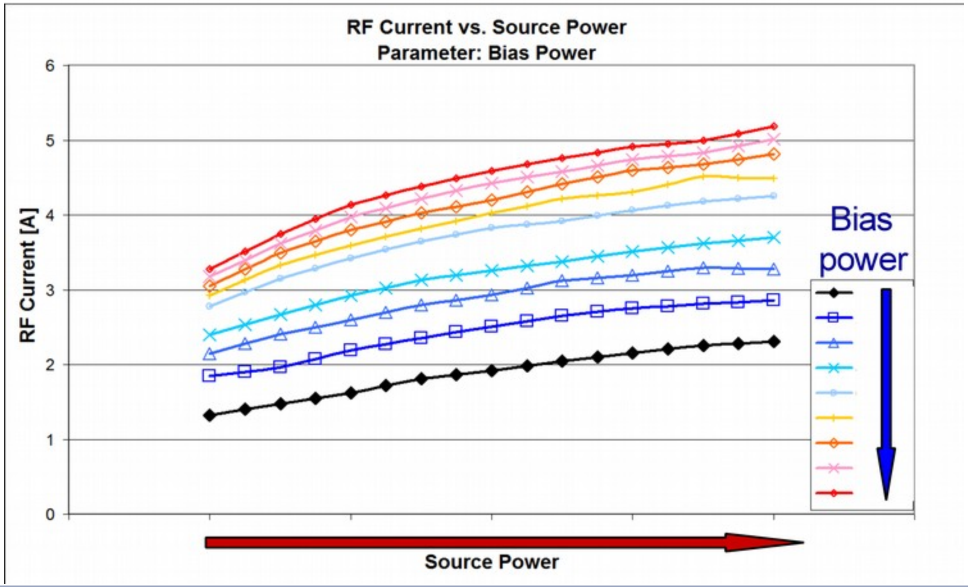
- **Negative Ions**
- Often 15 % drop in etch rate, no endpoint !
- Critical process issue, **not detectable by tool**.
- Instabilities are caused by switching H-mode to unstable E-mode – shown by electron collision rate.
- Instability depends on:
  - Chamber state.
  - Chamber temperature
  - Pre-process

E. Chasanoglou et al., TI Germany, E-H-Mode transition and its detection in SF_6 plasma during Si trench etch, APCM 2013, Dresden, Germany, 2013.

By courtesy of Texas Instruments

Example: Mask Etching in Cl_2 / O_2





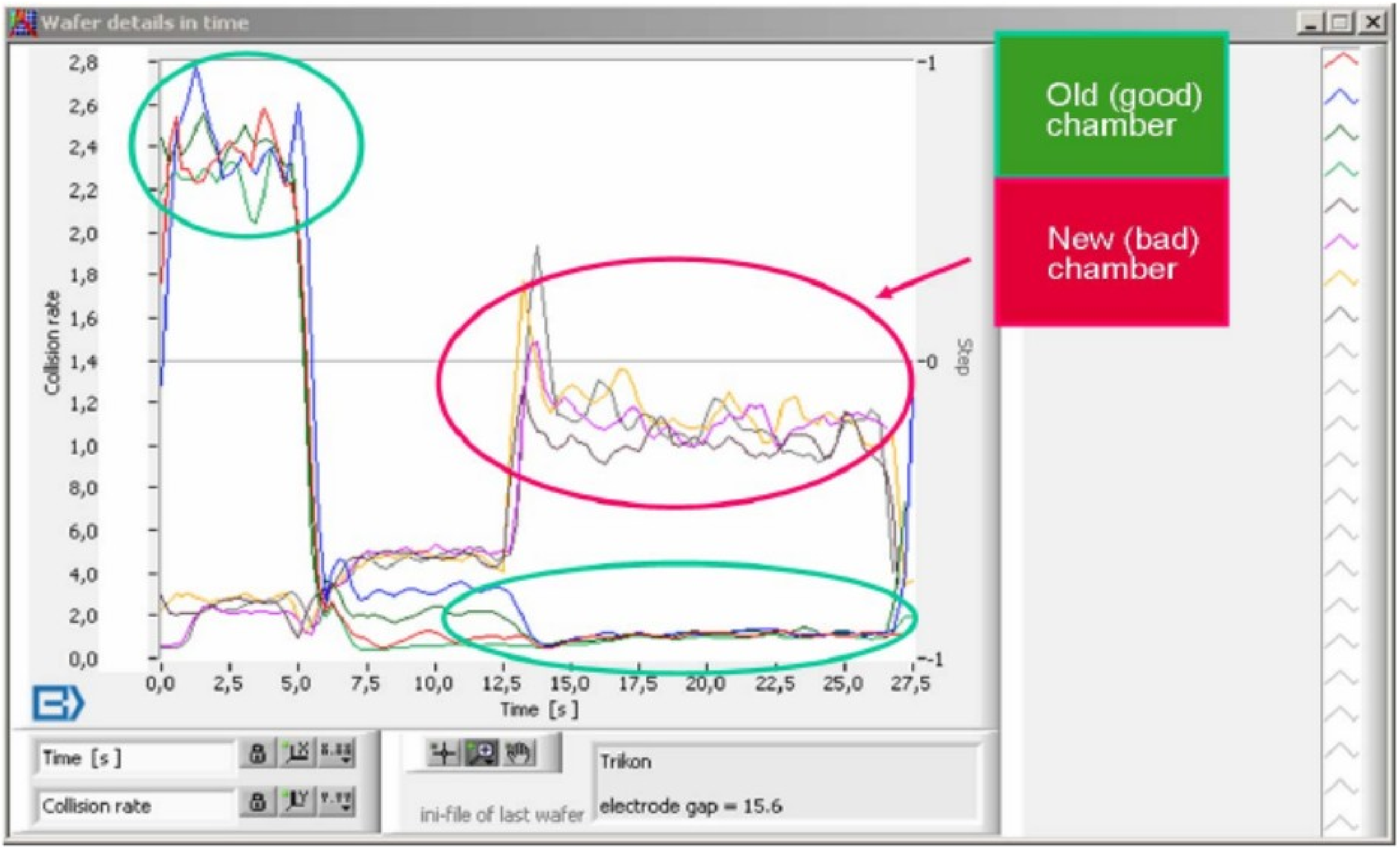
- **Interplay of Source and Bias Power**
- The process window with H-mode has only a small minimum
  → potentially unstable
  → supervision required.
- The RF current (and other tool parameters) do not indicate the occurrence of H mode.

By courtesy of ADVANCED MASK TECHNOLOGY CENTER a Joint Venture of GLOBALFOUNDRIES and Toppan Photomasks

A. Lajn, Process Stability in Photo Mask Manufacturing, APCM Conference 2014, 07.04.2014 - 09.04.2014, Rome, Italy

Example: Two Sputter Etch Chambers – one Recipe – Two Processes !

- **Deviation in source power**

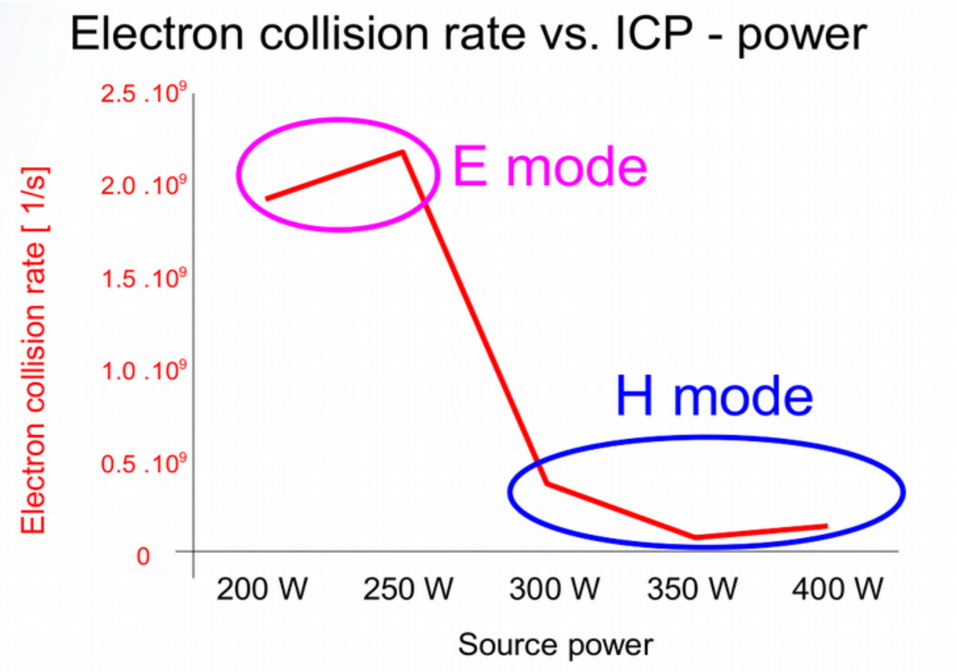


- Electron collision rate shows different plasma modes – representing also different process results !

E-H Mode Jump

- In case of high ICP-power losses the plasma remains in the E-mode.

- RF power losses depended on:
  - Aging of RF parts
    - Contacts
    - Eddy currents
    - Ceramic
  - Second source parts
  - Chamber improvement
  - Matchbox (new / old)
- **Deviation in source power**



By courtesy of Infineon

N. Urbansky et al., ISMI Symposium, Austin, TX, USA, 2011.

E-H Mode Jump and Etch Rate Check

- Process control by etch rate of test wafers
- Sputter etch process:
  Etch rate depends on ion energy and ion current:

$$E_H \cdot j^+_H = E_E \cdot j^+_E$$

Bias power ~ Sheath power >> bulk power (for 13.56 MHz)
Same recipe → same bias power in H-mode and in E-mode
Bias power $P_{bias} = U_{sheath}\, e\, j^+$

- E_H ion energy for H – mode
- E_E ion energy for E – mode
- j^+_H ion current for H – mode
- j^+_E ion current for E – mode

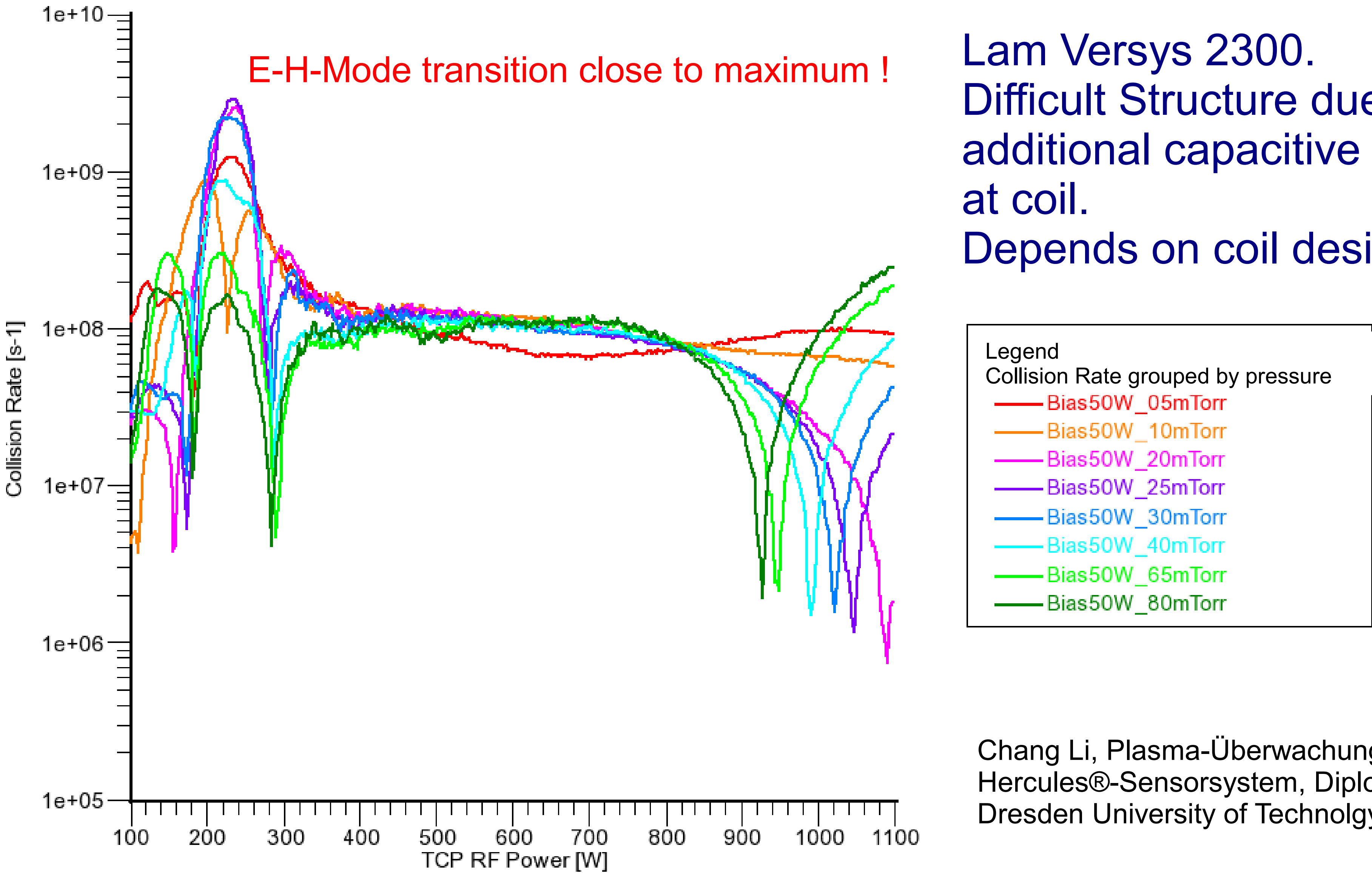
- E – mode: small ion density, but high ion energy
  → Crystal damages! → Yield losses!
- H – mode: high ion density but small ion energy.

By courtesy of Infineon

N. Urbansky et al., ISMI Symposium, Austin, TX, USA, 2011.

- Etch rate can be similar, chambers seems to be in spec!

Example: Electron Collision Rate vs. TCP Power:



Lam Versys 2300.
Difficult Structure due to additional capacitive coupling at coil.
Depends on coil design !

Chang Li, Plasma-Überwachung mit dem Hercules®-Sensorsystem, Diploma, Dresden University of Technolgy, 2016.

E-H Mode Transition – Electron Collision Rate

- The effective electron collision rate is based on a power dissipation approach and includes therefore collisional (ohmic) and collisionless (sheath) heating.
  - See also results at TEL VIGUS K. H. Baek et al., Journal of Vacuum Science & Technology A 35, 021304 (2017).

- Becomes difficult in case of two sheathes, e.g., without Faraday shielding at coil as in Lam Versys 2300.

Electron Heating – Key of Every Process Plasma

- A better separation of plasma physical effect should provide also a more sensitive detection of the H-Mode.

- Approach: Extraction of the electron heating in the sheath by a plasma physical model.

- Heating or cooling (net gain or loss) of all electrons during one RF cycle in plasma body, close to boundary sheath, given by the energy flux density, defined as:

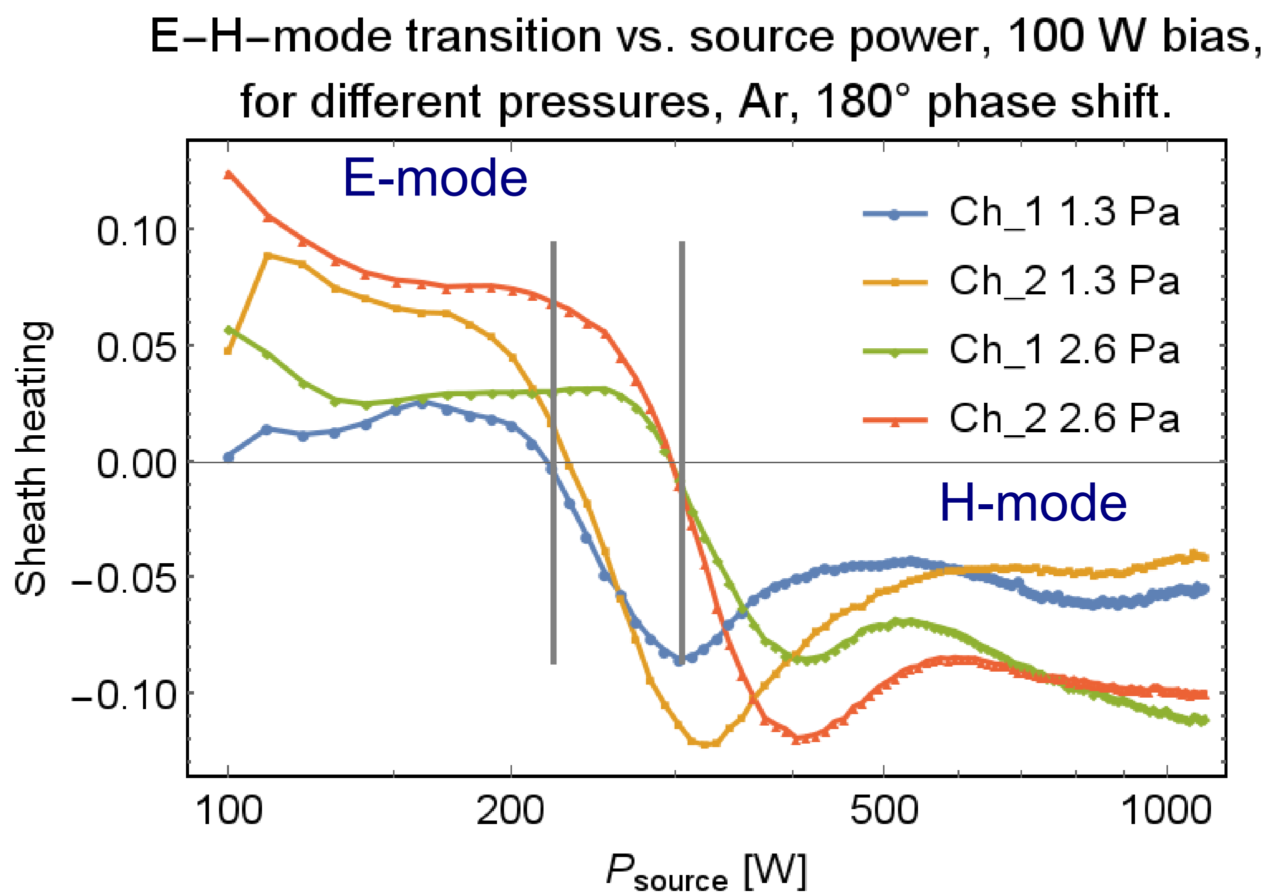
$$\bar{q}(x) = \int_T n(x)\, u(x,t)\, \frac{m}{2}\, u(x,t)^2\, dt$$

provides the so-called **sheath heating**.

K. H. Baek et al., Journal of Vacuum Science & Technology A 35, 021304 (2017)

Sheath Heating Shows E-H-Mode Transition Easily

- In the (capacitive) E-mode, a positive electron heating is mandatory – as shown here in the sheath heating.
- The E-H-mode is clearly identified in the range around 300 W.
- It shows an expected and well pronounced dependency on the pressure.



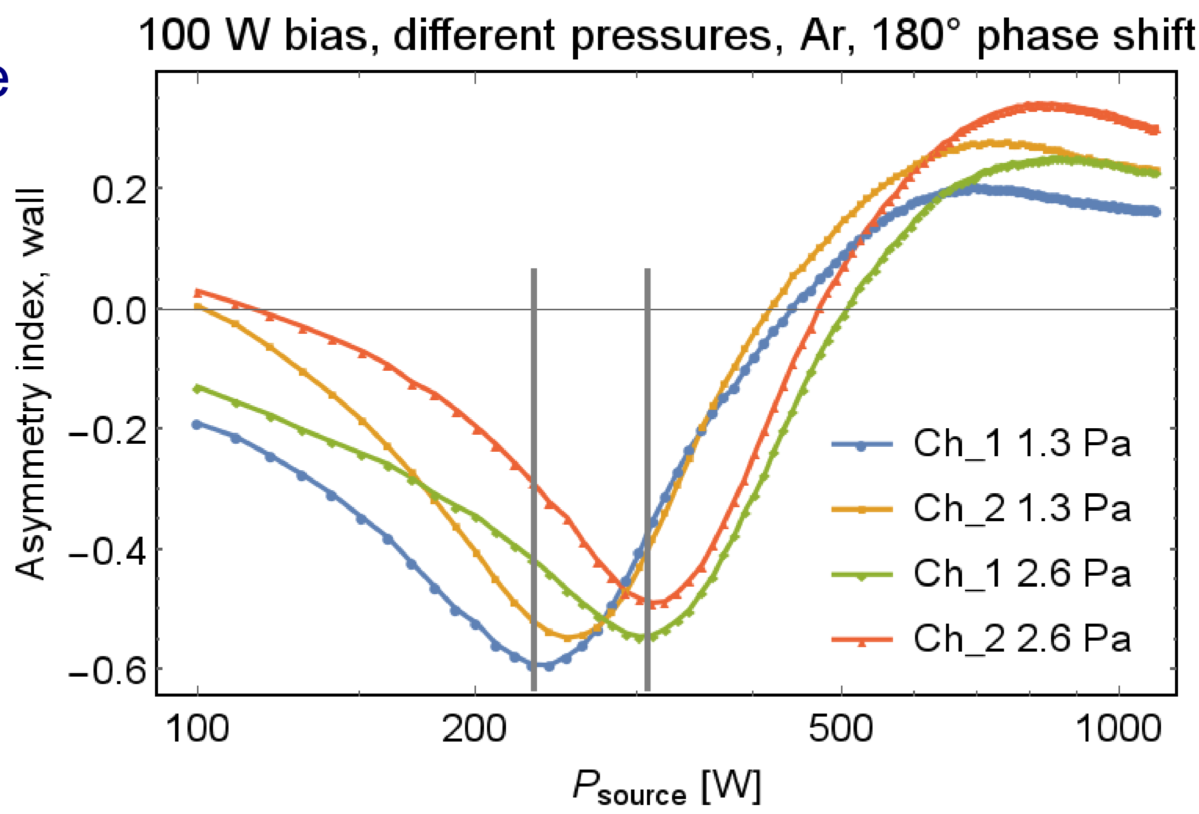
Negative Sheath Heating Indicates H-Mode !

Asymmetry Identifies Also E-H Mode Transition

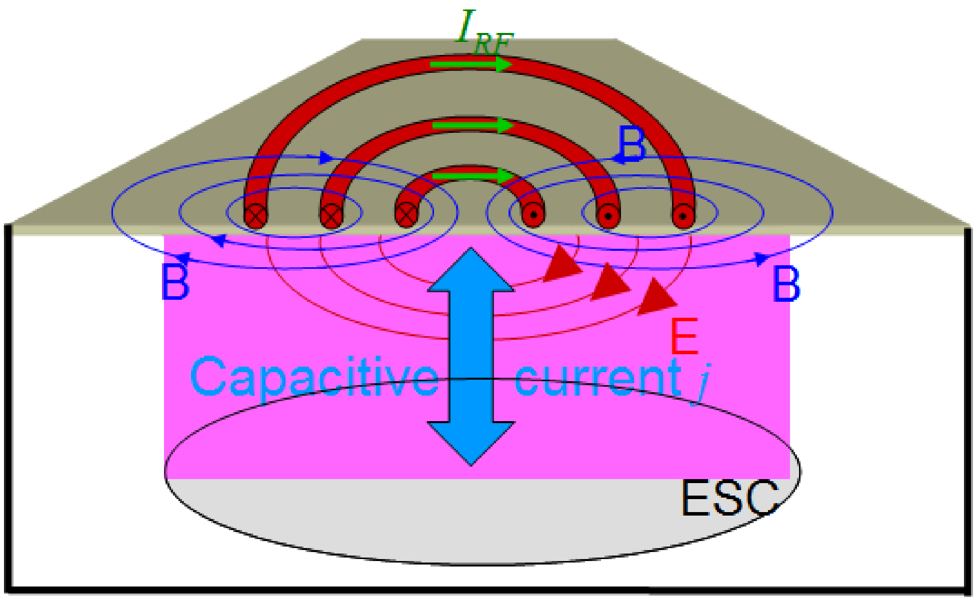
- The E-H-mode transition leads to a minimum of the plasma asymmetry.

- 180° phase shift of the generators leads to in-phase voltages at wafer and coil.
  → Large effective electrode
  → Inverse symmetry
  → low ion energy at wafer and coil

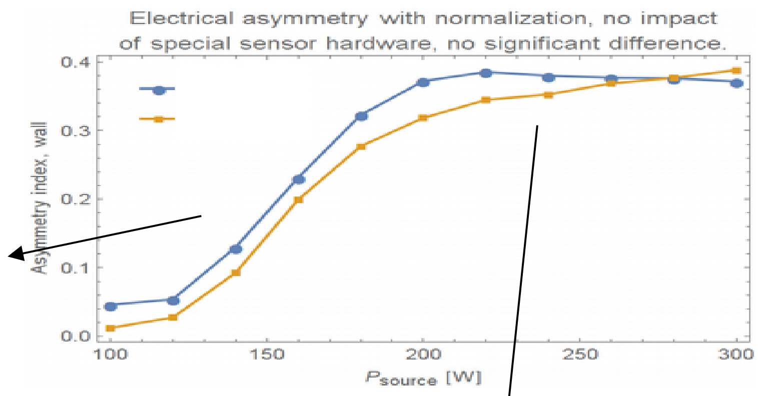
- In the H-mode at high source power, the substrate (bias) power plays no role
  → classical asymmetry > 0



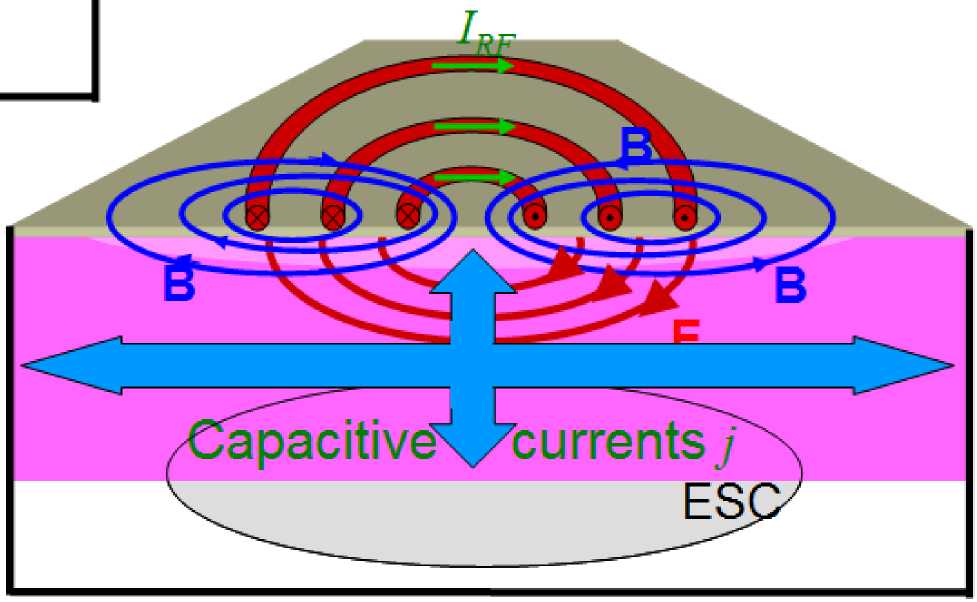
E-Mode→Symmetrical Plasma | H-Mode→Asymmetrical plasma



E-Mode
Symmetrical plasma

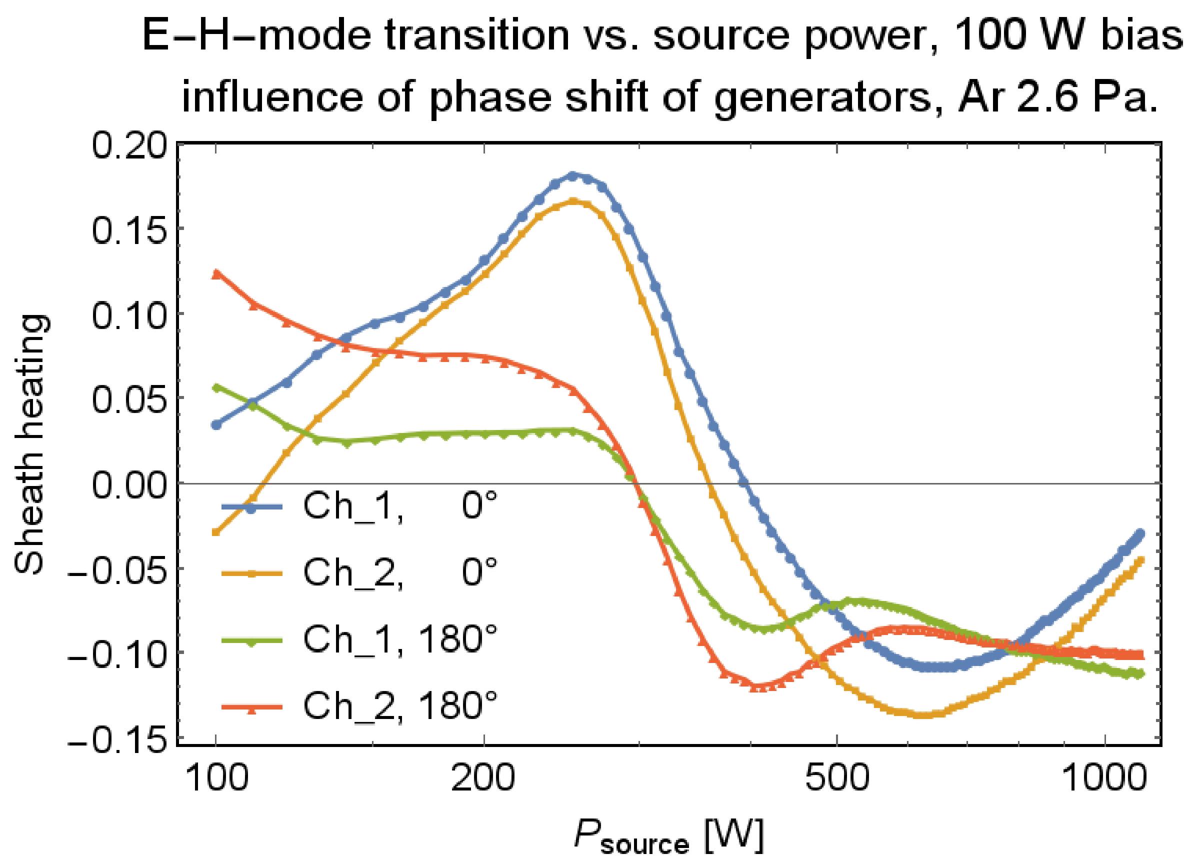


H-Mode
Asymmetrical plasma



Electron Heating Efficiency vs. Phase Shift

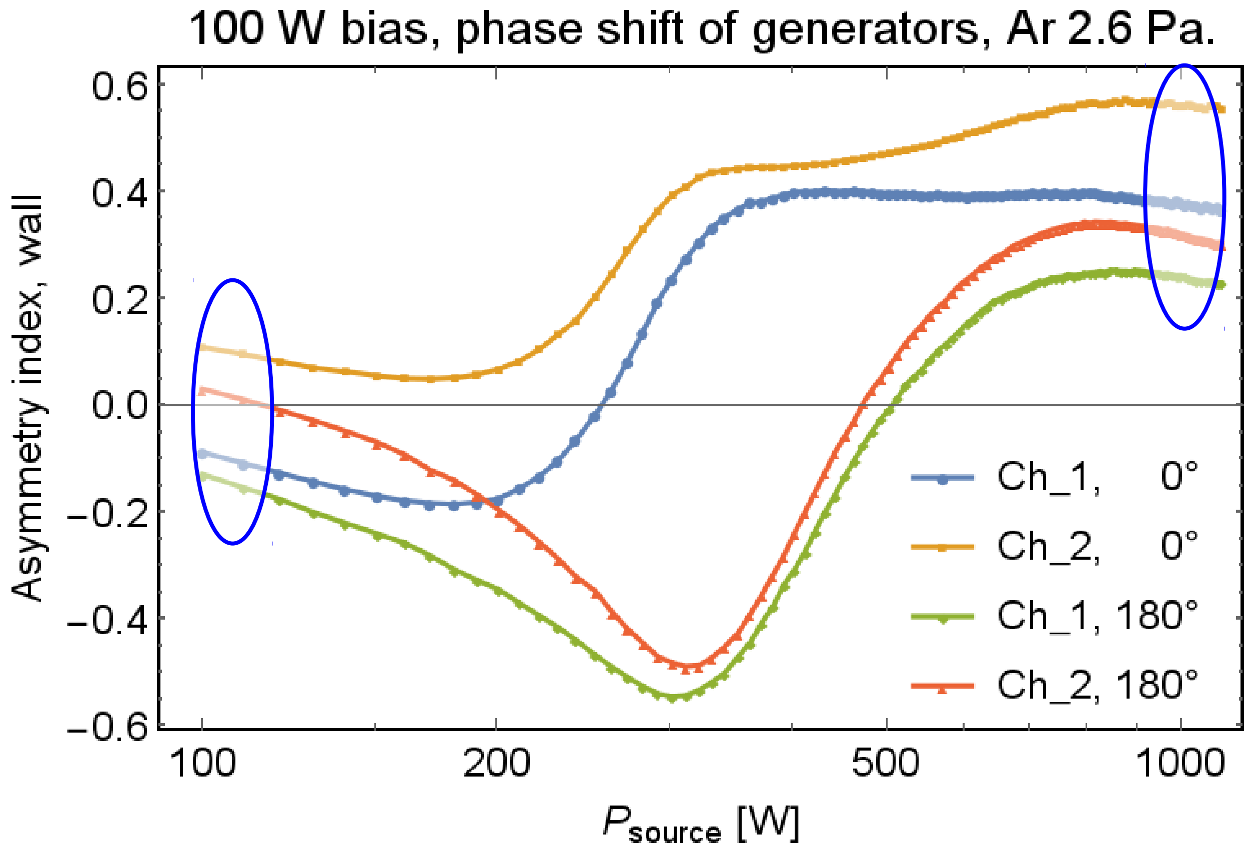
- For 100 W bias power and at very low source power the RF displacement current from the coil can be neglected.
- Thus there is no significant difference between 0° and 180° phase shift.
- At typical process powers, changes in the RF configuration can be easily detected.



Influence of Phase Shift

- A phase shift between the RF generators determines the effective geometry of the plasma.

  Thus, it shows a larger impact than the pressure.



- When one power dominates, there is only a weak influence of the phase shift.

Summary

- E-H Mode transitions in ICP chambers are not detectable by tool parameters.
- Electronegative gases as Cl_2 or SF_6 reduce the electron density and switch so from H mode to E mode.
  → Instabilities in production chambers !
- E-H Mode transitions cause critical plasma instabilities and process risk.
  → Damage by high energetic ions
  → Etch rate decline
  ...
- New, model-based parameters with already built-in plasma-sheath physics explain readily undesired changes in an ICP plasma.

Thanks for attention,

Questions ?