TECHNISCHE UNIVERSITÄT DRESDEN

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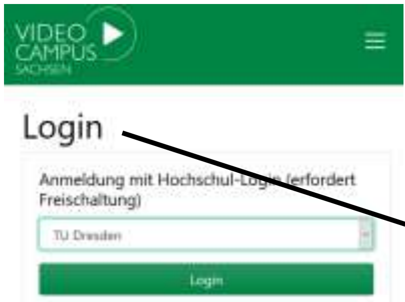

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Vacuum Technology
WS 20/21
Virtually presented
Lecture 7, Dec. 8, 2020

Prof. Dr. Johann W. Bartha

Inst. f. Halbleiter und Mikrosystemtechnik
Technische Universität Dresden

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"VT L07 a 09:31

0. Introduction

Air pressure as a force to the walls of an empty container

1. Gas kinetic

Pressure as momentum transfer, Mol & Molvolume, Pressure units Partial pressure, Boltzmann Velocity&Energy distribution, Impingement rate, monolayer coverage time,

2. Pressure Ranges

3. Vacuum technical terms

4. Vacuum generation

5. Pressure measurement

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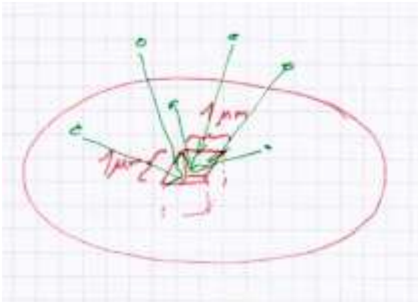

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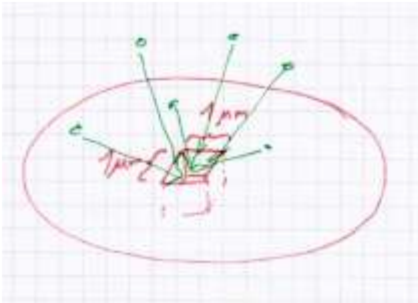

$$Z_a = \frac{1}{4} n\, v_{mean}$$

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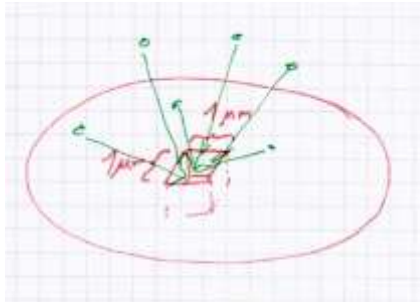

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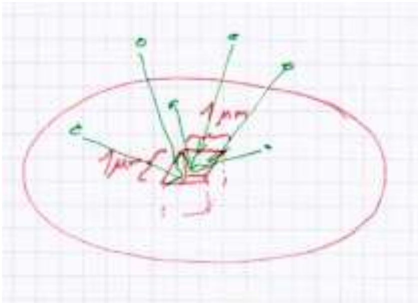

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$a = 1 \cdot 10^{19}$ [1/m²]

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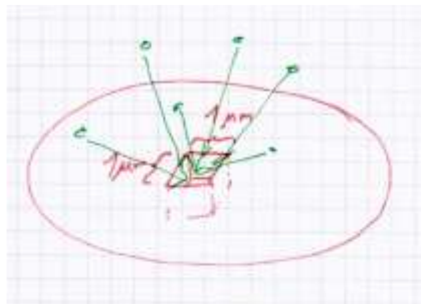

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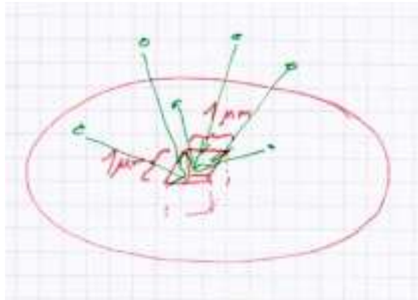

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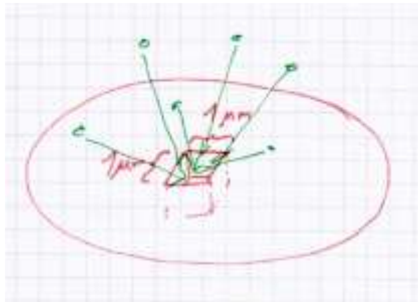

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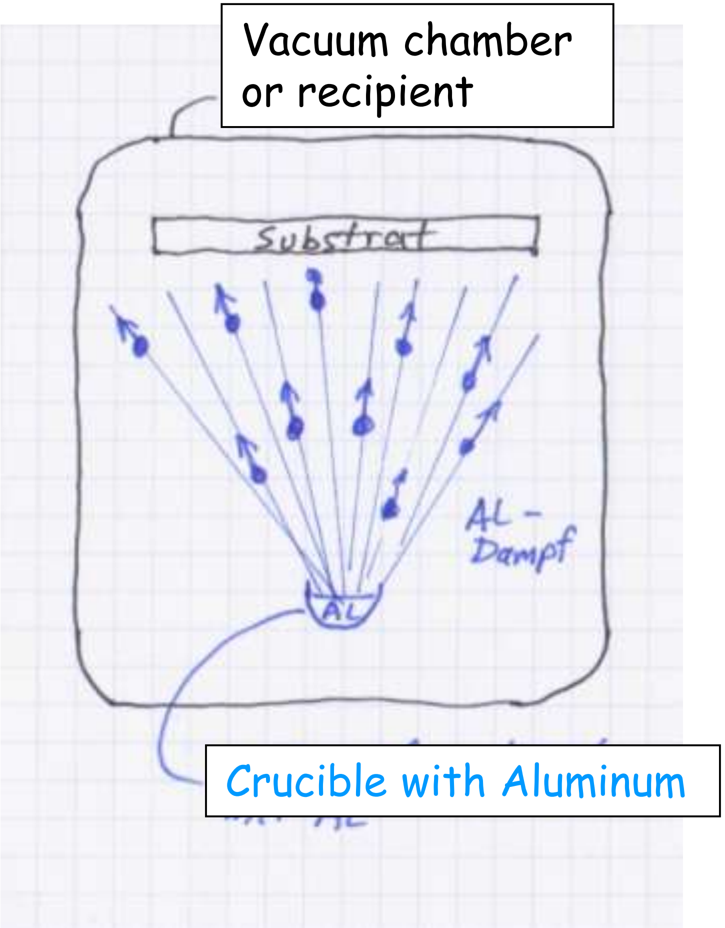
Application example



In a vacuum chamber Al is evaporated from a crucible on a substrate.

Application example

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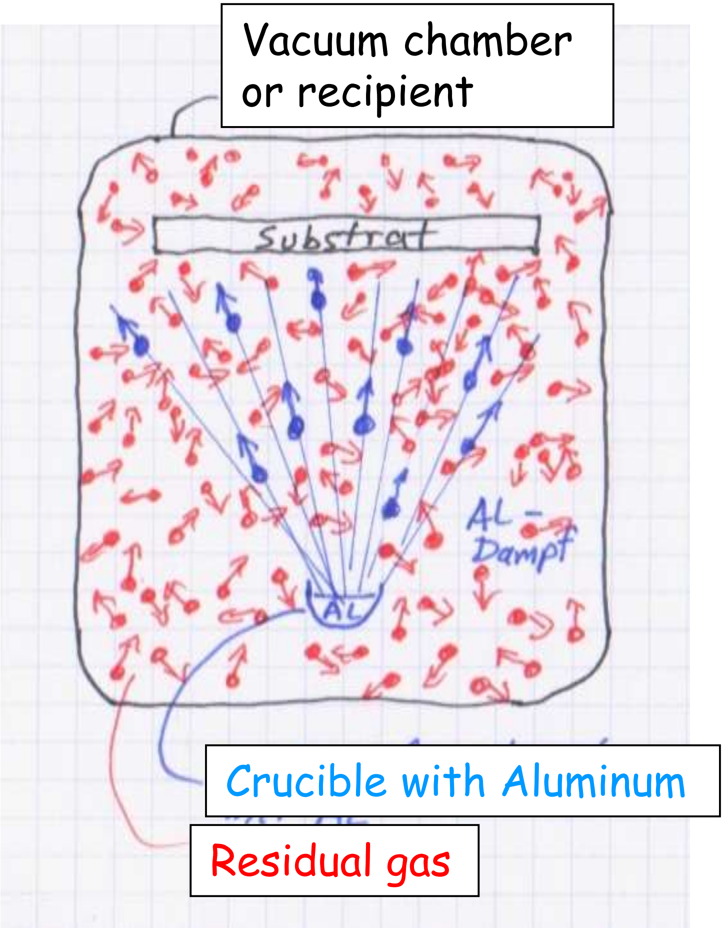
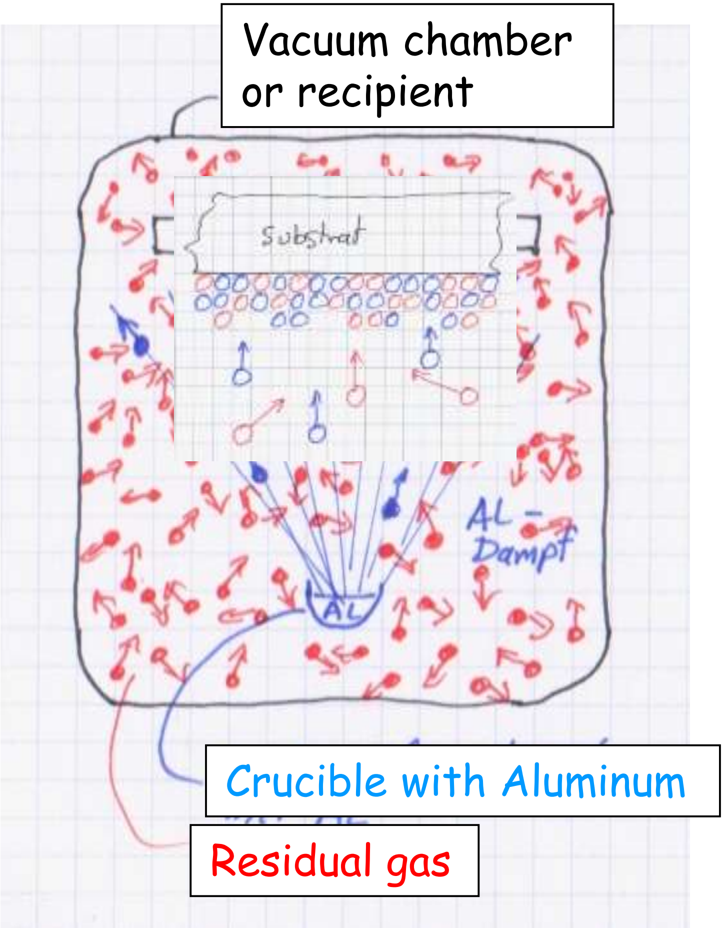


In a vacuum chamber Al is evaporated from a crucible on a substrate.

Inside of the recipient we have residual gas like O_2

Application example



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The film growing is therefore not pure aluminum but a mixture of Al and Al_2O_3!

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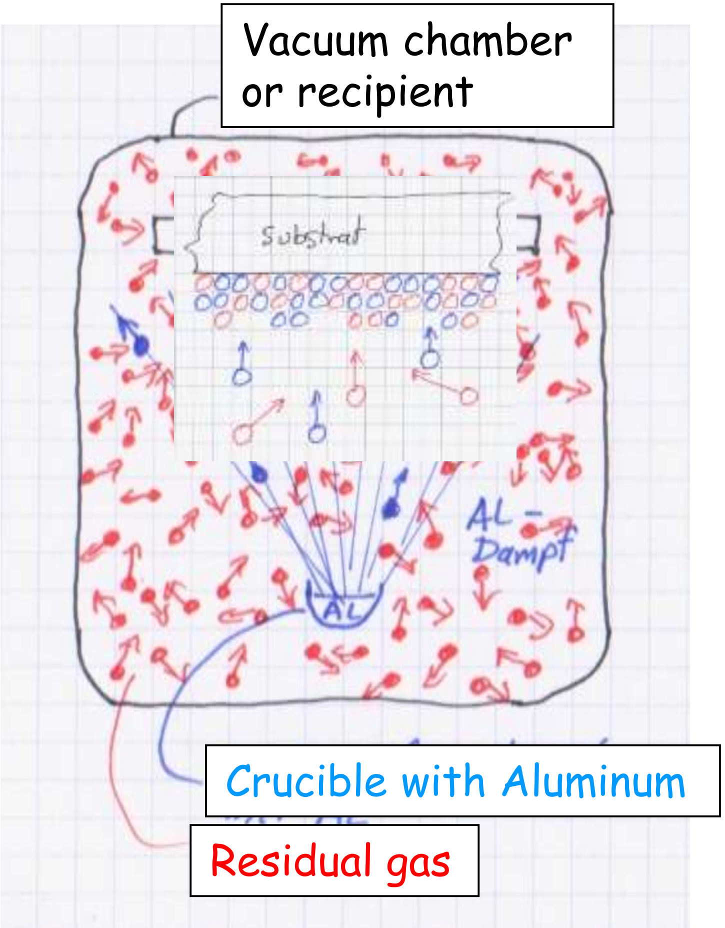

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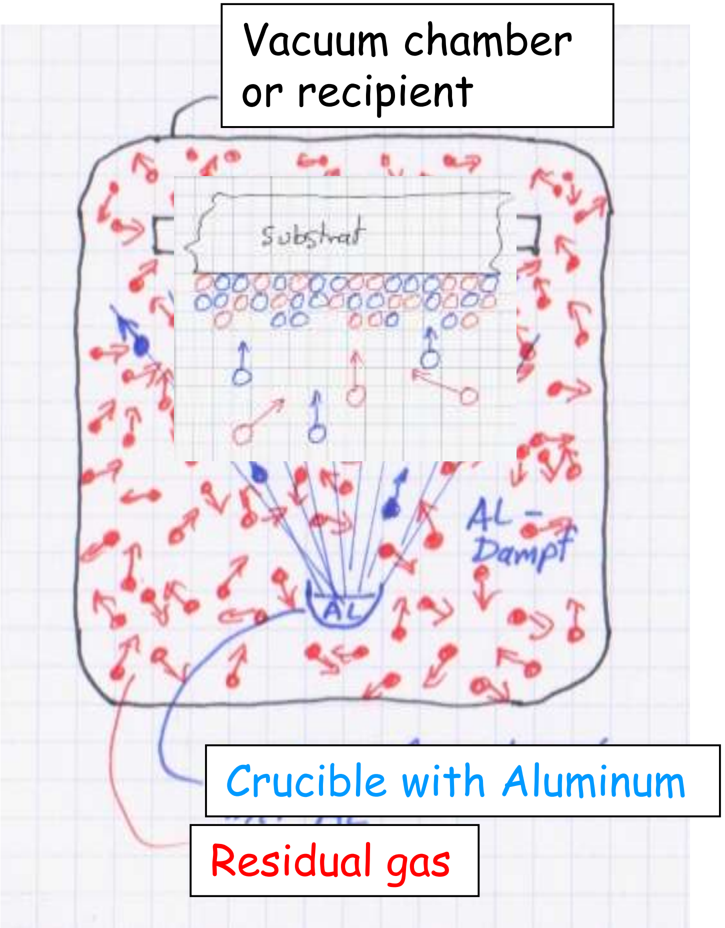
To get an idea on the requirements of the vacuum, we ask, at which pressure is the impingement rate of Al and O_2 equal. (Worst case! – Sticking coefficient = 1?)

Now we assume an Al growth rate of 1µm/min and a monolayer thickness of 0.3 nm.

Application example



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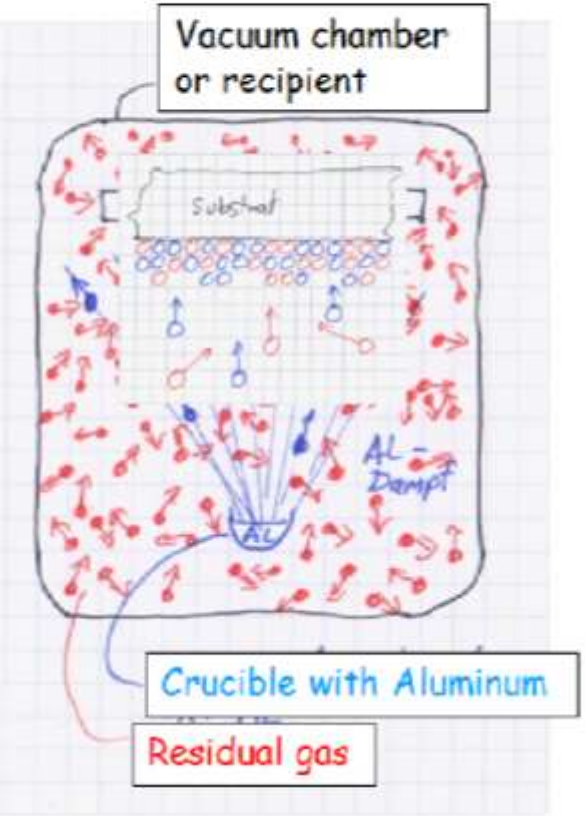


Impingement rate of Al: $1 ML = 0{,}3\ nm$

$1 \mu m/min = 3{,}3 \cdot 10^3\ ML/min$ respectively $55\ ML/s$

If $1 ML \triangleq 1 \cdot 10^{19}\ Al/m^2$ – $\underline{Z_{Al} = 5{,}5 \cdot 10^{20}\ Al/m^2 \cdot s}$

Impingement rate of O_2 when equivalent to that of Al:

$$P = Z_A \sqrt{2\pi m k T} \qquad m = 32\ amu$$

$$P_{O_2} \qquad Z_{Al} = Z_{O_2}! \qquad k = 1{,}38 \cdot 10^{-23}\ \frac{Nm}{K}$$

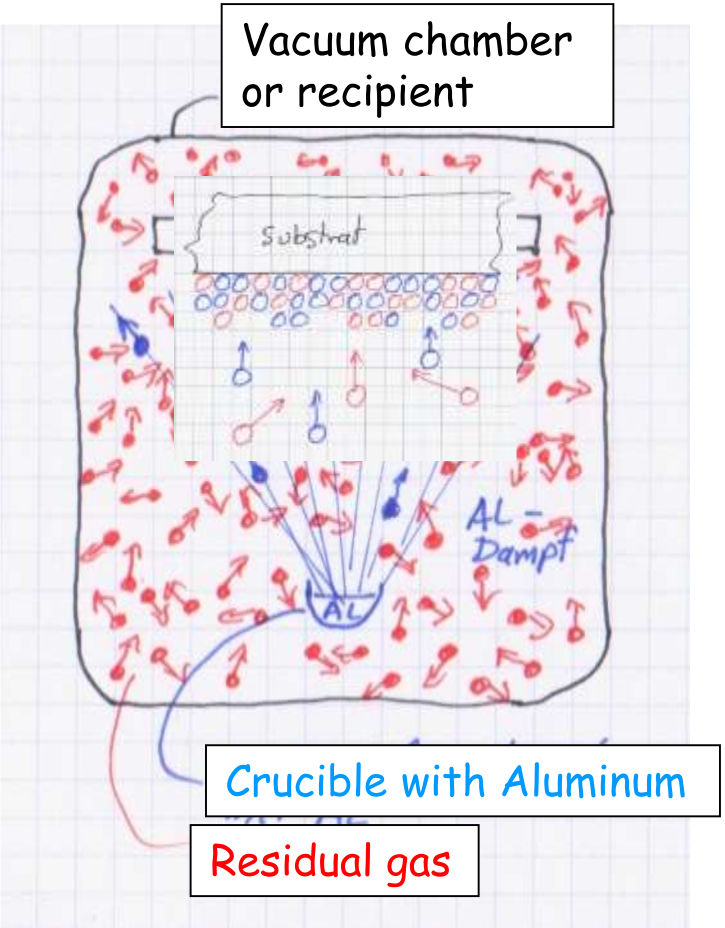
$$T = 293\ K$$

$$\Rightarrow P_{O_2} - 0\ 9\ Pa \triangleq 2 \cdot 10^{-4}\ mBar$$

Co: tamination below $1\% \Rightarrow P_{resi} = 2 \cdot 10^{-6}\ mBar$

Expected value in praxis $\boxed{P \approx 10^{-6}\ mBar}$

Application example



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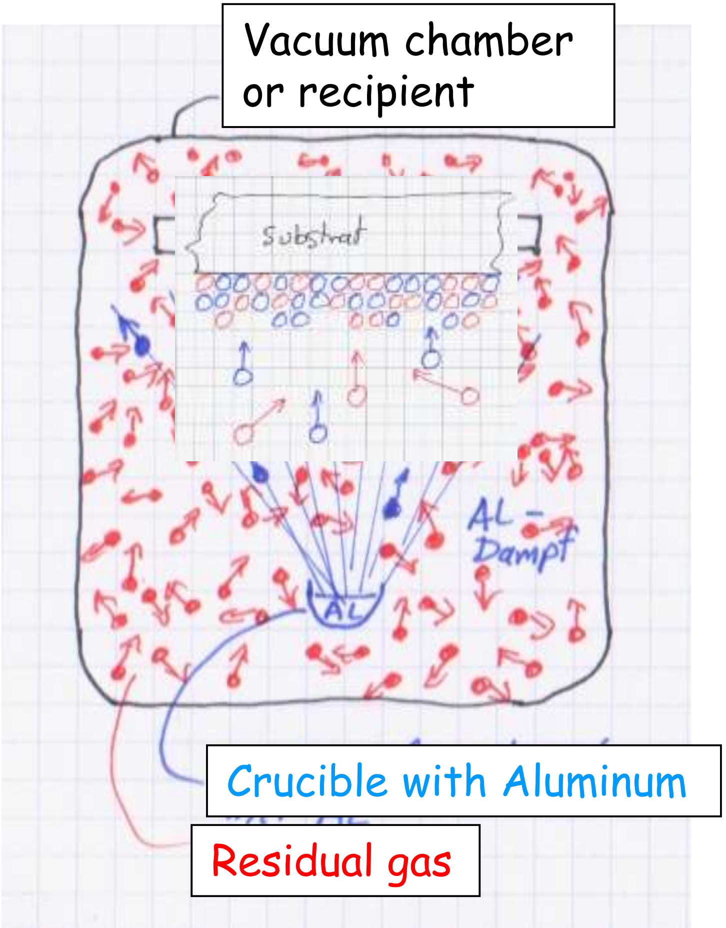

Impingement rate of Al:
1ML = 0,3 nm
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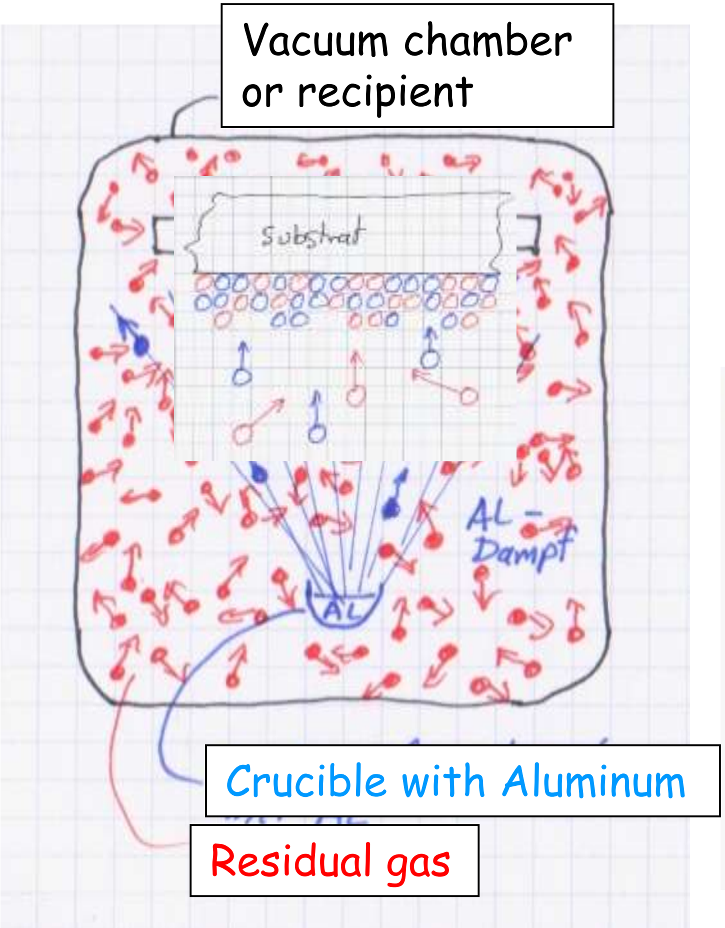

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Relation between pressure and impingement rate:

$$P = Z_A \sqrt{2\pi m K T}$$

P_{O_2} $Z_{AL} = Z_{O_2}$

$m = 32$ amu

$K = 1{,}38 \cdot 10^{23} \frac{Nm}{K}$

$T = 293$ K

$\Rightarrow P_{O_2} = 0{,}019\ Pa \mathrel{\hat{=}} 2 \cdot 10^{-4}$ mBar

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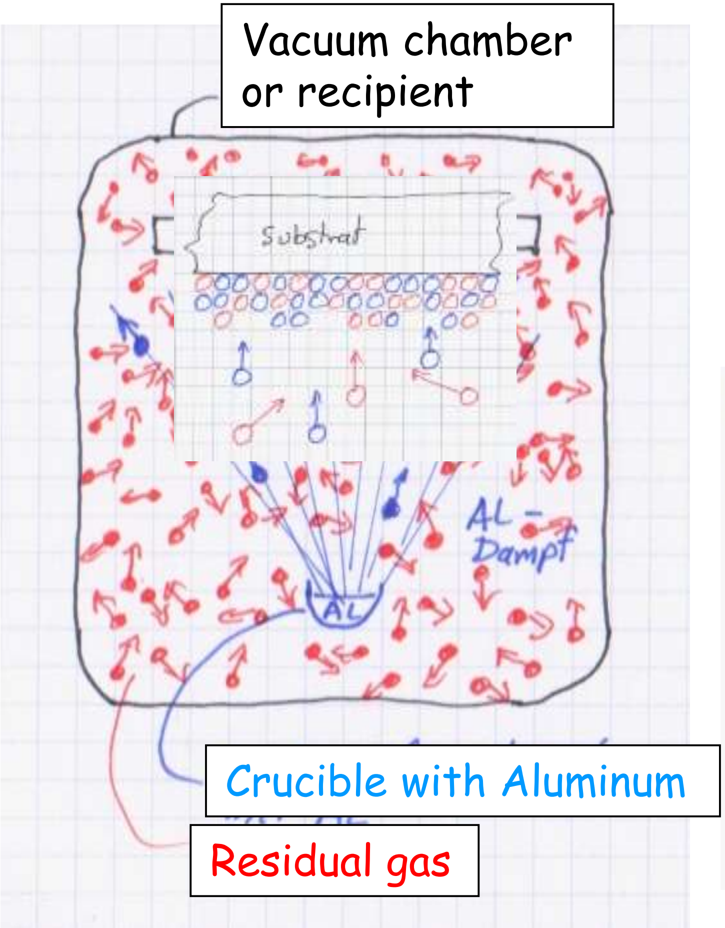

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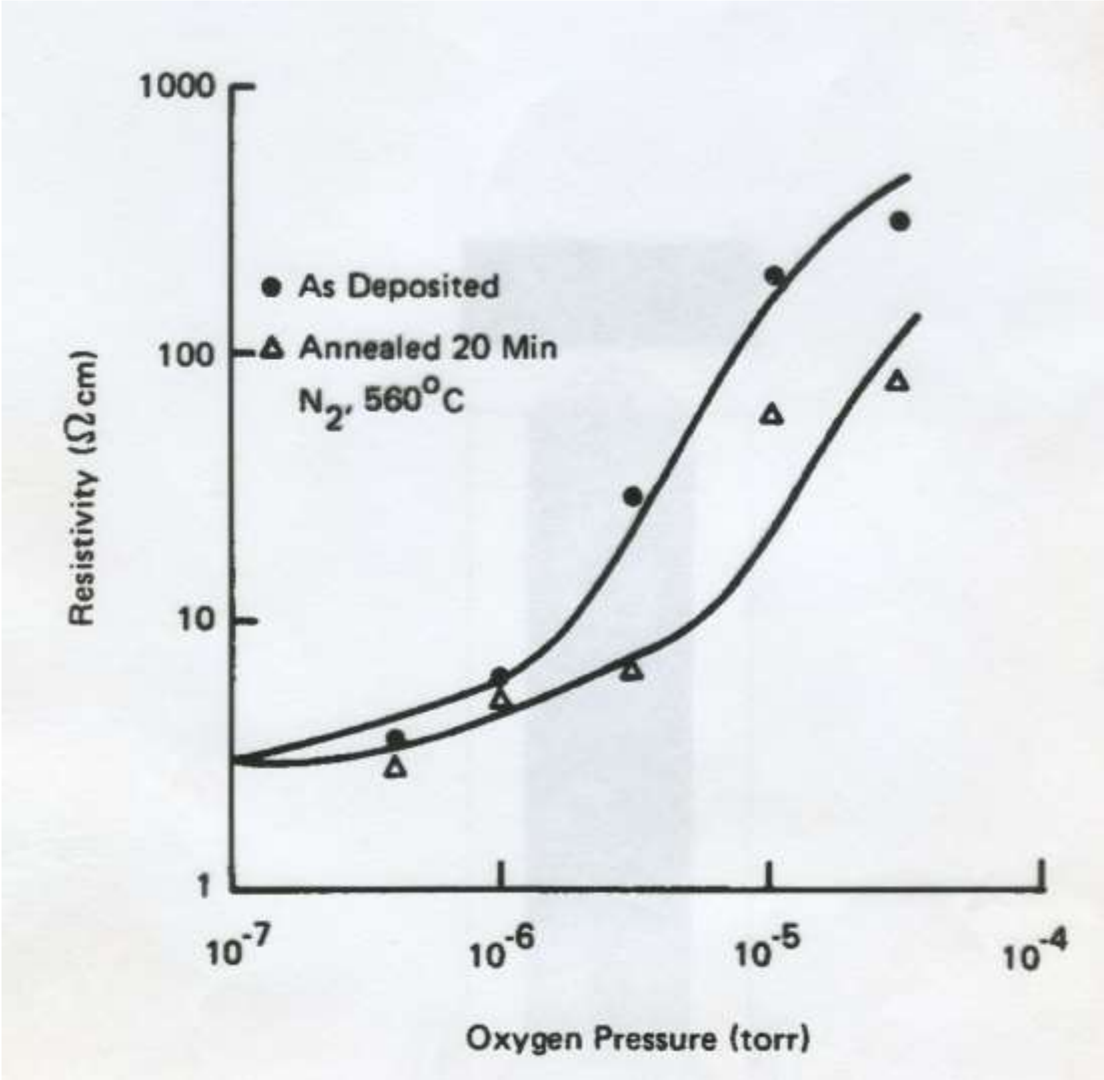
$T = 293$ K

$$\Rightarrow P_{O_2} = 0{,}019 \text{ Pa} \mathrel{\hat{=}} 2 \cdot 10^{-4} \text{ mBar}$$

If the contamination should be below 1% then it must be:
$P_{Residual} < 2 \cdot 10^{-6}$ mBar
Expected in praxis is $P_{recipiant} \sim 10^{-6}$ mBar!

Resistivity vs. residual pressure



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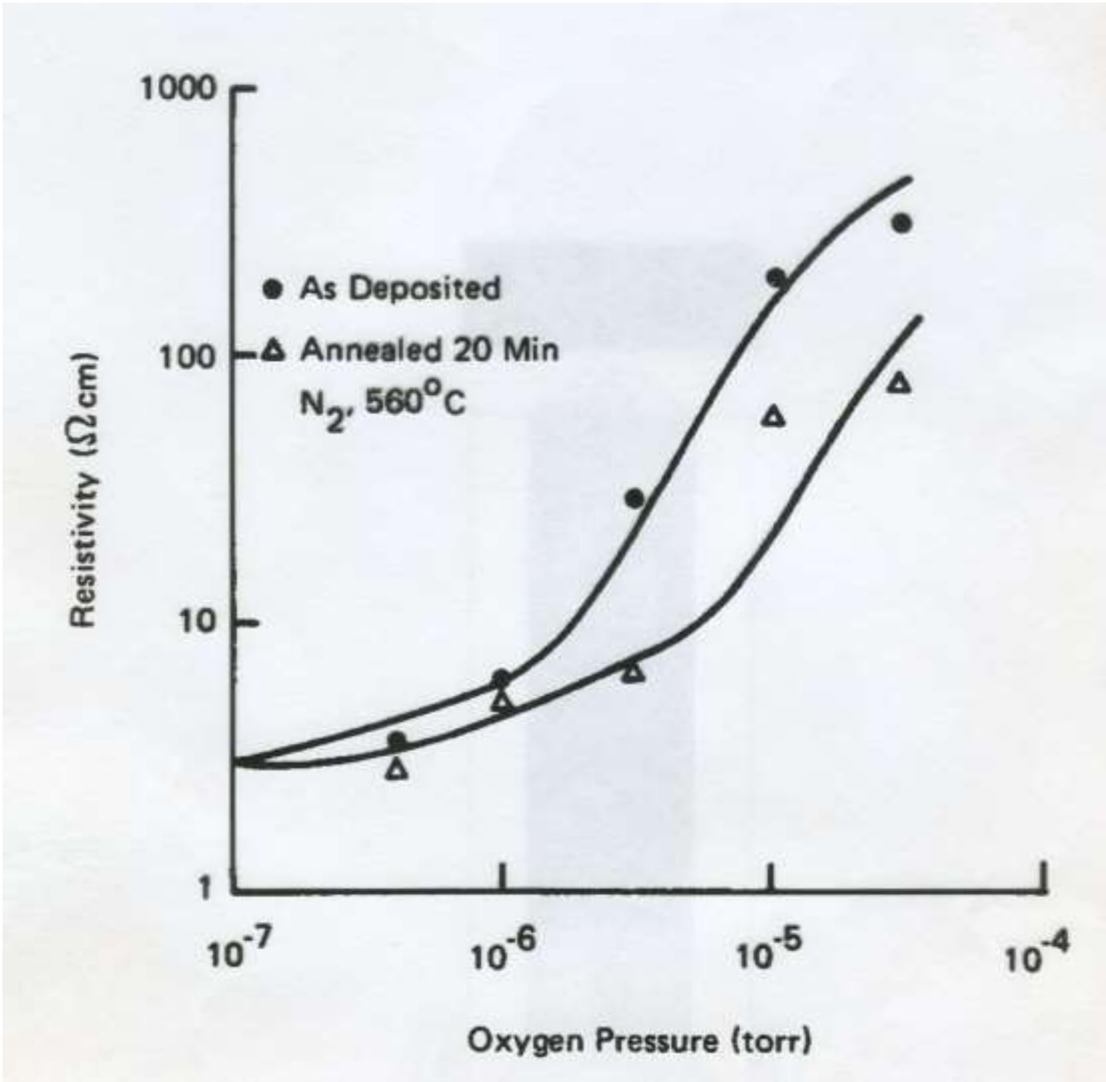
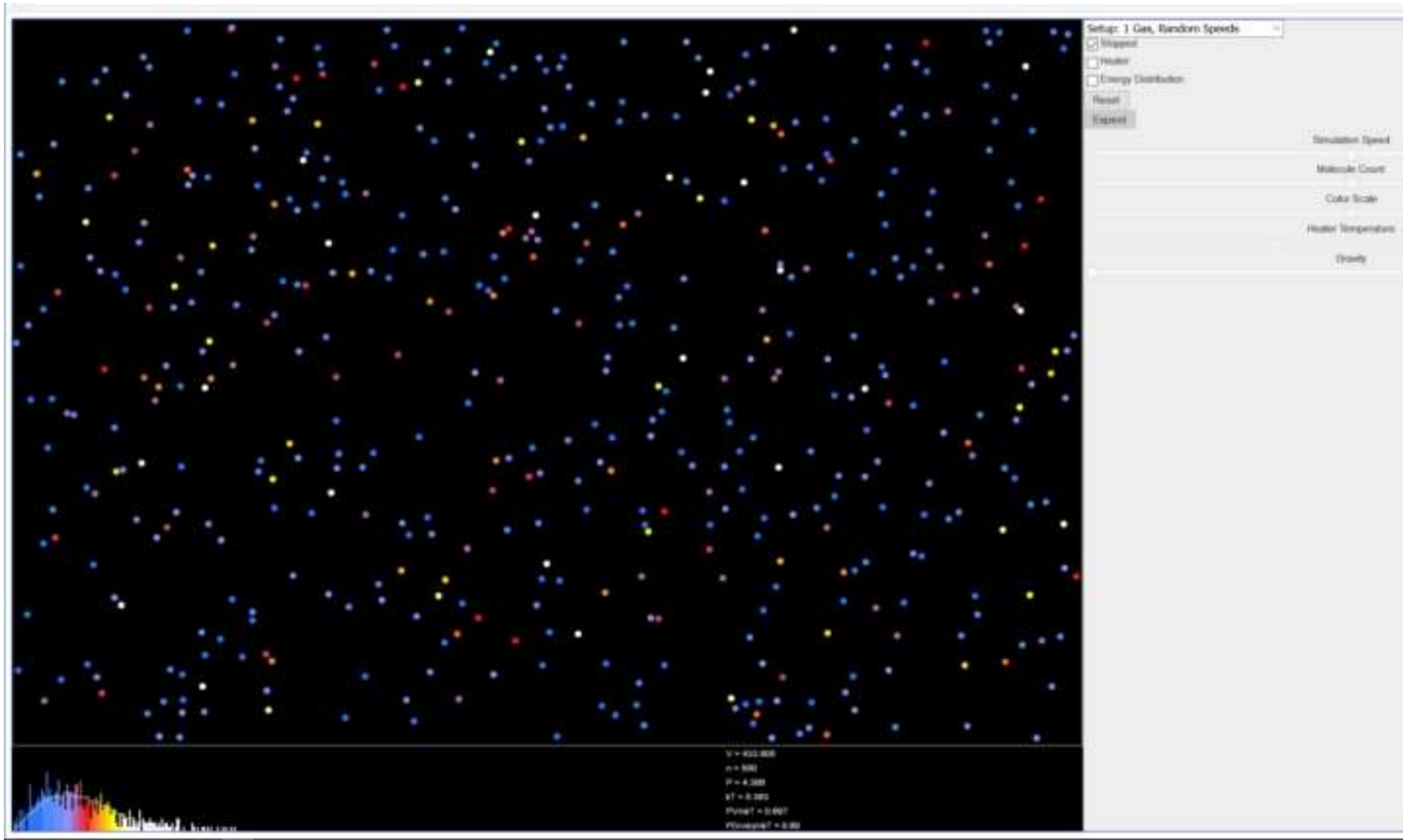


Mean free path (mfp)



http://www.falstad.com/gas/fullscreen.html

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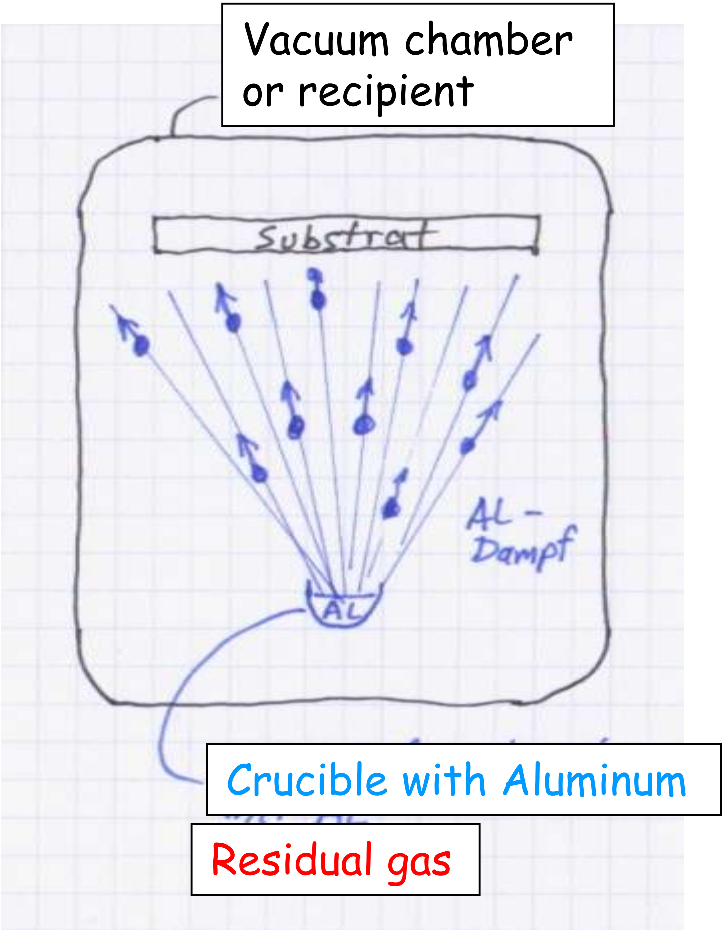

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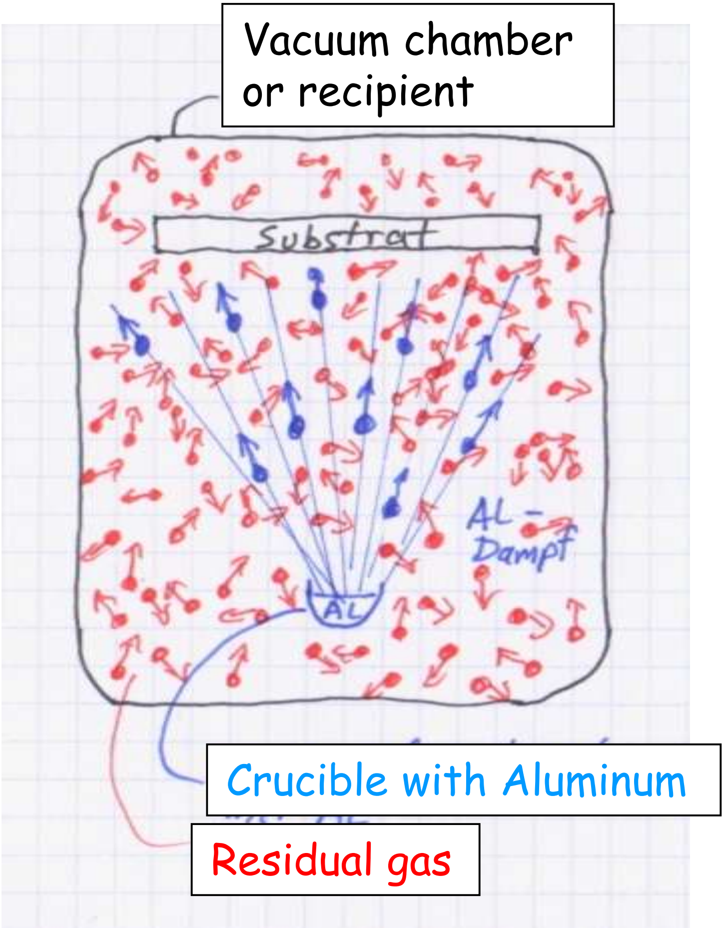

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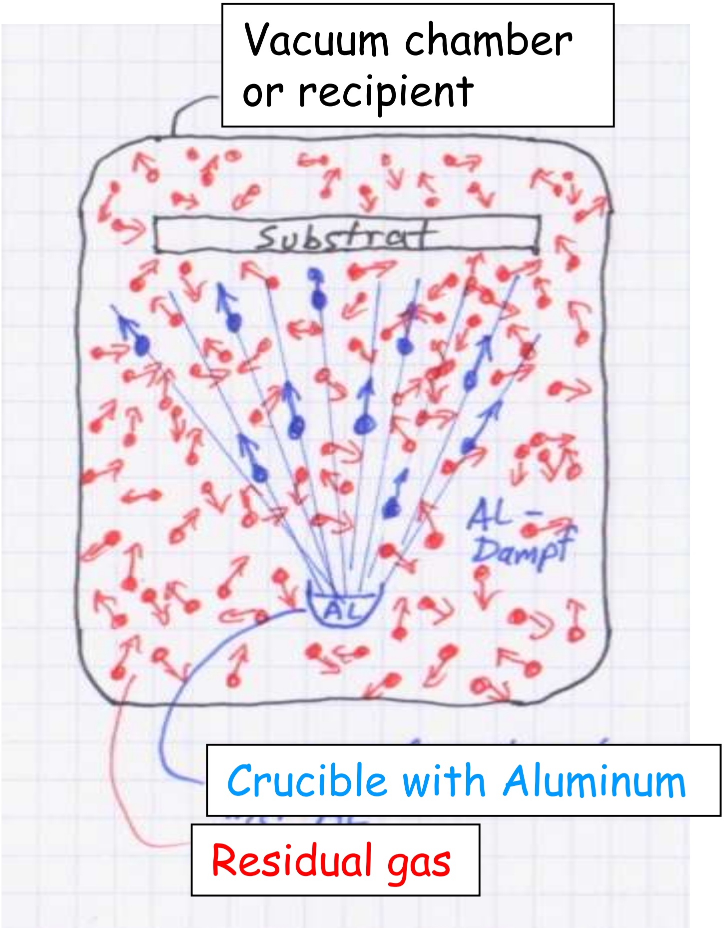
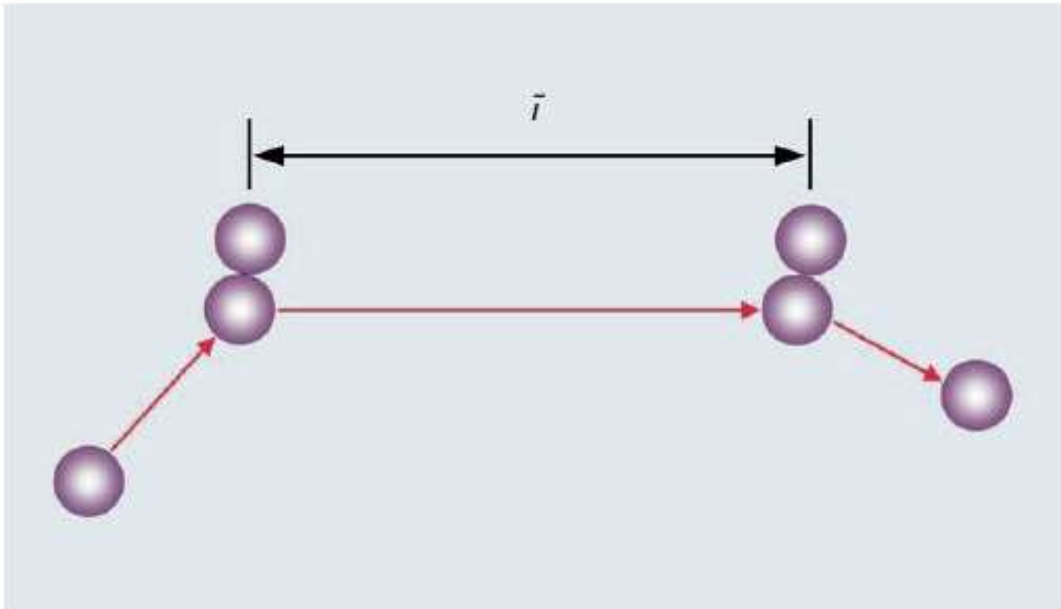


Mean free path

The mean free path is the mean path length that a molecule traverses between two successive impacts with other molecules.



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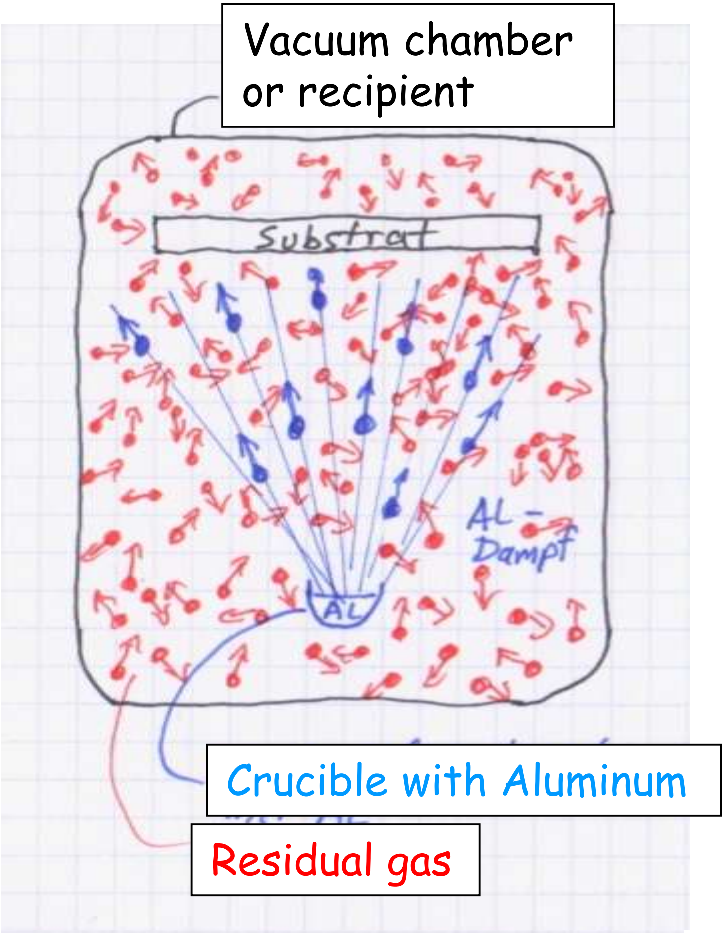

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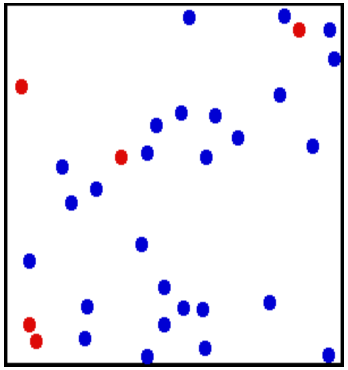

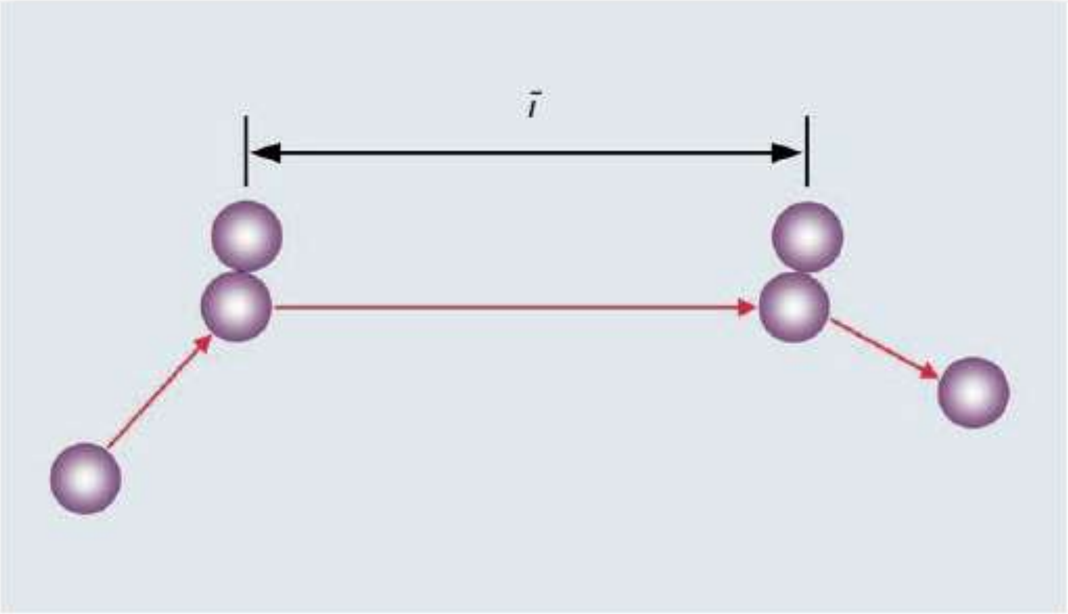

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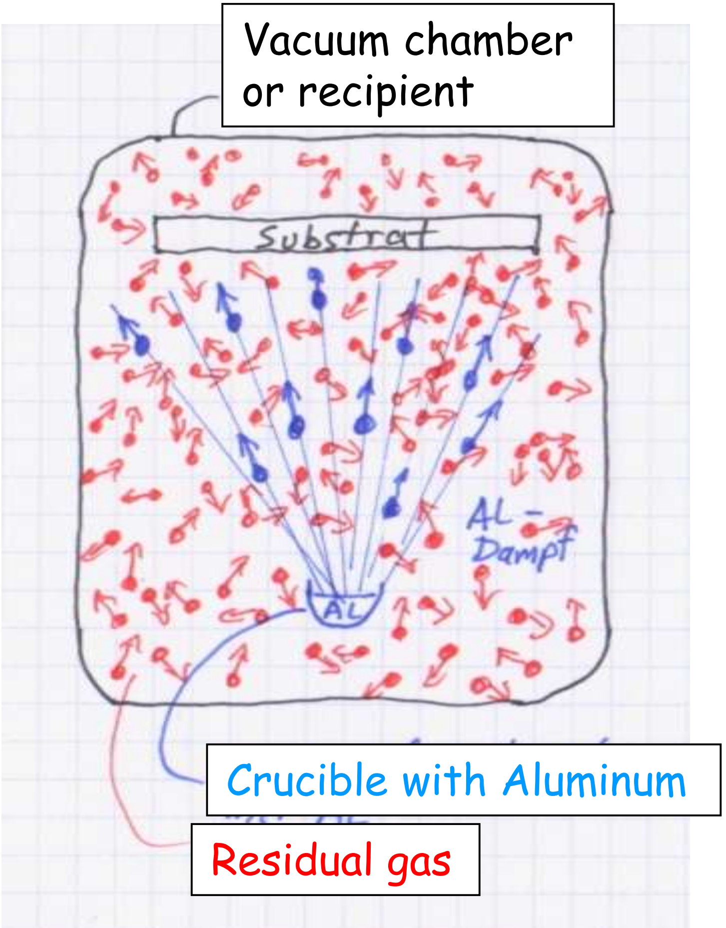

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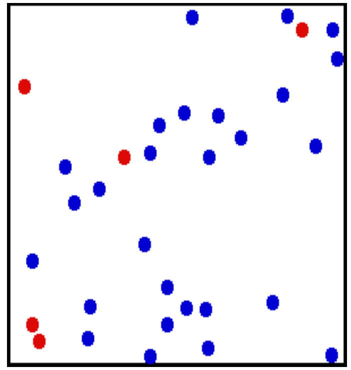
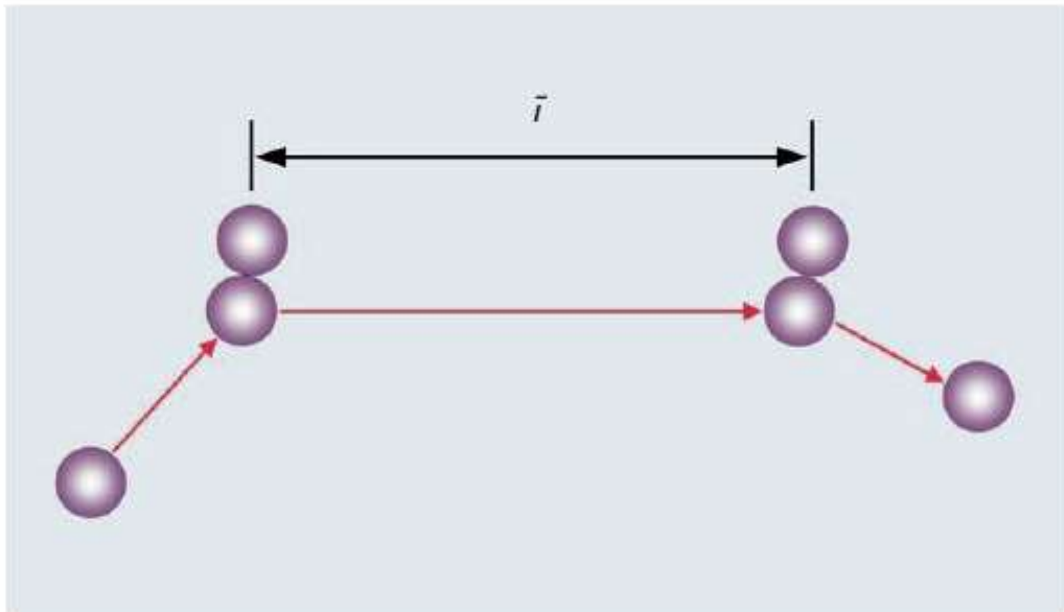
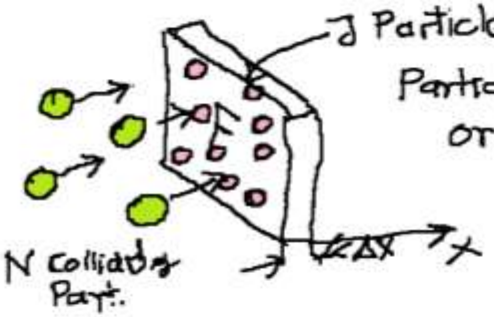


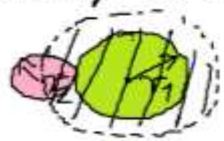




Particle density $n = \frac{J}{F \cdot \Delta x}$

or $J = n\, F \cdot \Delta x$

Probability for a collision W



Collision Cross section q_s

$q_s = (r_1 + r_2)^2 \pi$

Q: How many Particles arrive at x without collision ?

Probability for a scattering event $\quad W = \frac{\text{Area of all collision cross sections}}{\text{Area } F}$

From N approaching particles $\quad W = \frac{J \cdot q_s}{F}$

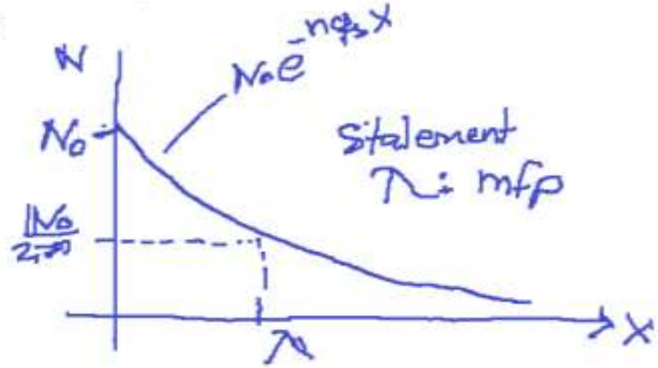
ΔN become scattered with probability W

$$\Delta N = -W \cdot N = -\frac{J \cdot q_s}{F} N = \frac{n \cancel{F} \Delta x \cdot q_s N}{\cancel{F}}$$

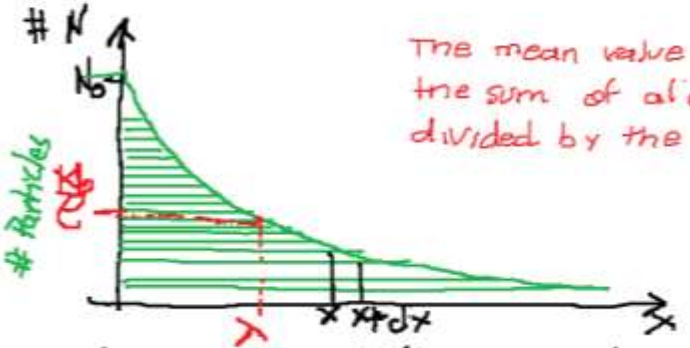
$$\frac{\Delta N}{N} = -n q_s \Delta x \qquad \Delta x \to dx \qquad \int_{N_0}^{N} \frac{dN}{N} = -\int_{x_0}^{x} n q_s \, dx$$

Boundary condition $N(x=0) = N_0$

$$N(x) = N_0 \cdot e^{-n q_s x}$$



Proof that λ is indeed the mean free path mfp



The mean value of all particles is the sum of all occuring pathes S divided by the initial particle # N_0!

$$N(x) = N_0 \cdot e^{-nq\,x} = N_0 e^{-\alpha x}$$

$$x = \frac{1}{\alpha} \Rightarrow N = \frac{N_0}{e}$$

- At the distance between x and x+dx $\alpha N(x)dx$ particles are scattered
- these particles passed the length x so the total path way of these particles is $x \cdot \alpha N(x) dx$
- So the total sum of all occuring pathes is the integral:

$$S = \int_0^\infty \alpha x\, N(x)\, dx = \int_0^\infty \alpha x\, N_0 e^{-\alpha x} dx$$

$$S = \alpha N_0 \underbrace{\int_0^\infty x\, e^{-x\alpha}}_{\text{Formula Table} = \frac{1}{\alpha^2}} = \alpha N_0 \frac{1}{\alpha^2} = \frac{N_0}{\alpha}$$

Since $S = N_0 \lambda$

$$\frac{S}{N_0} = \lambda = \frac{1}{\alpha} \quad \text{q.e.d.}$$

$$\boxed{\lambda = \frac{1}{\alpha} = \frac{1}{n q_s}}$$

Consideration of different cases

$$q_s = (r_1 + r_2)^2 \pi$$

$$\lambda = \frac{1}{\alpha} = \frac{1}{n q_s}$$

(1) target and colliding particles are identical

$$r_1 = r_2 = r \quad \Rightarrow \quad q_s = (2r)^2 \pi = 4\pi r^2$$

$$\lambda = \frac{1}{n 4\pi r^2}$$

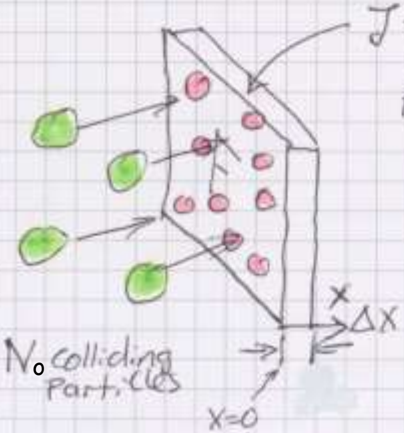
(2) colliding particles are very small
(electrons in a gas → plasma)

$$r_1 \ll r_2 = r \qquad \lambda = \frac{1}{n \pi r^2}$$

(3) In case colliding and target particles are equal in thermal equilibrium

$$\lambda = \frac{1}{n \pi 4 r^2 \sqrt{2}} = \frac{kT}{p\, 4\pi\, r^2 \sqrt{2}}$$

Mean free path & effective collision cross section



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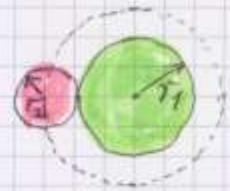
Probability for a collision



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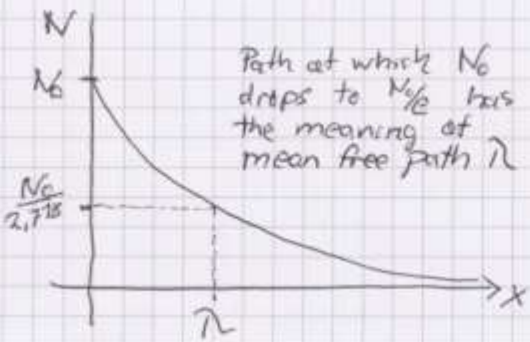

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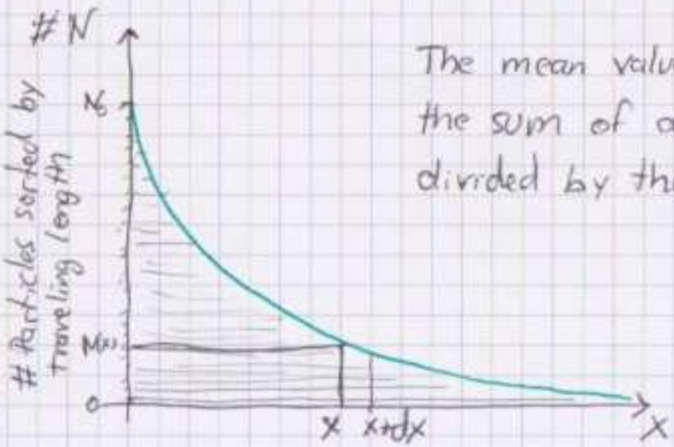

The mean value of all pathes is the sum of all occuring pathes S divided by the initial particle # N_0!

- At the distance between x and $x+dx$, $\alpha \cdot N(x) dx$ Particles become scattered
- These particles passed the length x meaning together the total pathway of these particles is $x \cdot \alpha N(x) dx$
- So the total sum of all occuring pathes S is:

$$S = \int_0^\infty \alpha x \, N(x) \, dx = \int_0^\infty \alpha x N_0 e^{-\alpha x} dx$$

$$S = \alpha N_0 \underbrace{\int_0^\infty x \cdot e^{-\alpha x}}_{\text{Formula table } = \frac{1}{\alpha^2}} = \alpha N \cdot \frac{1}{\alpha^2} = \frac{N_0}{\alpha}$$

Since $S = N_0 \cdot \lambda$

$$\frac{S}{N_0} = \lambda = \frac{1}{\alpha} \quad \text{q.e.d}$$

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Consideration of different cases

$$q_s = (r_1 + r_2)^2 \pi$$

$$\lambda = \frac{1}{\alpha} = \frac{1}{n q_s}$$

① target and colliding particles are the same:

$$r_1 = r_2 = r \quad \Rightarrow \quad q_s = (2r)^2 \pi = 4\pi r^2$$

$$\lambda = \frac{1}{n 4\pi r^2}$$

② colliding particles are very small (electrons in a gas → plasma)

$$r_1 \ll r_2 \qquad \lambda = \frac{1}{n \pi r^2}$$

③ In case colliding and target particles are in thermal equilibrium

$$\lambda = \frac{1}{n \pi 4 r^2 \sqrt{2}} = \frac{kT}{p 4\pi r^2 \sqrt{2}}$$

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Application example

Example: mfp of Ar (Ø=0,376 nm) at RT and $1 \cdot 10^{-5}$ mBar or $1\ 10^{-3}$ Pa?

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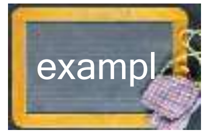


Application example

Example: mfp of Ar (Ø=0,376 nm) at RT and $1 \cdot 10^{-5}$ mBar or $1\ 10^{-3}$ Pa?

Example: Mean free path (MFP) of Ar at room temperature (RT) and $P = 1 \cdot 10^{-5}$ mbar ($\hat{=}\ 1 \cdot 10^{-3}$ Pa)

$r(\mathrm{Ar}) = 0{,}188$ nm

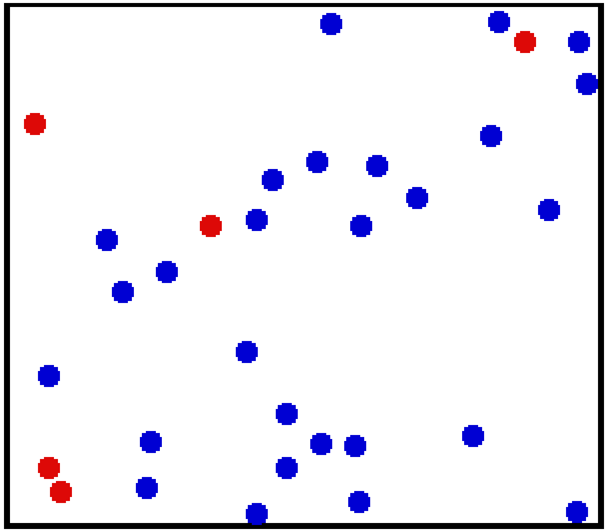
$K = 1{,}38 \cdot 10^{-23}\ \frac{\mathrm{Nm}}{\mathrm{K}}$

$T = 293$ K

$$\lambda = \frac{KT}{P\, 4\pi r^2 \sqrt{2}} = \underline{\underline{6{,}4\,\mathrm{m}}}$$

Mean Free Path

https://www.tec-science.com/thermodynamics/kinetic-theory-of-gases/mean-free-path-collision-frequency/



http://www.falstad.com/gas/

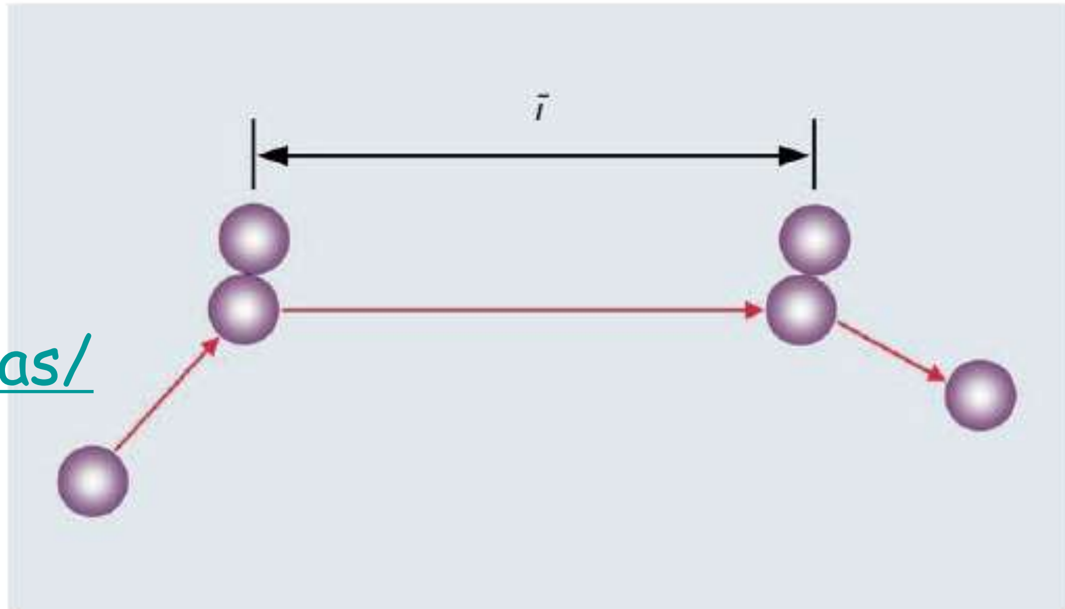
Mean free path

The mean free path is the mean path length that a molecule traverses between two successive impacts with other molecules. It depends upon molecular diameter d_m and temperature T in accordance with the following equation

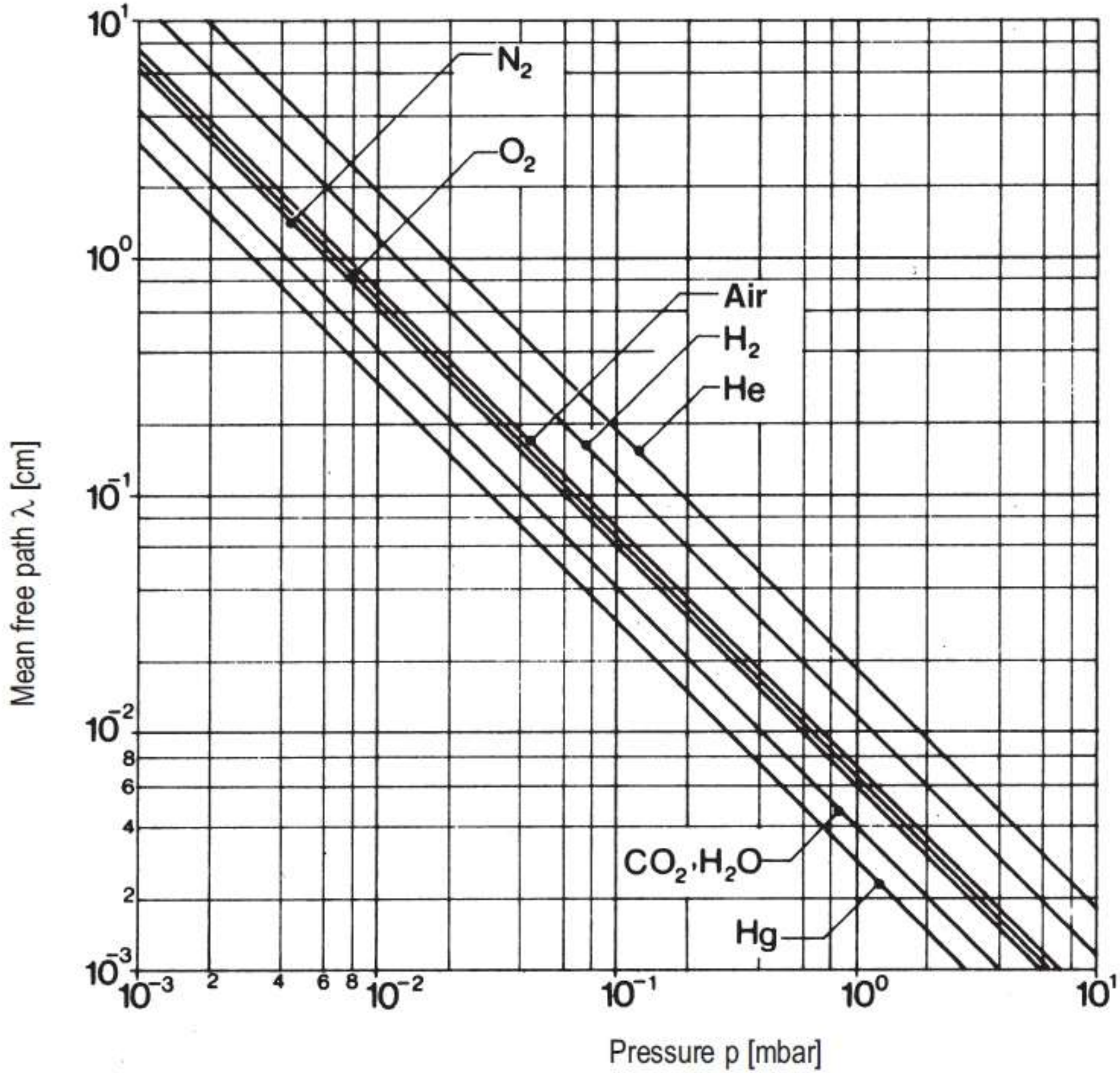
Mean free path

$$P \frac{k \cdot T}{\pi \cdot \sqrt{2} \cdot d_m^2}$$

and is of significance for the various flow types of a gas in a vacuum.



Mean Free Path



$$\lambda = \frac{kT}{p \cdot 4\pi r^2 \sqrt{2}} \Rightarrow p \cdot \lambda = \text{const.}$$

Determination of the atomic radius

Abbrev.	Gas	$C^* = \lambda \cdot p$ [cm · mbar]
H_2	Hydrogen	$12.00 \cdot 10^{-3}$
He	Helium	$18.00 \cdot 10^{-3}$
Ne	Neon	$12.30 \cdot 10^{-3}$
Ar	Argon	$6.40 \cdot 10^{-3}$
Kr	Krypton	$4.80 \cdot 10^{-3}$
Xe	Xenon	$3.60 \cdot 10^{-3}$
Hg	Mercury	$3.05 \cdot 10^{-3}$
O_2	Oxygen	$6.50 \cdot 10^{-3}$
N_2	Nitrogen	$6.10 \cdot 10^{-3}$
HCl	Hydrochloric acid	$4.35 \cdot 10^{-3}$
CO_2	Carbon dioxide	$3.95 \cdot 10^{-3}$
H_2O	Water vapor	$3.95 \cdot 10^{-3}$
NH_3	Ammonia	$4.60 \cdot 10^{-3}$
C_2H_5OH	Ethanol	$2.10 \cdot 10^{-3}$
Cl_2	Chlorine	$3.05 \cdot 10^{-3}$
Air	Air	$6.67 \cdot 10^{-3}$

Table III: Mean free path l
Values of the product c of the mean free path λ (and pressure p for various gases at 20 °C (see also Fig. 9.1)*

$$\lambda = \frac{KT}{p \cdot 4\pi r^2 \sqrt{2}} \quad \Rightarrow \quad p \cdot \lambda = \text{const.}$$

Determination of the atomic radius

$$r = \sqrt{\frac{KT}{\lambda p \, 4\pi \sqrt{2}}}$$

$T = 293\ K$

$K = 1{,}38\ 10^{23}\ \frac{Nm}{K}$

$C^*_{Ar} = 6{,}4 \cdot 10^{-3}\ mBar\ cm$

$$\Rightarrow \underline{r_{Ar} = 0.188\ nm}$$

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»Wissen schafft Brücken.«