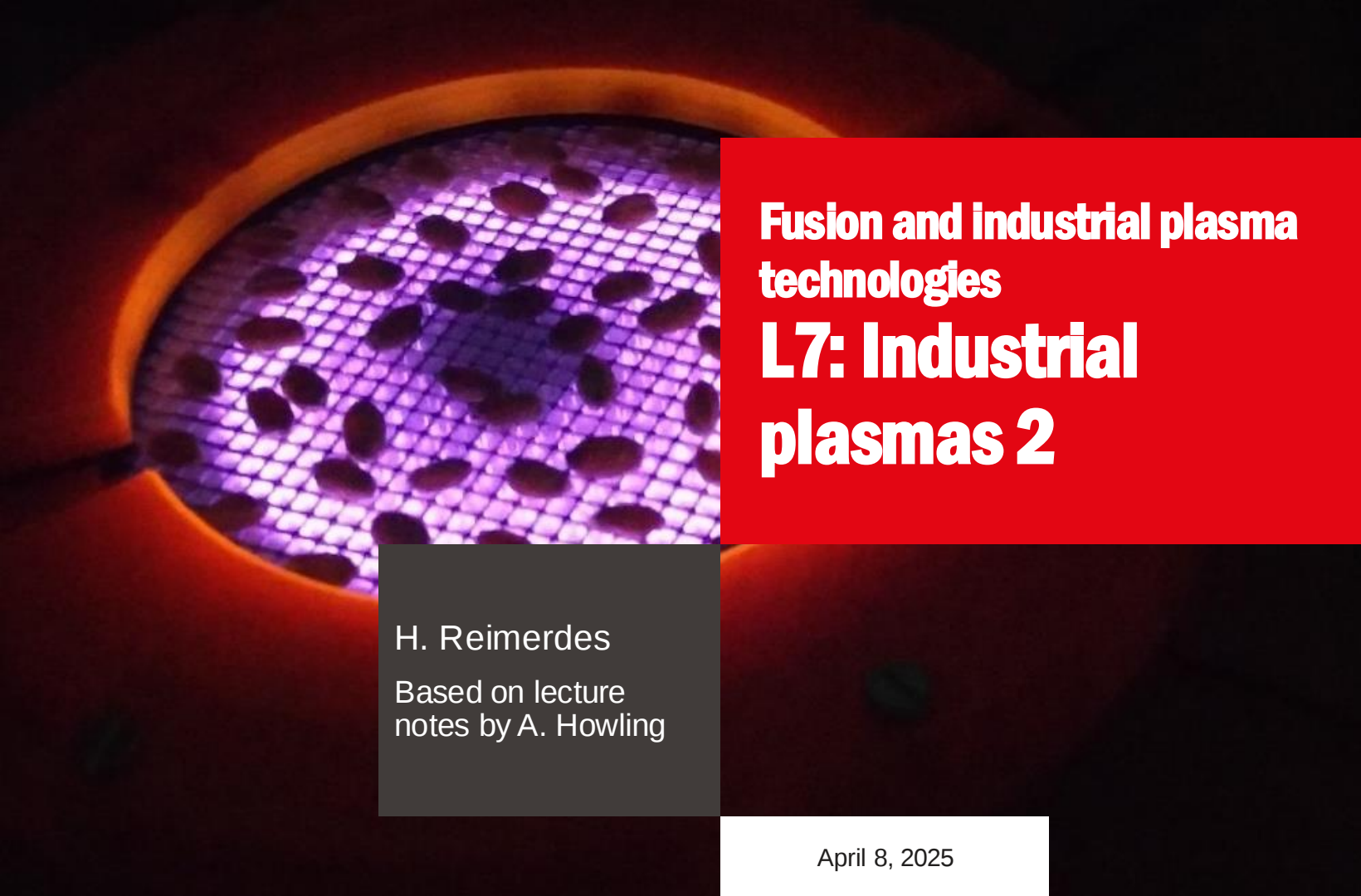




**Fusion and industrial plasma
technologies**

L7: Industrial plasmas 2

H. Reimerdes

Based on lecture
notes by A. Howling

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

} L7

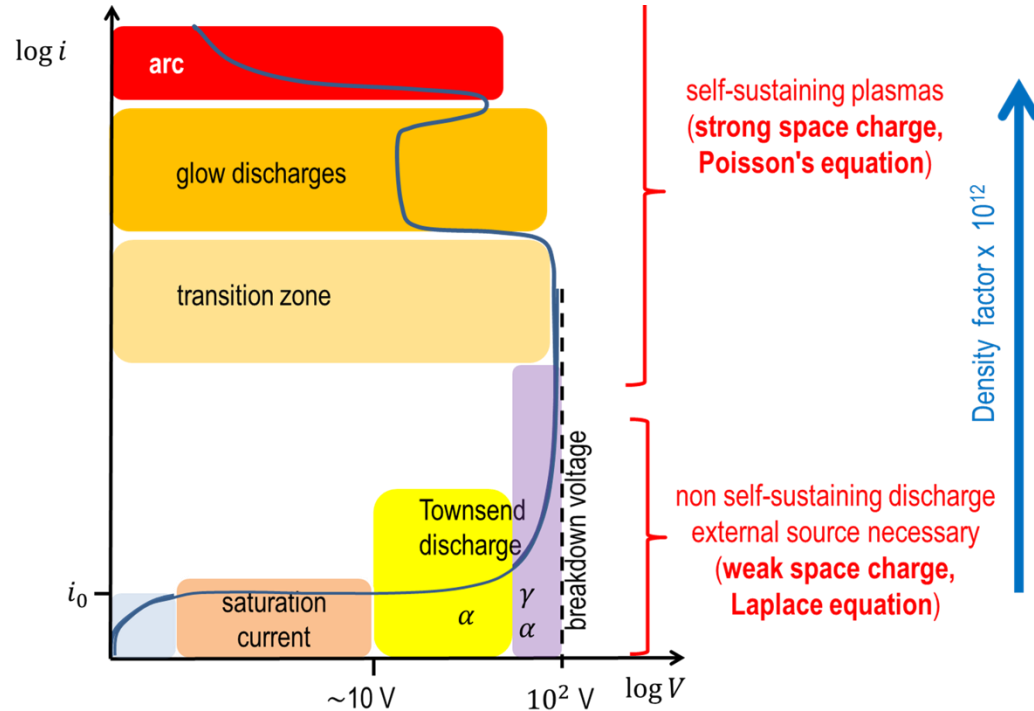
} L8

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



1. Introduction to basic industrial plasmas

- Plasma medicine

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3. **Sheath and plasma etching**

- Microelectronics

4. Plasma with insulating electrodes

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L7

L8

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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

Reminder: Maxwell-Boltzmann distribution

- Velocity distribution in an ideal gas in thermodynamic equilibrium

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

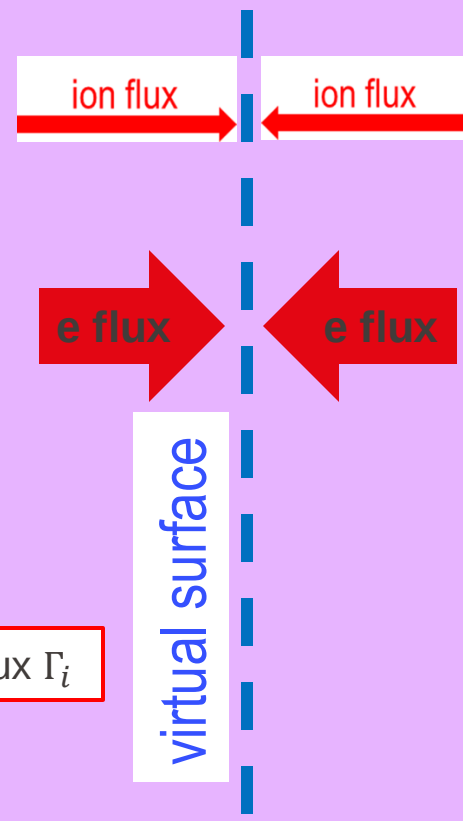
Distribution of speed $v = |\vec{v}|$

Formation of a sheath

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

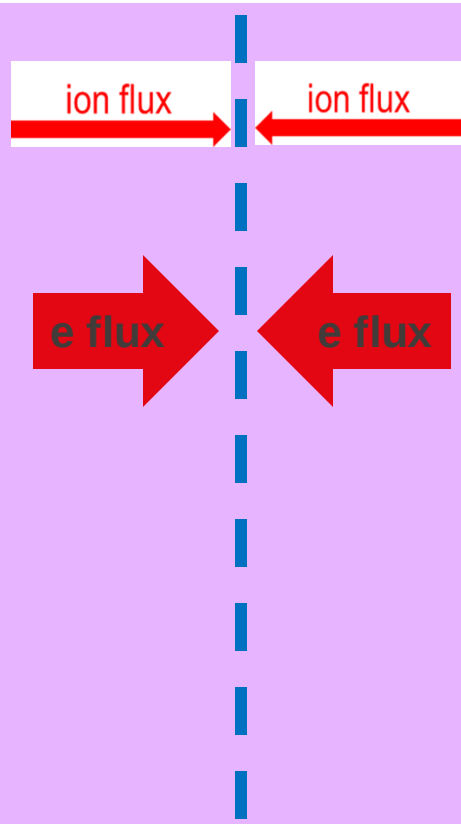
$$\text{Electron thermal flux } \Gamma_e = n_e \frac{\bar{v}_e}{4} = \frac{n_e}{4} \sqrt{\frac{8eT_e}{\pi m_e}}$$

$$\text{Electron thermal flux } \Gamma_e \gg \text{Ion thermal flux } \Gamma_i$$



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?

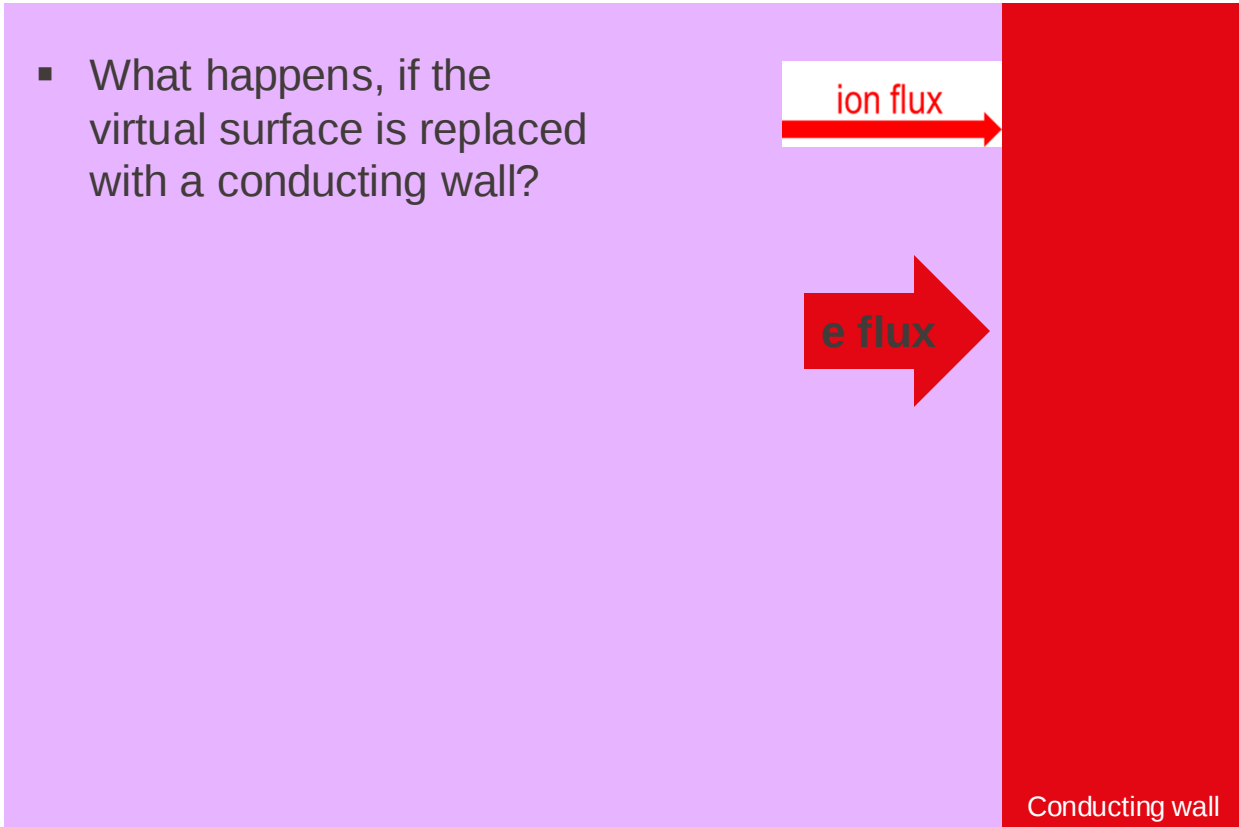
ion flux

A horizontal red arrow pointing to the right, labeled "ion flux".

e flux

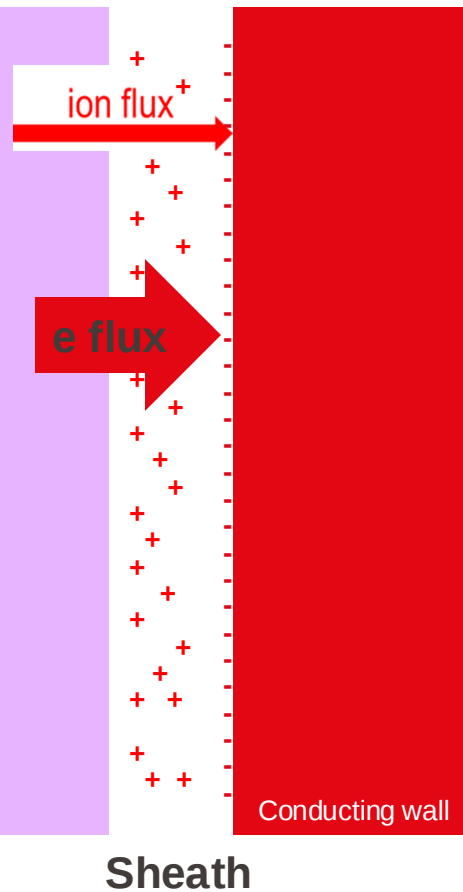
A large red arrow pointing to the right, labeled "e flux".

Conducting wall

The diagram shows a light purple rectangular region on the left, representing a plasma. To its right is a solid red vertical bar representing a "Conducting wall". Two red arrows, labeled "ion flux" and "e flux", point from the plasma region towards the wall.

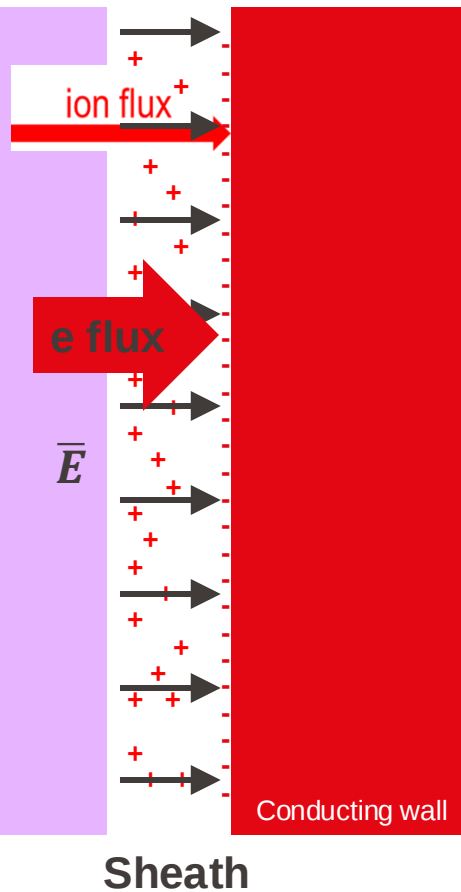
Formation of a sheath

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



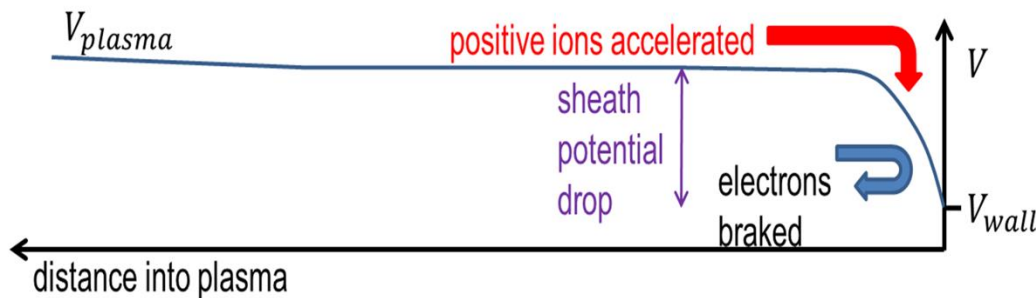
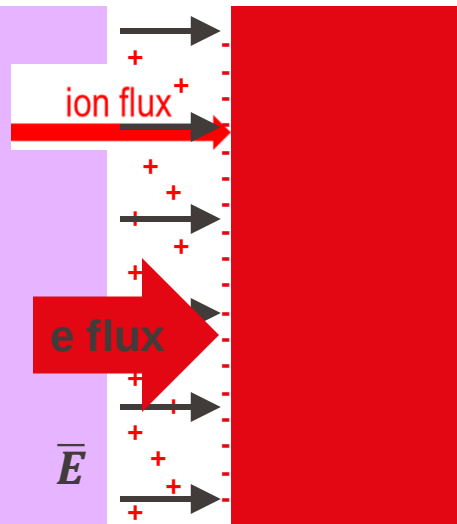
Formation of a sheath

- 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

$$E \approx 0$$

Gauss's law:

$$\nabla \cdot \vec{E} = \frac{\sigma}{\epsilon_0}$$

Gaussian surface

$$E = 0$$

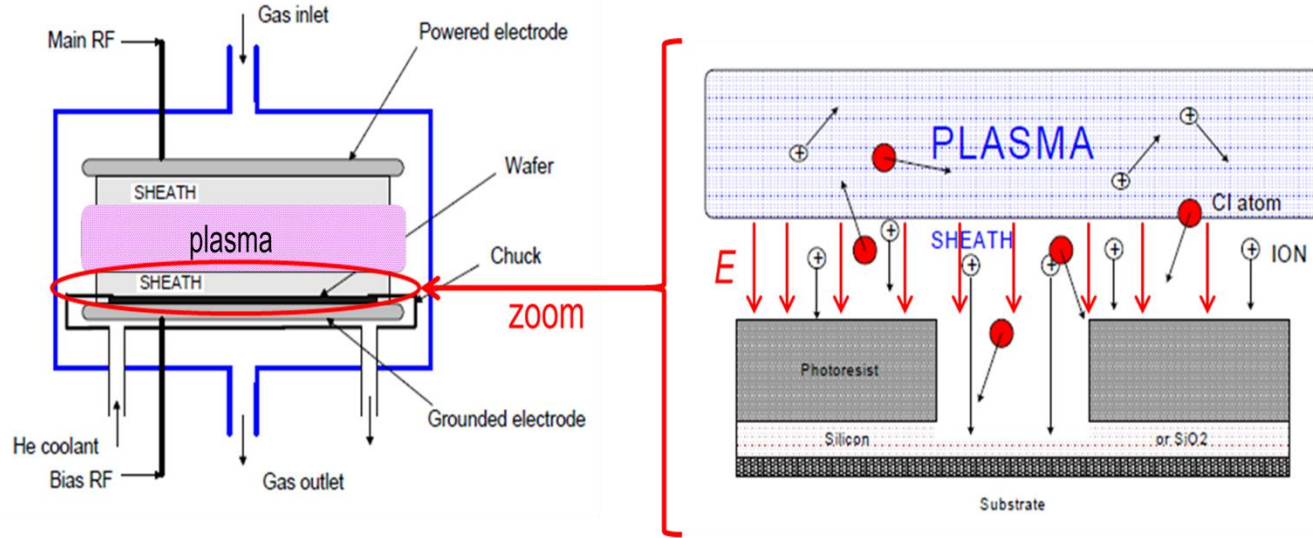
Conducting wall

Sheath

Some sheath properties

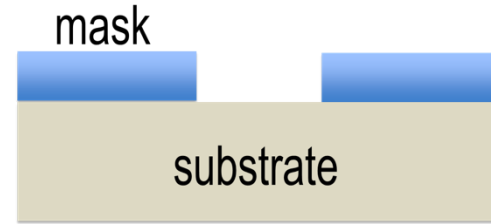
- Sheath provides transition between plasma and wall
- Positive space charge equal and opposite to negative surface charge
- Electric field guarantees ambipolar ion and electron fluxes to wall (floating)
 - Strong electric field and a positive ion flux, normal and directed towards the wall
- Plasma potential 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



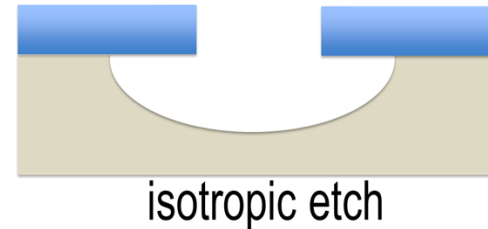
- Uniform electric field above a substrate
- Vertical flux of ions
- Photoresist feature $\sim 0.1\mu\text{m} \ll$ sheath width (mm)

- Examples of high-aspect ratio etching



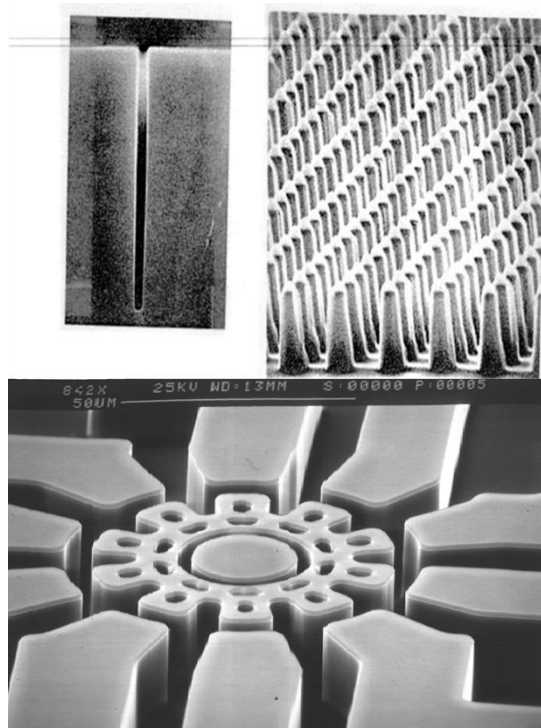
Chemical etching: $A + \text{srfc}[C] \rightarrow AC$

wet process



Plasma etch applications (dry etching)

- Examples of high-aspect ratio etching



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

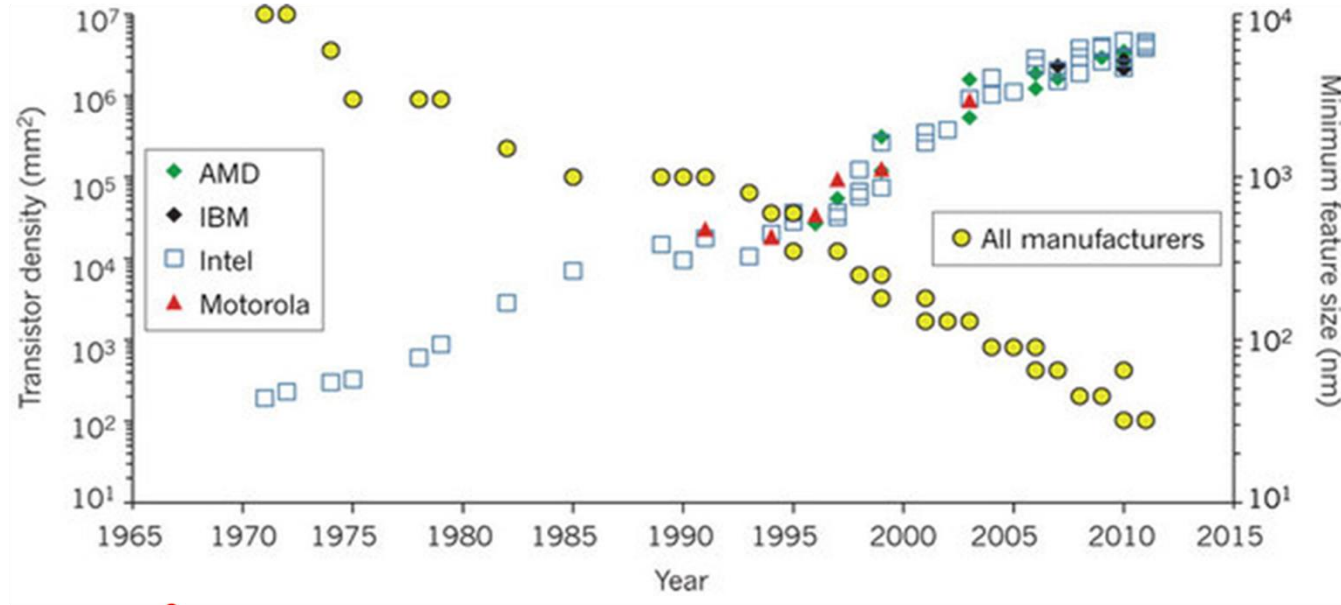
- Directionality of ions crossing the sheath provides anisotropic etching

dry process



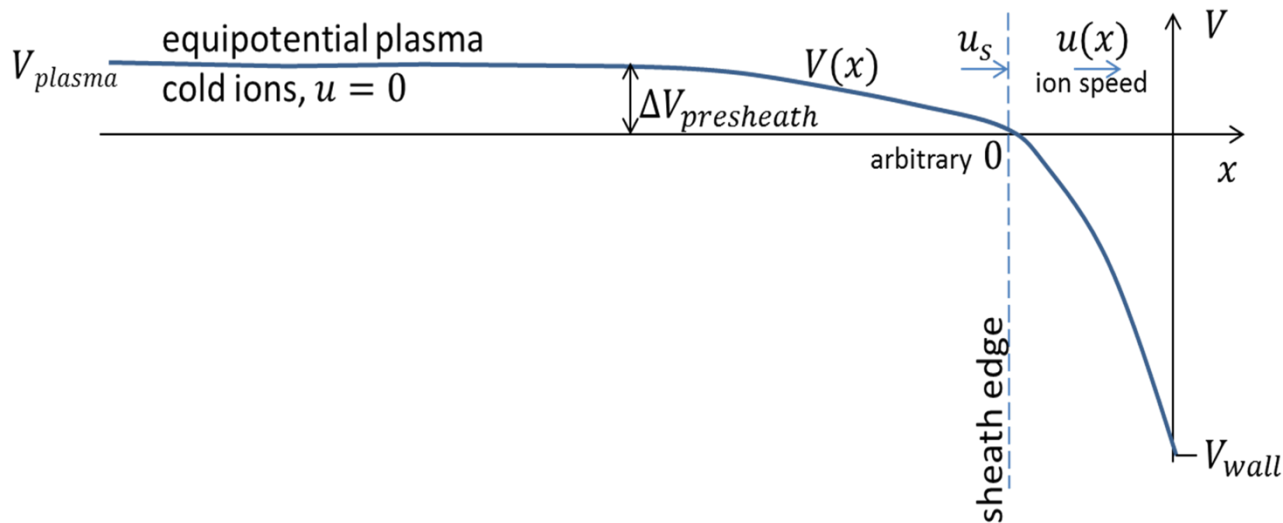
vertical etch

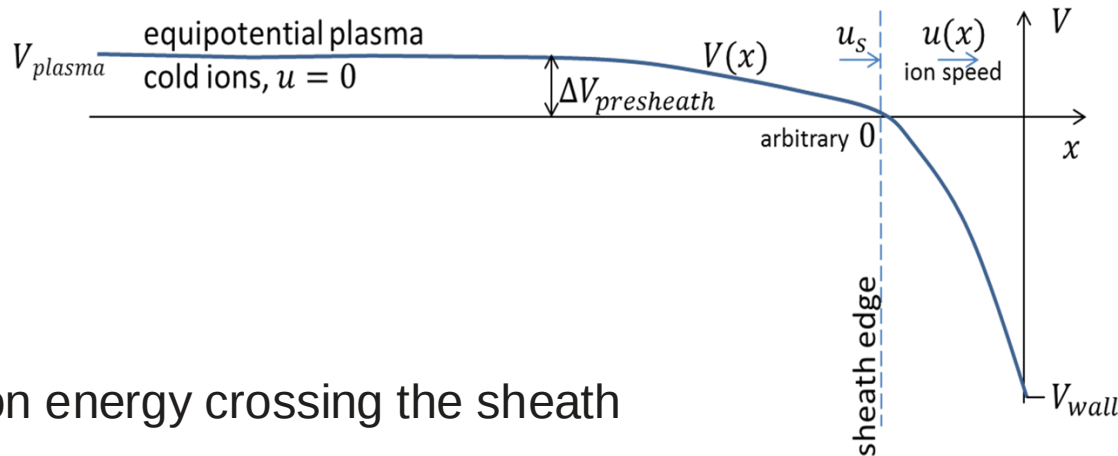
- Plasma processing is the only commercial technology capable of such control and indispensable for modern IC manufacturing!



- 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)

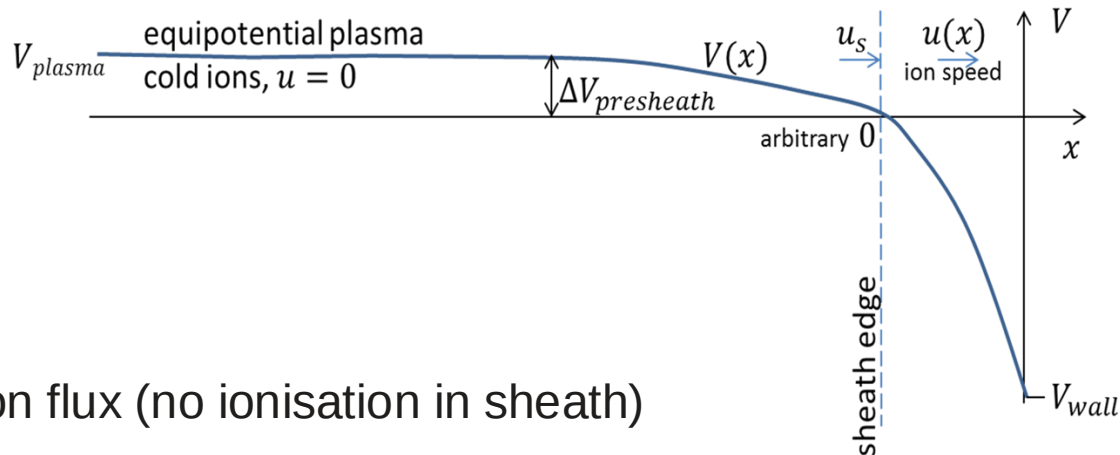




- Conservation of ion energy crossing the sheath (no collisions)

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

- Solve for u



- Conservation of ion flux (no ionisation in sheath)

$$n_i u = n_s u_s$$

- Solve for n_i

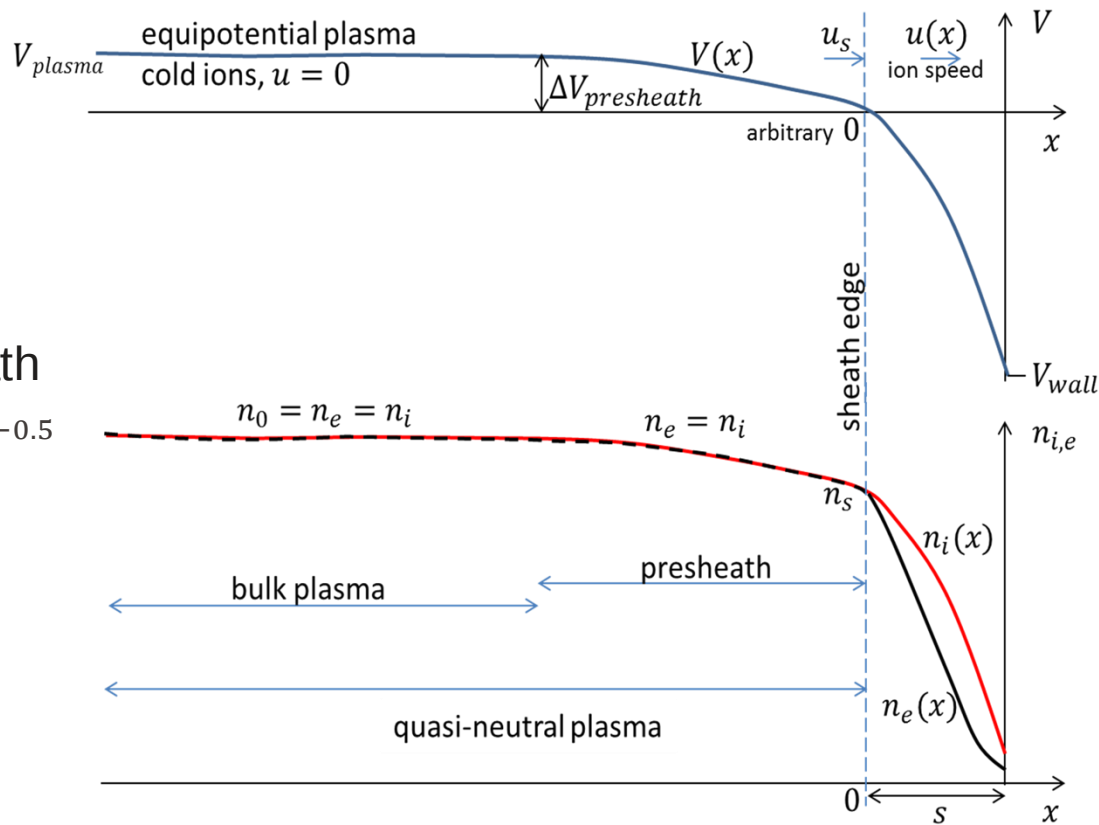
Ion and electron densities

- Ion density in sheath

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

- Electron density in sheath

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



- 1D Poisson's equation in sheath

$$\frac{d^2V}{dx^2} = -\frac{(n_i - n_e)e}{\epsilon_0}$$

Gauss's law
 $\nabla \cdot \vec{E} = \frac{\sigma}{\epsilon_0}$

- Substitute charge densities (see previous page)

$$\frac{d^2V}{dx^2} = \frac{en_s}{\epsilon_0} \left[\exp\left(\frac{V}{T_e}\right) - \left(1 - \frac{2eV}{Mu_s^2}\right)^{-0.5} \right]$$

- Taylor expand at the plasma-sheath interface

$$\frac{d^2V}{dx^2} = \frac{en_s}{\epsilon_0} \left[\left(1 + \frac{V}{T_e}\right) - \left(1 + \frac{eV}{Mu_s^2}\right) \right] = \frac{en_s}{\epsilon_0} \underbrace{\left[\frac{1}{T_e} - \frac{e}{Mu_s^2} \right]}_{\geq 0} V$$

- Require a physical, i.e. **non-oscillatory solution** ≥ 0

- The ion speed at the sheath entrance is $u_s \geq u_B = \sqrt{\frac{eT_e}{M}}$

Bohm's criterion

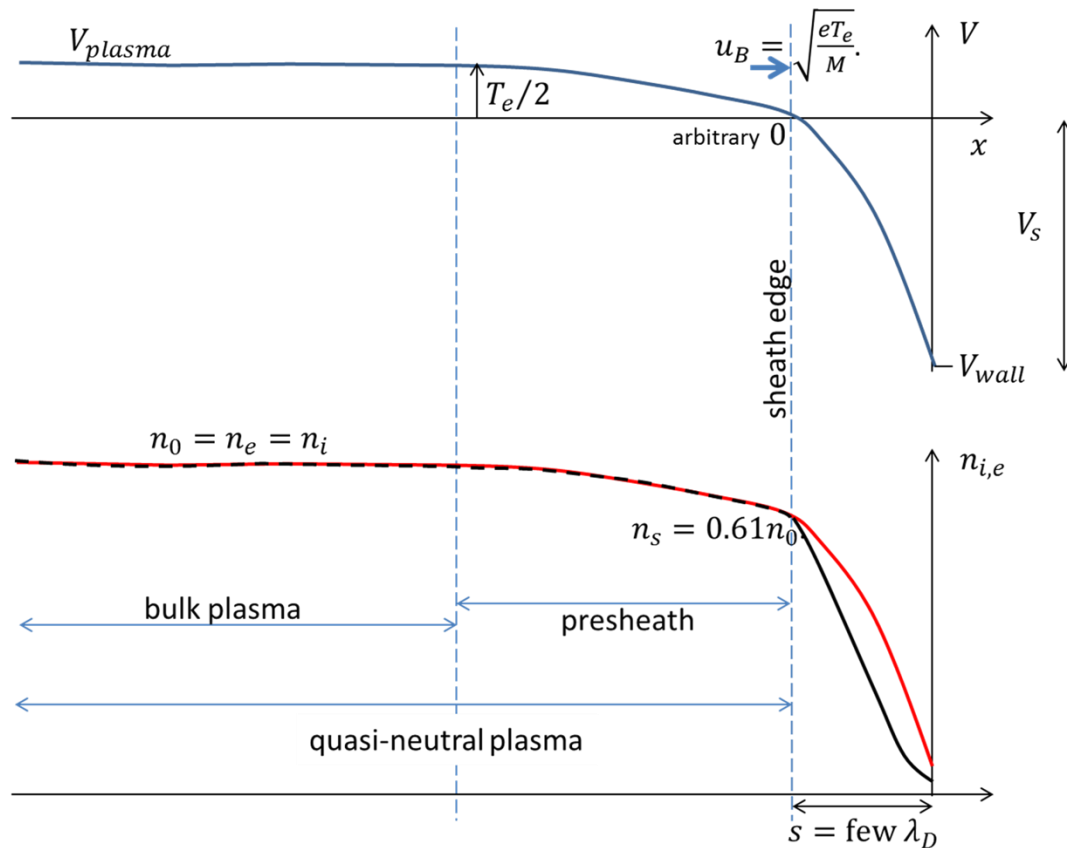
- Ion speed entering the sheath

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

- 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

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

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 $\rightarrow$ plasma density & electron temperature
 - Equally applies for a negatively biased wall $j_{\text{sat}} = e\Gamma_i$

Bohm's consequence #2: ion bombardment energy

- For a floating wall

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

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

- Total ion energy

$$\begin{aligned} \varepsilon_i &= e(V_{\text{plasma}} - V_{\text{wall}}) = e(V_{\text{pre-sheath}} + V_s) \\ &= e\left[\frac{T_e}{2} + \frac{T_e}{2} \ln\left(\frac{M}{2\pi m_e}\right)\right] \approx \frac{eT_e}{2} \ln\left(\frac{M}{2.3m_e}\right) \end{aligned}$$

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 ($\rightarrow$ 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 $\gg$ ion mobility
- Deduce basic properties of a sheath
- Directional ions in plasma etching indispensable for IC manufacturing
- Bohm velocity for ions into a sheath

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

- Ion flux to a wall (controls etch rate)

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

- Ion energy to a wall

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

Outline – Industrial plasmas

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**
 - RF – radio frequency, large area for solar cells

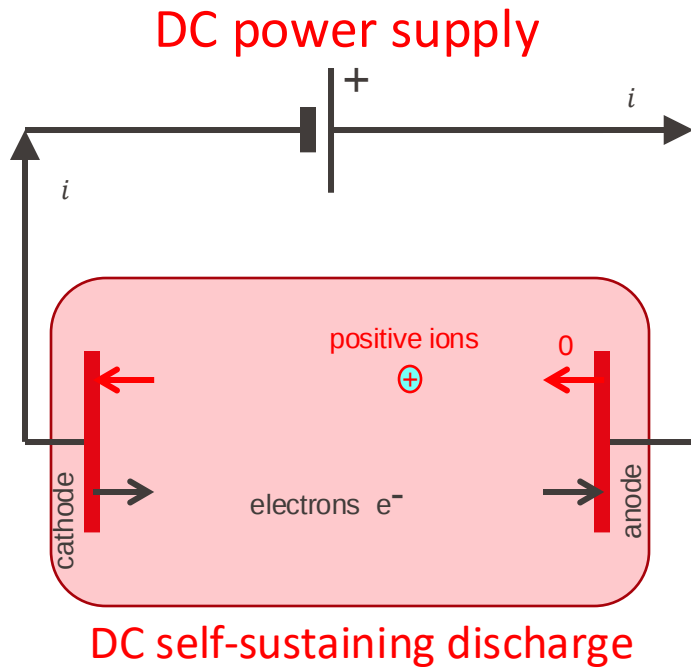
} L8

} L9

Material

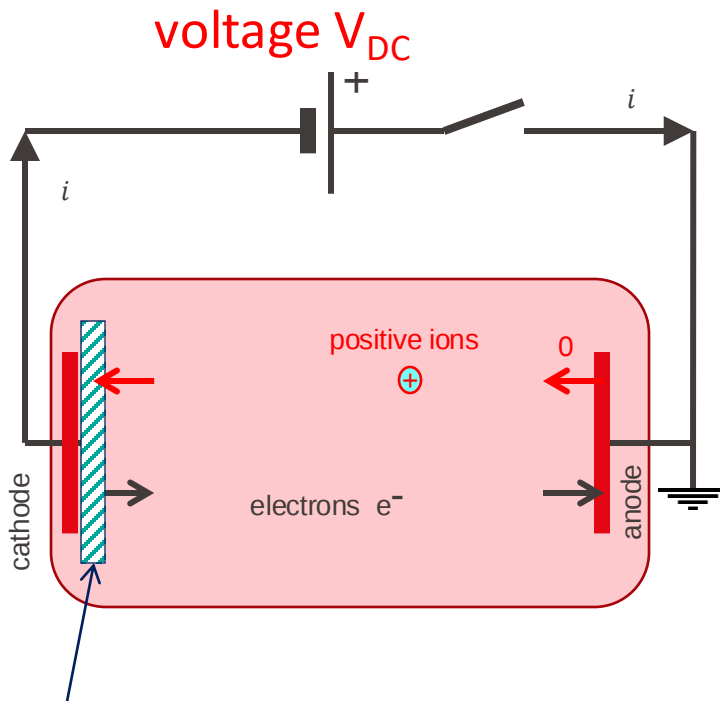
- See also EPFL MOOC “Plasma physics: Applications” #5a-g
 - https://courses.edx.org/courses/course-v1:EPFLx+PlasmaApplicationX+1T_2018

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

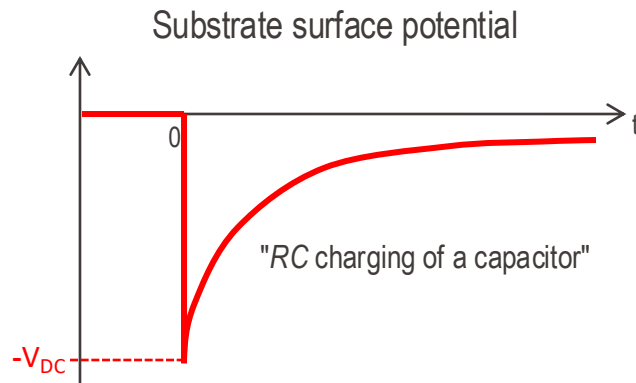


- The current everywhere is a **conduction current** due to moving charges
 - Electrons in the external circuit
 - Free ions and electrons in the plasma

Consider an insulating layer on an electrode

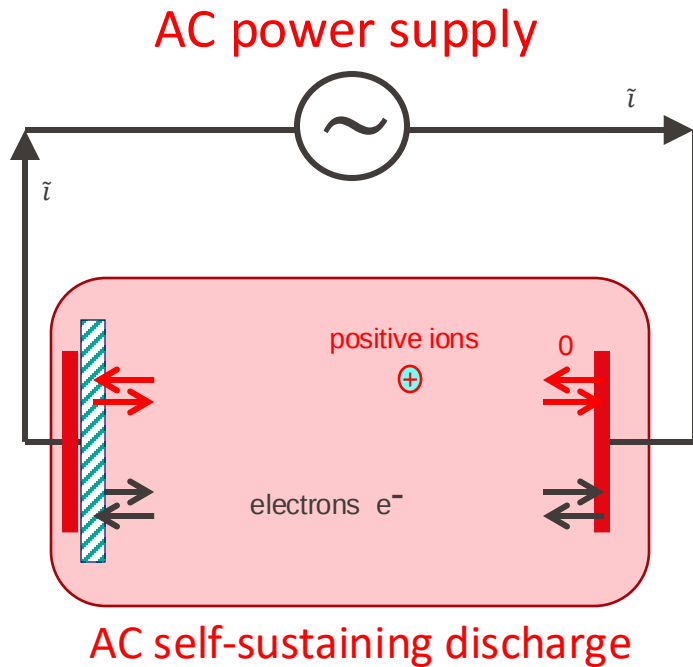


glass substrate, or an insulating film (SiO_x), etc.
This is a **dielectric** barrier



- 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 $\sim 5 \cdot 10^{16} \text{m}^{-3}$

- Ion plasma frequency

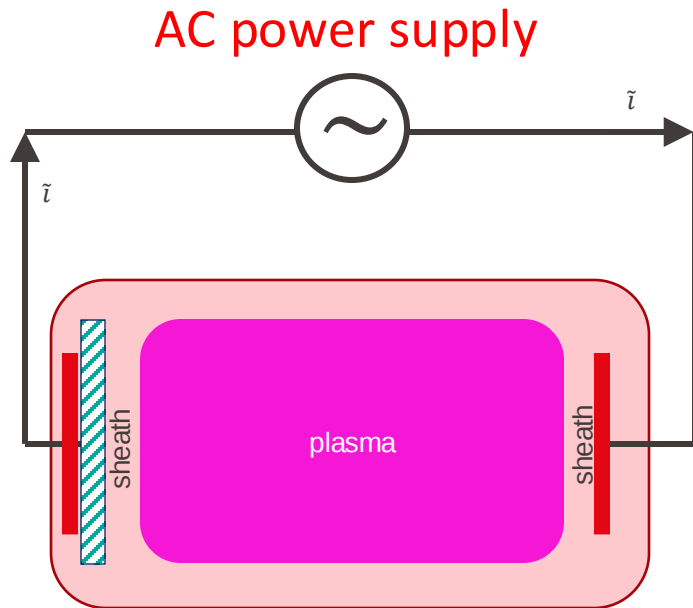
$$\frac{1}{2\pi} \sqrt{\frac{ne^2}{\epsilon_0 M}} \sim 2 \text{ MHz}$$

- Electron plasma frequency

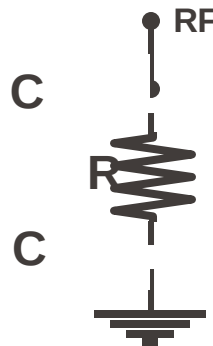
$$\frac{1}{2\pi} \sqrt{\frac{ne^2}{\epsilon_0 m_e}} \sim 500 \text{ MHz}$$

- 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

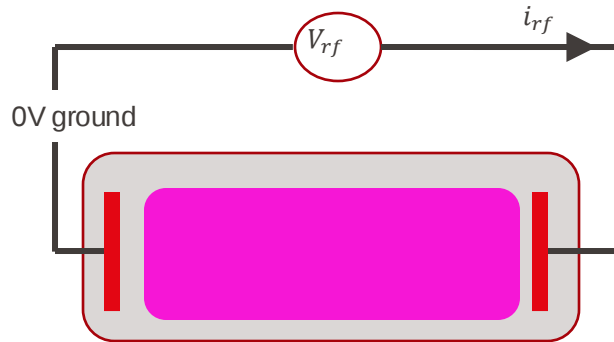


Simplified equivalent circuit for plasma

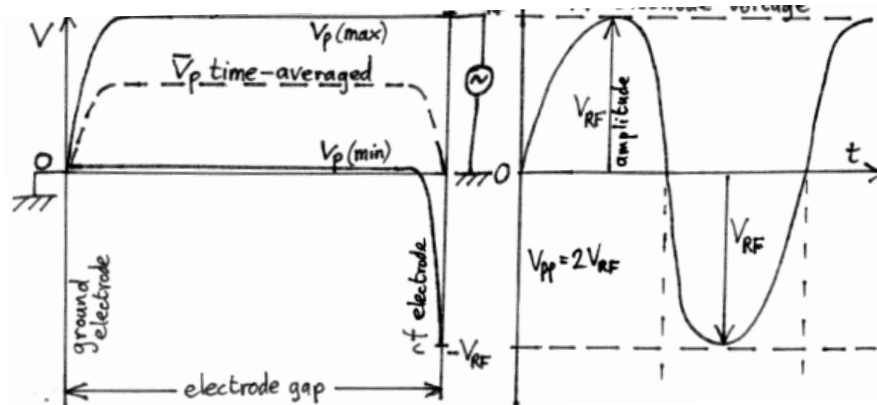


- RF current in circuit and plasma is a **conduction current** (moving charges)
- RF current in sheaths and the dielectric is a **displacement current**

Basics of radio-frequency plasma



- Plasma potential always positive with respect to most positive surface



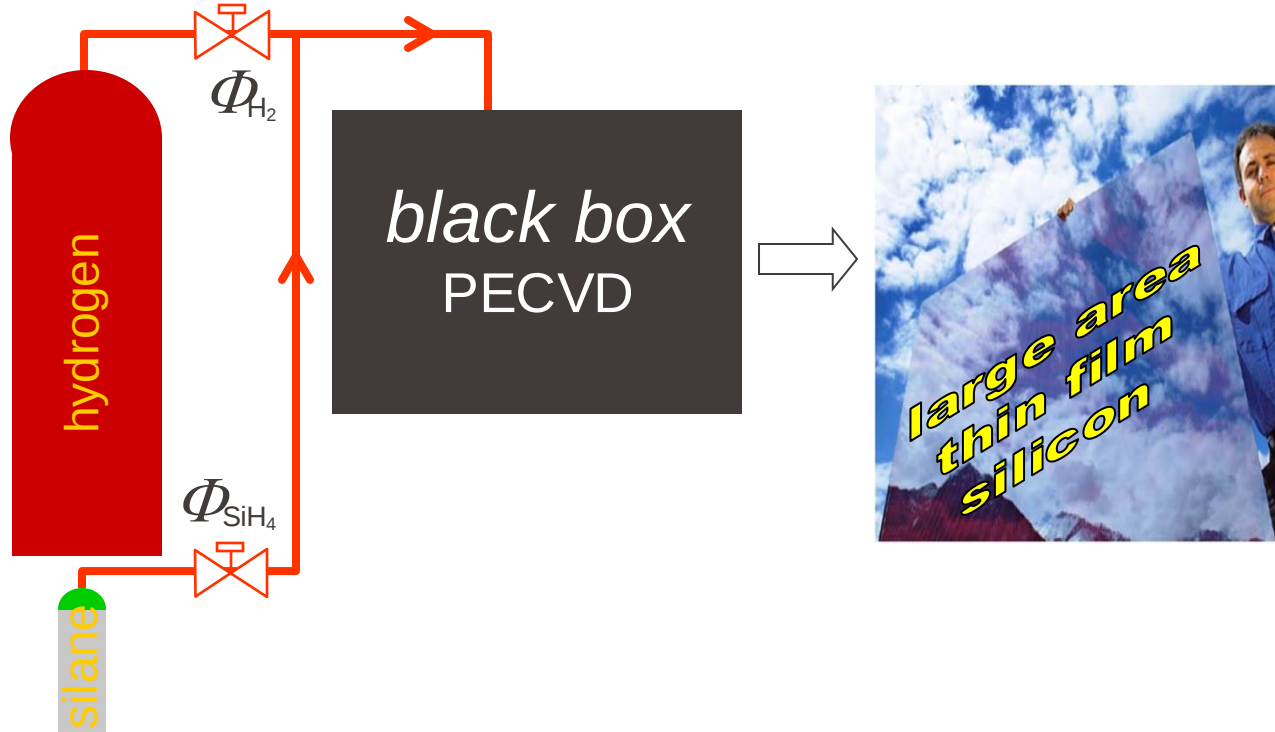
- Time-averaged sheath voltage
 $= \text{RF amplitude}/2$
 $= V_{p-p}/4$

➤ Method to choose ion energy $\varepsilon_i \sim V_{pp}/4 \rightarrow$ useful for etch control

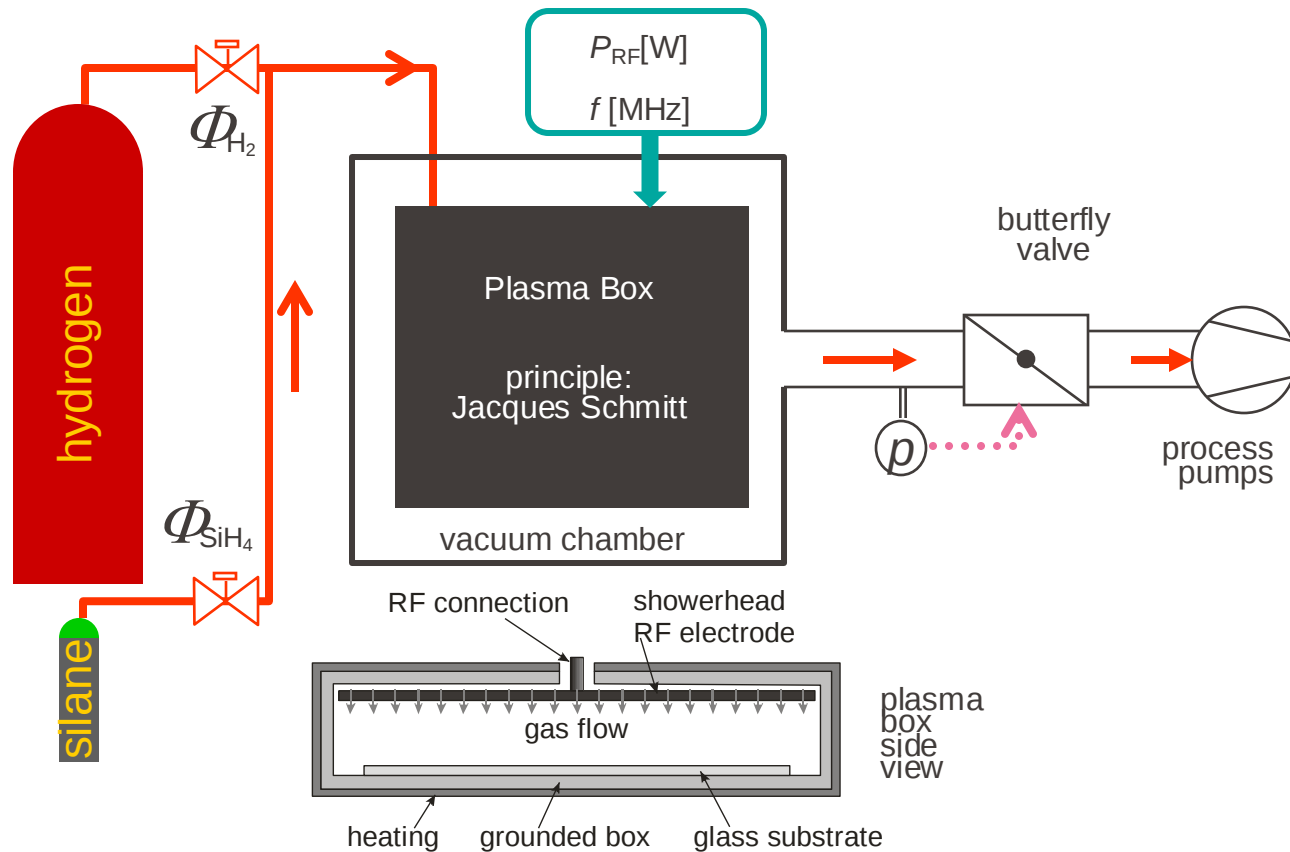
Large area RF capacitively-coupled reactors

- 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



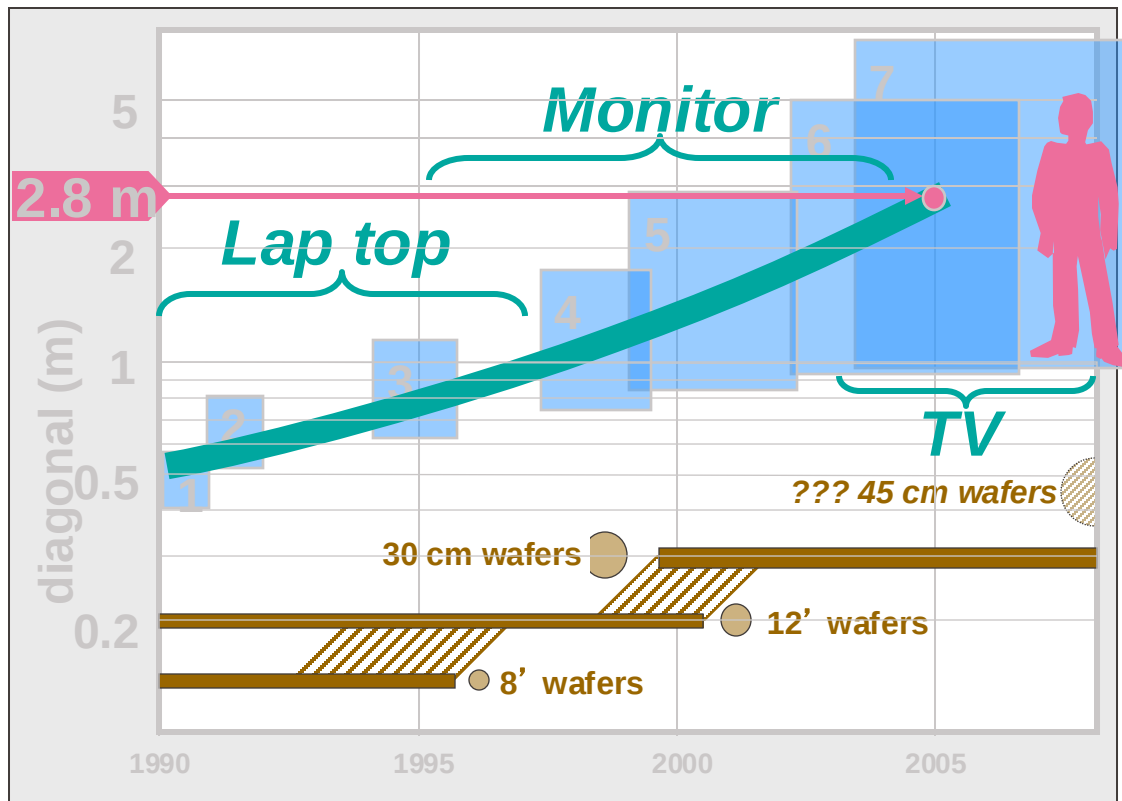
PECVD capacitive, parallel-plate RF reactor - some typical specificities



Front and back View Photo of KAI 20-1200



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

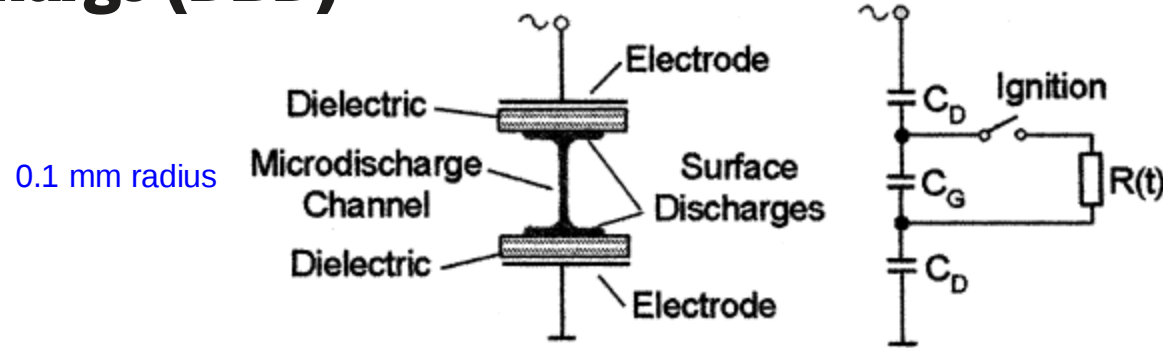


2. Ozon production by 3-body recombination



with M being any third body to carry off excess energy

Ozon production by Dielectric Barrier Discharge (DBD)



- 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 ($100 pC$) and local voltage is reduced in ns
- Arc extinguishes, but neighbouring arc can still strike
- High voltage alternates at $50 Hz$ to $100 MHz$
- 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

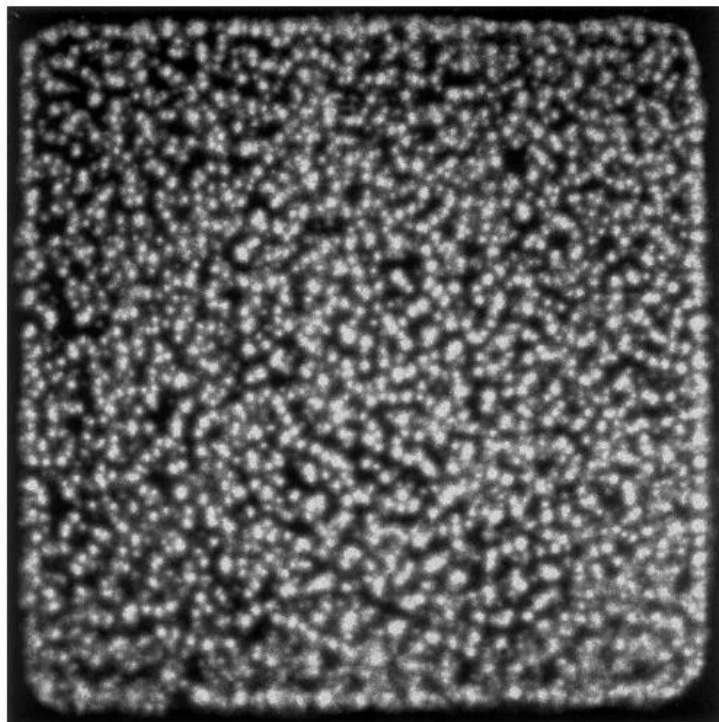


Fig. 3. End-on view of microdischarges in atmospheric-pressure air (original size: 6 cm × 6 cm, exposure time: 20 ms).

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:

$$v_{p,s} = \sqrt{\frac{2k_B T_s}{m_s}}$$

- Mean velocity:

$$\bar{v}_s = \sqrt{\frac{8k_B T_s}{\pi m_s}}$$

- Root-mean-square velocity:

$$v_{\text{rms},s} = \sqrt{\frac{3k_B T_s}{m_s}}$$