Reactor design for large area, thin film silicon deposition

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start by acknowledging:
Christoph Hollenstein, Laurent Sansonnens, Jacques Schmitt, Benjamin Strahm

I. **Introduction to plasma deposition of μc-Si:H. Upscaling from laboratory to production.** Gas uniformity in showerhead reactors.

II. Zero-dimension model: The "plasma dimension". Silane depletion. Importance of gas composition in the plasma.

III. Electromagnetic uniformity: finite RF wavelength in large area, VHF reactors.

IV. Time uniformity: rapid equilibration to steady-state process parameters. Direct pumping.

V. So where is the problem? Causes of non-uniformity. Some recommendations.

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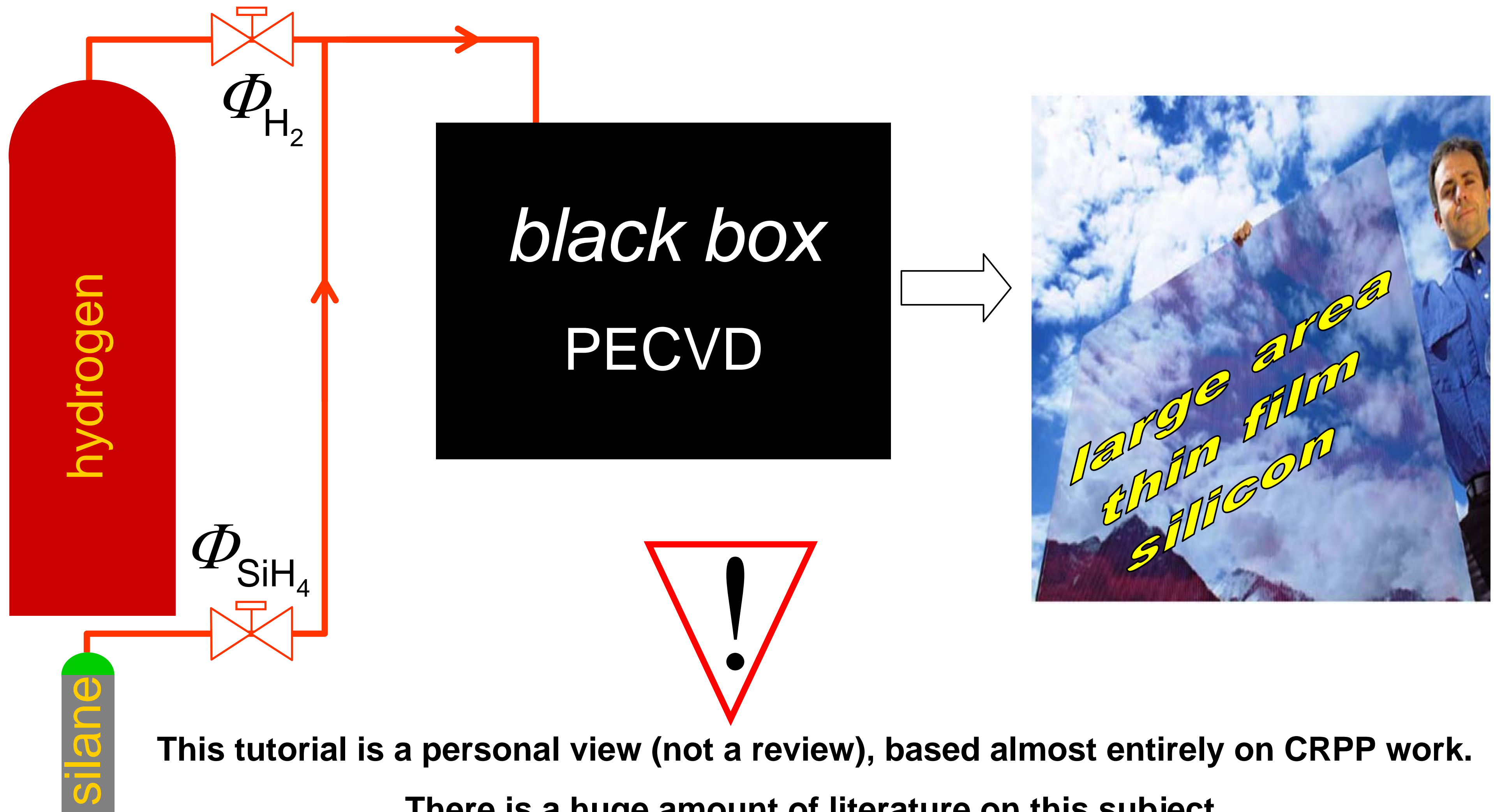
Plasma-Enhanced Chemical Vapour Deposition of thin film silicon

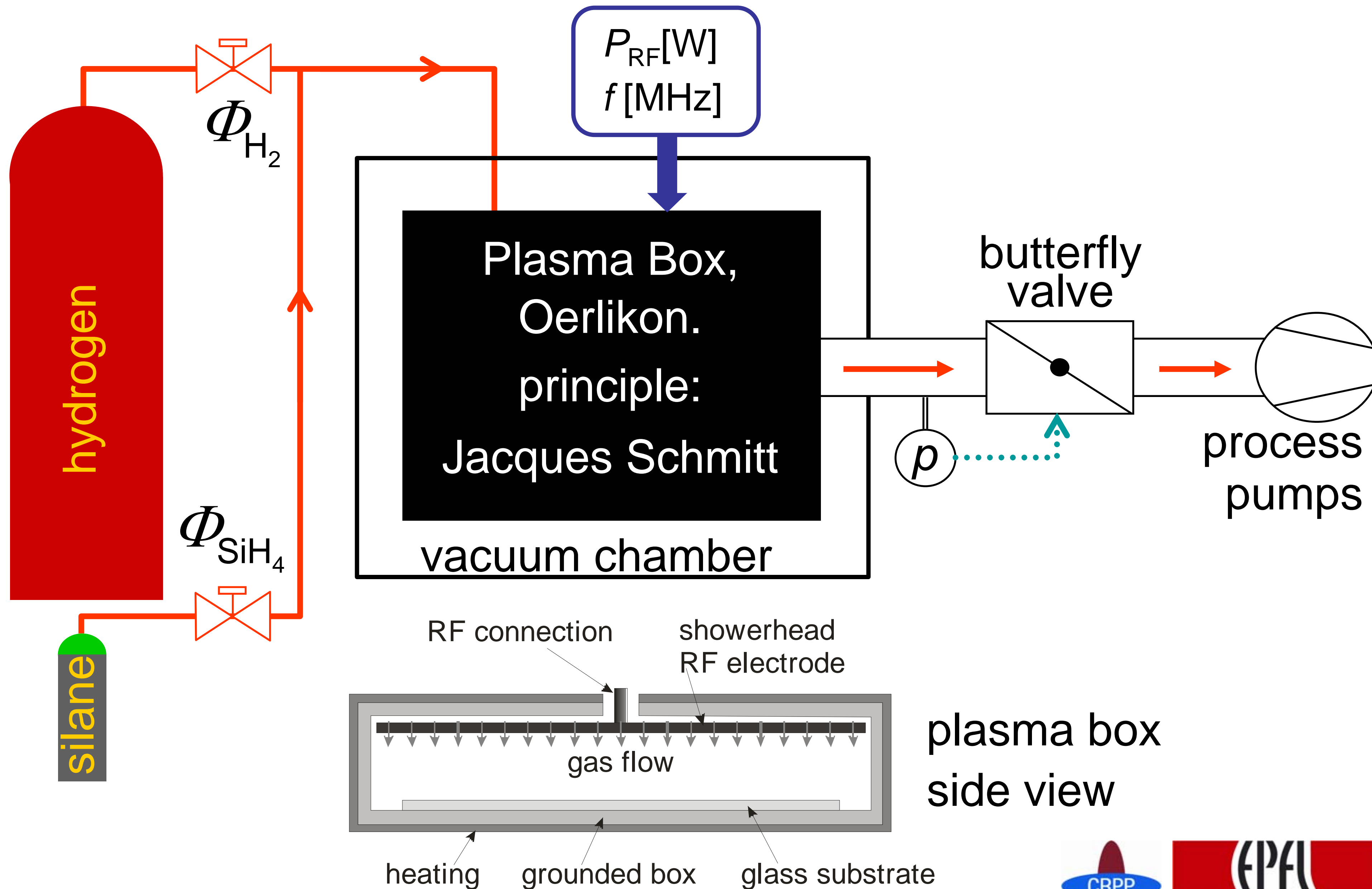


This tutorial is a personal view (not a review), based almost entirely on CRPP work.

There is a huge amount of literature on this subject,

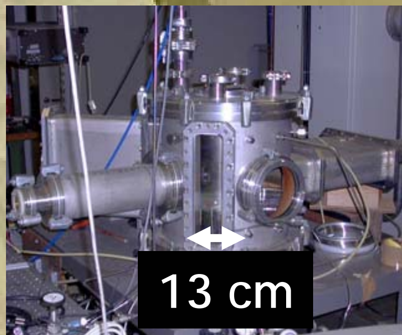
including work at Utrecht University by Professor W. J. Goedheer and colleagues.

PECVD capacitive, parallel-plate RF reactor - some typical specificities



Say you have discovered the perfect plasma process conditions for your laboratory device, area 1 cm^2, obtained in your small research reactor, electrode diameter 13 cm (that's your business)

Now you want to produce the same device, but at least 1 m^2, which is >10'000 times bigger (that's our business here)



3 m

Generation 7 glass substrate for multiple flat displays.

adapted from Jacques Schmitt 50th AVS Baltimore 2003

Solar cells: generally Generation 5, about 1.4 m^2.

Solar cell production

Large area (>1m^2)

High deposition rate (amorphous/microcrystalline)

Homogeneous (thickness <5%)

Homogeneous film quality (microcrystallinity)

Gas efficiency

Substrate diagonal trend

diagonal (m)

2

1

0.5

0.2

0.1

45 cm wafers

30 cm wafers

12'' wafers

8'' wafers

1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004

Meanwhile the specifications become tougher !

- particle probability and size further down

- uniformity below 5 % sometimes 1-2 %

J. Schmitt, M. Elyaakoubi, and L. Sansonnens,
Plasma Sources Sci. Technol. **11**, A206 (2002)

How to UPSCALE whilst maintaining PROCESS FIDELITY i.e. the same film properties everywhere?

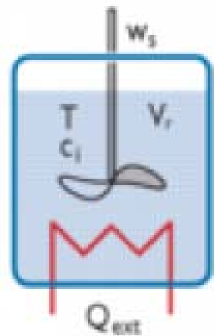
Need UNIFORMITY of thickness, crystallinity, etc, therefore must guarantee same plasma conditions, i.e.

- radical composition and densities
- electron, ion densities
- electron temperature
- RF voltage and power density
- ion bombardment energy

} uniform plasma, +/- 5% or better

...

Ideally require "perfectly-stirred batch reactor" over large area.



Laterally uniform, averaged over reactor height: we require the same plasma everywhere.

=> Need a large area plasma which can be described using a zero-dimensional model.

NB We have implicitly assumed a stationary substrate.

It would be more general to state:

- No plasma uniformity required for a moving plasma torch on a robot arm
- Linear plasma uniformity required for roll-to-roll reactors
- Uniform area plasma source required for batch reactors

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General principle:

Keep the same **intensive** (scale-independent) parameters

- pressure
- substrate temperature
- electrode gap
- gas flow ratios (input concentration)
- RF voltage across the electrodes
- RF frequency
- Gas depletion fraction (see section 2 for measurement method)

Scale up the **extensive** (scale-dependent) parameters in proportion to the increase in area

- gas flow rates
- RF power

... and hope for the best.

Here we will ignore the important mechanical and electrical engineering challenges

- electrode parallelism to +/- 1mm tolerance over 2 x 2 m^2 electrodes
- significant thermal expansion (several mm differential expansion between centre and edge)
- RF power feed-lines for several kW (ohmic heating due to skin currents)
- etc

“Today, the vast majority of PECVD tools in production are still good old RF capacitors” J. Schmitt 50th AVS conference, Baltimore (2003)

- but general approach valid for any dissociation source, whether using plasma (ECR etc) or other (hotwire CVD etc.)

Simplest solution: Buy an ideal showerhead reactor which has:

• Uniform gas inlet flow, uniform pressure, and uniform temperature (isothermal reactor).

• Uniform plasma (laterally over the substrate, not across the gap) of charged and neutral radical and gas species

• Instantaneous plasma equilibration on ignition.

No apologies here for an "old school" approach: We try to guarantee that each parameter is individually uniform, so that the operation window is wide; a robust process.

Constrast this with "empirical compensation" techniques where individual non-uniformities are intended to balance each other out - this leads to very narrow (i.e drift sensitive) operation space; and the parameters have to be re-engineered for any change to the process recipe.

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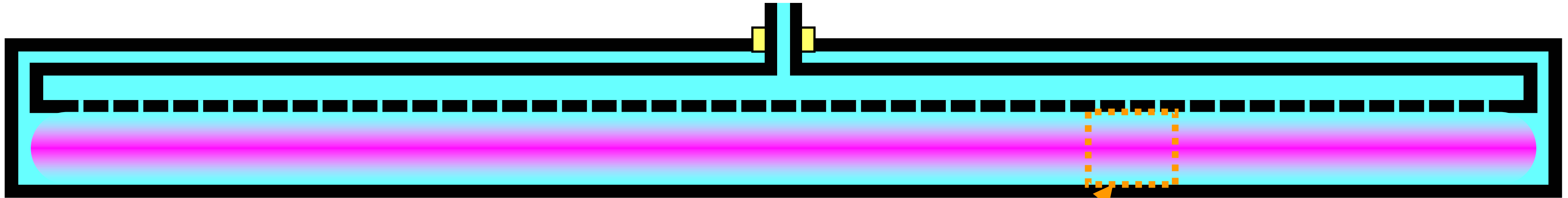
The partial pressures of all species are uniform for a showerhead reactor with a uniform plasma



dn_i/dt = Shower - div(velocity) + destruction + synthesis = 0

If **Shower = uniform**

and **p = uniform** ← No pressure variations due to viscous flow

and **n_e = uniform,** ← Uniform plasma

there exists a uniform solution with constant partial pressure for all species.
A zero-dimensional model can be used.

Jacques Schmitt Orleans ISPC XV 2001.

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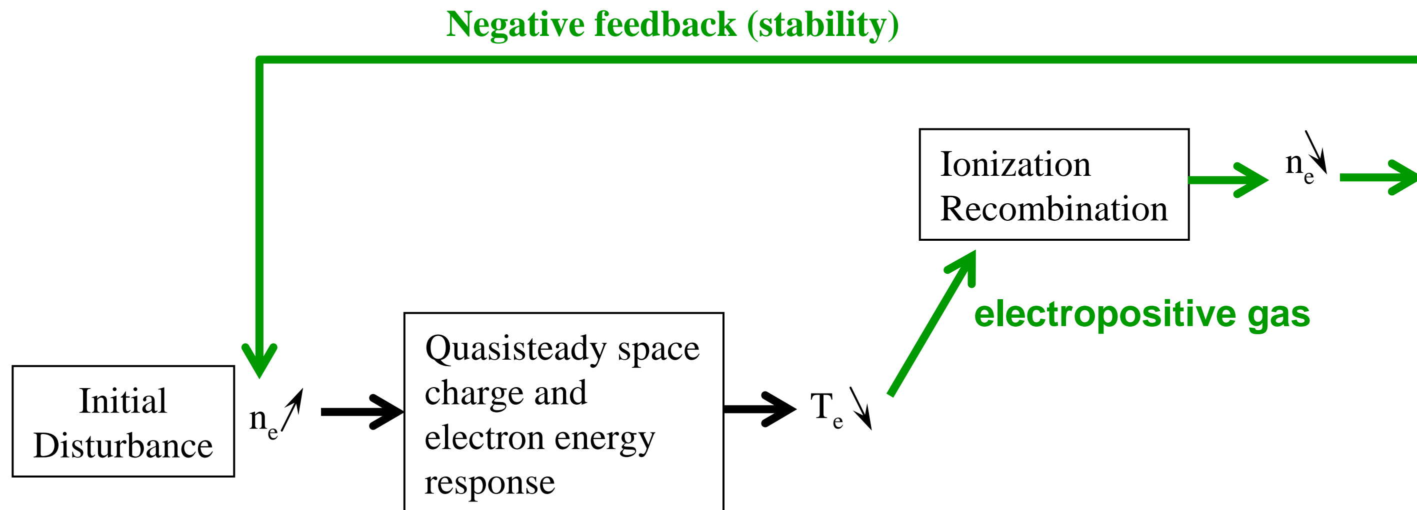
NB We have taken for granted that the plasma can spread out uniformly.

Why does the plasma not shrink to a fluctuating filament?

A negative feedback loop ensures the plasma uniformity in an ideal, uniform reactor :



W. L. Nighan and W. J. Wiegand, *Phys. Rev A* **10**, 922 (1974)
A. Descoeudres, L. Sansonnens, Ch. Hollenstein, *Plasma Sources Sci. Technol.* **12**, 152 (2003)

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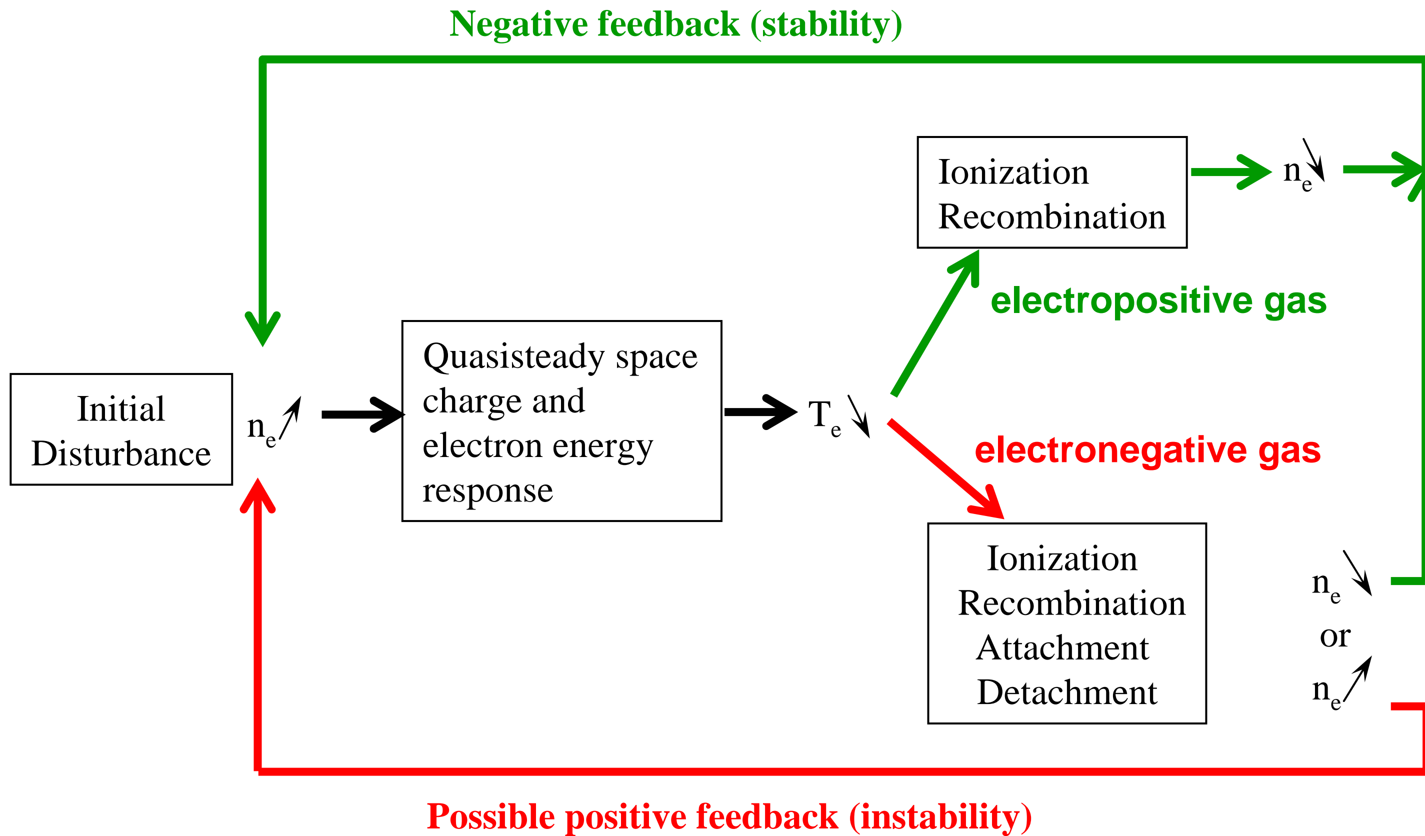
...but some electronegative plasmas (for example, halogen gases for etch-cleaning) can shrink and not reach into the corners. This is related to the attachment instability (positive feedback), and depends on the electron-temperature dependence of the electron-attachment cross-sections.

Proposition: add more electropositive gas to boost the negative feedback loop.



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Intermediate Conclusions

- Use a showerhead reactor with uniformly distributed gas inlet flow Q, and 'uniform pressure'.

The pressure non-uniformity $\frac{\Delta p}{p}$ due to viscosity η is given by $\frac{\Delta p}{p} \approx \frac{6\eta Q}{H^3 p^2}$, for electrode gap H.

'Uniform pressure' therefore requires:

- flow rate not too high;
- pressure not too low;
- electrode gap not too small (inverse cube dependence!)

- A plasma which is unstable (to infinitesimal perturbations in n_e or T_e) will not be uniform even in a perfectly-uniform reactor (eg some types of electronegative gas plasmas).

Ref. L. Sansonnens, A. A. Howling, Ch. Hollenstein, *Plasma Sources Sci. Technol.* **9**, 205 (2000).