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

Ch. Li¹, F. Hoffmann², M. Klick³, J. Bartha¹, L. Eichhorn³
¹ Dresden University of Technology
² Infineon Technologies Dresden
³ Plasmetrex GmbH
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

CF₄ → Plasma → CF₂, F → Wafer
Heating of Electrons is the Key of Plasma Chemistry

**Capacitive Coupling – E-field**
- Sheath heating
- Collisional heating

**ICP – H-field**
- Inductive heating

**Electron energy and density**
- Rate
- Uniformity
- Selectivity
- Damaging
- ...

---

17th APCM
Ireland, Dublin 2017

plasmex
plasma metrology experience

technische universität
Dresden

infineon
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$_2$

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 $\rightarrow$ Pressure and (unknown) gas temperature

- Chemistry and chamber wall state (secondary electron emission)

- Negative ions reduce the electron density:
  - $\rightarrow$ E-Mode also over 1 kW in 200 mm chamber
  - $\rightarrow$ 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$_2$

- **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

---

**Plasma etcher, ICP/CCP, Coil at ceramic dome**

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.
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

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

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:

\[ E_H \cdot j^+_H = E_E \cdot j^+_E \]

- \( E_H \) 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.

➢ Etch rate can be similar, chambers seems to be in spec!
Example: Electron Collision Rate vs. TCP Power:

E-H-Mode transition close to maximum!

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.

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.

E–H–mode transition vs. source power, 100 W bias, for different pressures, Ar, 180° phase shift.

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

Capacitive currents $j$

Electrical asymmetry with normalization, no impact of special sensor hardware, no significant difference.
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\textsubscript{2} or SF\textsubscript{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 ?