Electron Heating and Process Characterization in Reactive Low-pressure Plasmas

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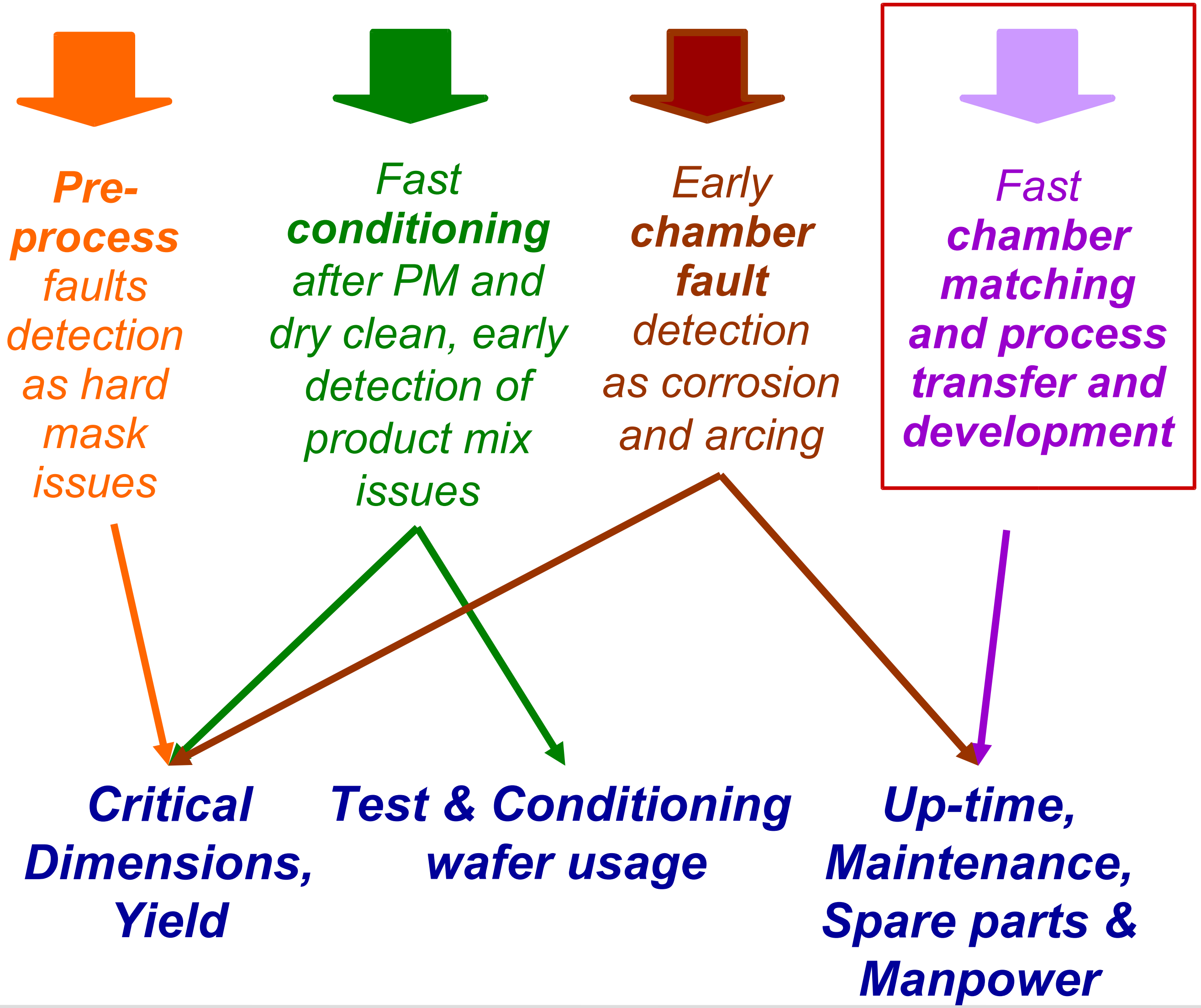
The need for process control under industrial conditions



Pre-process *faults detection as hard mask issues*

Fast ***conditioning*** *after PM and dry clean, early detection of product mix issues*

Early ***chamber fault*** *detection as corrosion and arcing*

Fast ***chamber matching and process transfer and development***

Critical Dimensions, Yield

Test & Conditioning wafer usage

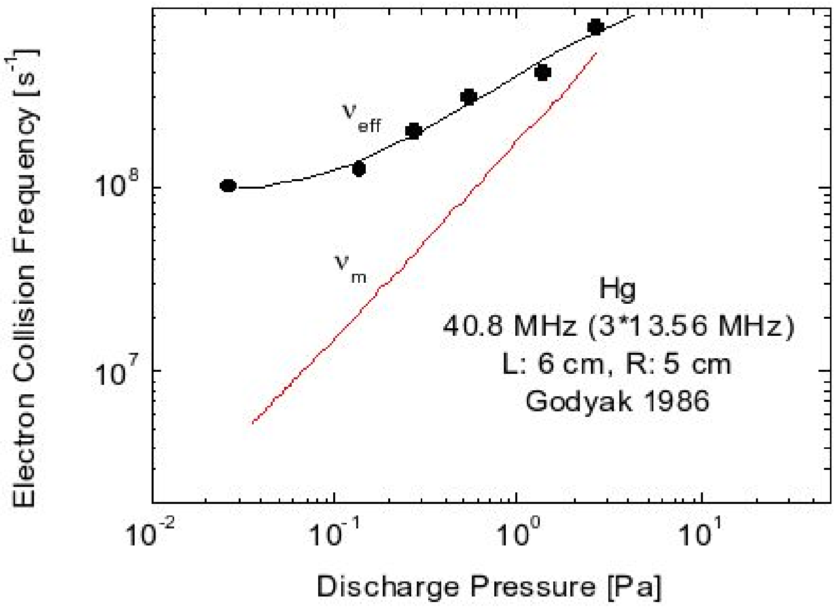
Up-time, Maintenance, Spare parts & Manpower

Background

- The shrinking of the critical dimensions of the electronic devices requests new process approaches in lithography as well as plasma etching and deposition. In particular the development in plasma etching was also driven by the demand of higher productivity and process stability. One of the most important challenges to plasma etching is a high aspect ratio - to be etched at significantly lower pressure. The transport processes of the reactive neutrals depends reciprocally on the process pressure so that at lower pressure the transport of the reactive species from the plasma bulk to the wafer's surface as well as the dilution and removal of byproducts is less restricted by collisions and the process productivity increases.
- In order to avoid loss in selectivity, a higher frequency and so a lower ion energy should be used.
- The major change in pressure concerns the plasma physics - the electron heating. The decrease of process pressure requests an increase of the driving RF frequency in order to increase the efficiency of collisionless and now dominating heating mechanisms.

Electron heating and new tools

- Well above 10 Pa (75 mTorr) the energy transfer from the electric field to the real energy carriers, the electrons, is based on ohmic heating (by collisions - ν_m in diagram).
- At lower pressure the heating of electrons does not depend directly on the pressure via electronic collisions at lower pressure (see ν_{eff} in diagram).
- Therefore the dependence of the plasma parameters on the recipe parameters is completely different to the classical plasma etch regime.



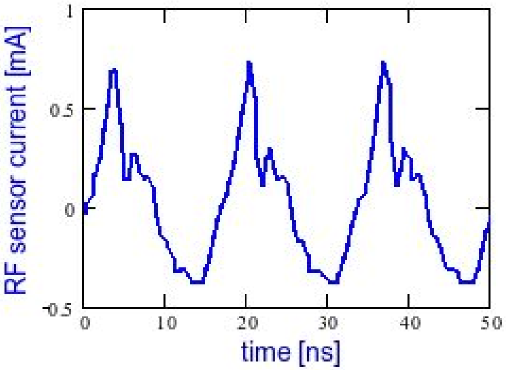
- This is more important owing to a new tool generation as TEL® SCCM® or Applied Materials® HART® TS operating at higher frequencies and at lower pressure but obtaining higher plasma densities.

Model approach and measurement

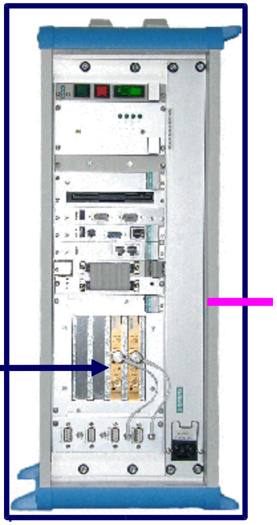
- The known models for the stochastic heating are compared and these models are shown to be insufficient to reflect or explain the experimental results in particular at lower pressure. Thus a new and extended but simple model (from the mathematical point of view) was developed and used in this paper.
- The effective collision frequency ν_{eff} of electrons in capacitively driven industrial chamber using Ar/Kr, Cl_2 and BCl_3 has been investigated using **S**elf-**E**xcited **E**lectron **R**esonance **S**pectroscopy (**SEERS**). The most prominent features are the steep increase of ν_{eff} at low power inputs in all the three gases and a slight but systematic decrease of ν_{eff} vs. the pressure p for Ar/Kr and BCl_3 over the whole pressure range token into account.

  A VI-probe (Z-Scan) between match box and chamber was used to determine the plasma resistance (real part of plasma impedance).

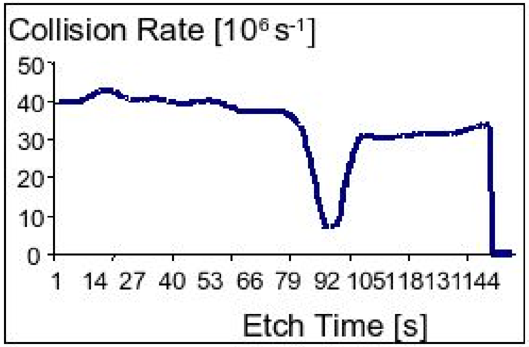
Experimental setup



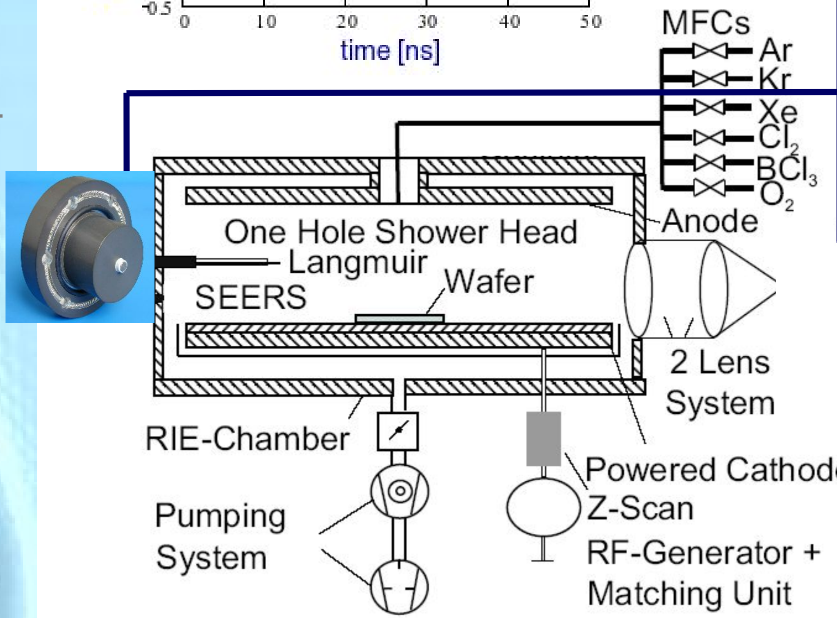
Hercules® APC xM



Measurement signal



Plasma parameters,
e.g., electron collision rate.



RF frequency: 13.56 MHz

SEERS model limits:
- RF frequency 6 - 100 MHz
- Pressure < 40 Pa (300 mTorr)

Model description I

The permittivity of the plasma

$$\frac{\epsilon}{\epsilon_0} = 1 + \frac{\omega_\mathrm{e}^2}{\mathrm{i}\omega\left(\mathrm{i}\omega + \nu_\mathrm{m}\right)}$$

provides for the dissipated, ohmic power including local resonance effects and higher harmonics of the RF current

$$\bar{S}_\mathrm{ohm} = \frac{m_\mathrm{e}\nu_\mathrm{m}}{e_0^2 n_\mathrm{e}}\, l \left(1 + 2\frac{\omega_k^2}{\omega_\mathrm{e}^2}\right) \sum_k \frac{1}{2} j_k^2 = \frac{1}{\omega_\mathrm{p,e}^2}\, l \left(1 + 2\frac{\omega_k^2}{\omega_\mathrm{e}^2}\right) \sum_k \frac{1}{2} j_k^2$$

and allows the definition of an effective electron collision rate

$$\nu_\mathrm{eff} = \nu_\mathrm{m}\left(1 + 2\frac{\omega_k^2}{\omega_\mathrm{e}^2}\right) + \nu_\mathrm{sh}$$

including stochastic or pressure heating via ν_sh.

ω_e: plasma electron eigen frequency; m_e, e_0: electron mass and charge

ν_m: collision rate for momentum transfer

S_ohm, ohmic power density, j_k: k^th harmonic of RF current

Model description II

- Following the pressure heating approach, the collisionless heating depends on the gradient of the ion density in the sheath [G. Gozadinos, M. M. Turner, and D. Vender, Phys. Rev. Lett. 87, 1].
- The collision rate ν_{sh} can be roughly estimated to be

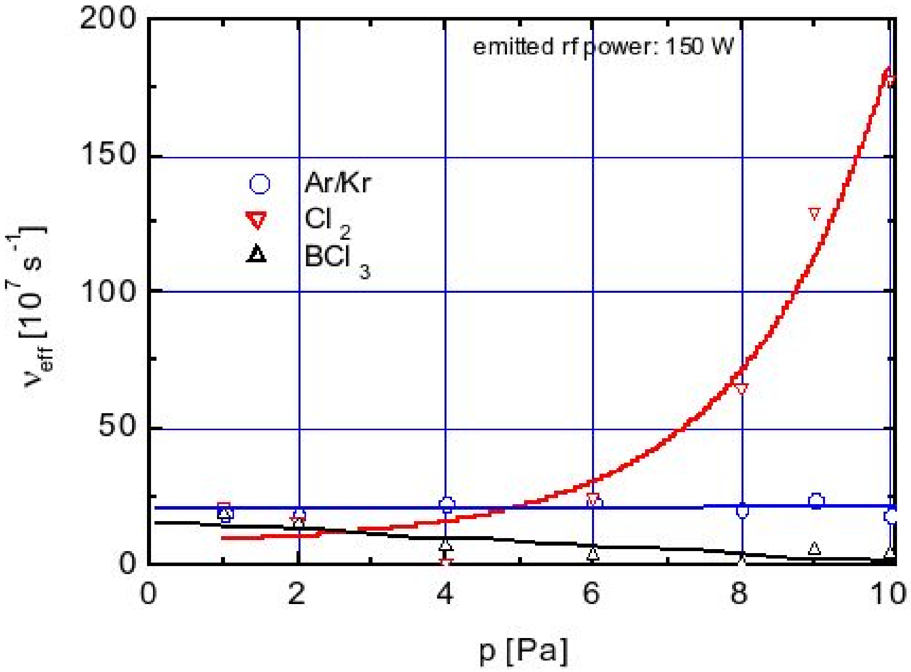
$$\nu_{\mathrm{sh}} \approx \frac{\nu_{\mathrm{sh}}\,\big|_{p=0}}{1+\left(\bar{s}\,\frac{\sigma_{N+}\,p}{k_{\mathrm{B}}T_{\mathrm{N}}}\right)^{\frac{1}{2}}}$$

and provides a decrease of ν_{sh} with increasing pressure [G. Franz, M. Klick, JVST A, submitted for publication].

Temperature of neutral gas T_{N}, cross section of ions $\sigma_{\mathrm{N+}}$, pressure p, Boltzmann constant k_{B}, sheath thickness s.

Pressure and electron heating in reactive plasmas: Inert and reactive gases

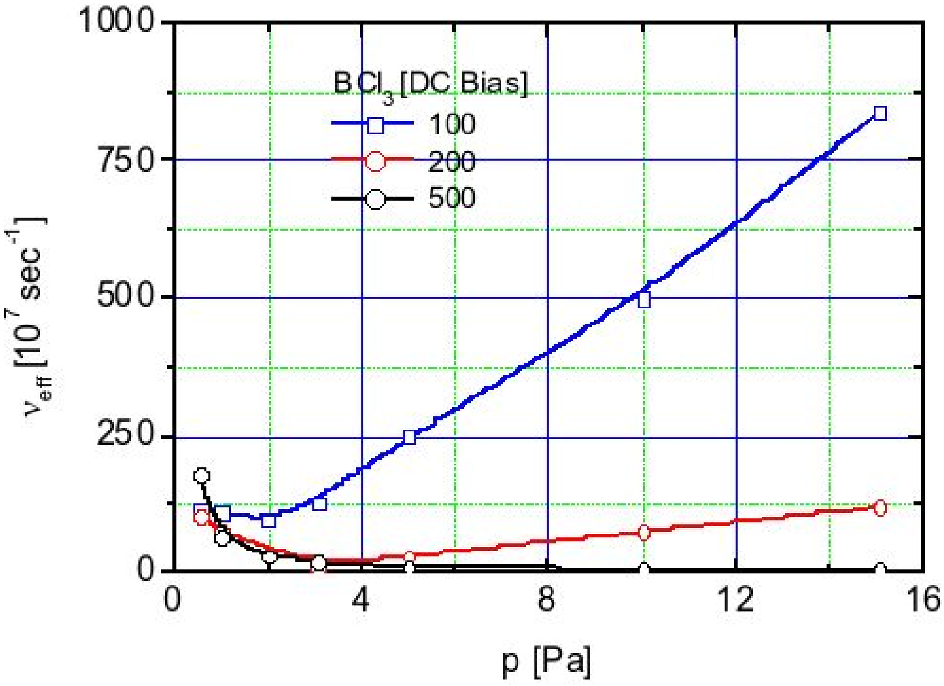
- The process pressure, strictly speaking the density of the gas, has a large impact onto the electron heating.
- The diagram shows the electron collision rate to depend on the pressure for different DC Bias or RF power, respectively.
- The transition from stochastic to ohmic heating depends mainly on the process pressure and the gas used (cross section σ_{N+} and collision rate ν_m).



G. Franz, M. Klick, JVST A, submitted for publication.

Pressure and electron heating in reactive plasmas: BCl_3

- The electron collision rate depends in BCl_3 on the pressure as expected and different for low and high DC Bias or RF power, respectively.
- At high DC bias there is no ohmic heating within the whole pressure range under investigation. This effect is expected to be caused by less electron attachment (→ negative ions) due to a higher electron temperature.

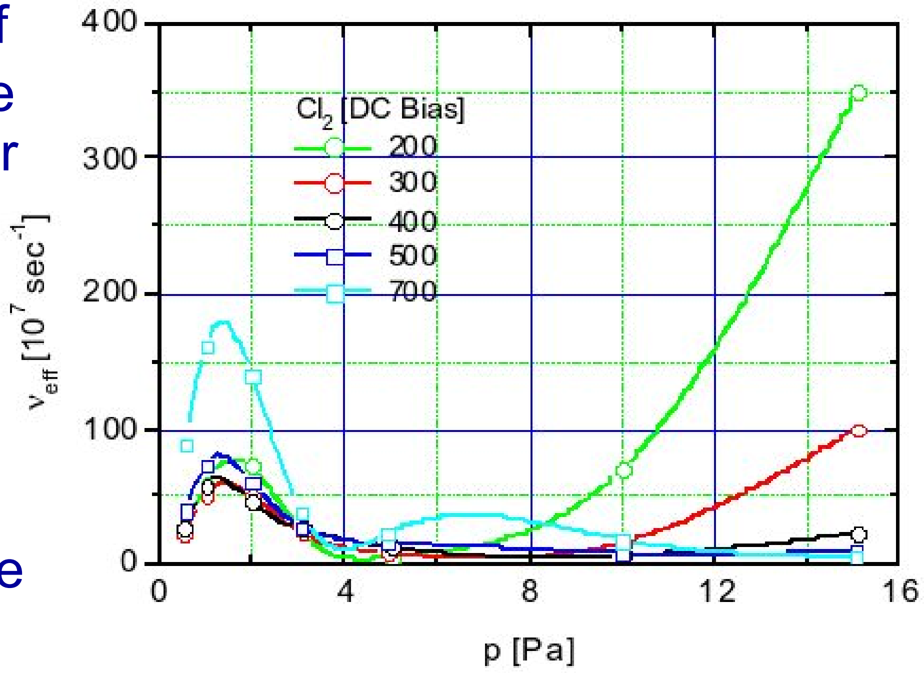


- This is an example of a gradual transition from stochastic to ohmic heating driven by the process pressure but it also depends on the RF power.

G. Franz, M. Klick, JVST A, submitted for publication.

Pressure and electron heating in reactive plasmas: Cl_2

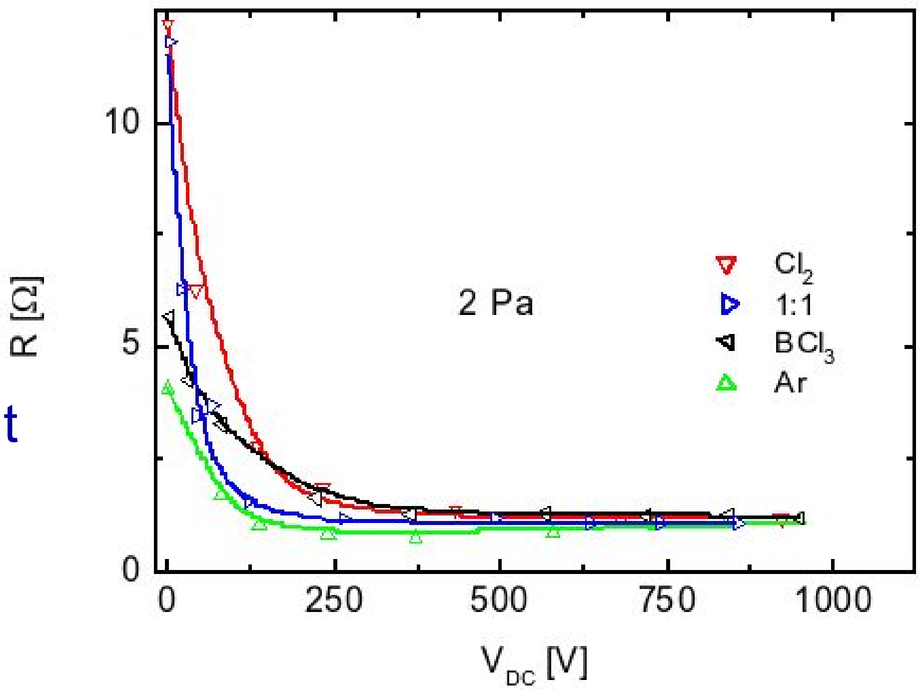
- In Cl_2 the dependence of the electron collision rate on the pressure is similar to BCl_3.
- The maximum at very low pressure is caused by the increased efficiency of the stochastic heating at lower pressure where the ions are in collisionless regime within the sheath.



G. Franz, M. Klick, JVST A, submitted for publication.

Pressure and plasma resistance in reactive plasmas

- By means of a VI-probe the plasma resistance was measured. Despite the ionic 'resistance' is still included, the increase of the resistance at low DC Bias indicates significant change in the electron heating.
- The dependence of the ohmic plasma resistance is determined by the drastic change of ν_{eff} (up) and the variation of electron density n_e (down) at low DC Bias.

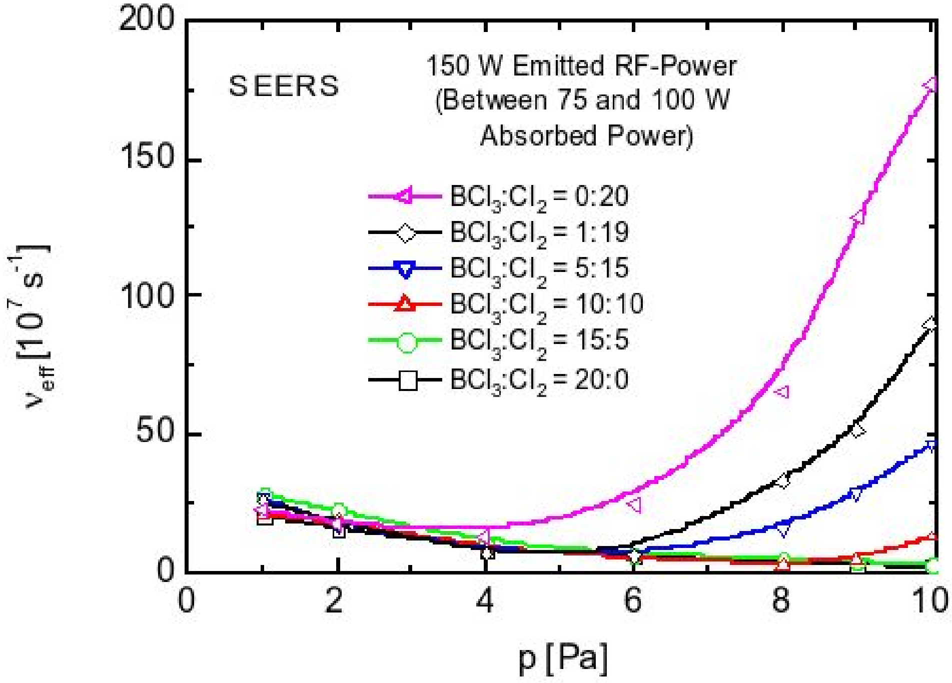


- This is in agreement to the assumption of the dominating ohmic heating at low DC Bias as proposed before.

G. Franz, M. Klick, JVST A, submitted for publication.

Chemistry and electron heating

- For process development, often the gas mixture in the recipe is changed having also influence onto the plasma’s physics.
- The diagram shows a very smooth transition from Cl_2, early ohmic heating, to BCl_3 where at least for this RF power of 150 W, no ohmic heating can be observed.
- BCl_3 still remains even at the highest discharge pressures in the regime of stochastic heating.



- This is a classical example of a gradual transition from stochastic to ohmic heating. Stepwise dilution of Cl_2 with BCl_3 leads to a continuous transition to the stochastic regime.

G. Franz, M. Klick, JVST A, submitted for publication.

Summary

- The two electron heating mechanisms in RF plasmas are shown a strong dependence on process gas, pressure and RF power.
- Stochastic heating is the dominating electron heating mechanism of the new tool generation operating at lower pressure.
- Changing the chemistry can impact the plasma physics dramatically.
- Therefore plasma processes can operate in different regimes – depending on the recipe. Slight changes of the recipe can influence process parameters as the etch rate strongly if the balance of the electron heating mechanisms is affected.