Hercules application note

Inductively coupled plasma with bias power

Interaction of two couplings in case of the same frequency – role of phase shift

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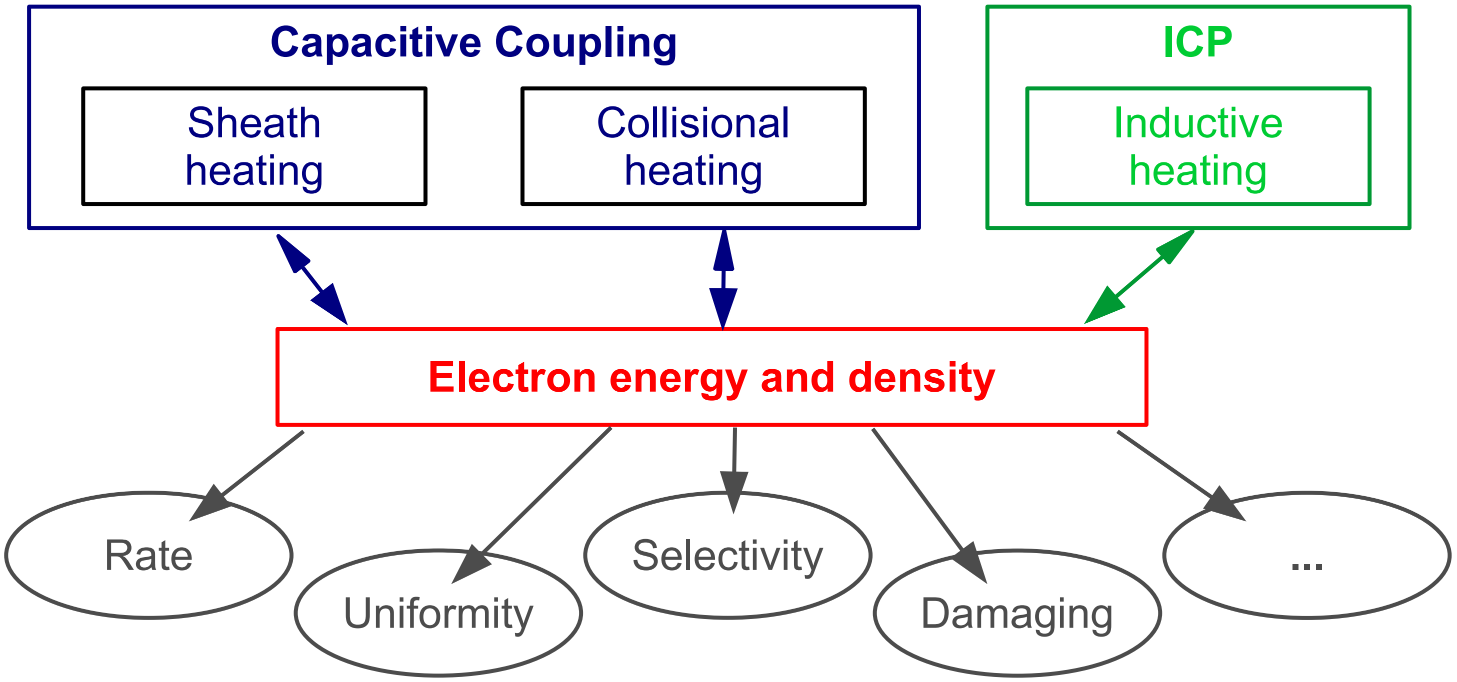
Summary

- ICP/CCP chambers with a single frequency are sensitive to phase angle adjustment between source and bias power generator. Potential issues:
  - Influences chemistry by electron heating (ER,CD) and ion energy (ER, selectivity)
  - Chamber mismatching in CD, ER, and selectivity
  - RF bias power matching instability
  - The capacitve coupling of the coil is weaker by design as found in modern Lam chambers (DfM and later).
- SEERS measurements are also affected, the SEERS model does not know about the two RF currents, it just measures the total current. Using real examples, this application note explains how to understand the results.
- Parameter range: Low pressure, below 20 Pa (150 mTorr)
- Chambers concerned
  - All Lam TCP, Versus, and Kiyo chambers without frequency shift, in particular TCP SE & PTX 9X00
  - Trikon/Aviza/SPTS HSE, CSE, Omega_201, DSi, DSi-v, Rapier
  - Applied Materials DPS II (300 mm)
- Solution: Deeper understanding and suitable parameters

Content

- Motivation
  - Electron heating – a fundamental process issue
  - Ion energy and symmetry
- Short summary and guide for chamber matching
- Asymmetry and electron heating vs. area ratio
- Real tools – Influence of phase shift
  - How plasma parameter and process reflect the 2^{nd} capacitive coupling
  - Effect of phase relation on process
  - Change of source and bias power

Heating of electrons is the key factor for plasma chemistry



Heating of electrons is the key factor for plasma chemistry

- The heating of electron can only be explained by kinetic model including the harmonics of the RF current. At typical pressures as for ICP processes like DRIE a suitable plasma parameter is

$$\text{SheathHeating} = \frac{\text{net energy gain of electrons per RF cycle}}{\text{maximum energy of electron}}$$

- In the low pressure range, well below 10 Pa (75 mTorr), there are some interesting relations to other plasma parameters

$$\text{SheathHeating} \approx \frac{32}{27} \frac{\nu_{eff}}{\omega_{rf}}$$

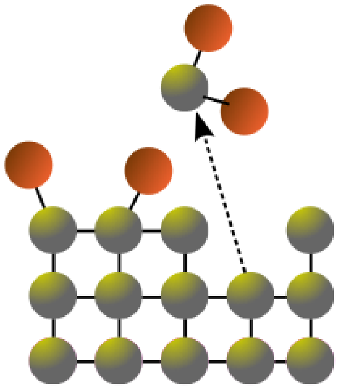
The definition of the effective collision ν rate is based on the dissipated power for heating of electrons, more details can be found in J. Vac. Sci. Techn. **A 35**, 021304 (2017); doi: 10.1116/1.4968206.

Ions:

Surface reaction in plasma processes

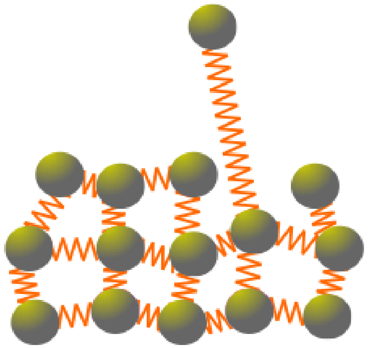
- The etch surface reactions are chemically or/and physically driven. There are three basic mechanisms, normally appearing as combination of at least two of them.

Chemistry



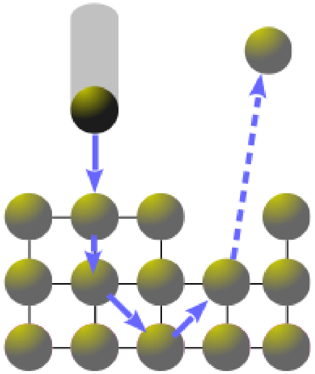
Rate depends on also on reactant flux

Temperature



Rate depends on temperature, Arrhenius Law

Collisions



Rate impact energy depends roughly as $(E_{ion} - 10\ E_{bond})^{1/2}$

Keren J. Kanarik, Samantha Tan, and Richard A. Gottscho, "Atomic Layer Etching: Rethinking the Art of Etch", J. Phys. Chem. Lett. 2018, 9, 4814−4821

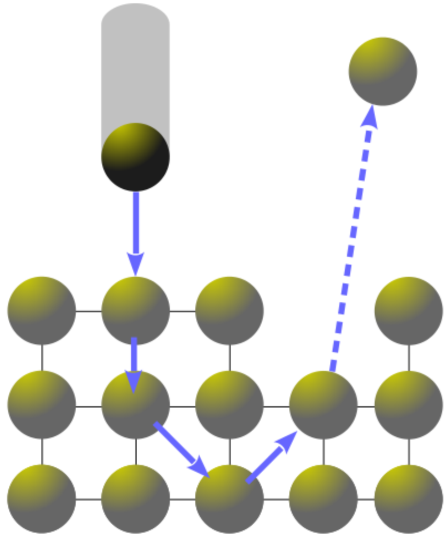
Ions:

Particle removal by collisions

- A high-energy object hitting the surface can eject an atom if, through the transfer of momentum, the atom accumulates enough kinetic energy in the upward direction to overcome E_{bond}.

- An Ion or a fast neutral can produces a "hot spot" of ~3000 K.
  The ejection of atoms is known as physical sputtering. For Si, the observed sputtering threshold ion energy is ~50 eV, or roughly 10 times its E_0 of 4.7 eV.

- With chemically reduced E_{des}, the mechanism is referred to as reactive sputtering, and the threshold ion energy is lowered to 16 eV for chlorinated Si. The removal rate depends on the square root of the ion energy above a threshold. This mechanism is anisotropic, as only atoms near the impact site are affected.



Keren J. Kanarik, Samantha Tan, and Richard A. Gottscho, "Atomic Layer Etching: Rethinking the Art of Etch", J. Phys. Chem. Lett. 2018, 9, 4814−4821

Ions provide activation energy and remove byproducts

- The asymmetry of the plasma can be defined by the sheath voltages at the chamber wall (W) and the driven electrode (E).

$$A = \frac{U_E - U_W}{\hat{U}_E + \hat{U}_W} = \frac{-U_{bias}}{\hat{U} - \hat{U}_{bulk}} = \frac{\beta - 1}{\beta + 1}$$

- The sheath voltage of the boundary sheath in front of the wafer corresponds to the ion energy in case of no collisions

$$U_E \approx \hat{U}\,\frac{1+A}{2}$$

and depends on the tool parameter peak voltage and the plasma asymmetry.

- On the other hand, etch rate and selectivity depend on the ion energy.
The sheath voltage of the boundary sheath in front of the chamber wall

$$U_W \approx \hat{U}\,\frac{1-A}{2}$$

influences the chamber conditioning.

- Whereas the peak voltage depends directly on the RF power, the asymmetry depends only on chamber geometry and surface conditions.

Short summary and guide for chamber matching

- Vary the phase angel between ICP and CCP generator systematically to determine the working point of different chambers.

- Check with the parameters RF wall current, Asymmetry, and SheathHeating where the real working point is located at the current recipe.

- Compare the different chambers.

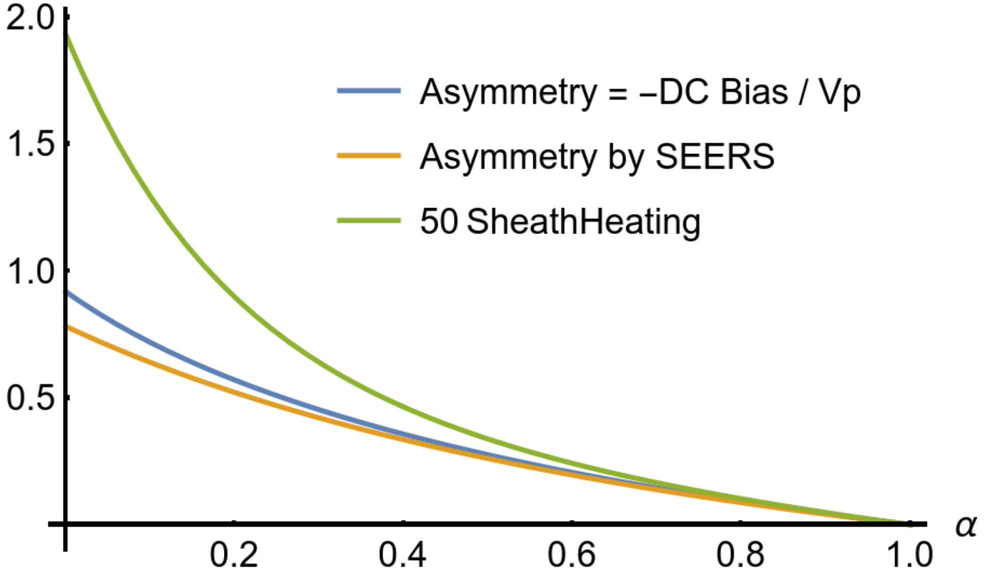
- How to get the right working point?
  - Choose a phase angel where is no tiny positive or even virtually negative real part of the load impedance.
  - Otherwise C_{load} in bias matchbox stops at maximum value
    → mismatch and instabilities.

Asymmetry vs. area ratio without 2nd capacitive coupling

- The area ratio α is defined as driven electrode area over all grounded areas in contact with the plasma.
  - $\alpha = 0 \rightarrow$ Asymmetry $\approx 1 \rightarrow$ maximum ion energy at wafer.
  - The main part of sheath heating does not work properly in symmetric plasmas $\alpha = 1 \rightarrow$ Asymmetry $= 0$, even harmonics disappear here.

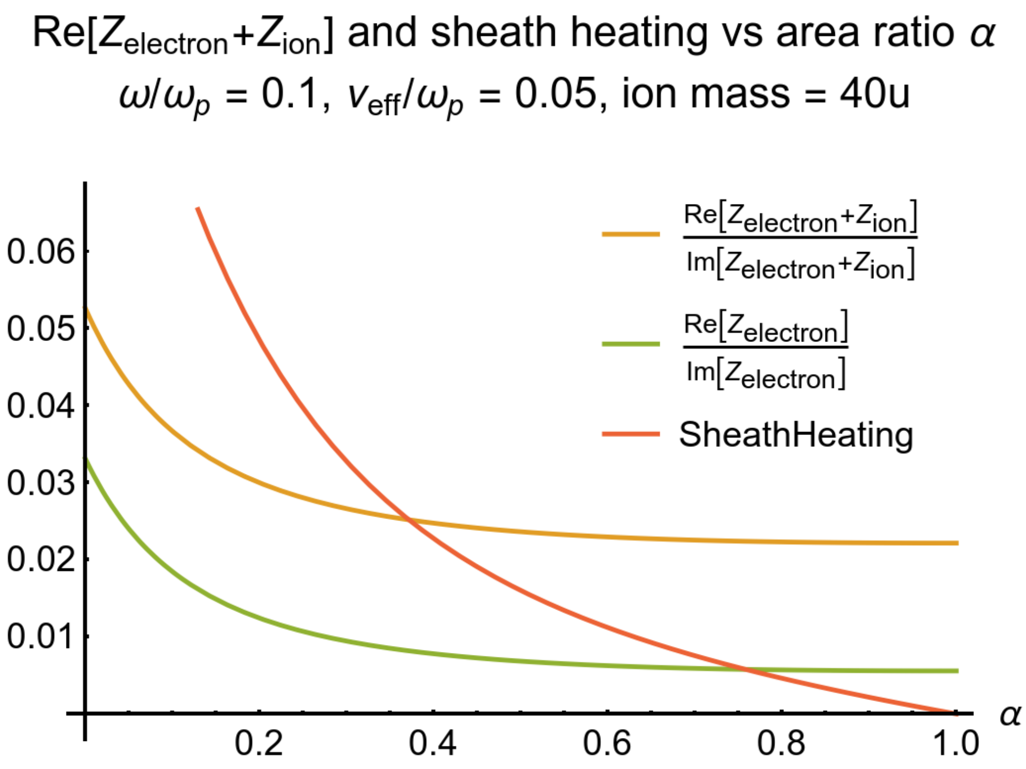
- Typical applications:
  - Chamber cleaning at Lam SPEED $\alpha \gg 1$, high ion energy at wall.
  - Transition from DSi to Dsi-v (liner added for less chamber volume), α varies.

Influence of second capacitive current with varying phase, 0% of coil current.
$\omega/\omega_p = 0.07,\ v_{eff}/\omega_p = 0.05$



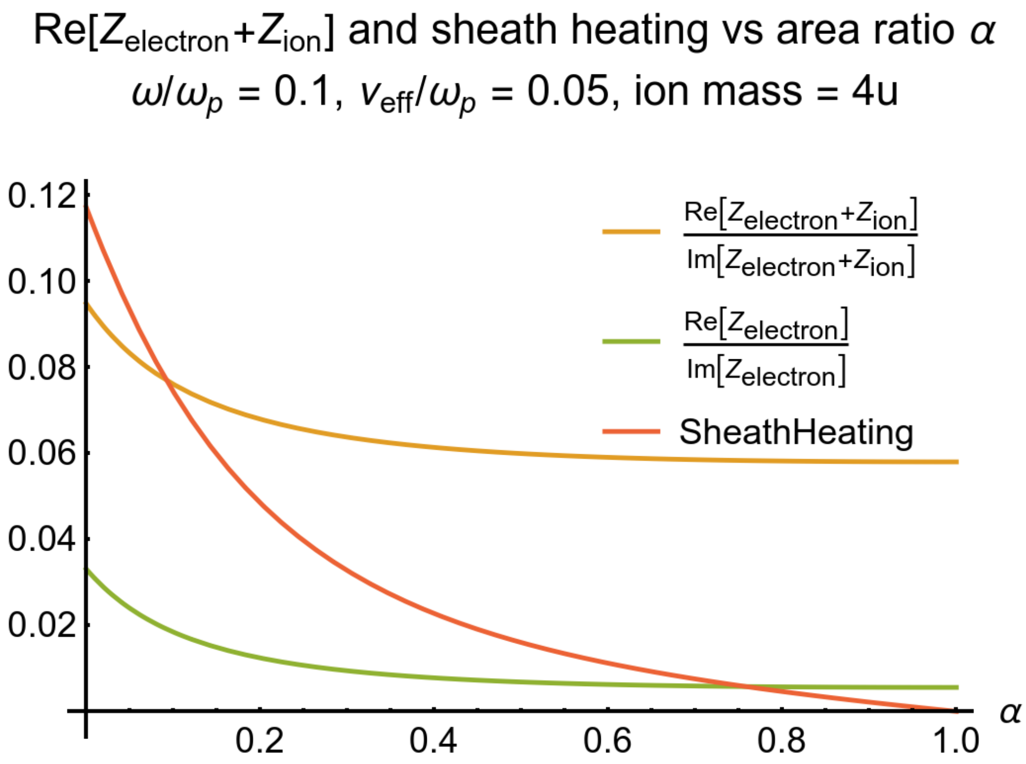
Real part of matchbox load impedance – heavy gases as Ar

- Through the dominating power dissipation by ions, in comparison to electrons, the variation of the real part of the load impedance is not that large.
- The real part of the plasma impedance is crucial for the RF matching mainly reflected by C_{load}.
- Chamber cleaning at Lam SPEED Transition from DSi to Dsi-v (line added for less chamber volume)



Real part of matchbox load impedance – light gases as He

- For light gases as He, the power dissipation by ions is larger, the variation of the real part of the load impedance by electron heating is small.



1st conclusions – 2nd capacitive coupling not considered yet.

- Ion enhanced processing is usually more efficient than pure thermal or chemical reactions. Control of the ion energy is therefore the key capability.

- The ion energy depends on
  - an intensity parameter peak voltage depending on the RF power
  - and the chamber asymmetry

- The asymmetry based on DC bias over peak voltage fits to the asymmetry calculated by means of a model based on the harmonics of the RF current.

- The asymmetry is an important process parameter, in particular together with RF peak voltage.

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FDC by Hercules and tool parameters: SheathHeating

A negative SheathHeating is necessary but not sufficient for bias matching issues. There are three possible root cases:

- The driven electrode is larger than the grounded electrode incl. chamber wall. In this case the electrons are still heated but the direction of the heat flow changes and leads to a negative sign of SheathHeating. This is fixed by chamber design, e.g. some mask etchers or PECVD (Lam SPEED) chambers in clean mode, it should not change in time.
  → not crucial

- The electrons are really cooled in the boundary sheath at the driven electrode. Depending on the phase angle, this can happen in ICP chambers if the plasma is in the desired H mode. Here SheathHeating can be used as indicator for the desired H mode, see examples.
  → **maybe crucial**

- Due to a critical phase relation of the capacitive coupling at coil and driven electrode the bias matching is not stable.
  → crucial

  Measure
  Check if C_{load} of the bias match is at or close to the upper limit by tiny or negative real part of bias load impedance.

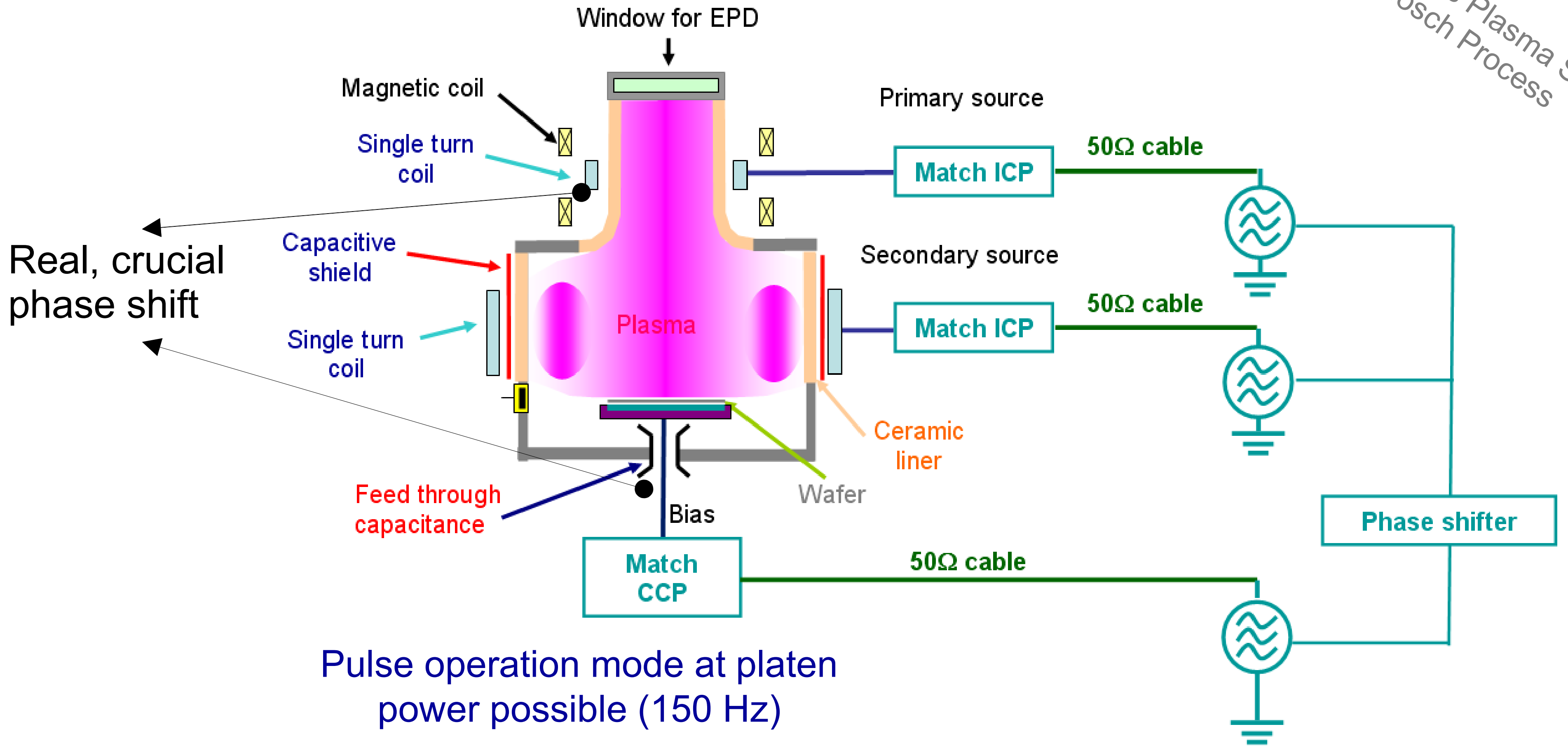
FDC by Hercules and tool parameters: Asymmetry

- Variations of the Asymmetry from chamber to chamber result in different ion energy distribution. Finally this causes
  - different etch rate and
  - etch profile.
- Potential root causes
  - Surface condition changed
  - Geometry changes (DSi → Dsi-v)
  - Second source parts

Content

plasma metrology experience

Setup of SPTS Omega® Rapier and DSi



Pulse operation mode at platen power possible (150 Hz)

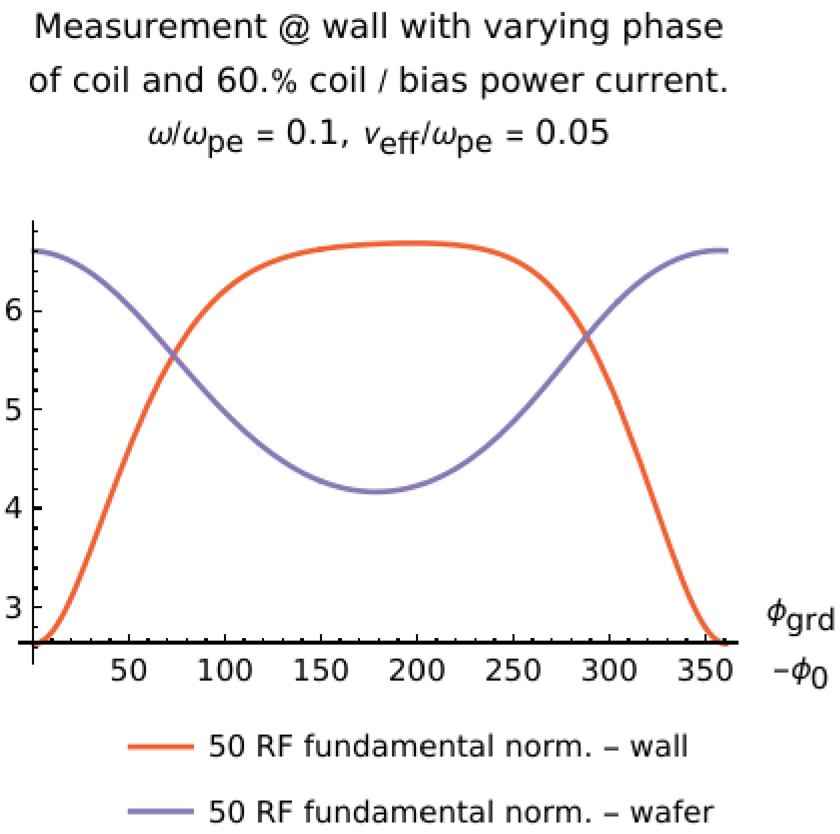
Phase shift – Main issues

- The crucial phase relation is that of the currents in the plasma. The effect is well pronounced if both currents are of the same order of magnitude.
- It depends on
  - phase delay of the Matchboxes,
  - phase shift of output and control signal (CEX) of the generators,
  - cable length between generator and matchboxes.
- Matchboxes
  - Source Match controlled: appr. 0° at low pressure,
  - Source Match not controlled: away from 0°, depending on mismatching,
  - Bias Match controlled, appr. 180° at low pressure.
- Often only the phase offset of the generators is given. It depends also on the reference: source or bias.
- Within this note, the phase delay is always given with respect to the source generator. **With unknown hardware, one has to take into account always an unknown phase offset.**

How can the real phase delay be determined ?

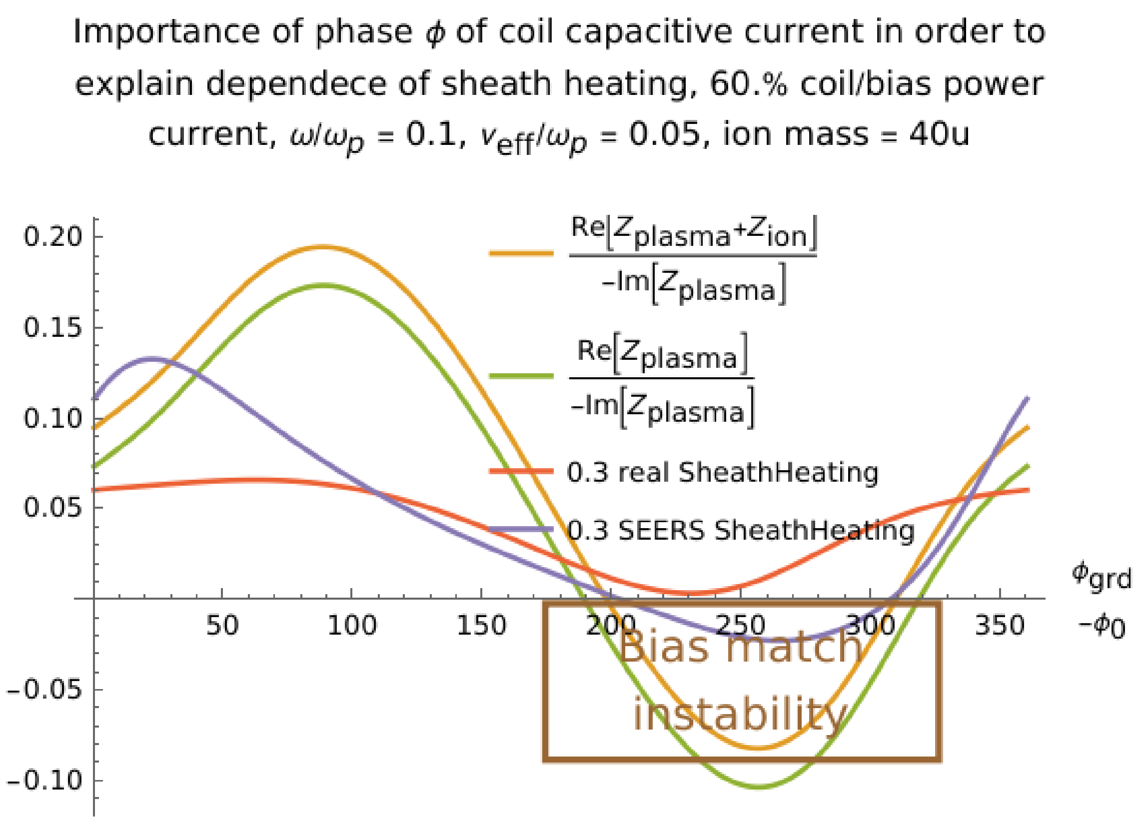
- If both current are in phase, the total current reaches its maximum. The phase shift of the bias matchbox is already taken into account, therefore we finds that point at 180°.

- For these two current being out of phase, a part of the current from the wafer in compensated or flows back when the bias power is small. In the first case C_{load} reaches its maximum, in the second case the bias matchbox gets out of control.



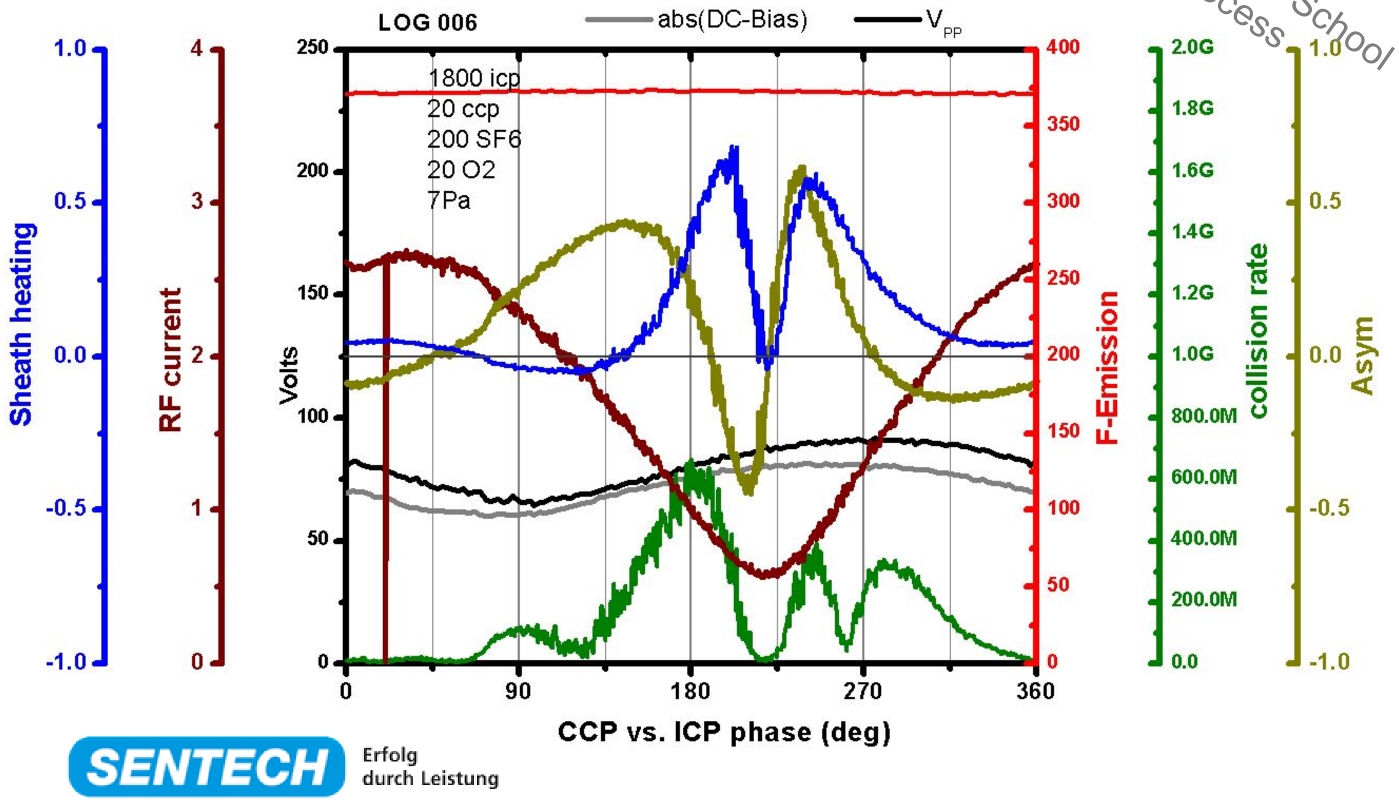
Why does a phase shift disturb bias matching?

- At most of ICP process chambers, there is also a strong capacitive coupling into the plasma, due to the high voltage at the hot end of the coil.
- From the point of view of the bias matchbox, this can lead to tiny positive or even virtually negative real part of the load impedance.
- Typical effect: C_{load} in bias matchbox stops at maximum value.
- The sheath heating delivered by SEERS is also influenced by the second RF current which is measured by the Hercules system.
- Thus, SEERS SheathHeating helps to discover the instability range of bias matching.



Phase Angle vs. Process Stability – High Power ICP

- Phase shift of generators – not of currents in plasma.
- In particular the SheathHeating and Asymmetry show where this low pressure but high power process is unstable – when the currents are out of phase @ Minimum of wall current at 220°!
- Almost no change in F emission → Source work in H mode – no impact of phase angle as expected.



Phase delay – Matching instabilty

- The capacitive current from the source, changes also the phase angle of the load of the bias matchbox out of expected interval from 0° (resistive) and -90° (capacitive). In this case the bias matchbox cannot match, reflected power occurs.

- Here also the model indicates a range of instability.

Effect of phase relation on process – E mode example

- As an example a typical unstable process are discussed, mainly to discover the root course of the instability.

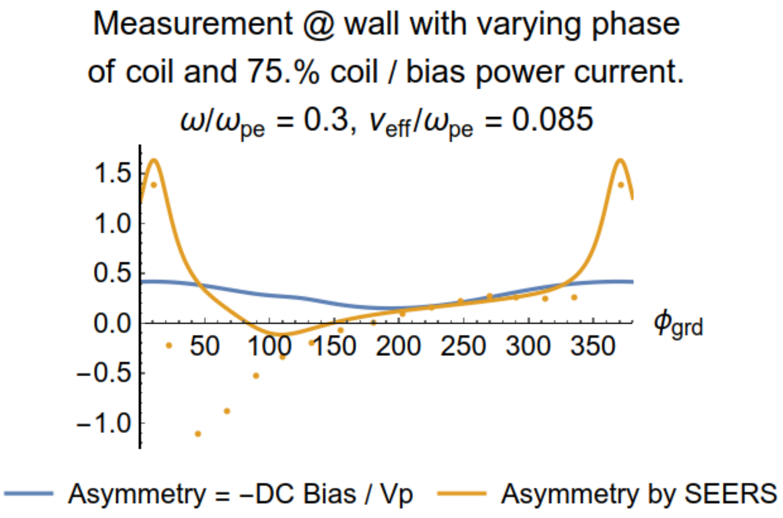
- In order to explain the SEERS measurement, we use a virtual plasma (model) together with the SEERS model. So we can distinguish between artifacts and real changes of the plasma. These data are always represented by a solid line.

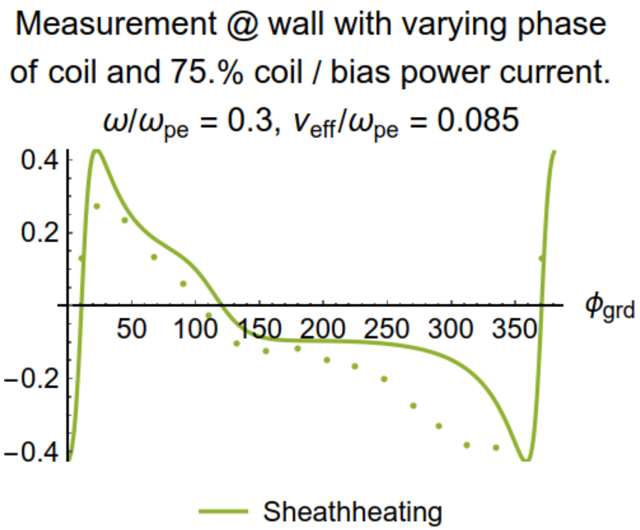
- Please have in mind that also different cable length' between the generators and matchboxes vary the phase angle.

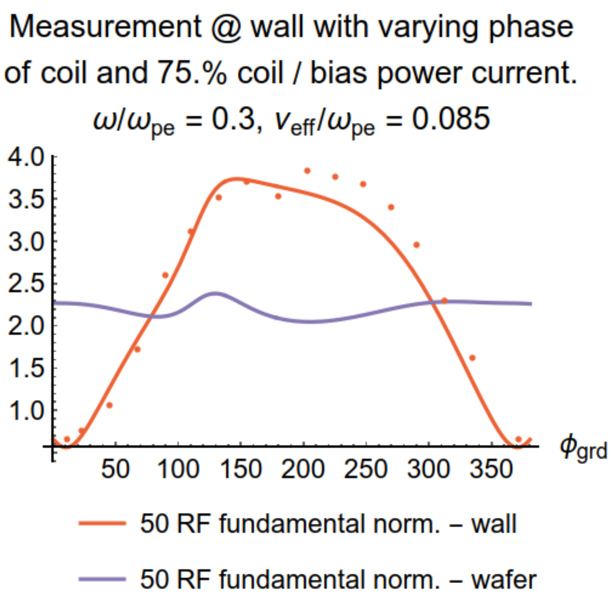
- Often it is useful to vary the phase between source and bias generator in order to see hidden dependencies and evaluate the stability of working point (recipe).

- Typical, critical boundary conditions are:
  - Lam® TCP® 9400
  - Low source and bias power
  - Low process pressure < 2 Pa = 15 mTorr
  - Electronegative, halogen gases as SF_6 or Cl_2

Phase variation between source and bias power – stable working point ?







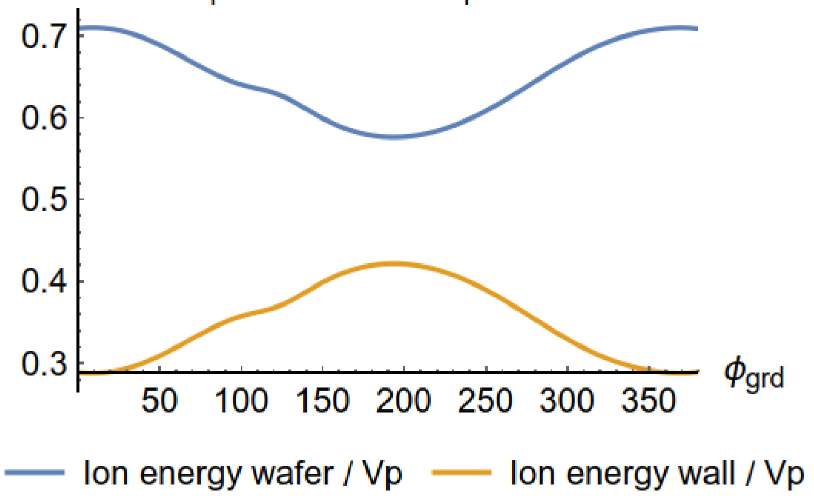
- Lam® TCP® 9400
  280 W source, 10 W bias, 5 mTorr, electronegative halogen gas, bias generator as master.
- The points are measured. A nonlinear plasma model is parameterized by extended SEERS measurement vs phase (solid lines). The model is fitted for all three parameters in parallel.
- Real Asymmetry and SEERS Asymmetry does not fit whole range. The wall current varies much more that the wafer current.
- The mean electron density in sheath is very low $\omega/\omega_{pe} = 0.3 \rightarrow n_e = 3 \cdot 10^7$. That means the plasma is definitely in E mode.

Phase variation between source and bias power – stable working point ?

- The electron density at wafer side is very low, $3 \cdot 10^7$ cm^{-3}, the collision rate as expected $2.4 \cdot 10^7$/s, effective area ratio A_{wafer} / $A_{wall,effective}$ = 1.5.
- There are some reasons for the low electron density
  - Electronegative gas
  - E-mode, mainly ions are accelerated
  - About 10 cm distance to source, densities drop down away from source.
- This low density causes a sheath resonance close to the generator frequency affecting the ion energy.
- Thus, phase angle has no big effect on the ion energy at the wafer. But ion energy, etch rate, and selectivity depend heavily on the plasma density.
- The high effective area ratio indicates that only a small part of the chamber wall gets RF current. This corresponds well to the very low density. The plasma reaches the wall only close to the source.

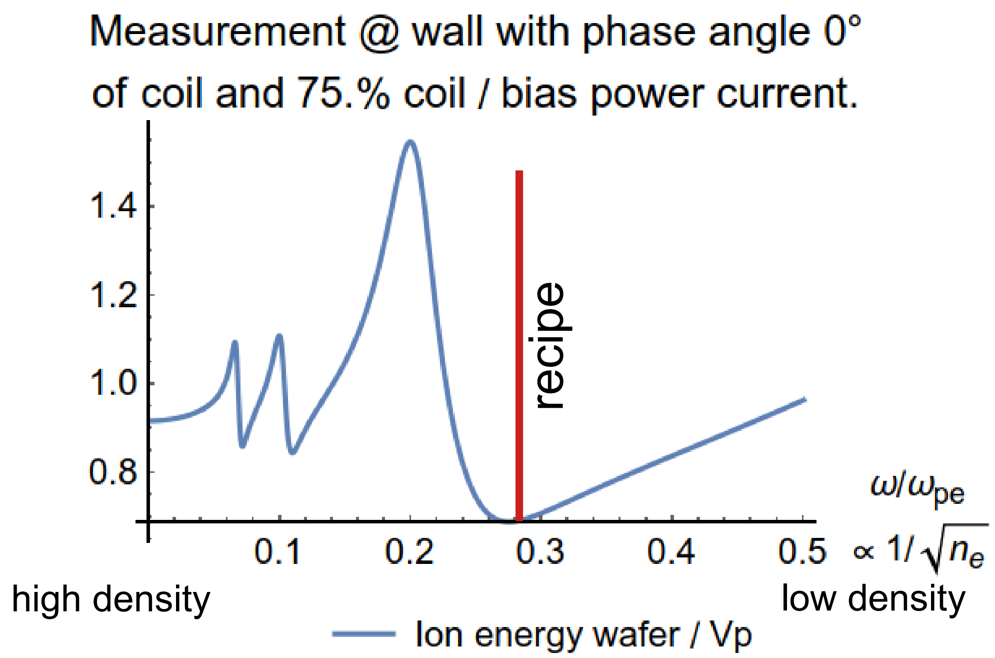
Measurement @ wall with varying phase of coil and 75.% coil / bias power current.

ω/ω_{pe} = 0.3, ν_{eff}/ω_{pe} = 0.085



Ion energy affected by sheath resonance at wafer → unstable process

- 0° phase delay between the RF generators.
- There are two sheath resonances, series and parallel. Due to the low electron density, the generator frequency is close to these resonance frequencies.
- What makes a plasma density variation, e.g., chamber conditioning:
  At the determined working point (recipe), the ion energy reaches its minimum and minimizes the physical impact on the wafer surface. In combination with the very low bias power of 10 W there is a more or less chemical process with only small surface damaging.
- This sounds good but:
  Dominating resonance effects in plasmas cause always a bad process stability. Small variation of the chamber wall conditions or effective plasma power cause undesired process results – in agreement with the real process performance.



Summary of E mode example

- ICP etcher should not be run at low ICP power so that the H more is not achieved:
  - Probably the plasma runs in the unstable range between E and H mode.
  - There is maybe a higher density at the source but due to the height of the chamber the density at the wafer can be very low. Local resonances occur then close to the sheath at the wafer with big effect on the ion energy – unfortunately strongly depending on the chamber conditioning.
  - Is also the bias (bottom) power very low, the is a well pronounced dependency on the phase angle and so also on the phase shift of the matchboxes at source and wafer.

- The best method is a phase variation to validate the working mode of chamber and process.

- Alternative: Two-frequency plasmas.

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Change of ratio of bias and source power

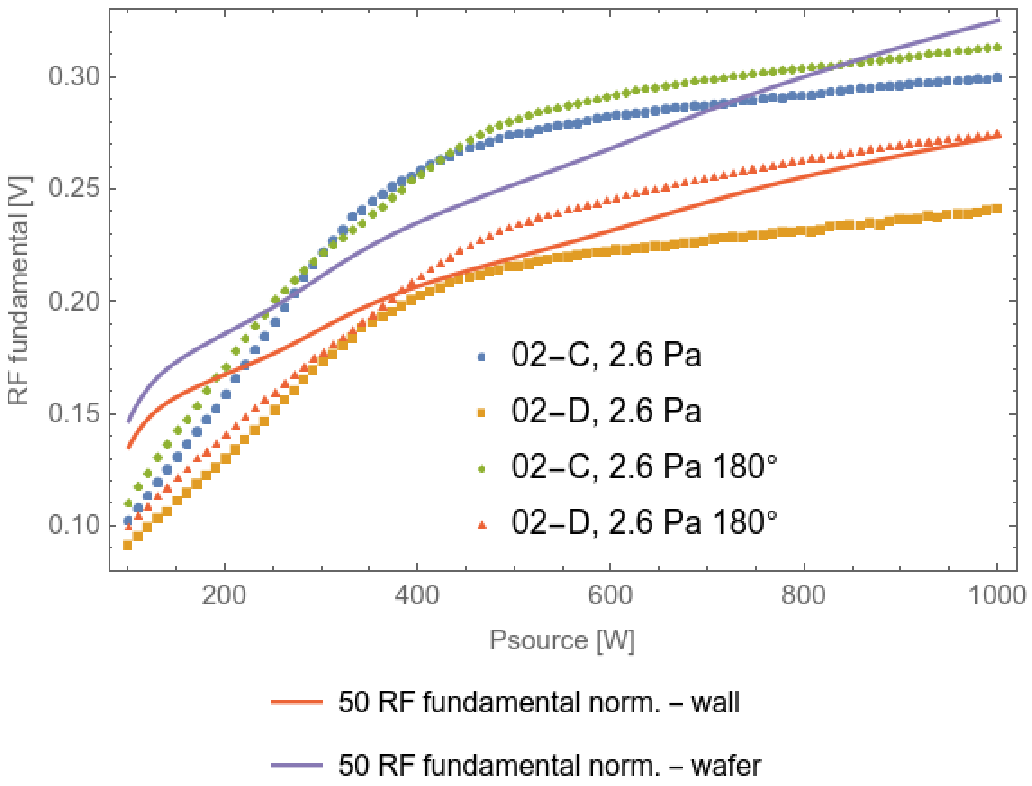
- The bias matchbox provides appr. 180° phase delay. So the phase angle is always related to the point of measurement. Usually we give the phase relation of the RF generators as done by the tool.
- Please note:
  Thus, 0° at the plasma is **not** the normal case, it requires appr. 180° phase shift of the two generators.
- At low power, the plasma is in the so-called (capacitive) E mode, and switches into the (desired, inductive) H mode at some 100 W, depending on the electron density.
- This mode changes causes a totally different electron heating regime so that the change SheathHeating is very complicated and should be used here.
- In order to explain the SEERS measurement, we use a virtual plasma (model) together with the SEERS model. So we can distinguish between artifacts and real changes of the plasma. These data are always represented by a solid line.

Change of source power at Lam Kiyo Star 200 mm

- The chamber mismatch plays here a bigger role than the phase angle. This is due to the special coil design of the coil minimizing the capacitive coupling.

- 180° phase shift at the generators leads to approx. 0° at the plasma and leads to a larger total current at the chamber wall as shown at higher source (top) power.

- There is only a change in the slope of the RF current at the wall vs. the source power. A detection of the heating mode requires a troublesome measurement of the full source power range. As we will see at the next pages, there are better opportunities.

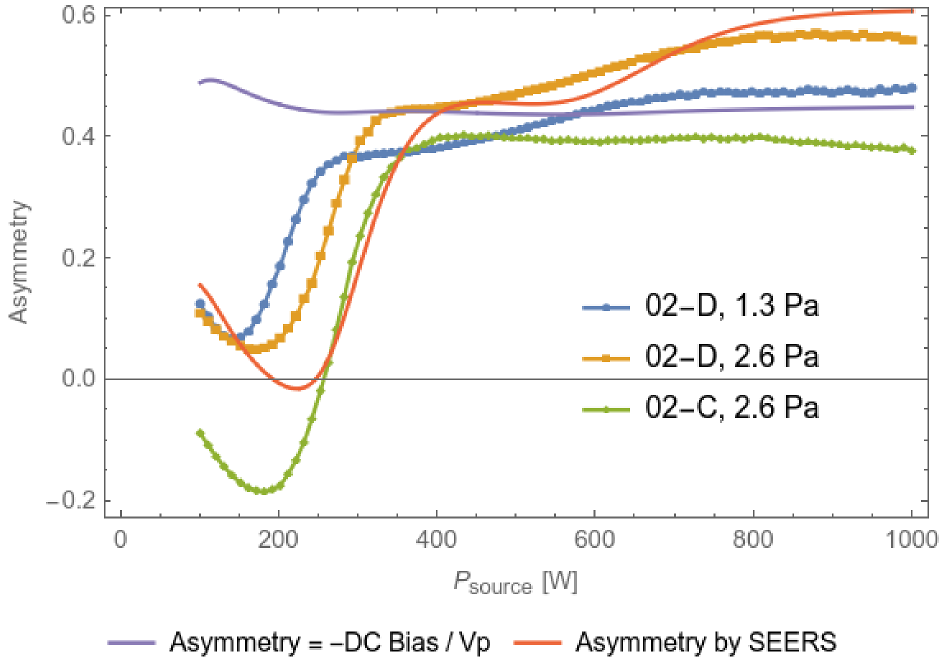


E-H Mode Detection and Chamber Comparison in Lam Versus 2300, Ch. Li, F. Hoffmann, M. Klick, J. Bartha, L. Eichhorn, E-H Mode Detection and Chamber Comparison in Lam Versus 2300, 17th APCM Conference, Dublin, IRELAND, 2017.

Change of source power at Lam Kiyo Star 200 mm

- 0° phase delay of the RF generators → appr. 0° at plasma.
- In contrast to the RF current, the Asymmetry shows the shift clearly. But we recognize the jump at 300 W, clearly indicating the change into the H mode.
- The SEERS Asymmetry from the measurement fits properly with that from the plasma model.
- But this change of the SEERS Asymmetry is not a real change of the symmetry of the plasma, it is an artifact as we can readily see if we compare to the Asymmetry defined by DC bias and peak voltage.

Normalization to fundamental removes uncertainty from special sensor hardware.



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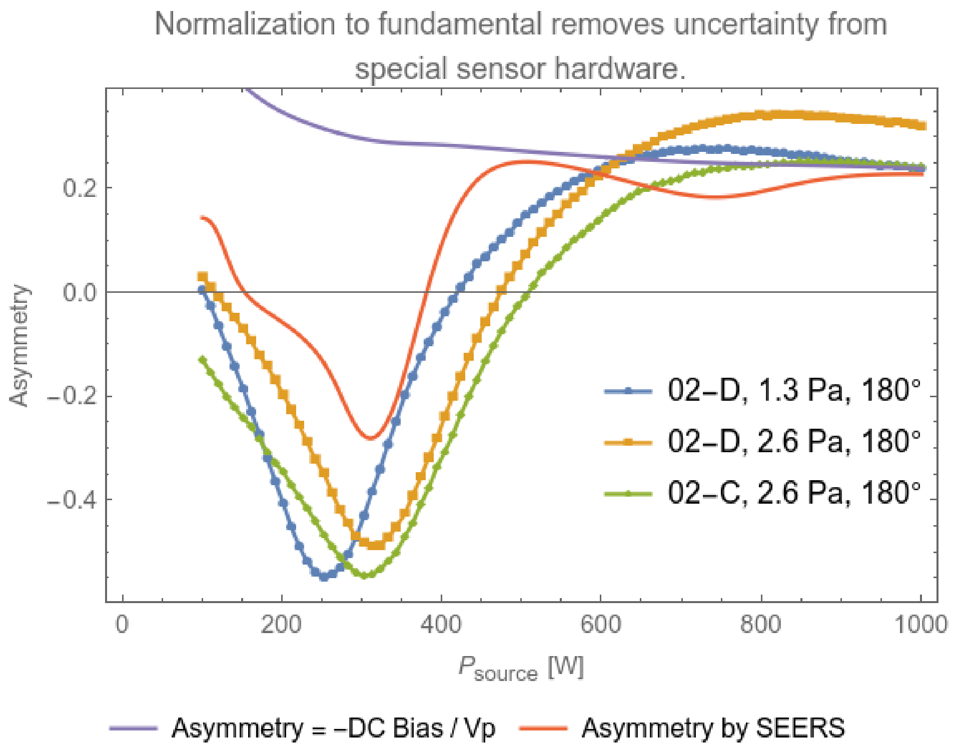
Change of source power at Lam Kiyo Star 200 mm

- 180° phase delay of the RF generators
  → appr. 0° at plasma.

- The transition into the H mode comes later here, at appr. 400 W.

- Due to the other phase delay, the Asymmetry defined by DC bias and peak voltage changes in particular at low source (top) power. But the huge change of the SEERS Asymmetry is an artifact.



E-H Mode Detection and Chamber Comparison in Lam Versus 2300, Ch. Li, F. Hoffmann, M. Klick, J. Bartha, L. Eichhorn, E-H Mode Detection and Chamber Comparison in Lam Versus 2300, 17th APCM Conference, Dublin, IRELAND, 2017.

Links to additional publications of other ICP source power related issues

- *Instability due to non-functional RF generator synchronization*
  https://www.plasmetrex.com/ref/applications/2012/S6-4_Bauer-TI.pdf

- *E-H-mode transition due to changed source match efficiency*
  https://www.plasmetrex.com/ref/applications/2011/1-5_Urbansky_Infineon.pdf

- *E-H-Mode transition and its detection in SF6 plasma during Si trench etch*
  https://www.plasmetrex.com/ref/applications/2013/S7-1_Chasanoglou_TI.pdf