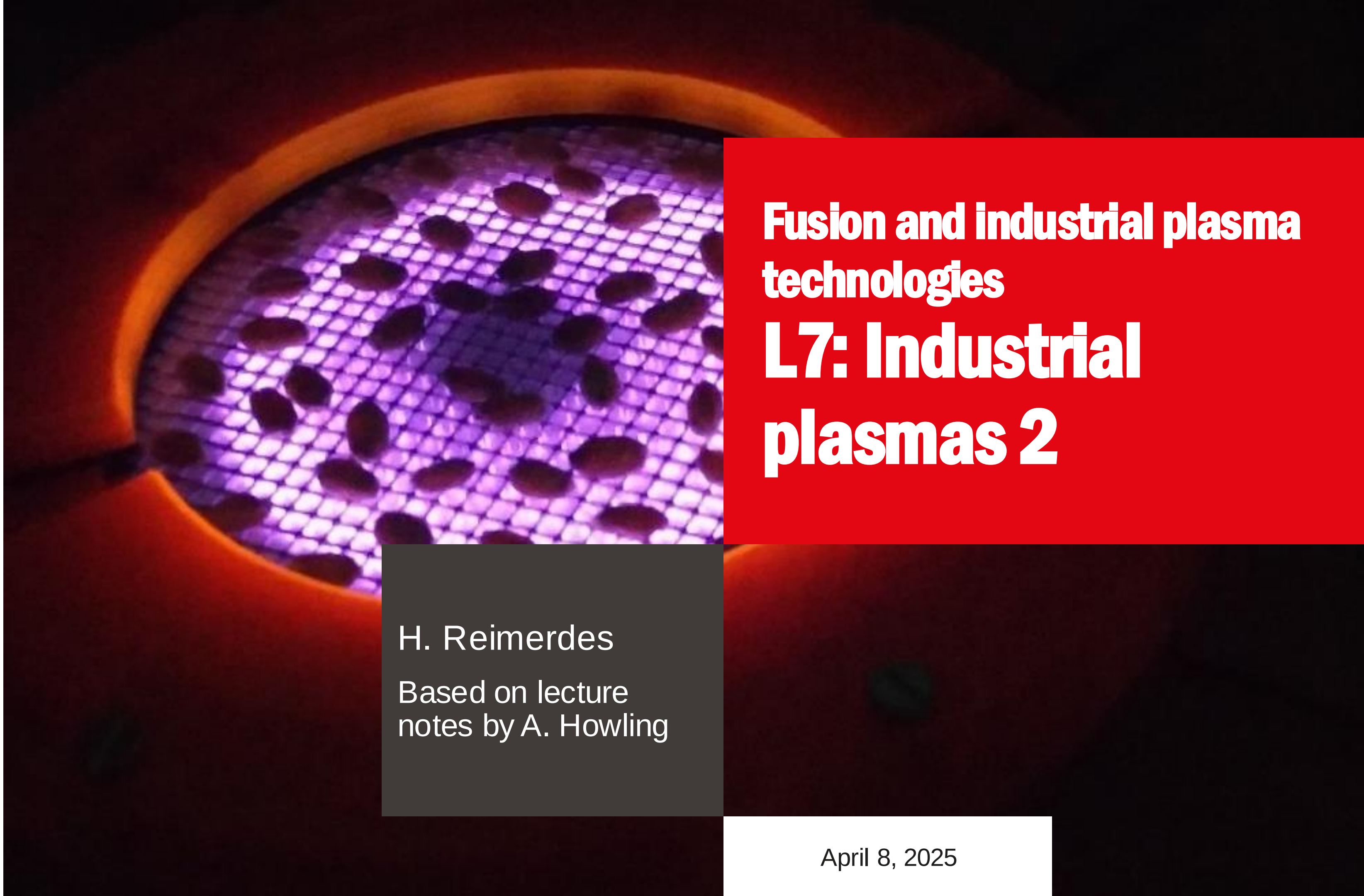
EPFL



Fusion and industrial plasma technologies

L7: Industrial plasmas 2

H. Reimerdes

Based on lecture notes by A. Howling

April 8, 2025

Swiss Plasma Center

Outline

1. Introduction to basic industrial plasmas
   - Plasma medicine
2. Breakdown and Paschen's law
   - Communication satellite
3. Sheath and plasma etching
   - Microelectronics
4. Plasma with insulating electrodes
   - Large area displays/solar cells

L6 (items 1–2)

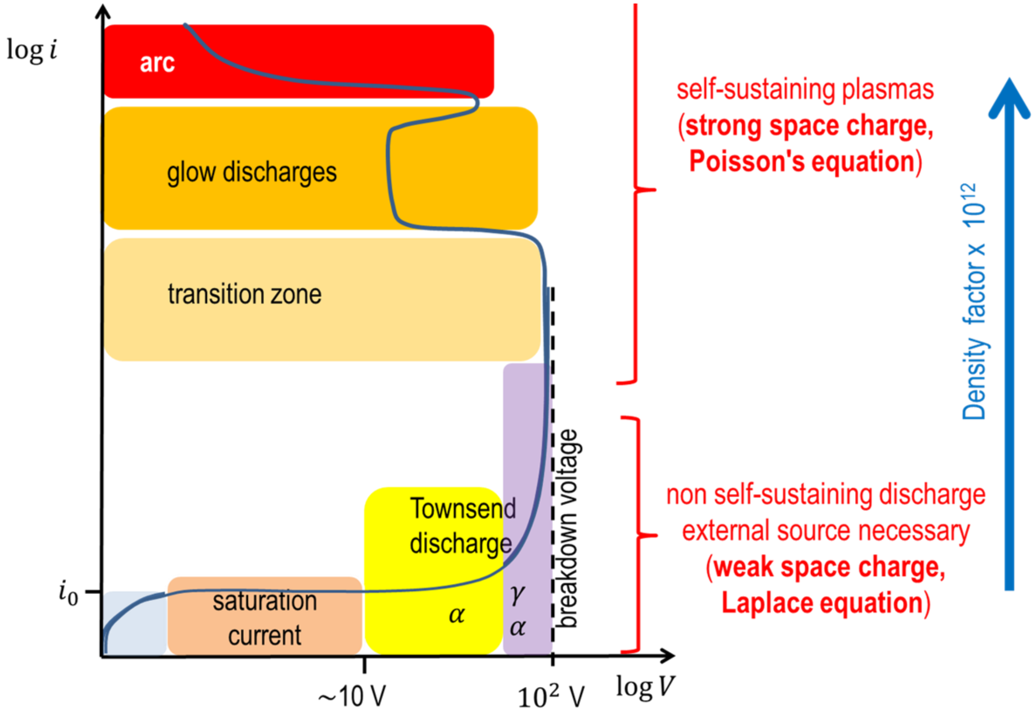
L7 (items 3–4)

Material

- See also EPFL MOOC "Plasma physics: Applications" #5a-g
  - https://courses.edx.org/courses/course-v1:EPFLx+PlasmaApplicationX+1T_2018
- M. Lieberman & A. Lichtenberg, "Principles of plasma discharges and materials processing", Section 6.1-6.2

Formation of a plasma

- Development from Townsend discharge to plasma glow and arc



Outline

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Reminder: Maxwell-Boltzmann distribution

- Velocity distribution in an ideal gas in thermodynamic equilibrium

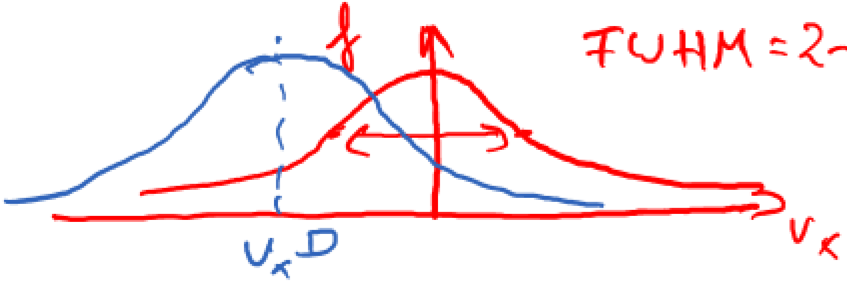
$$f_s(\vec{v}) = \left(\frac{m_s}{2\pi k_B T_s}\right)^{3/2} e^{-\frac{m_s \vec{v}^2}{2k_B T_s}}$$

Distribution of velocity in one direction

$$f_s(v_x) = \iint f_s(v_x, v_y, v_z)\, dv_y\, dv_z \approx \left(\frac{m}{2\pi kT}\right)^{0.5} e^{-\frac{m v_x^2}{2kT}}$$

Gaussian with $\sigma^2 = \frac{kT}{m}$

$FWHM = 2\sqrt{2\ln 2}\cdot\sigma$



Reminder: Maxwell-Boltzmann distribution

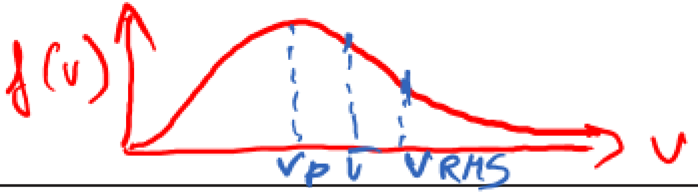
- Velocity distribution in an ideal gas in thermodynamic equilibrium

$$f_s(\vec{v}) = \left(\frac{m_s}{2\pi k_B T_s}\right)^{3/2} e^{-\frac{m_s \vec{v}^2}{2 k_B T_s}}$$

Distribution of speed $v = |\vec{v}|$

$v = \sqrt{v_x^2 + v_y^2 + v_z^2}$: $dv_x dv_y dv_z = v^2 dv \, d\Omega$ ← 4π

$$f(v) = \left(\frac{m}{2\pi k_B T}\right)^{3/2} 4\pi v^2 e^{-\frac{mv^2}{2k_B T}}$$



$v_p = \sqrt{\frac{2kT}{m}}$

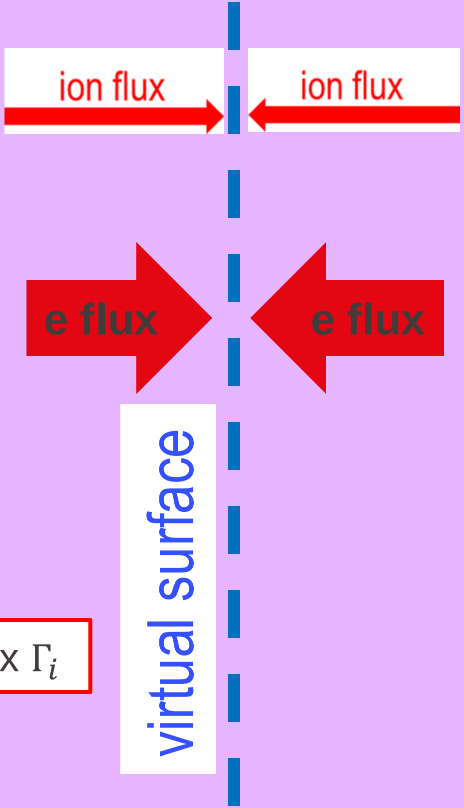
$\bar{v} = \sqrt{\frac{8kT}{\pi m}}$

$v_{rms} = \sqrt{\frac{3kT}{m}}$

Formation of a sheath

Ion thermal flux $\Gamma_i = n_i \frac{\bar{v}_i}{4} = \frac{n_i}{4}\sqrt{\frac{8eT_i}{\pi m_i}}$

Electron thermal flux $\Gamma_e = n_e \frac{\bar{v}_e}{4} = \frac{n_e}{4}\sqrt{\frac{8eT_e}{\pi m_e}}$

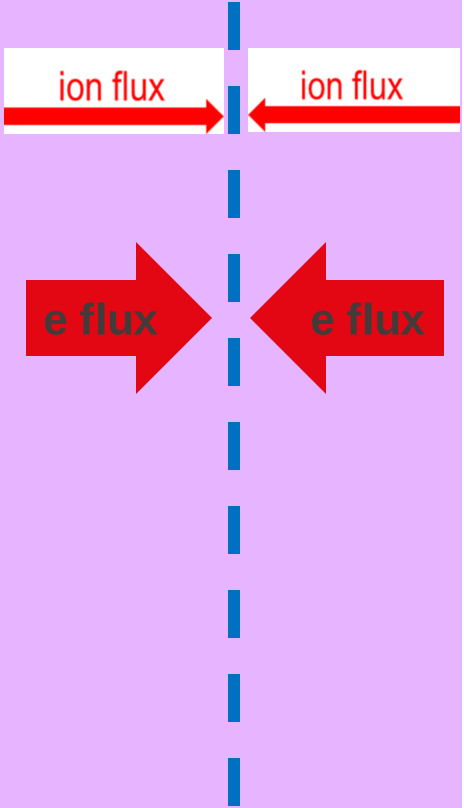


Electron thermal flux $\Gamma_e \gg$ Ion thermal flux Γ_i

Formation of a sheath

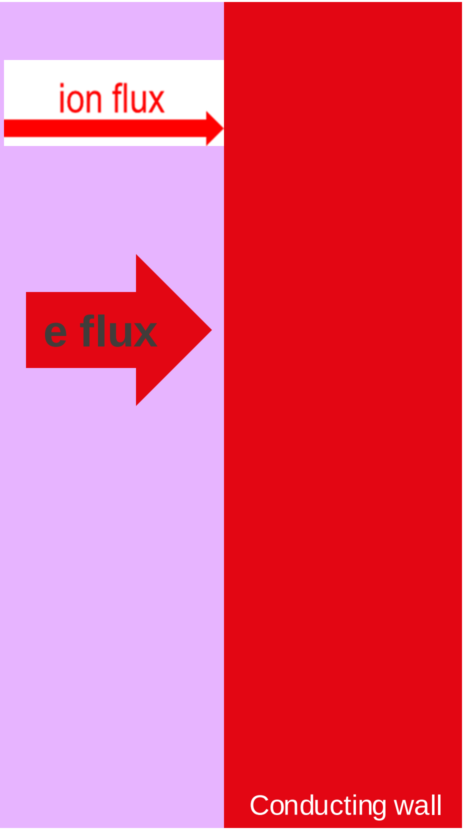
- So far, the plasma was always in isolation from its environment

- However, a plasma-wall interaction is unavoidable and necessary for plasma applications (deposition, etching, surface modifications, etc.)



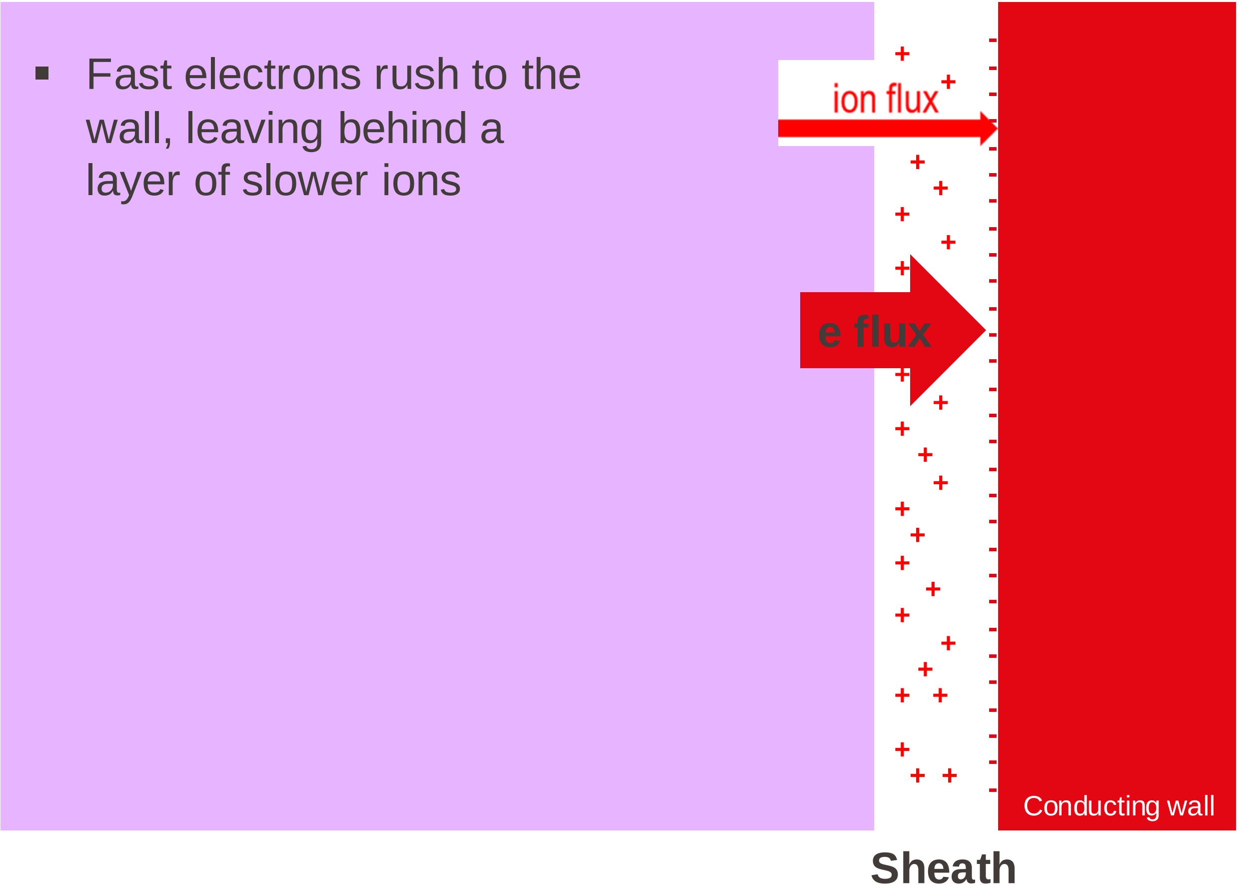
Formation of a sheath

- What happens, if the virtual surface is replaced with a conducting wall?



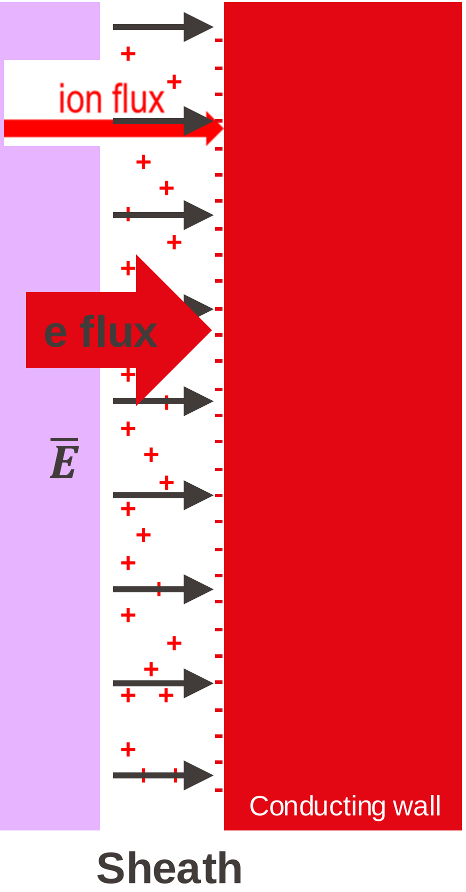
Formation of a sheath

- Fast electrons rush to the wall, leaving behind a layer of slower ions



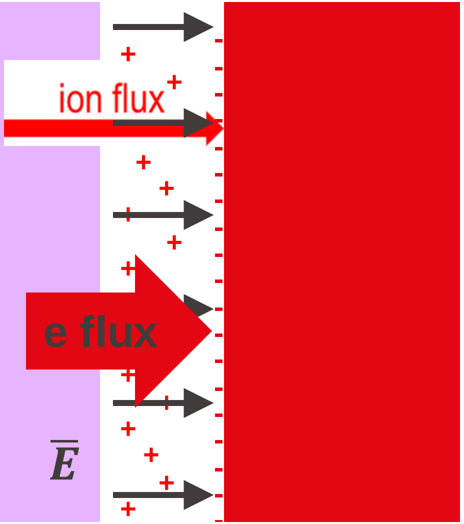
Formation of a sheath

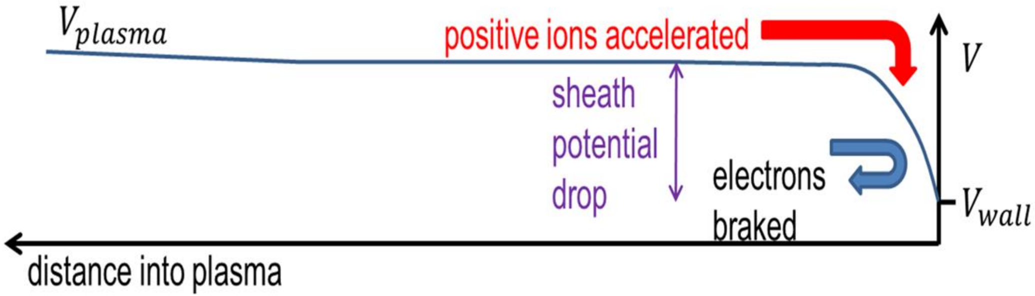
- Fast electrons rush to the wall, leaving behind a layer of slower ions
- Plasma potential increases until fluxes become equal



Formation of a sheath

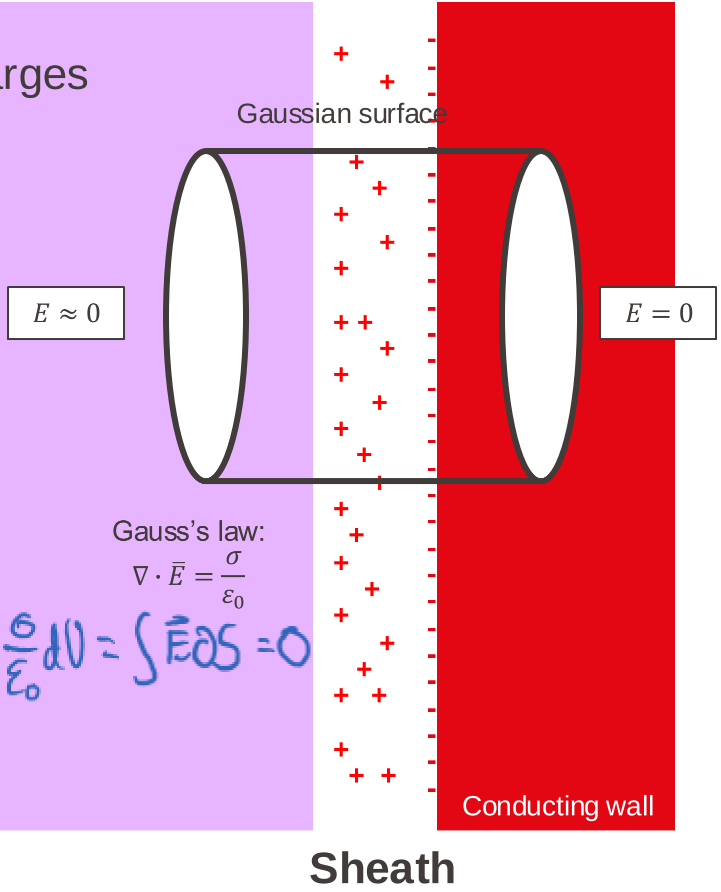
- Fast electrons rush to the wall, leaving behind a layer of slower ions
- Plasma potential increases until fluxes become equal
- Directional ion flux due to sheath electric field





Formation of a sheath

- Volume free of a net-charges



Gauss's law:

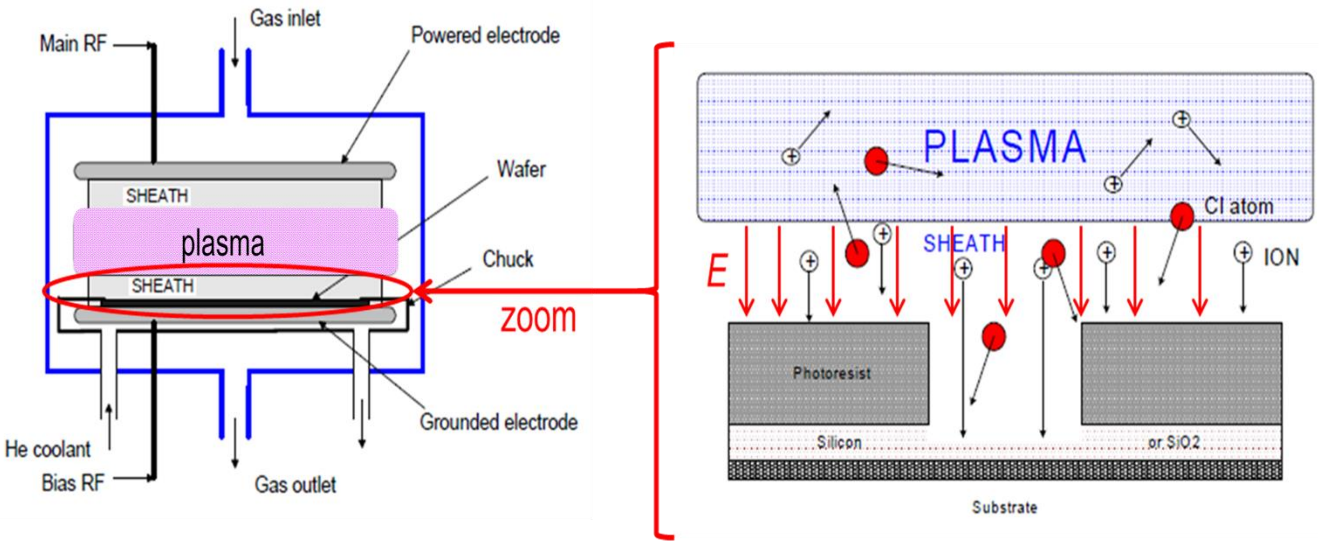
$$\nabla \cdot \bar{E} = \frac{\sigma}{\varepsilon_0}$$

$$\int \frac{\sigma}{\varepsilon_0} dV = \int \vec{E}\, \partial S = 0$$

Some sheath properties

- Sheath provides transition between plasma and wall
- Positive space charge equal and opposite to negative surface charge
- Electric field guarantees ambipolar ion and electron fluxes to wall (floating)
  - Strong electric field and a positive ion flux, normal and directed towards the wall
- Plasma potential is always positive with respect to most positive surface
- Thin layer, several Debye lengths thick, due to Debye screening of sheath potential

Plasma etch applications



- Uniform electric field above a substrate
- Vertical flux of ions
- Photoresist feature ~0.1$\mu m \ll$ sheath width (mm)

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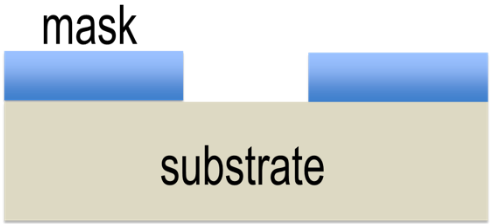
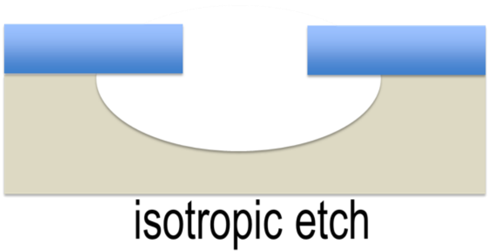
Plasma etch applications

- Examples of high-aspect ratio etching



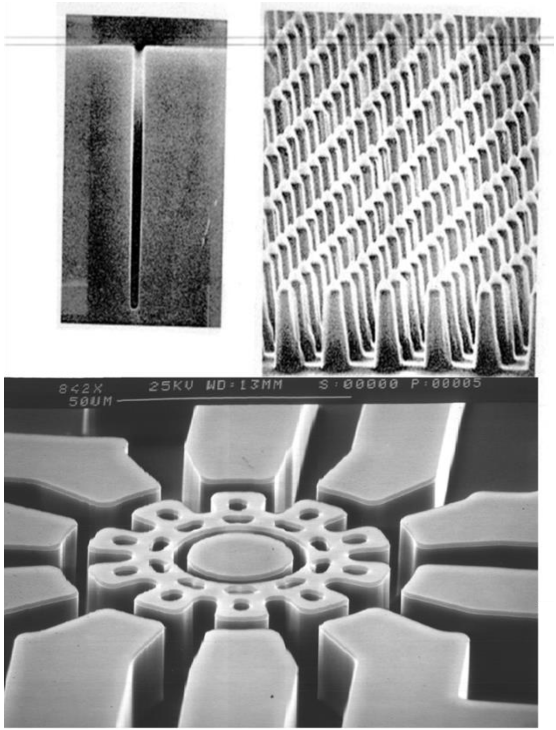
Chemical etching: $A + \mathrm{srfc}[C] \rightarrow AC$

wet process



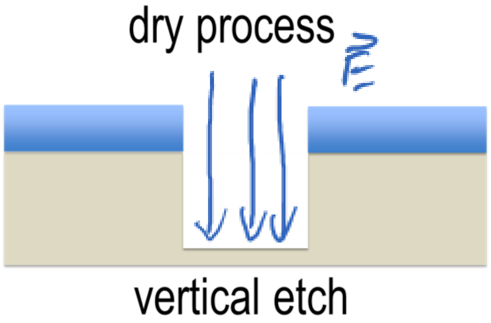
Plasma etch applications (dry etching)

- Examples of high-aspect ratio etching



Reactive-ion etching: $A^{+} + \mathrm{srfc}[C] \rightarrow AC$

- Directionality of ions crossing the sheath provides anisotropic etching



➢ Plasma processing is the only commercial technology capable of such control and indispensable for modern IC manufacturing!

Plasma etch applications

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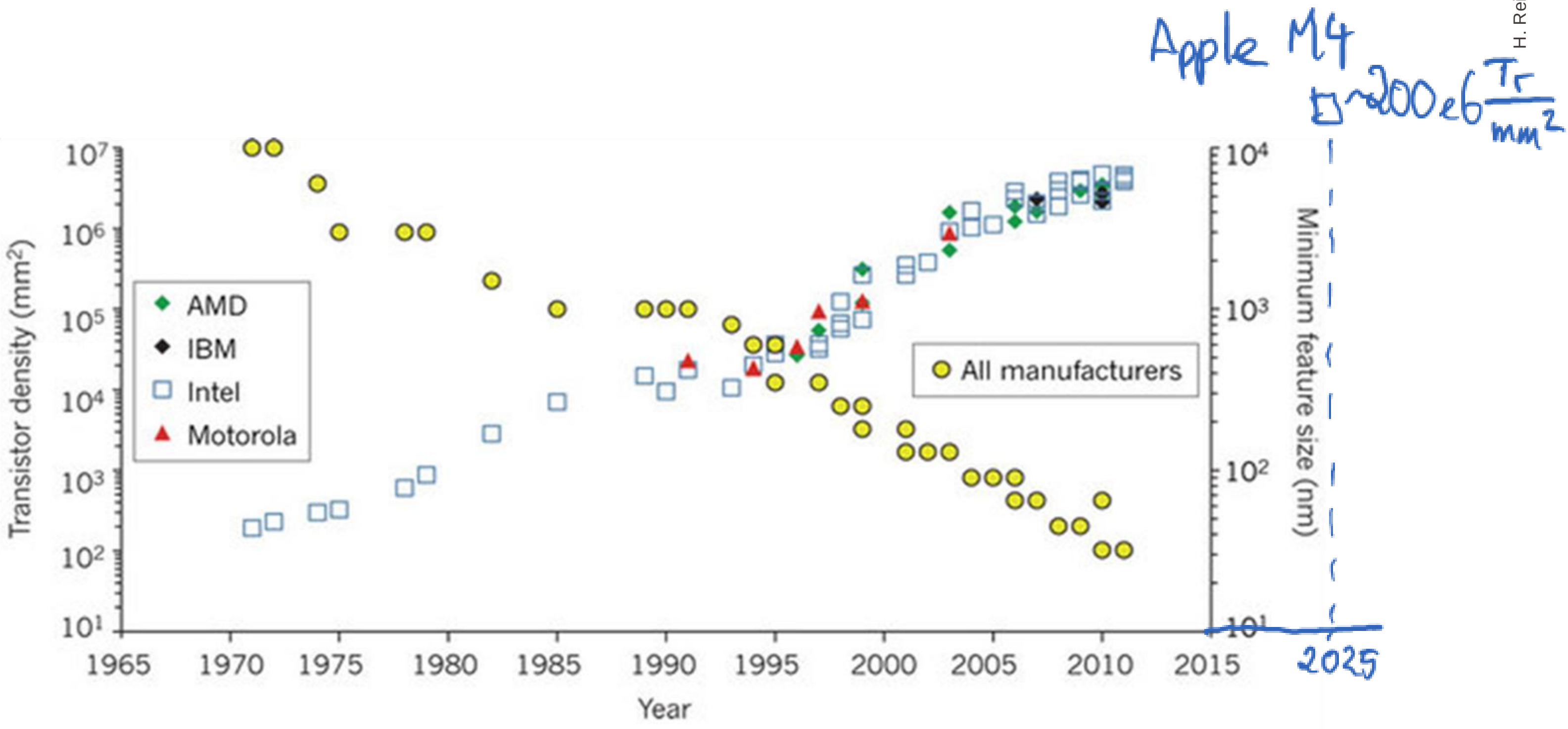
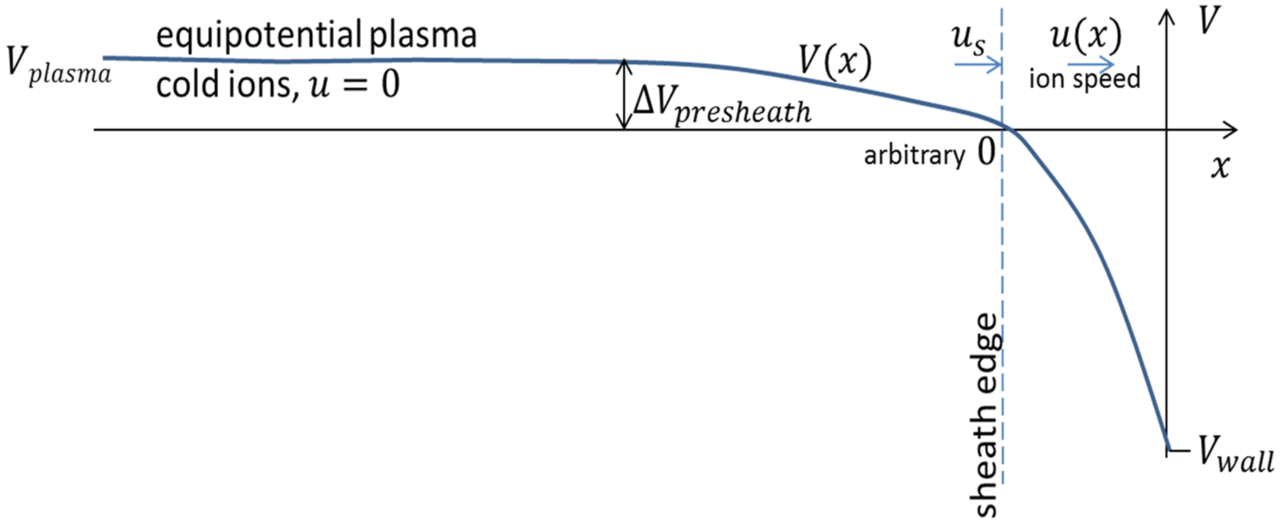
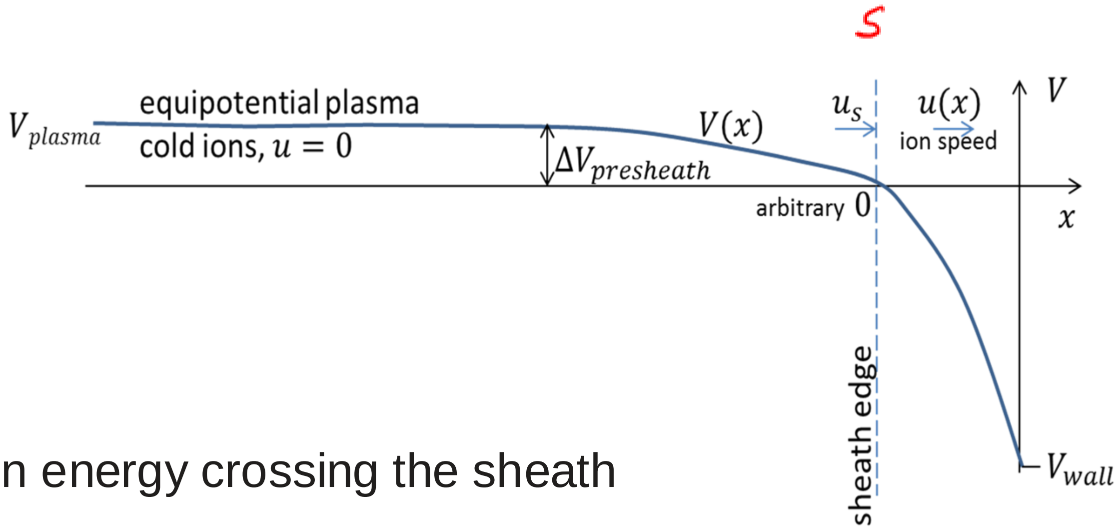


- First p-n junction transistor – Shockley, Sparks, Teal - ~1951
- Basis for integrated circuits invented by Kilby and Noyce
- Early integrated circuits (1961 Fairchild camera) had 25 - 40 μm feature sizes
- Number of transistors per circuit doubles every couple of years (Moore's law, 1965)

Sheath potential (qualitative)



Ion velocity



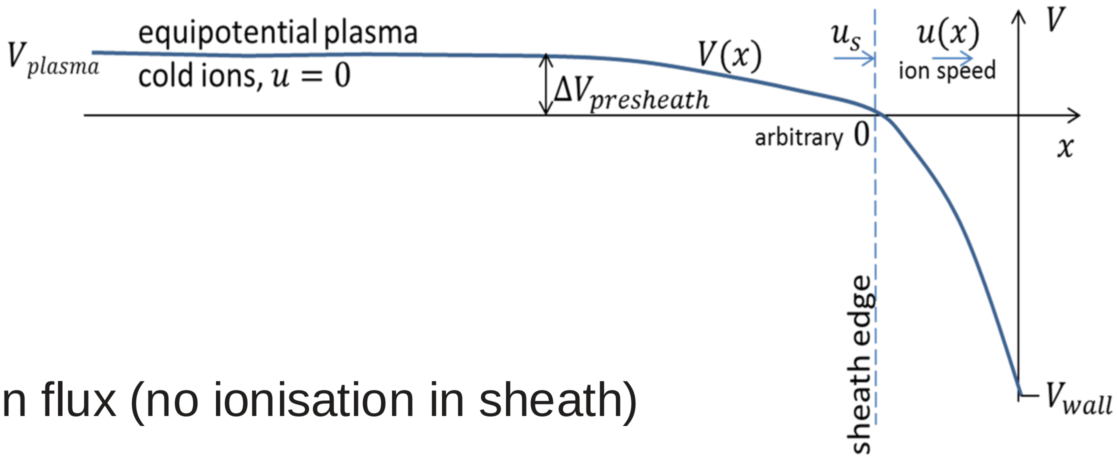
- Conservation of ion energy crossing the sheath (no collisions)

$$\frac{1}{2}Mu^2 + eV = \frac{1}{2}Mu_s^2$$

➢ Solve for u

$$u(x) = \left[\frac{2}{M}\left(\frac{1}{2}Mu_s^2 - eV\right)\right]^{\frac{1}{2}} = \left(u_s^2 - \frac{2eV(x)}{M}\right)^{\frac{1}{2}} = u_s\left(1 - \frac{2eV}{Mu_s^2}\right)^{1/2}$$

Ion density



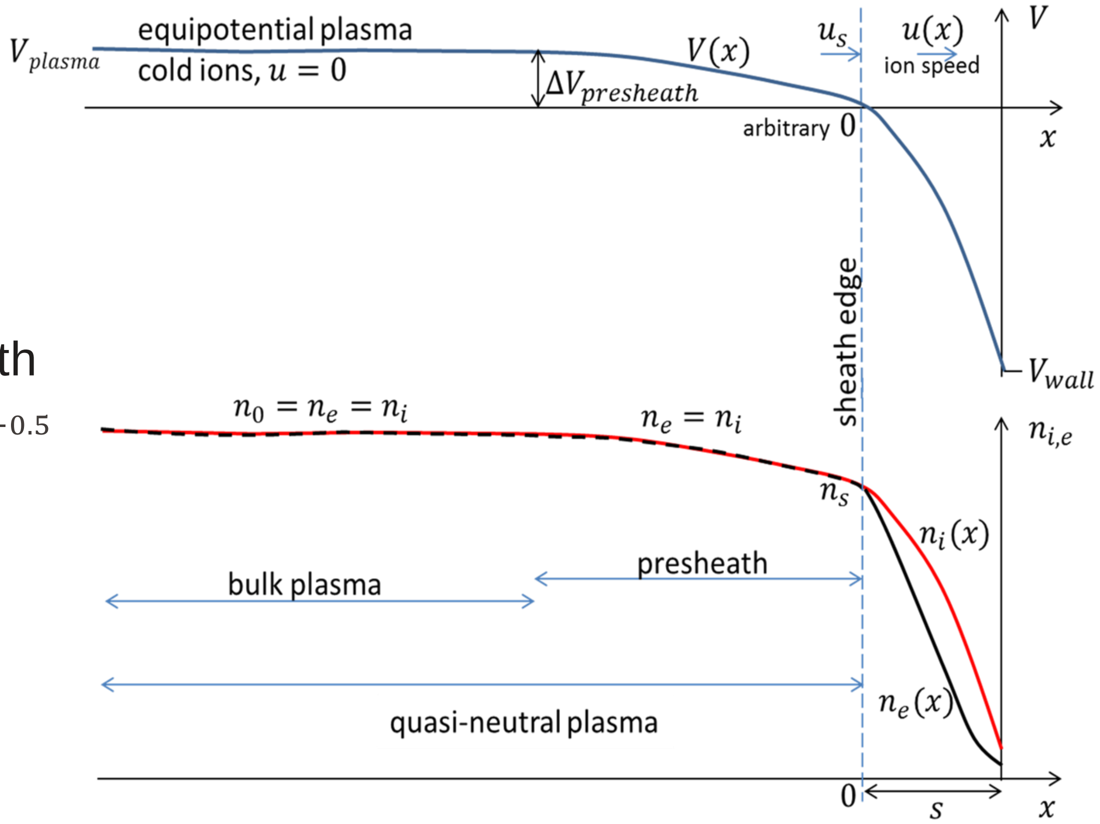
- Conservation of ion flux (no ionisation in sheath)

$$n_i u = n_s u_s$$

- Solve for n_i

$$n_i(x) = \frac{n_s u_s}{u(x)} = \frac{n_s}{\sqrt{1 - \frac{2eV(x)}{M u_s^2}}}$$

Ion and electron densities



- Ion density in sheath

$$n_i = n_s \left(1 - \frac{2eV}{Mu_s^2}\right)^{-0.5}$$

- Electron density in sheath

$$n_e = n_s \exp\left(\frac{V}{T_e}\right)$$

Bohm's criterion

Gauss's law
$\nabla \cdot \bar{E} = \frac{\sigma}{\varepsilon_0}$

- 1D Poisson's equation in sheath $$\frac{d^2V}{dx^2} = -\frac{(n_i - n_e)e}{\varepsilon_0}$$

- Substitute charge densities (see previous page)

$$\frac{d^2V}{dx^2} = \frac{en_s}{\varepsilon_0}\left[\exp\left(\frac{V}{T_e}\right) - \left(1 - \frac{2eV}{Mu_s^2}\right)^{-0.5}\right]$$

- Taylor expand at the plasma-sheath interface

$$\frac{d^2V}{dx^2} = \frac{en_s}{\varepsilon_0}\left[\left(1 + \frac{V}{T_e}\right) - \left(1 + \frac{eV}{Mu_s^2}\right)\right] = \frac{en_s}{\varepsilon_0}\underbrace{\left[\frac{1}{T_e} - \frac{e}{Mu_s^2}\right]}_{\geq 0}V$$

  - Require a physical, i.e. non-oscillatory solution

➢ The ion speed at the sheath entrance is $u_s \geq u_B = \sqrt{\frac{eT_e}{M}}$ **Bohm's criterion**

Bohm's criterion

- Ion speed entering the sheath

$$u_s \geq u_B = \sqrt{\frac{eT_e}{M}}$$

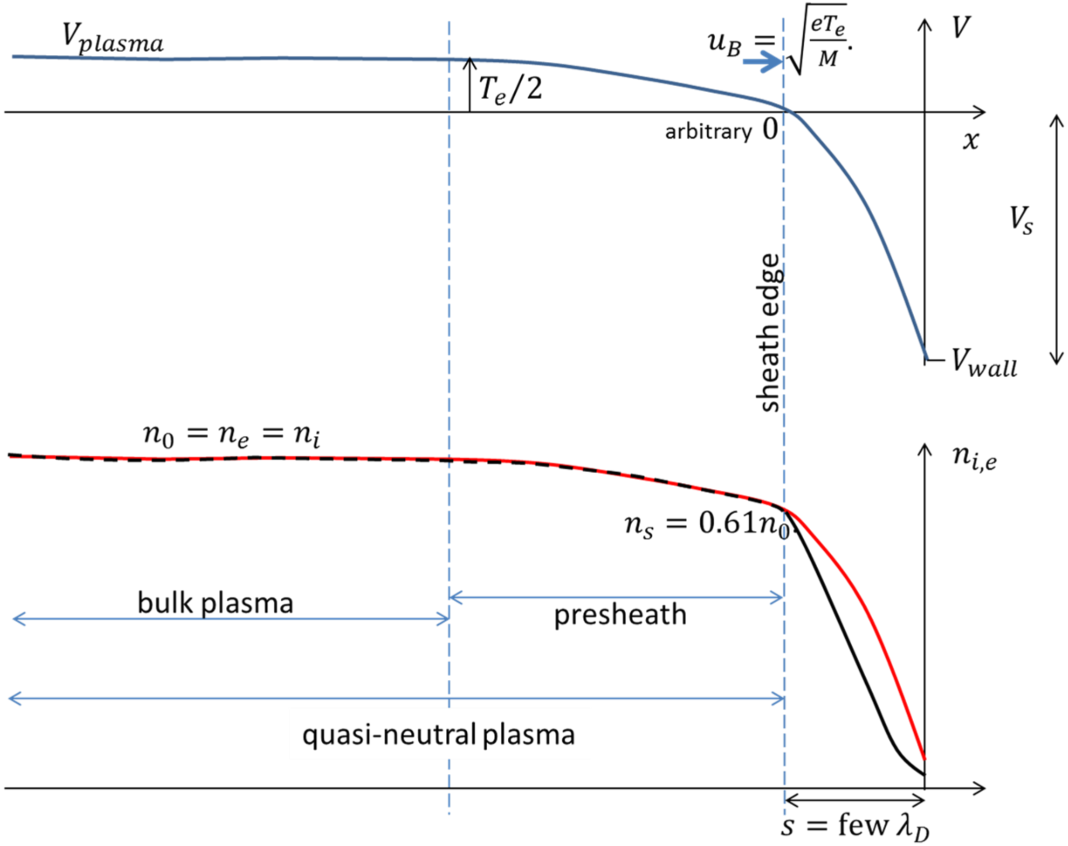
➢ The ion velocity depends on the electron temperature

➢ The ions are accelerated to an energy $\frac{1}{2}Mu_B^2 = eT_e/2$ in the presheath
→ the presheath potential drop is $V_{\text{presheath}} = T_e/2$

➢ The electron, hence, plasma density at the sheath edge is

$$n_s = n_0 \exp(-V_{\text{presheath}}/T_e) = n_0 e^{-0.5} = 0.61 n_0$$

Re-visit potential and density profiles



Bohm's consequence #1: ion flux and etch rate

- Bohm's criterion $u_B = \sqrt{\frac{eT_e}{M}}$ applies in all cases since the maximum potential drop in the pre-sheath cannot be $\gg T_e/2$ (Debye screening)
- Collision-less sheath: ion flux into sheath = ion flux to the wall

$$\Gamma_i = n_s u_B = n_s \sqrt{\frac{eT_e}{M}} \approx 0.61 n_0 \sqrt{\frac{eT_e}{M}}$$

  - If the wall is electrical floating, there is no current to the wall: $\Gamma_i = \Gamma_e$

➢ The ion flux controls the etch rate → plasma density & electron temperature

  - Equally applies for a negatively biased wall $j_{\mathrm{sat}} = e\Gamma_i$

Bohm's consequence #2: ion bombardment energy

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- For a floating wall

$$\Gamma_i = n_s u_B \overset{!}{=} \Gamma_e = \frac{\bar{v}_e}{4} n_{e,\mathrm{wall}} = \frac{\bar{v}_e}{4} n_s \exp\left(\frac{V_{\mathrm{wall}}}{T_e}\right) = \frac{1}{4}\sqrt{\frac{8eT_e}{\pi m_e}}\, n_s \exp\left(\frac{V_{\mathrm{wall}}}{T_e}\right)$$

$u_B = \sqrt{eT_e/M}$

  - Potential drop in the sheath $V_s = -V_{\mathrm{wall}} = \frac{T_e}{2}\ln\left(\frac{M}{2\pi m_e}\right)$

- Total ion energy

$$\varepsilon_i = e\left(V_{\mathrm{plasma}} - V_{\mathrm{wall}}\right) = e\left(V_{\mathrm{pre-sheath}} + V_s\right)$$

$$= e\left[\frac{T_e}{2} + \frac{T_e}{2}\ln\left(\frac{M}{2\pi m_e}\right)\right] \approx \frac{eT_e}{2}\ln\left(\frac{M}{2.3 m_e}\right)$$

Ex.: Ar $M=40$

$V_s = 4.7\, eT_e$

$\varepsilon_i = 5.2\, eT_e$

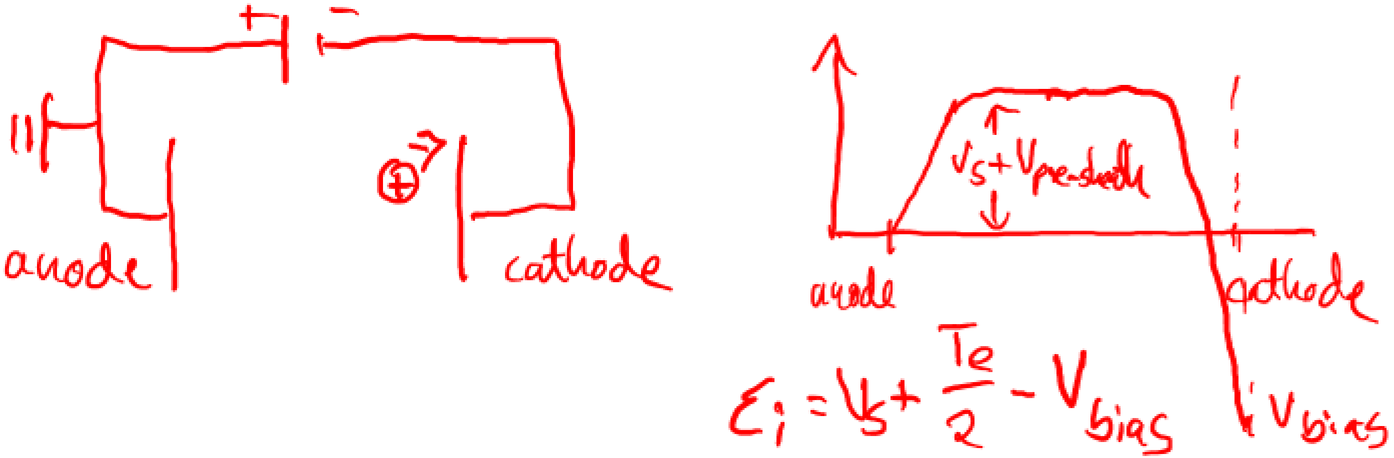
is controlled by ion mass and electron temperature

- Can be increased by biasing!

Bohm's consequence #2: ion bombardment energy

- Increase ion energy by a negative bias of the wall (→ electrode)

Plasma in front of an electrode



➢ Bias drives a current up to j_{sat}

Summary of sheaths and plasma etching

- Sheath formation due to fact that

electron mobility ≫ ion mobility

- Deduce basic properties of a sheath
- Directional ions in plasma etching indispensable for IC manufacturing
- Bohm velocity for ions into a sheath

$$u_\mathrm{B} = \sqrt{\frac{eT_e}{M}}$$

- Ion flux to a wall (controls etch rate)

$$\Gamma_i = 0.61 n_0 \sqrt{\frac{eT_e}{M}}$$

- Ion energy to a wall

$$\varepsilon_i = \frac{eT_e}{2} \ln\left(\frac{M}{2.3 m_e}\right) \sim 5.2 eT_e$$

Outline – Industrial plasmas

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   - Communication satellite

L8

3. Sheath and plasma etching
   - Microelectronics
4. **Plasma with insulating electrodes**
   - **RF – radio frequency, large area for solar cells**

L9

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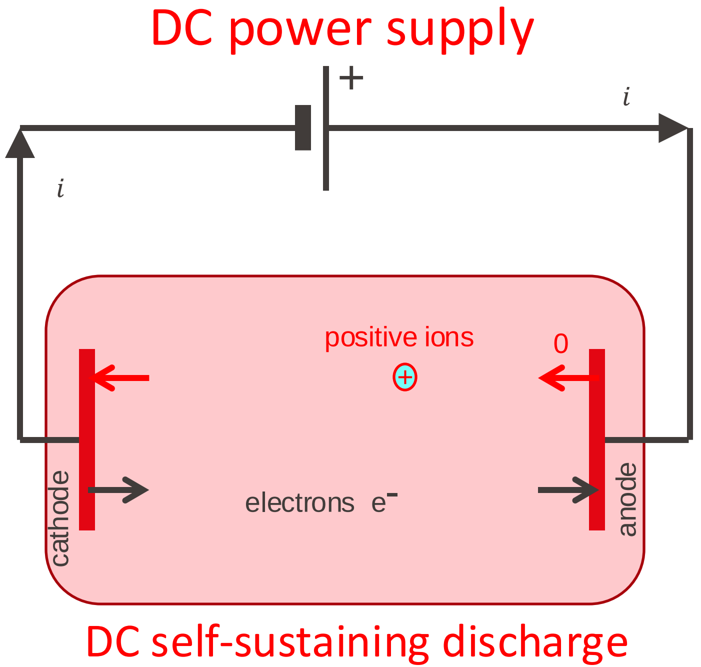
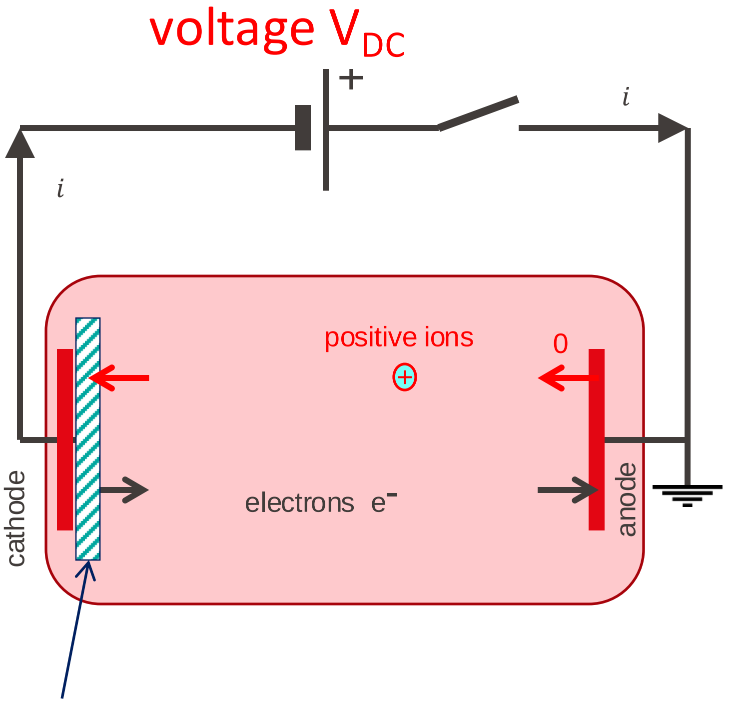
Can we use DC (Direct Current) for all plasma processing?

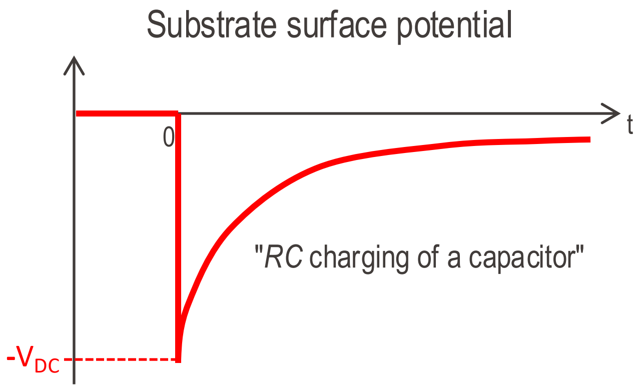


- The current everywhere is a conduction current due to moving charges
  - Electrons in the external circuit
  - Free ions and electrons in the plasma

Consider an insulating layer on an electrode

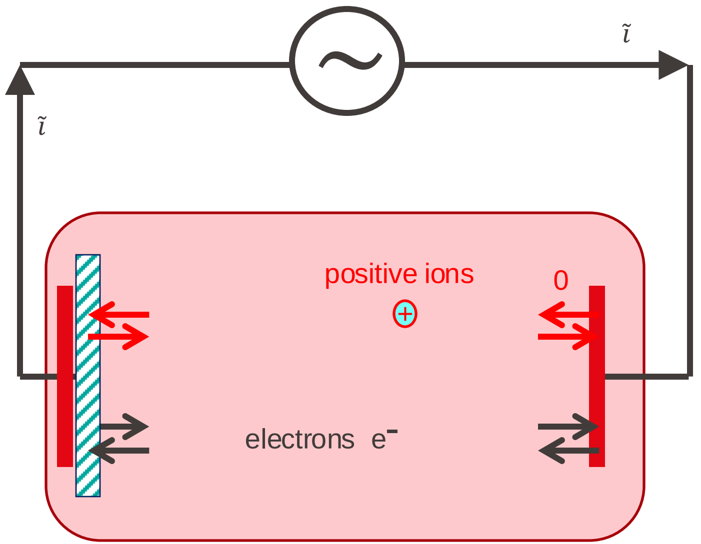


glass substrate, or an insulating film (SiO_x), etc.
This is a dielectric barrier



- Close the switch at time *t=0*
  - Plasma breaks down
  - Ions arrive at the glass surface
  - The insulating surface charges up
  - The surface voltage rises
  - The discharge voltage falls
  - The E-field is too low for ionization
  - The discharge current falls to zero

Need to use AC (Alternating Current) for continuous plasma processing



- An insulating surface is alternately charged up, then *discharged* by the opposite field direction
  - Typical plasma density $\sim 5 \cdot 10^{16} \mathrm{m}^{-3}$
  - Ion plasma frequency

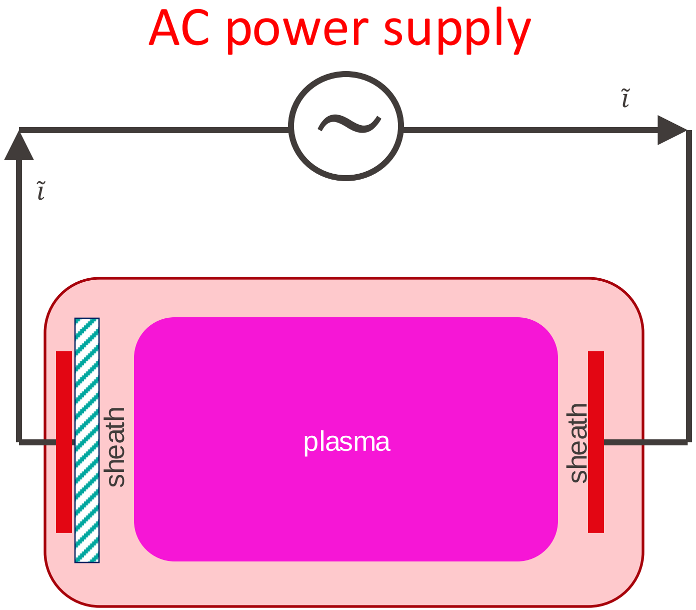
$$\frac{1}{2\pi}\sqrt{\frac{ne^2}{\varepsilon_0 M}} \sim 2\ \mathrm{MHz}$$

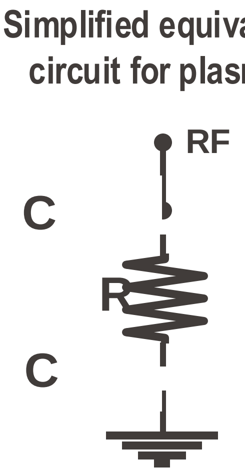
  - Electron plasma frequency

$$\frac{1}{2\pi}\sqrt{\frac{ne^2}{\varepsilon_0 m_e}} \sim 500\ \mathrm{MHz}$$

- At the industrial (ISM) frequency **13.56 MHz**
  - Electrons can follow the *E*-field
  - Ions only see the time-averaged *E*-field

RF (radio-frequency) capacitively-coupled plasma for plasma processing





- RF current in circuit and plasma is a conduction current (moving charges)
- RF current in sheaths and the dielectric is a displacement current

Basics of radio-frequency plasma

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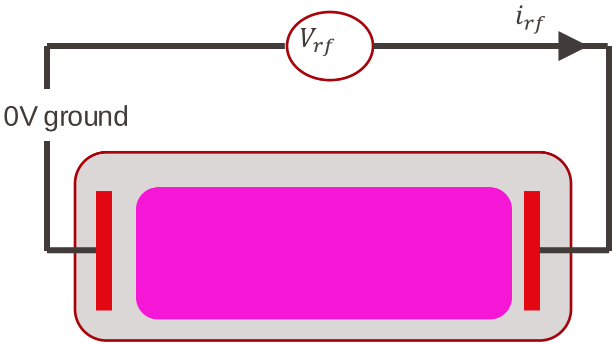
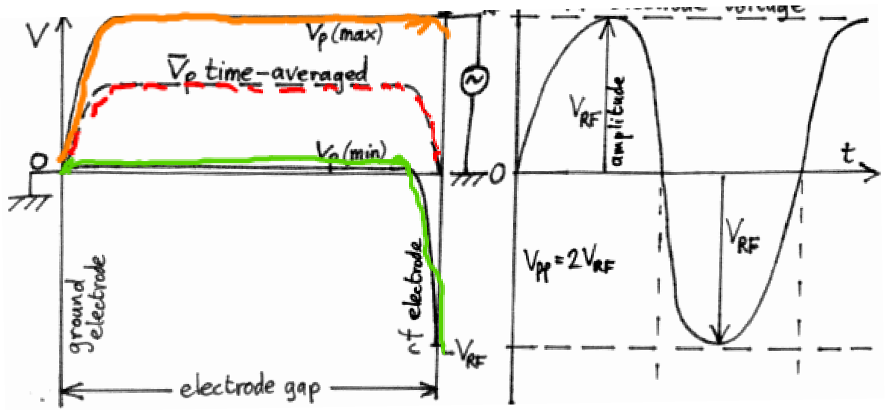


- Plasma potential always positive with respect to most positive surface



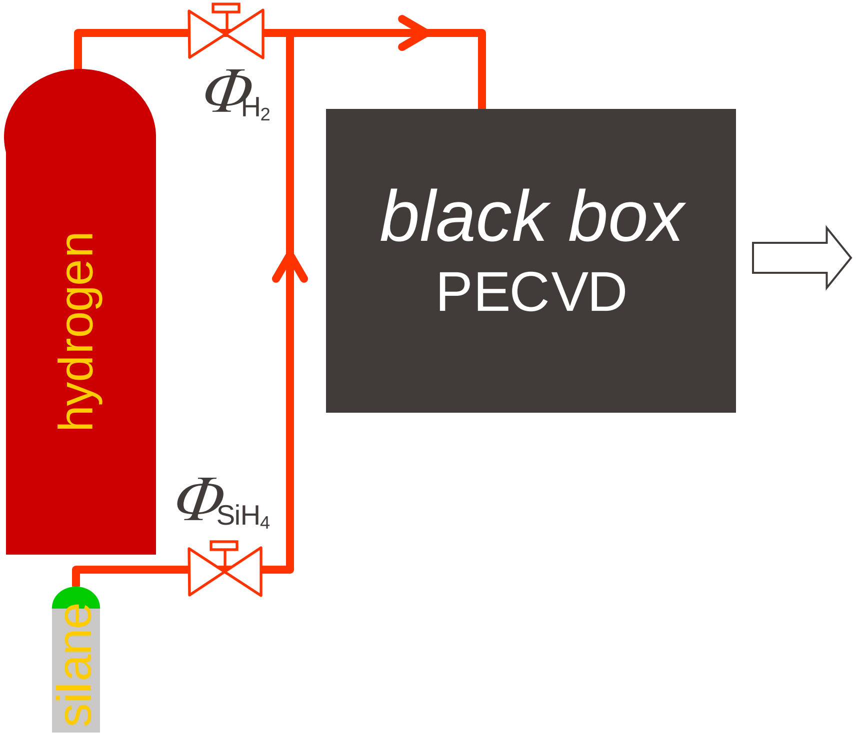
- Time-averaged sheath voltage
  = RF amplitude/2
  = $V_{p-p}/4$

➢ Method to chose ion energy $\varepsilon_i \sim V_{pp}/4$ → useful for etch control

Large area RF capacitively-coupled reactors

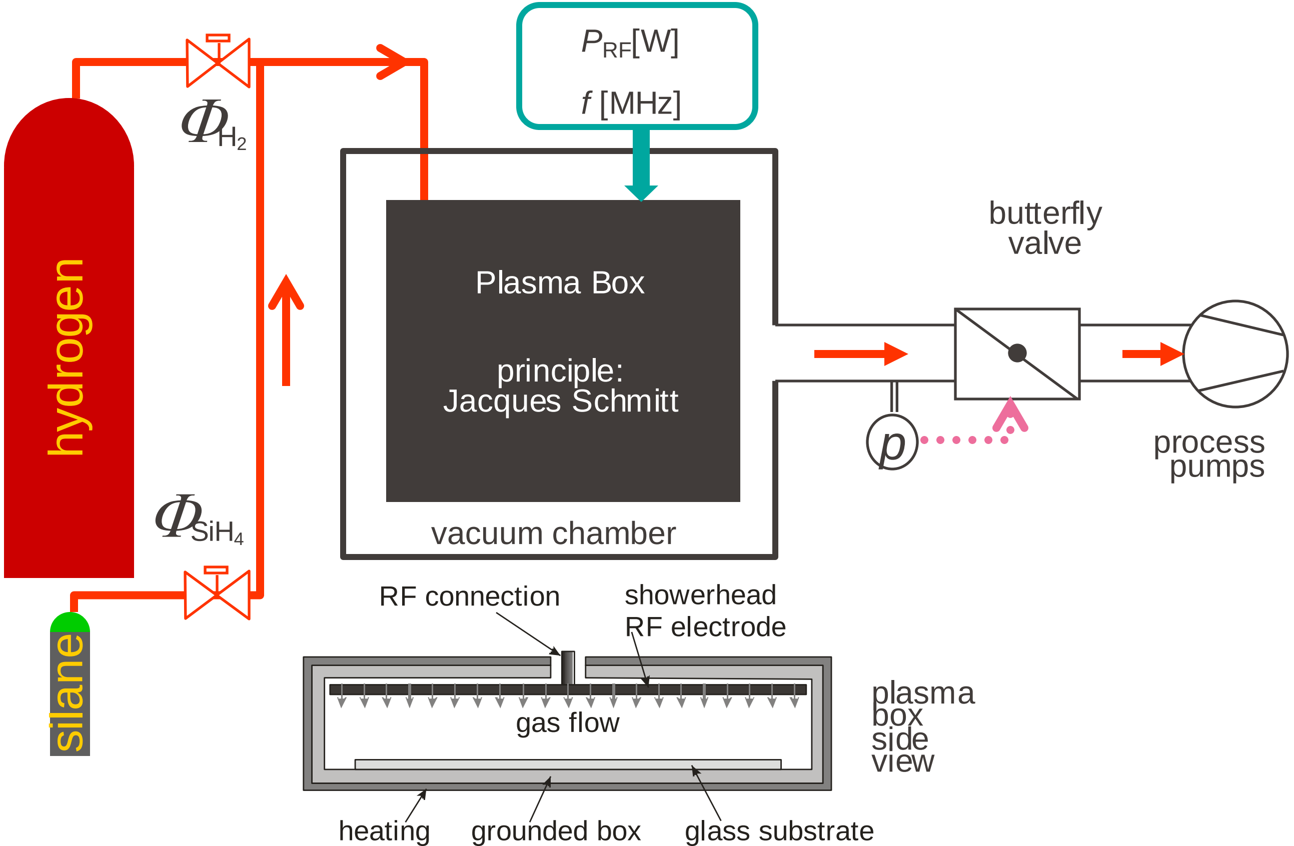
- Concentrate on plasma processing for large area electronics
  - Thin film transistors for flat panel LCD displays
  - Photovoltaic solar panels
- Swiss industries (historic)
  - Balzers displays
  - Unaxis Displays
  - Unaxis Solar
  - Oerlikon Solar/TEL Solar

Plasma-Enhanced Chemical Vapour Deposition (PECVD) of thin film silicon



J. Perrin, et al., Plasma Phys. Control. Fusion 42 (2000) B353

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



Commercial reactors

Front and back View Photo of KAI 20-1200

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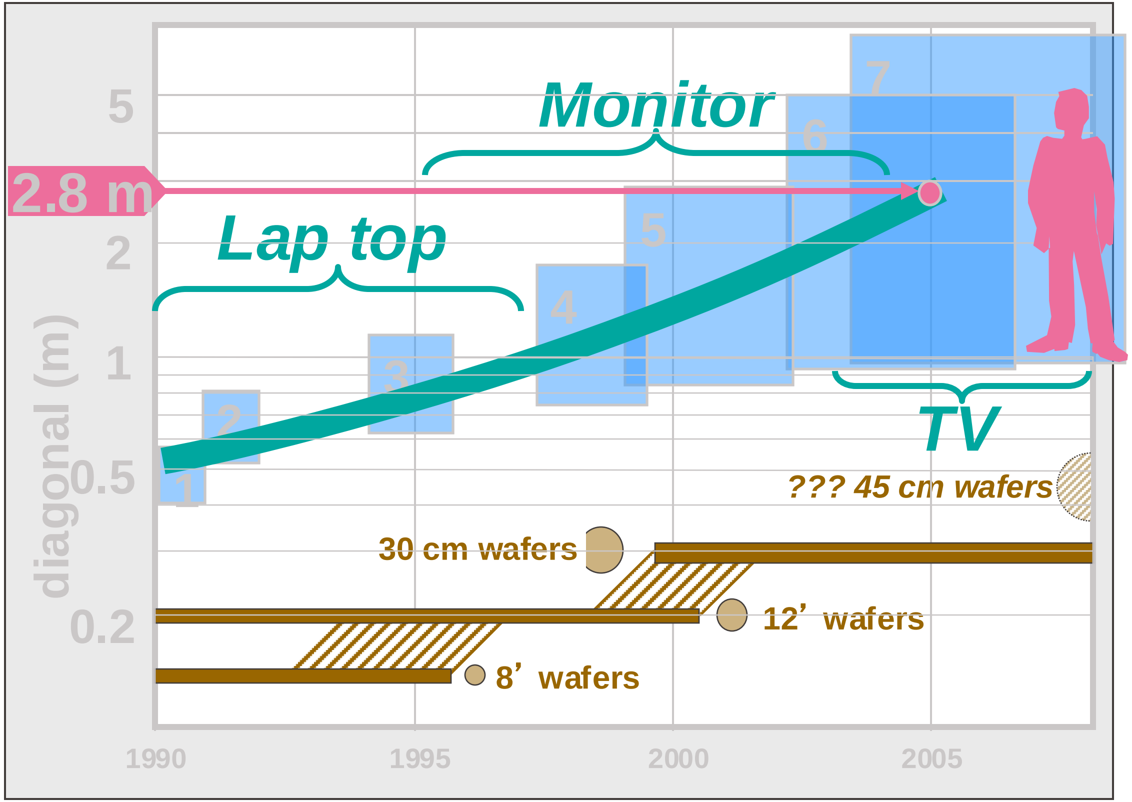
Substrate size trend



Summary of plasma with insulating electrodes

RF capacitively-coupled plasma

- Conduction current in plasma, displacement current in sheaths/dielectric
- Industrial frequency 13.56MHz between ion and electron plasma frequency
- Sheath voltage and ion energy $V_{p-p}/4$

➢ Large area, RF capacitively-coupled plasmas for solar cells

Dielectric Barrier Discharge (DBD) for the production of Ozone O_3

- Ozone is a powerful oxidizing agent, far stronger than O_2 (used for sterilization of water on industrial scale)
- Ozone can be used for combustion reactions and combusting gases
  - Provides higher temperatures than combusting in O_2
- Ozone has a half-life of approximately a day at room temperature

Ozone production by plasma chemistry

1. Plasma dissociation of oxygen

$$e + O_2 \rightarrow O + O + e$$

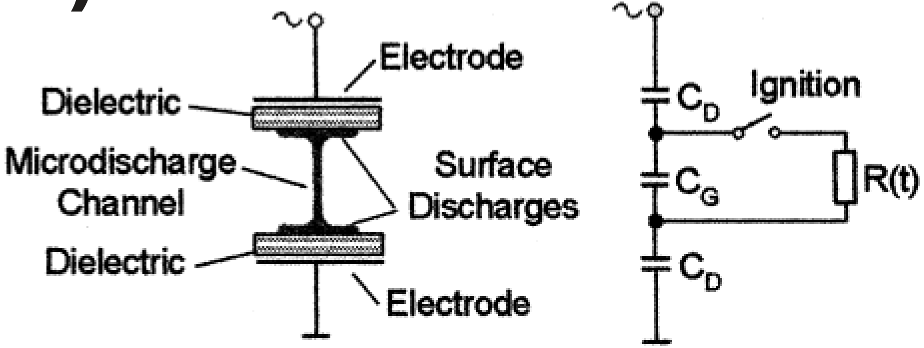
2. Ozon production by 3-body recombination

$$O + O_2 + M \rightarrow O_3^* + M \rightarrow O_3 + M$$

with *M* being any third body to carry of excess energy

Ozon production by Dielectric Barrier Discharge (DBD)

0.1 mm radius



- High voltage $10^2 - 10^4 V$ causes local breakdown between the electrodes at atmospheric pressure ($10^{14} - 10^{15}$ electrons$/cm^3$)
- A filamentary discharge occurs at this position with avalanche flow of electrons (streamer) $100 - 1000\ A/cm^2$
- Dielectric surface charges up ($100pC$) and local voltage is reduced in ns
- Arc extinguishes, but neighbouring arc can still strike
- High voltage alternates at $50Hz$ to $100MHz$
- The dielectric 1) limits energy of individual discharges (mJ)
  2) distributes the arcs over the entire area

Photograph of DBD arcs through a transparent electrode

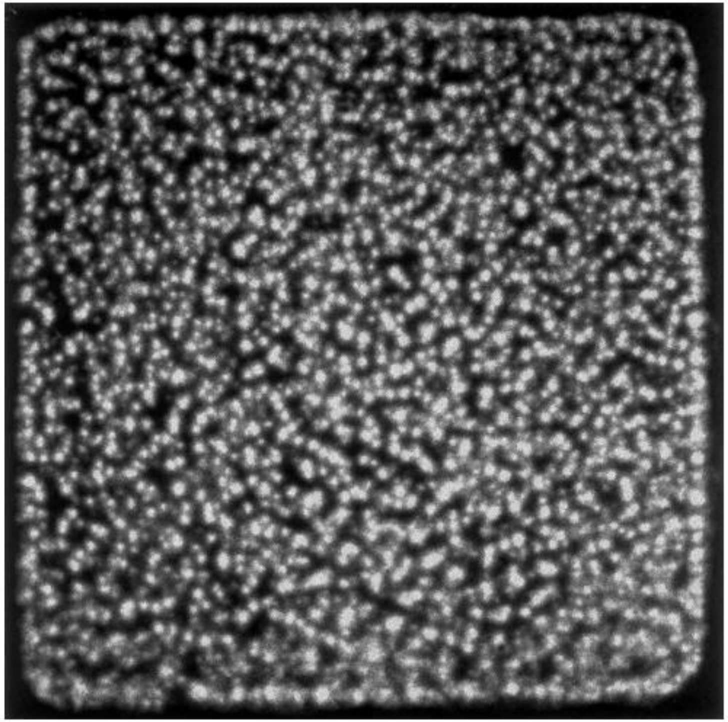


Fig. 3. End-on view of microdischarges in atmospheric-pressure air (original size: 6 cm × 6 cm, exposure time: 20 ms).

Summary of plasma with insulating electrodes

RF capacitively-coupled plasma

- Conduction current in plasma, displacement current in sheaths/dielectric
- Industrial frequency 13.56MHz between ion and electron plasma frequency
- Sheath voltage and ion energy $V_{p-p}/4$

➢ Large area, RF capacitively-coupled plasmas for solar cells

Dielectric Barrier Discharge

- Transient (ns), filamentary arcs, atmospheric pressure

➢ DBD Ozon generation for water purification

Reminder: Maxwell-Boltzmann distribution

- Velocity distribution in an ideal gas in thermodynamic equilibrium

$$f_s(v) = \left(\frac{m_s}{2\pi k_B T_s}\right)^{3/2} e^{-\frac{m_s v^2}{2k_B T_s}}$$

  - Most probable velocity: $$v_{\mathrm{p},s} = \sqrt{\frac{2k_B T_s}{m_s}}$$
  - Mean velocity: $$\bar{v}_s = \sqrt{\frac{8k_B T_s}{\pi m_s}}$$
  - Root-mean-square velocity: $$v_{\mathrm{rms},s} = \sqrt{\frac{3k_B T_s}{m_s}}$$