Sustainable Plasma Technology

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- Can I use a good working recipe for all products?
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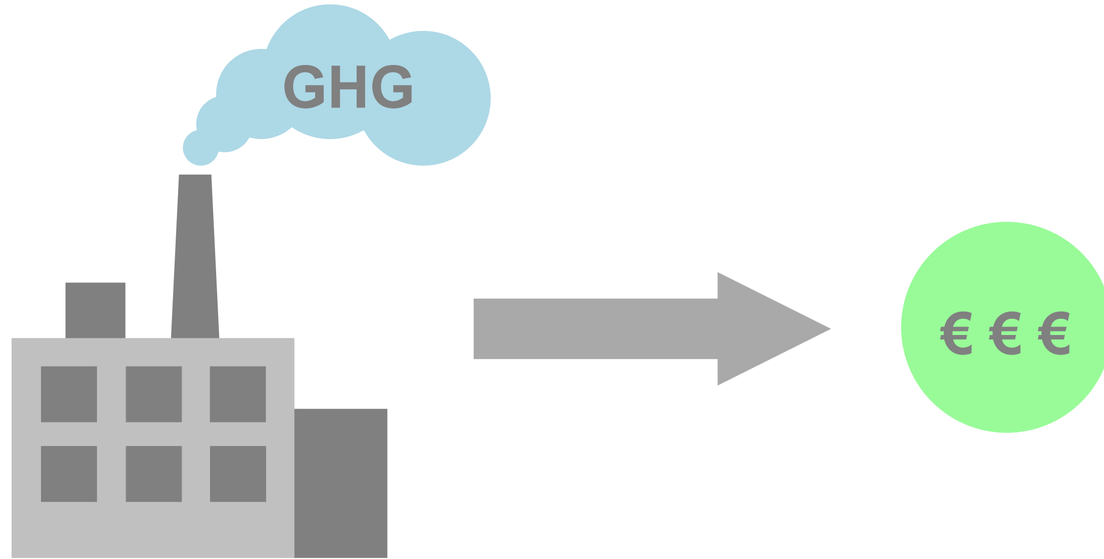
Motivation: Save Money (and the Planet) with Plasma Science?

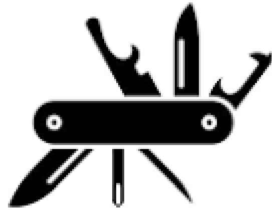
- Semiconductor fabs must reduce greenhouse-gas (GHG) emissions while maintaining performance.



- Thoroughly understood Plasma Physics helps in many aspects to reach this goal

Motivation: Save Money (and the Planet) with Plasma Science?

- For many people a plasma tool is like any other tool. It must be sharp, easy to use and cheap.



- The costs are a matter of throughput, the manufacturers care about the ease of use, and process engineers make it sharp. Who cares about environment? The Fab? The tool maker or the process engineer?

- With a little bit of understanding, plasma processes can be adjusted to “just what you need, nothing more”. Enabling to save money & armful by products.

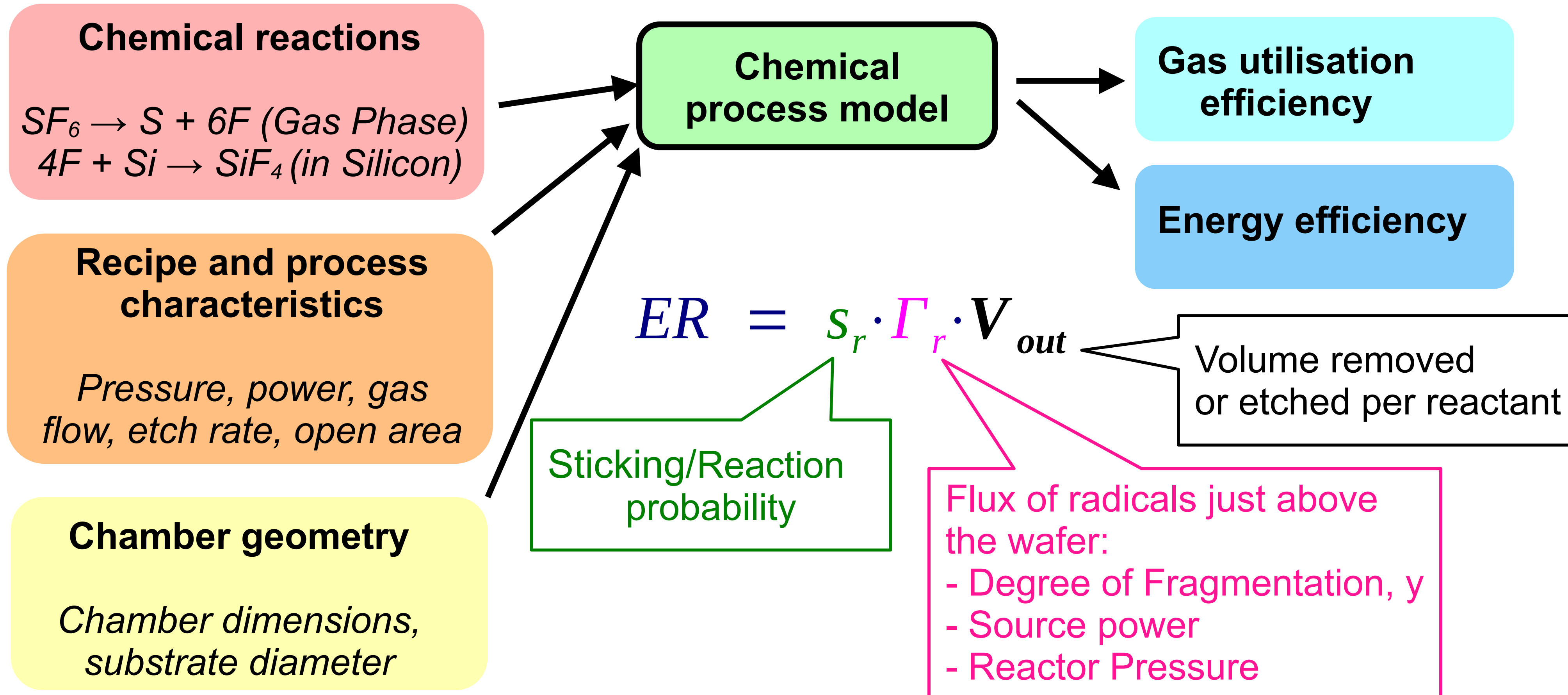
- We are presenting two examples, that are real cases from the microelectronics and from the MEMS industry.

An example from the MEMS industry: One Recipe for all Products?

- Si Trench etch with SF_6
- Tool / Wafer:
  - SPTS Rapier 200
  - Wafer size [mm]: 200
- **Large product mix in the Fab, open areas ranging from 1% to 90%**
  - **Same process for all?**

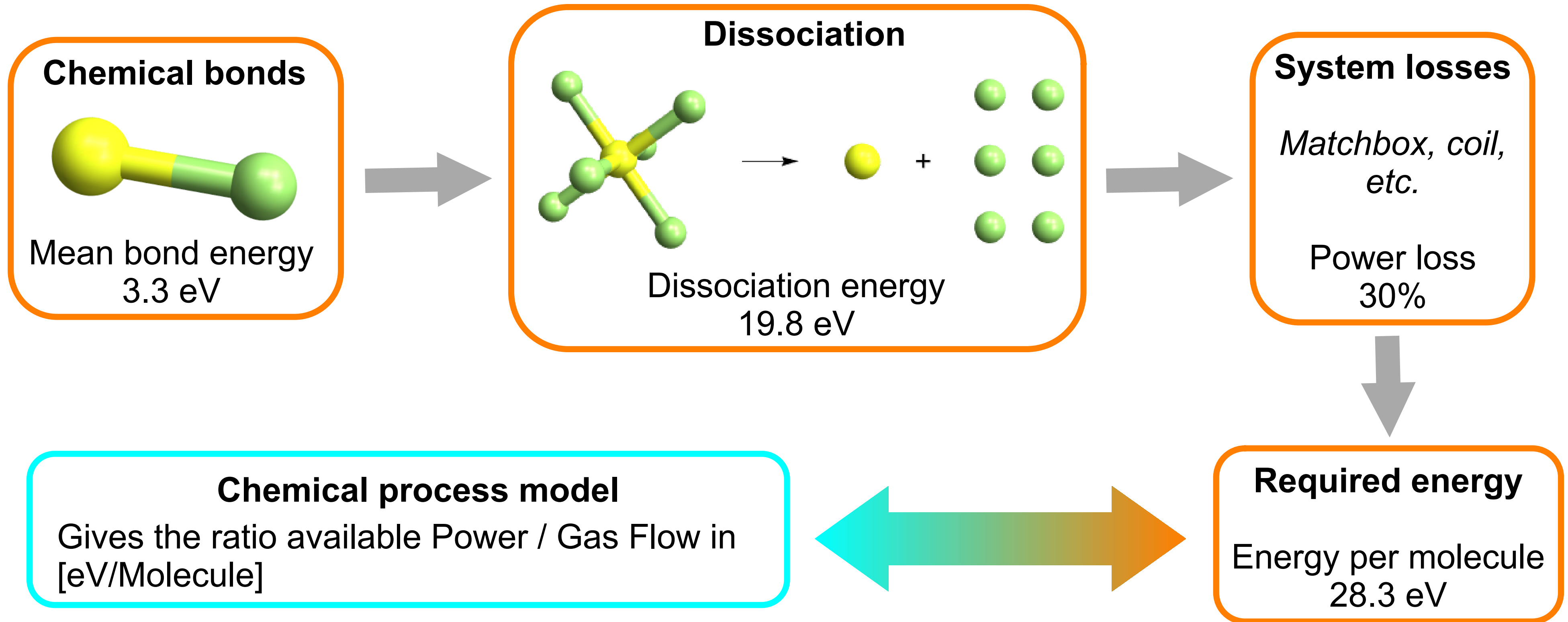
Process of Record	
SF6 Flow [sccm]	800
Pressure [Pa]	3.3
Source Power [W]	3500
Performance	
Open Area	68 %
Etch Rate [µm/min.]	16

Chemical Process Model: Inputs / Outputs

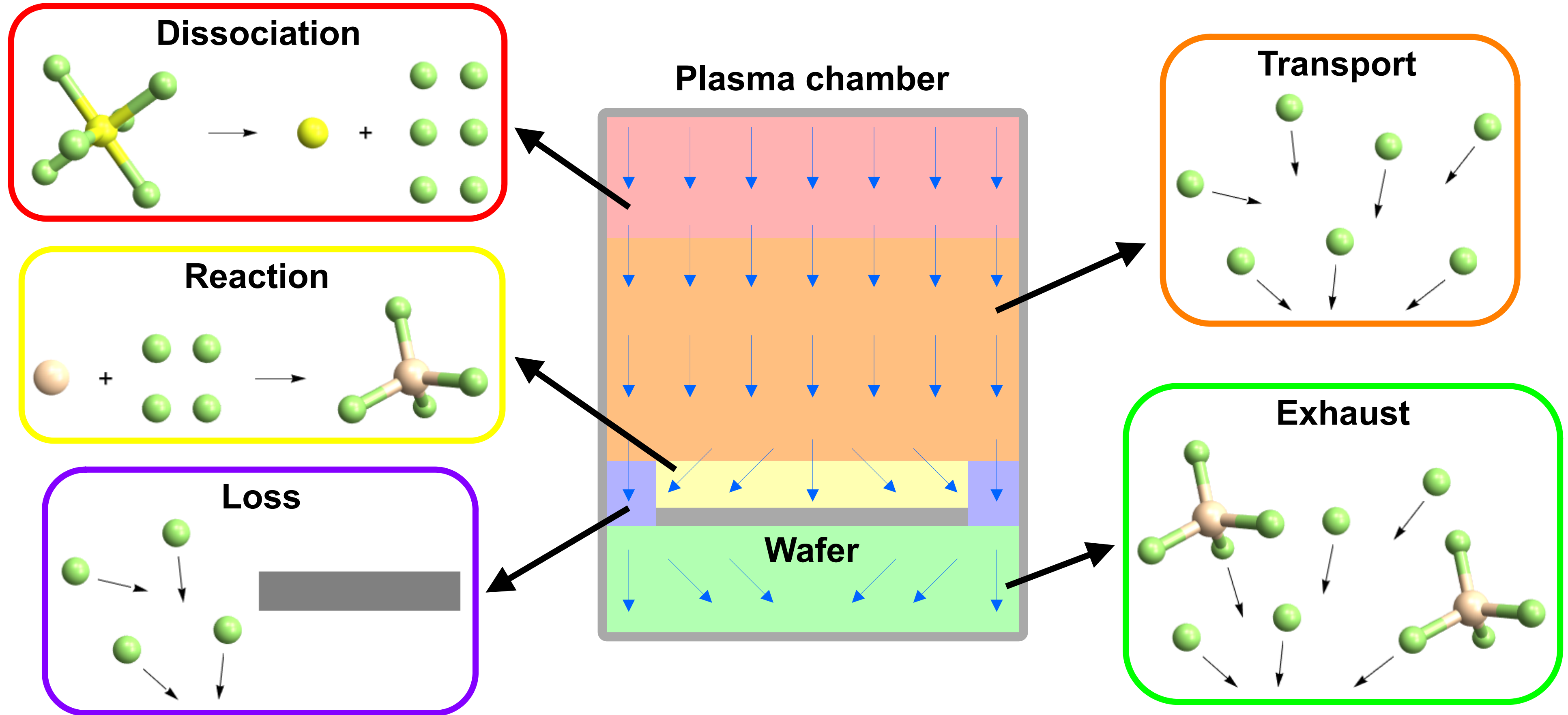


Chemical Process Model: Energy for Dissociation

- Source power determines the degree to which the process gas dissociates.

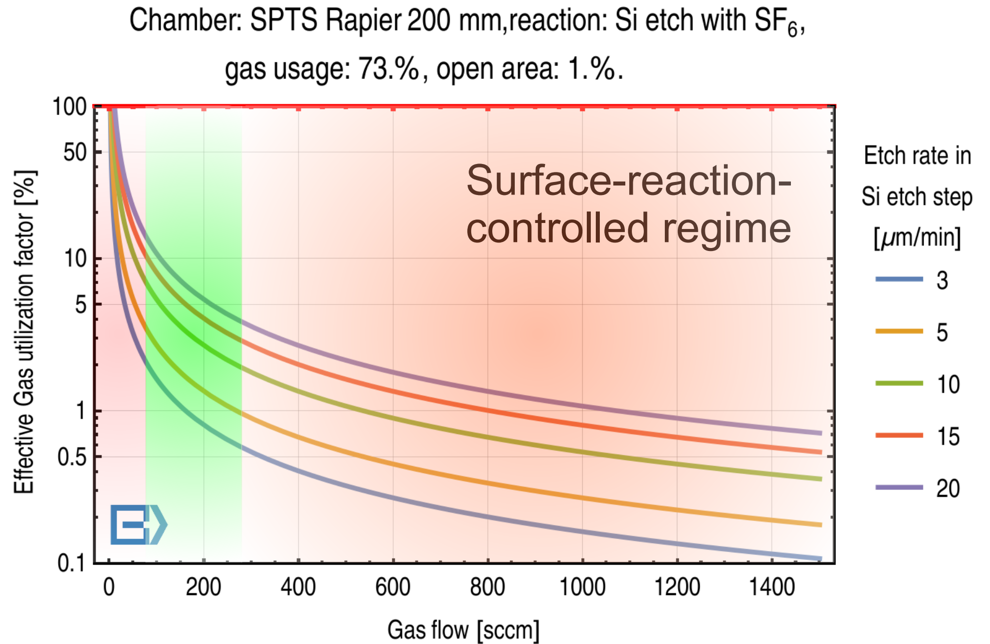


Advanced Process Model: Process Zones



Advanced Process Model: Typical Results

- The effective gas utilisation factor and etch rate vs. gas flow and open area.
- On the right hand side, the process is limited by the surface chemistry rate.
  - The Etch Rate is controlled by the pace of surface reactions
  - High gas flows means low effective utilization factor → increase of waste
- On the left hand side, the process is controlled by transport of the species to the surface.
  - Each radical that reaches the surface reacts immediately!
  - Small changes in gas flow lead to large changes in utilization factor→ stability?



T. Dikacz et al., "Chemical Models and Energy Balance for Optimal Gas Utilisation". Sustainable Plasma Technologies Workshop, Plasmetrex GmbH. November 4th 2025, Berlin, Germany.

Chemical Process Model: Comparing Numbers

- For an open area of 1%, only a small fraction of incoming gas actually reacts on the wafer.

Small open area … 1 %

Process of Record → Si ER ~ 5.3 µm/min.

Large open area … 68%

Process of Record → Si ER ~ 16 µm/min.

Energy required per molecule: 28.3 eV
Energy available per molecule:
P_{source} / $I_{gas,total}$ [eV] = 61.1

Small open area	
Process gas flux directly used SF6 [sccm] =	2.08
Utilization factor process gas SF6 [%] =	0.26

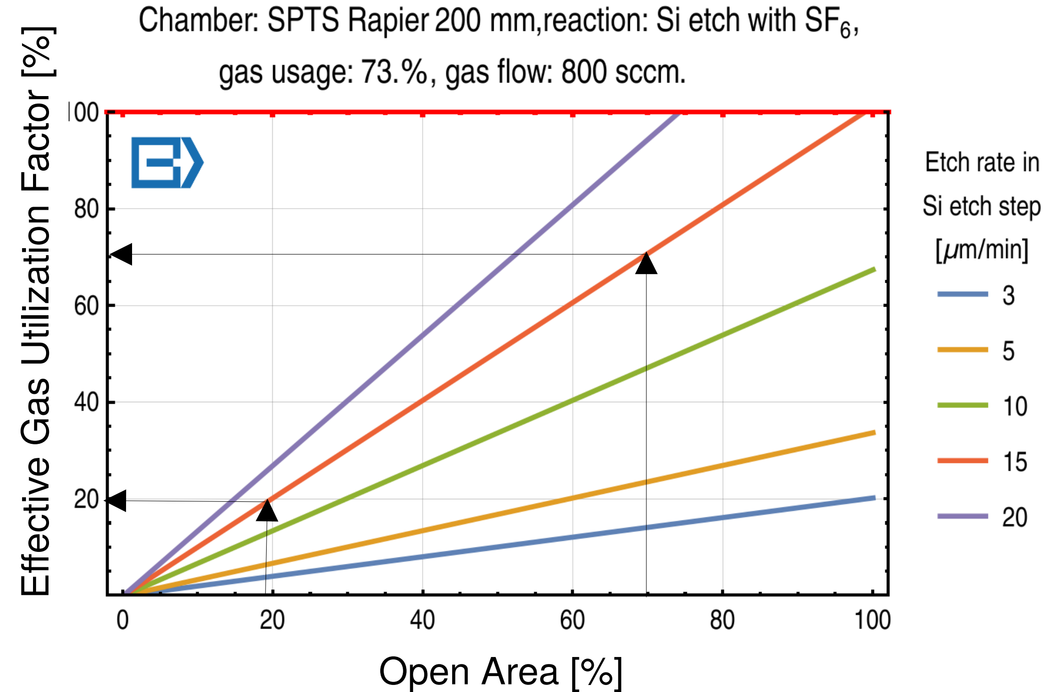
Large open area	
Process gas flux directly used SF6 [sccm] =	432.
Utilization factor process gas SF6 [%] =	54.

Radicals are oversupplied
Surface-reaction-controlled process

Radicals are depleted
Transport-controlled process

Gas Utilization vs. Open Area

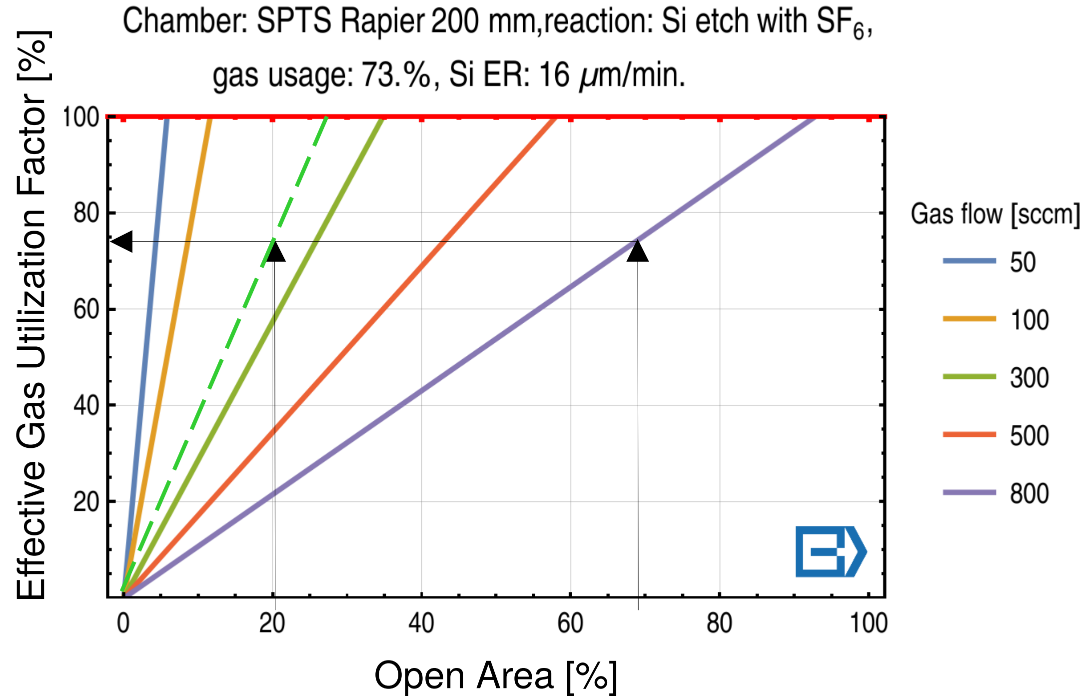
- The model shows that if the open area is reduced with constant gas flow and Power, the gas utilization factor will drop adequately.
- Example: Open Area of 68% → Utilization factor approx. 70% Open Area 20% → Utilization 20% in the best case.
- 80% of the produced radical fly to the exhaust without reacting!
- In the worse case, there will be additionally a process regime to "Chemistry limited process" that will also lead to slower etch!



Gas Utilization vs. Open Area

- When the Open Area is reduced, the most important parameter to change is the flow!

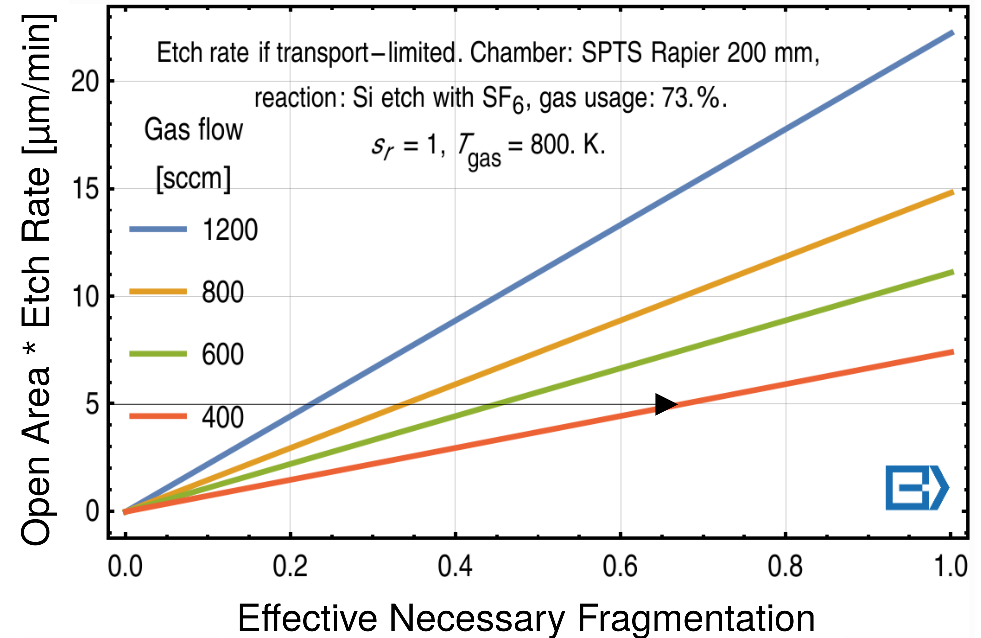
- Example: Open Area of 68% / 800 sccm SF6 → Utilization factor approx. 70% Open Area 20% / approx. 280 sccm → Utilization 70% in the best case.
  → No waste of radicals!



Open Area vs. Source Power

- If the flow of gas is decreased while keeping the product Open Area x ER constant, automatically the degree of fragmentation increases

- There is now more energy per molecule.

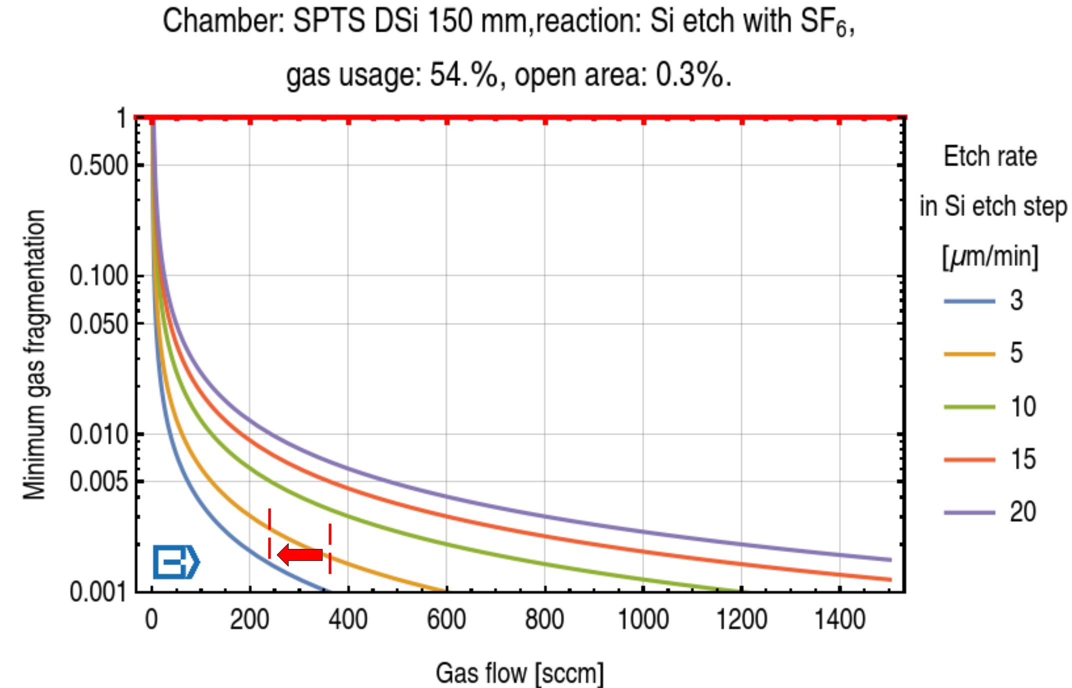


Implementation: DSi Etch

- SPTS 150mm Dsi: 380 sccm SF_6/ 2.5kW Source. Open Area 0.3%. ER= 4.6 µm/min (orange).

- This process is already in the surface-reaction limited regime.
- The required fragmentation of is about 0.2 %.
  - The flow of F radicals (SF_6) can be reduced for higher efficiency.

- As a proof of concept, 100 sccm SF_6 where replaced by 100 sccm Ar, keeping all other parameters constant.



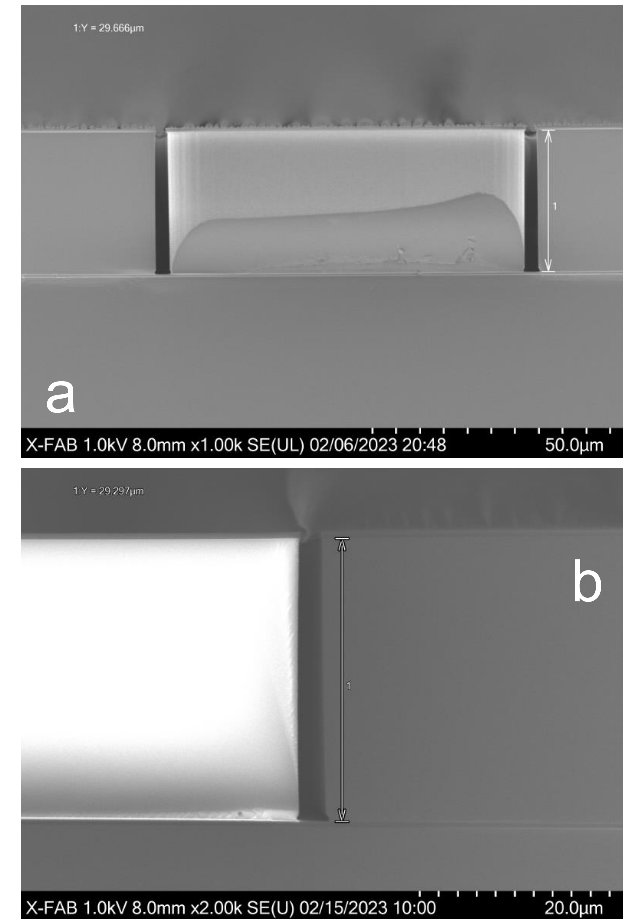
Implementation: DSi Etch

	Standard Process (a)	Optimized Process (b)
Step 1	330 sccm SF_6	230 sccm SF_6 + 100 sccm Ar
Step 2	430 sccm SF_6	330 sccm + 100 sccm Ar.

- ER – no significant difference
  - Etch depth:

    Standard Process (a) 29.7 µm

    Optimized Process (b) 29.3 µm



Summary

- The chemical process model links recipe parameters, chamber geometry, and reaction chemistry to predict gas utilisation and energy efficiency.

- This enables to identify the actual process regime: Reactive oversupply and depletion depending on the amount of material to be etched
  - Small Open Area → surface-reaction-controlled, radicals oversupply → Waste of Gas and Power
  - Large Open Area → transport-controlled, depletion increase of flow / power can lead to faster ER

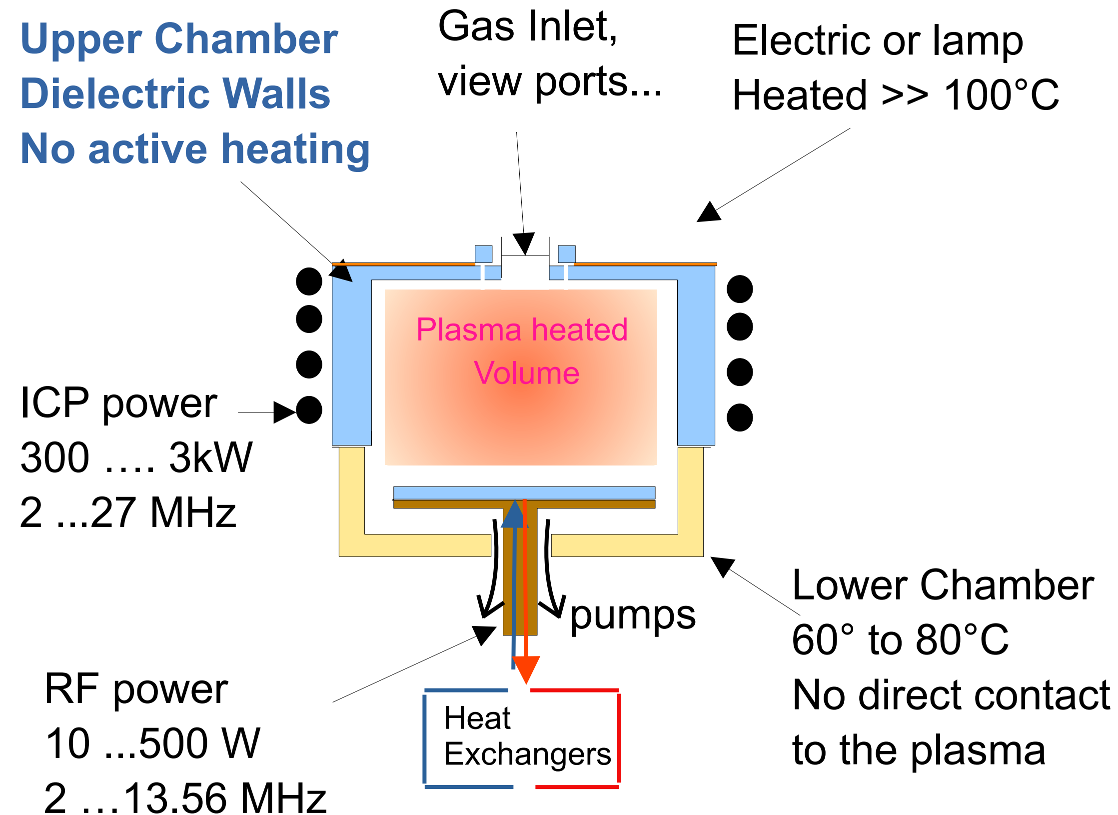
- The model results show that gas flow can be reduced without reducing etch rate, lowering both process cost and greenhouse-gas emissions.

Chamber Dry Clean: How much is enough? Example: Microelectronics

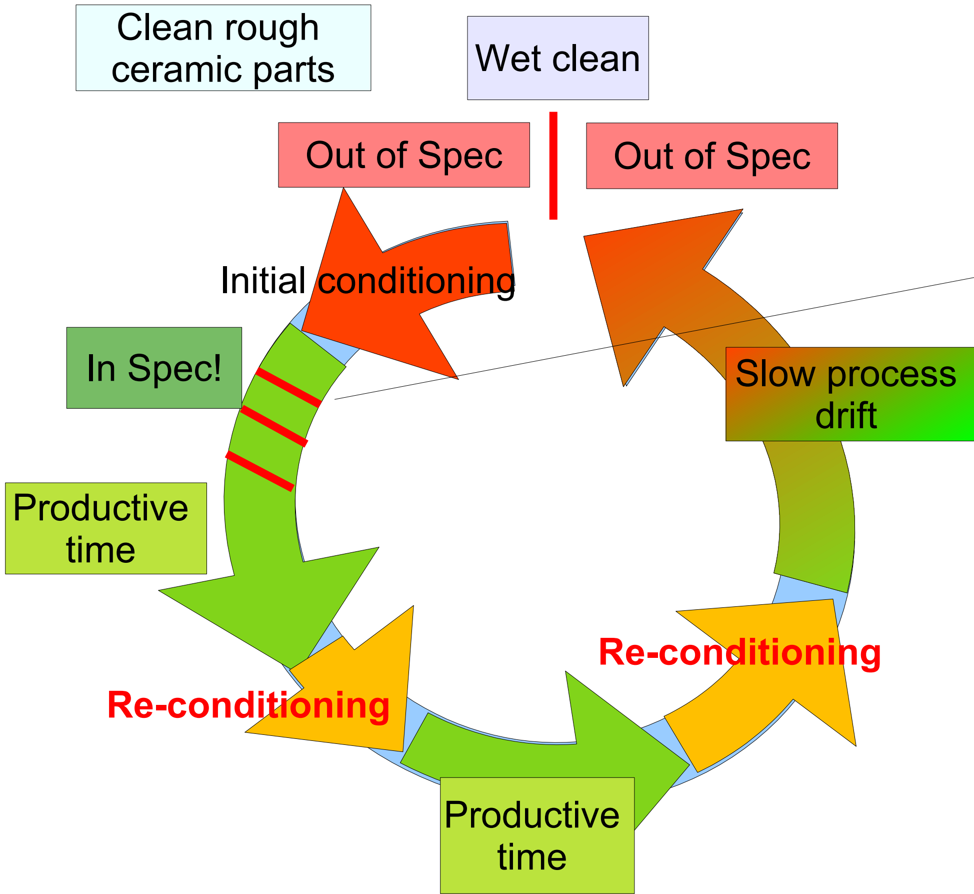
- Running chamber dry clean ensures that each wafer is processed under the same chamber conditions. It provides as well a long term stability and increases the mean time between clean, MTBC.
- At a same time, it requires engineering efforts, increases the consumption of high Global Warming Potential (GWP) gases and of raw material (Wafer, PR,…) and none of what is neutral to the environment.
- Dry cleans are intended bring the chamber to a "state" at which the process is performing as expected. Interestingly, This chamber state is mostly sensed indirectly, by performing tests on wafers, ER, particles,...
- Is this the right way to go?

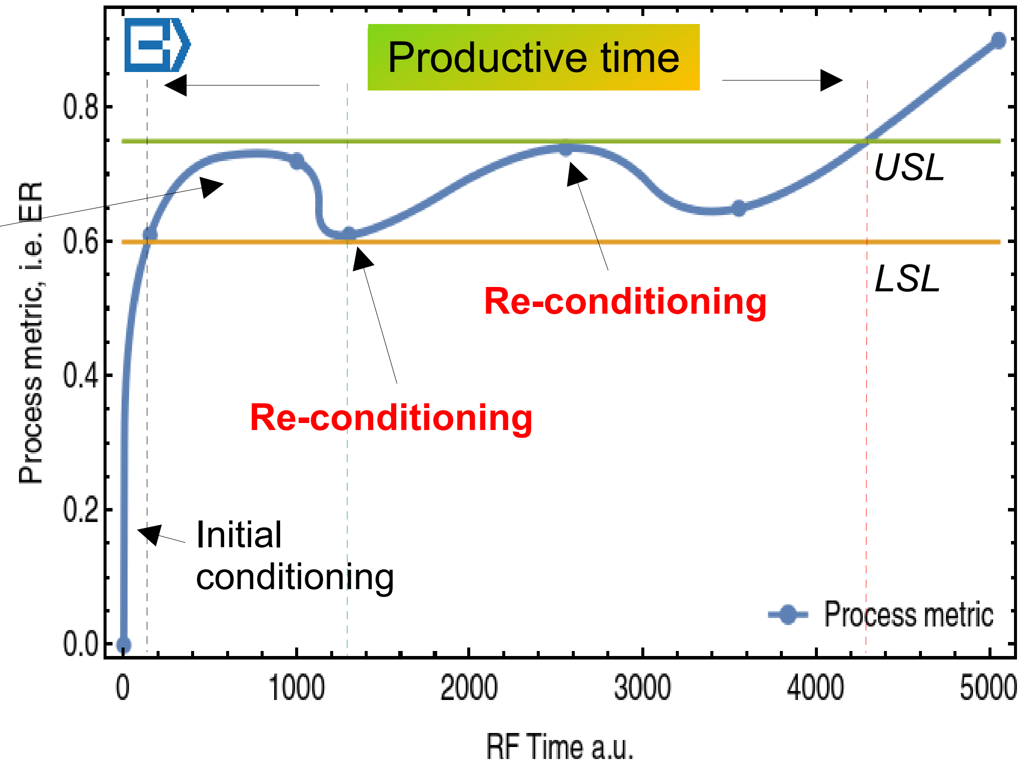
Case Study: Dry Cleans in an Etch ICP Reactor

- Chamber using Dry Cleans
  - No upper chamber heating
  - Optional Induction plate electrical heating
  - Waferless dry clean after x wafer
  - Usual dry clean gas: NF_3 (not only)
  - Short initial conditioning and re-conditioning later.
  - Chamber state "floating" within limits but steady by-products built up.
  - Process is allowed to drift within limits, request sharp monitoring.



Overview of a Production Cycle with Chamber Dry Cleans

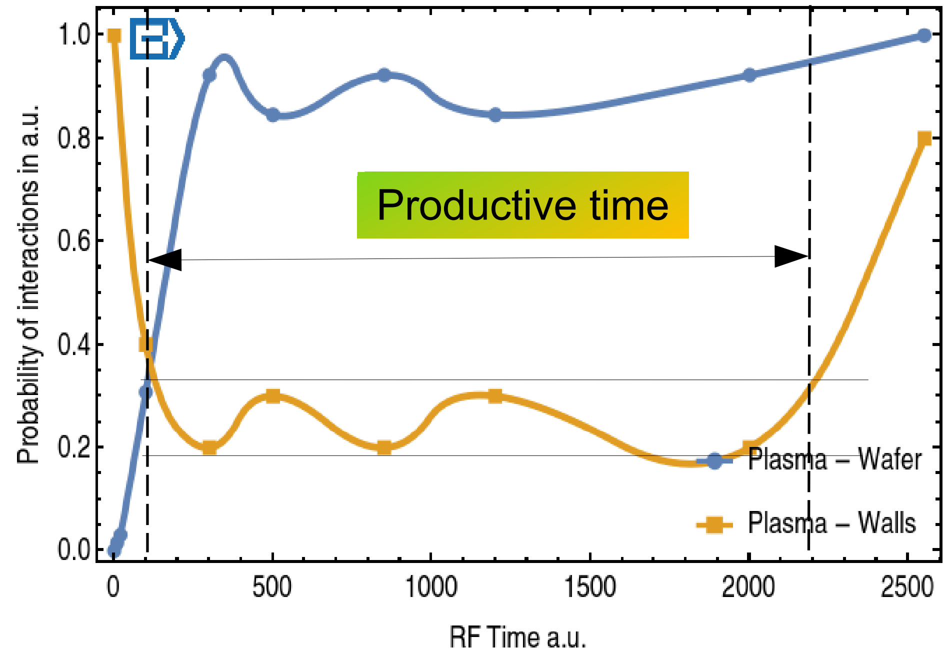




M. Lapeyrade et al., "Recovering after Chamber Wet Clean: Sustainability through Controllability". Sustainable Plasma Technologies Workshop, Plasmetrex GmbH. November 4th 2025, Berlin, Germany.

The Key Point: Interactions Plasma – Walls

- The state to find is where:
  - Interactions Plasma - Walls are minimum.
  - A Wafer metric can only indirectly pick up the point.
- What is the adequate **metric?**
  - To quantify the **probability of Interactions Plasma – Walls?**
  - **How do I define the "state"** where my process can be run within specifications?



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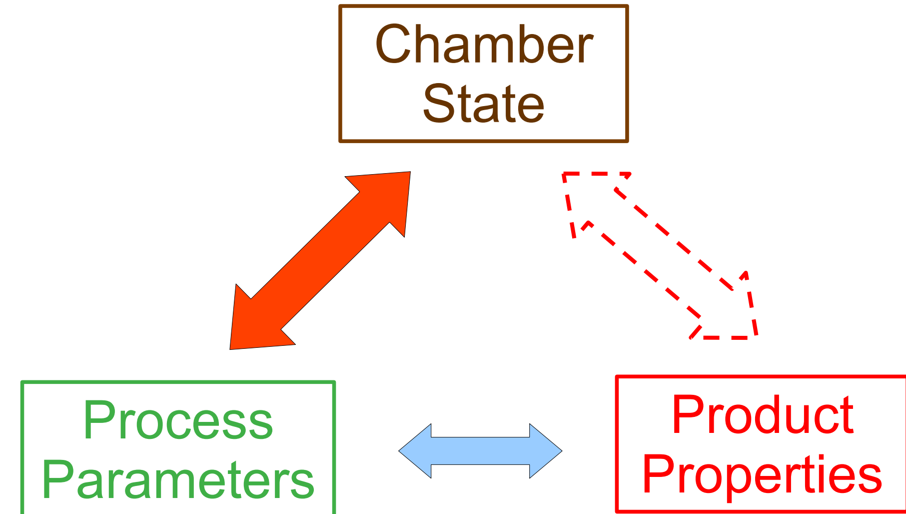
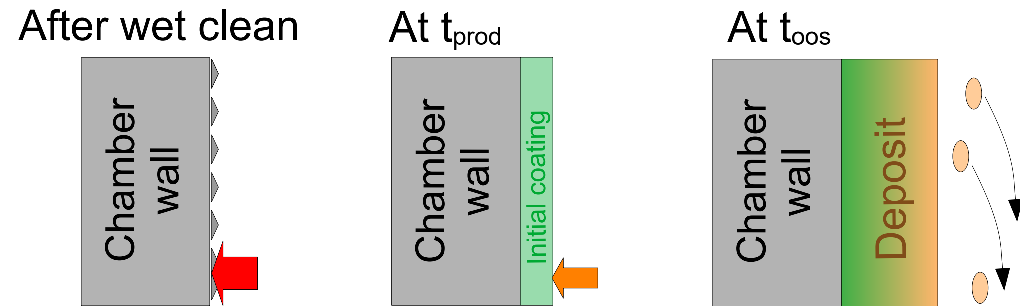
Process and Equipment Interaction: Defining the “Normal” State

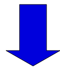
- During a wet clean, clean ceramic parts are inserted others are washed with solvents. Rough clean walls are not atomically clean and will interact strongly with the active species from the plasma.
- Adsorption and desorption will take place, as well as chemical reactions like etching and deposition until a thin stable layer covers the full surface. This layer behaves “quasi-neutral” against the plasma.
- ***The 'normal' state is the state in which the process was qualified!***
- The goal of conditioning is to bring the chamber in the state at which the process was developed.
- Without any chamber monitoring with adequate sensors, It is very tricky to find a good and cheap solution for the conditioning.

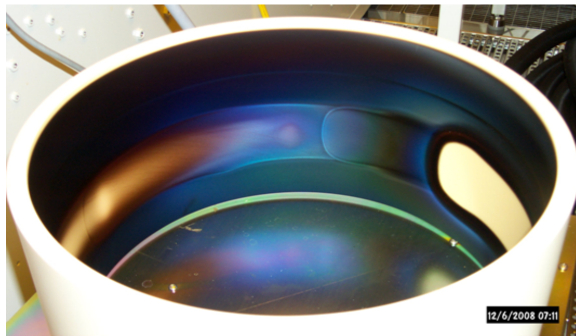




What is Influencing the Plasma?

Manufacturing cycle





Influencing the Plasma:

- Chemical activity of chamber walls
  - Adsorption and desorption
  - Recombination of neutrals and ions
- Secondary electron emission
  - Depends on the wall material
  - Plasma density close to wall → uniformity
- Gas flow change due to roughness
  - Primarily for high gas flow
  - Gas distribution in the chamber
  - Loading effects → uniformity
- Gas temperature
  - Heat flow plasma → gas → chamber wall / liner
  - Affects all of the above
- **All these affect the Plasma Density significantly!**

Monitoring the Chamber State With Plasma Parameters

- Plasma key parameter: the density of neutrals n_n . Controlled by the pressure p, by the gas temperature T_{gas} and by the gas flow (MFC).

- In the case of interactions Plasma-Walls there are additional flows:
  - a) coming from the walls
  - b) going to the walls

$$n_n = \frac{P_{gas}}{T_{gas}} = \left[\frac{q_{pV}(T_0)}{T_0} + I_p^{walls} \right] \cdot \frac{1}{S_{eff}}$$

MFC (→ $q_{pV}(T_0)$); Pressure Control (→ $\frac{1}{S_{eff}}$); walls (→ I_p^{walls})

- When the density is increasing, electrons find more collision partners (inversely when decreasing), the collision rate changes linearly with n_n.

$$\nu_e = \bar{v}_e n_{gas} \sigma_{e,gas} = \bar{v}_e \sigma_{e,gas} \frac{p}{T_{gas}}$$

Kept constant (→ p); Collision rate (→ ν_e); Thermal velocity of electrons (→ $\bar{v}_e$)

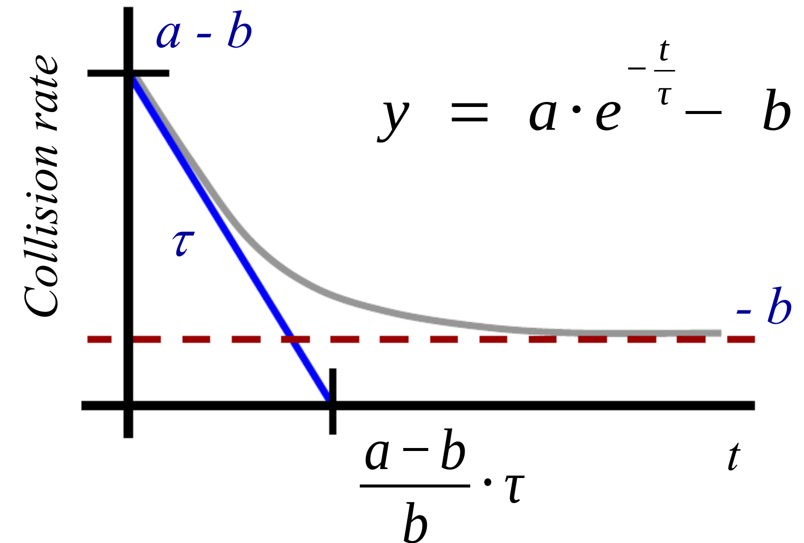
- Gas Heating Mechanisms:
  - Heavy particle collisions
    - Fast ions → neutral in boundary sheath
  - Electron → neutral collisions
    - In the hot skin layer

- **But :** $T_{gas} \neq T_{wall}$

Monitoring the Chamber State with the Electron Collision Rate

- The typical evolution of the electron collision rate with time when material is etched from the walls is an exponential decay.

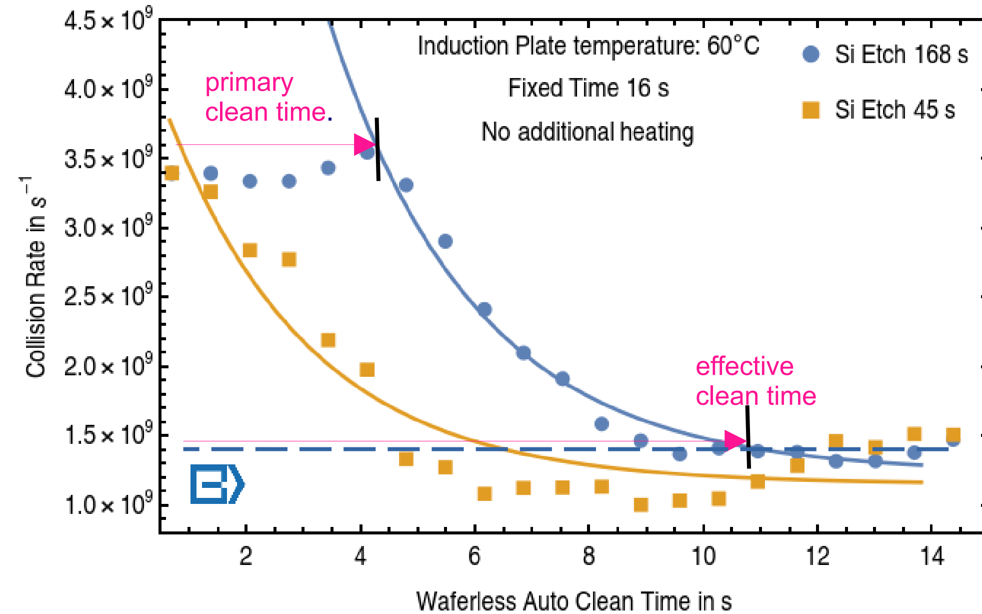
- Many parameters can be extracted using an exponential decay model:
  - **The ground level of the chamber →** **$t \rightarrow \infty$; $y \rightarrow -b$**. No significant flux from or to the walls.
  - **$t = 0$; $y = a - b$;** knowing b , a can be calculated
  - **$t = \tau$;** (the time constant), $y \approx y_0/e$ Speed at which the residues are cleaned off the walls.



- Process Stop Criteria can be calculated (and not “guessed”). Examples:
- $t_{stop} = (a-b)/b\ \tau$
- $y - b < 1\%$

Collision Rate vs. Process Time at LAM 2300 Kiyo

- Collision rate during Waferless Auto Clean (WAC) after long/short Si Etch.
- Long Si Etch: ν is constant during 4.5 s. No change in the gas phase → Flow from the walls is constant during the etch of the deposited layer: Primary clean time.
- After 4.5 s, exponential decay constants are fairly identical at a value of 2.5 s for both processes. → Flow from the walls is decreasing
- After 11 s WAC process (6 s respectively), the collision rate levels off 1.5 10^9 s^{-1}. Chamber walls are at ground state



Influence of the Top Chamber Window Temperature on the STI Etch Process, D. Shamiryan, E. Danilkin, S. Tinck, M. Klick, A. Milenin, M.R. Baklanov, T.W. Boullart, ECS Transcations, 27 (1) 731 - 736 (2010)

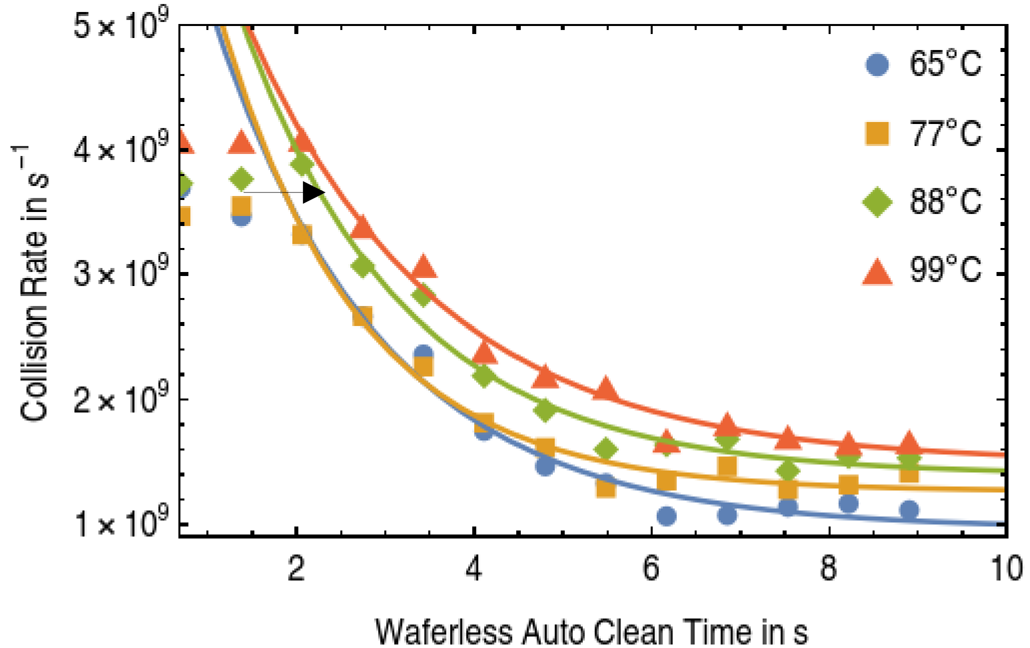
Collision Rate vs. Quartz Plate Temperature at LAM 2300 Kiyo

- The diagram shows the collision rate measured during (WAC process) after 4 wafers processed with short Si Etch at different quartz plate temperature between 65°C and 99°C. No Chamber Wall heating.

- Higher plate temperature → slightly longer primary clean time.
  - Less deposition on the window means more deposition on the walls.

- The decay rate depends on the temperature:

T°C	65	77	88	99
τ	1.55	1.57	1.84	2.13



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Conclusions

- Optimizing the dry clean process (WAC) is a matter of monitoring the interactions between Walls and Plasma to achieve an accurate real time control of the chamber state.

- A parameter that is close to the plasma is necessary, such as the electron collision rate, provides a good metric for a reliable monitoring.

- With this metric, strategies (process, hardware, …,) can be developed to minimize the time required to reach the steady state, reduce the consumption of GHG and increase the productive time.

Thank you for your attention!

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