Plasma Physics for Microelectronics Technology

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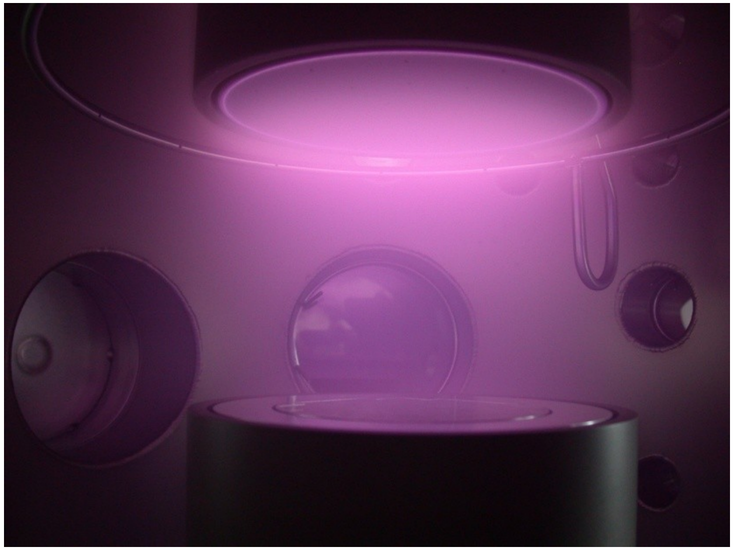
Outline

1. Plasma technology in Greifswald / Germany
2. Support of industrial applications:
   example EUV lithography
3. Excursus in plasma physics
4. Plasma generation in chambers

Introduction



Plasma:

gas with properties:

- electrical conducting
- radiating
- reactive

Species:

beside molecules and atoms

- free electrons, ions
- excited atoms and ions
- dissociation products, radicals

Plasma physics in Greifswald

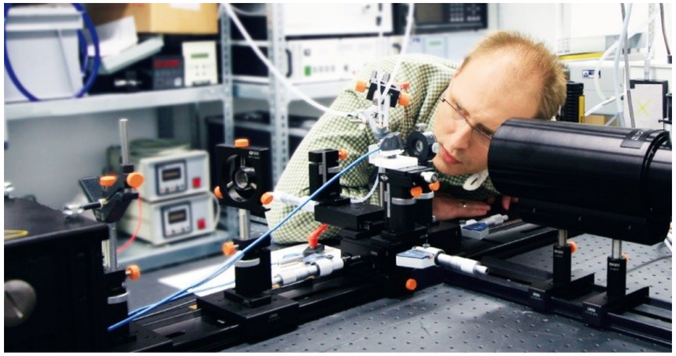
Hanse Town Greifswald

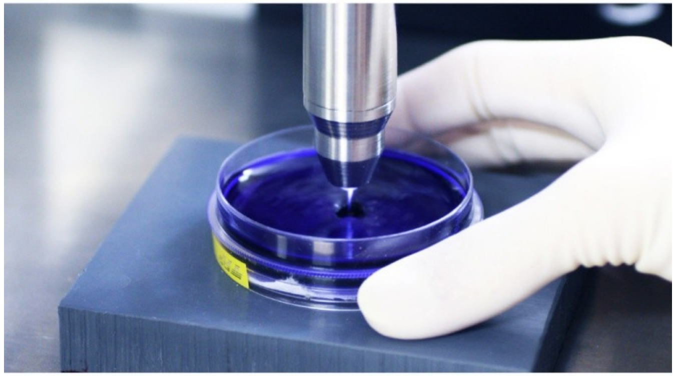
Leibniz-Institute for Plasma Science and Technology e.V.

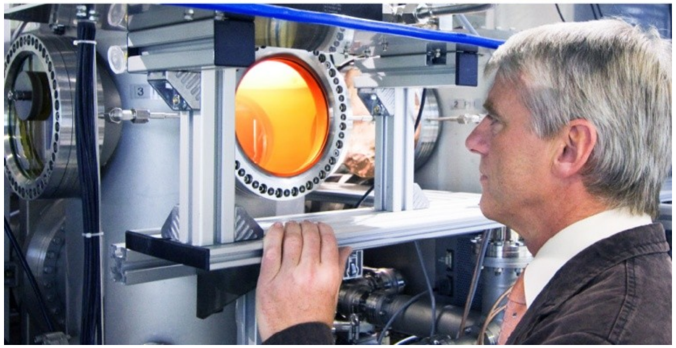
Institute of Physics,
Ernst-Moritz-Arndt University

Leibniz Institute for Plasma Science and Technology e.V. (INP Greifswald)

- 1.1.1992 foundation of the INP
- Biggest non-university research institution for low temperature plasmas in Europe
- Annual budget 2012: 15.8 Mill. € (6.4 Mill. € third-party funds),
- Currently 179 employees (111 scientists and engineers)
- Application-oriented basic research “From the idea to the prototype”
  - Plasmas for materials and energy
  - Plasmas for environment and health

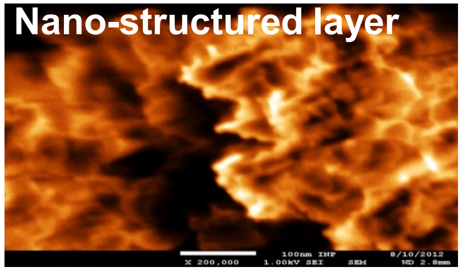






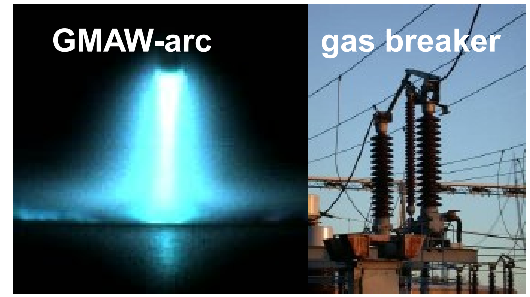
Research area Materials and Energy

Surfaces / Coatings



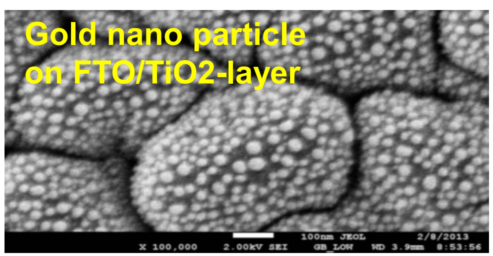
- PE-CVD processes for functional coatings
- Coatings with atmospheric pressure plasma jets

Welding / Switching



- Diagnostics and simulation of arcs and thermal plasmas in production and electrical engineering

Catalytic materials



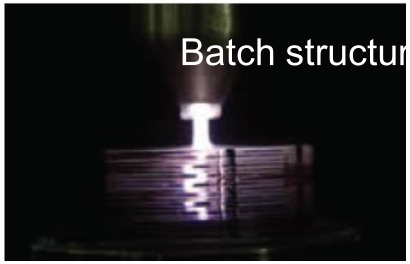
- Catalytic materials for hydrogen technology and photo-voltaic (fuel cells, water dissociation)
- Plasma processes for metal-polymer composites

Plasma monitoring

- Diagnostics of transient molecular species with laser absorption spectroscopy (TDLAS, QCLAS)
- Study of plasma chemical processes

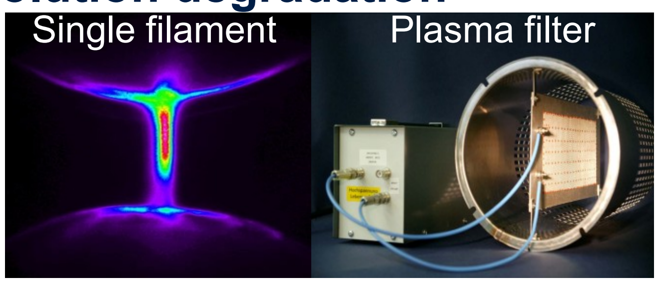
Research area Environment and Health

Bioactive materials



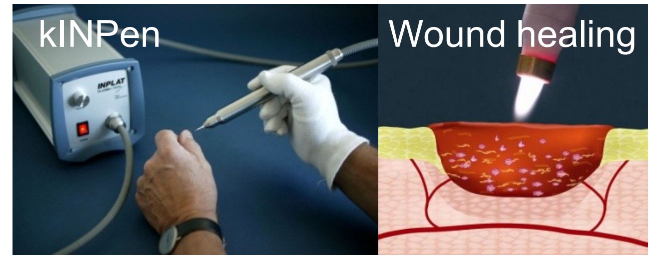
- PE-CVD processes at atmospheric pressure
- Cell adhesive coatings
- surfaces for medical devices

Polution degradation



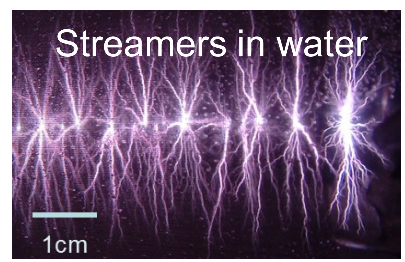
- Study of dielectric barrier discharges (filaments, micro discharges)
- Treatment of exhaust gases, aerosols, odours, VOC

Plasma medicine / Decontamination



- Study of plasma-cell interaction, use of atmospheric pressure plasmas
- Decontamination of packaging, food, medical devices

Bioelectrics



- Study of multi-phase discharges (corona in water)
- Disinfection of water
- Treatment of drug remnants

INP Greifswald

2. Support of industrial applications of low-temperature plasmas

- an example from microelectronics technology

Current challenge for next generation micro processors production:

- Patterning features less than 22 nm by lithography

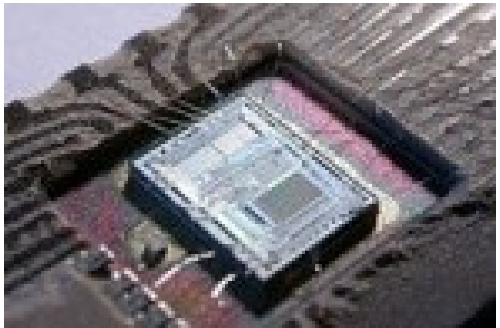
Lateral resolution:

Abbé formula

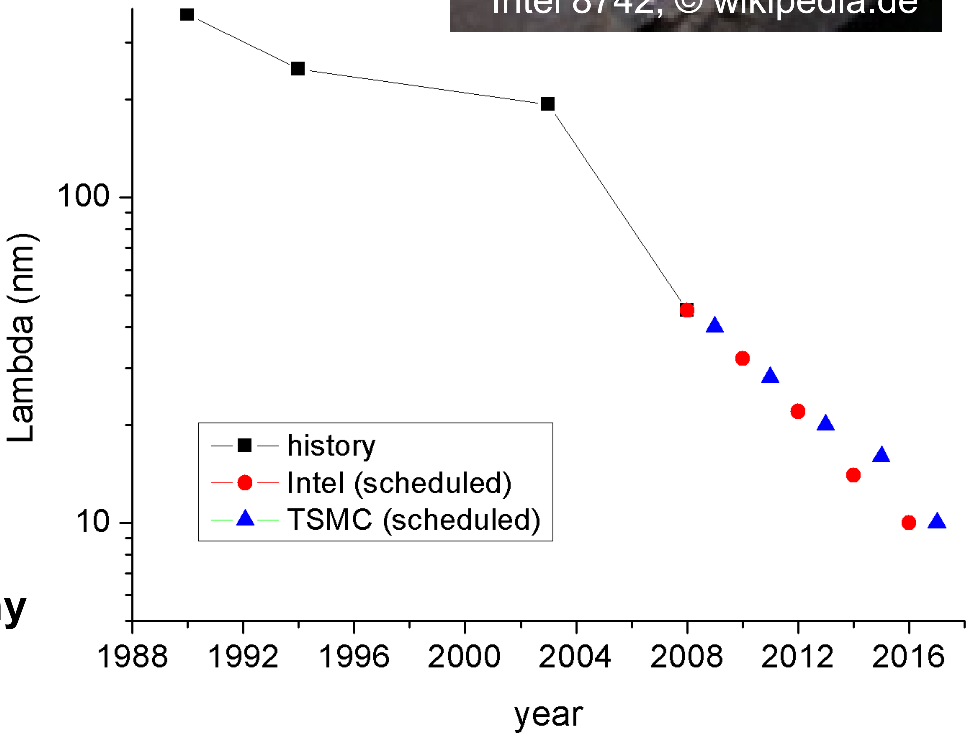
$$\Delta x = \frac{k\lambda}{NA}$$

- $NA = n \sin \Phi$ (numerical aperture – up to 0.85)
- *k*-factor – up to 0.3

Change from UV (193 nm) to EUV (13.5 nm) lithography

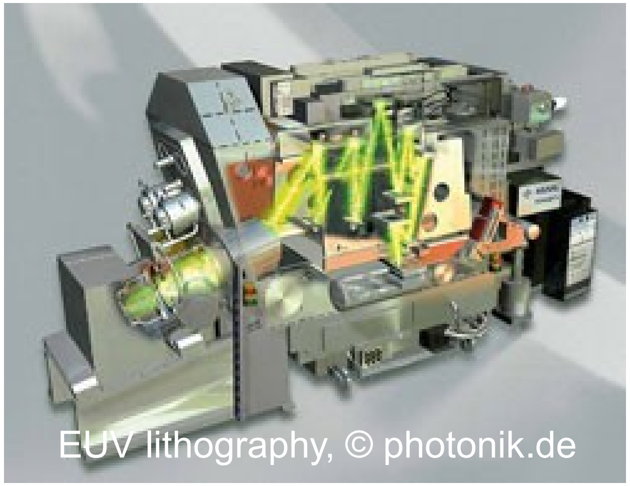


Intel 8742, © wikipedia.de



EUV lithography for next generation microprocessors

- EUV: 13.5 nm equals
  photon energy 90 eV
- patterning features less than 22 nm


EUV lithography, © photonik.de

Challenges:

- generation of EUV radiation
- focussing of EUV radiation by mirrors
  – lifetime of mirrors, degradation of reflectivity
- masks for EUV lithography
  – lifetime / degradation of photoresists
- contamination (chambers, mirrors, masks)

EUV generation

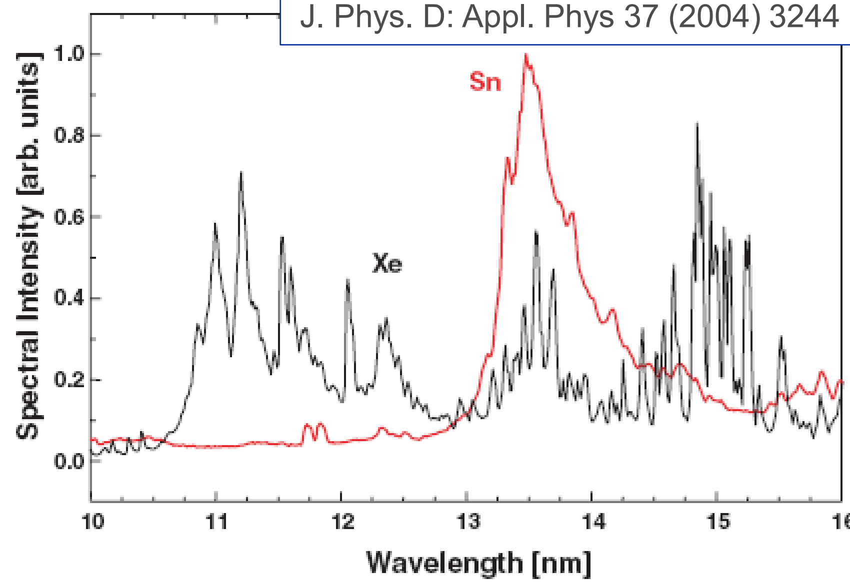
EUV emission

- emission by de-excitation of multicharged ions
- typically in a hot dense plasma (20 eV, Z=10 for Xe)

Requirements

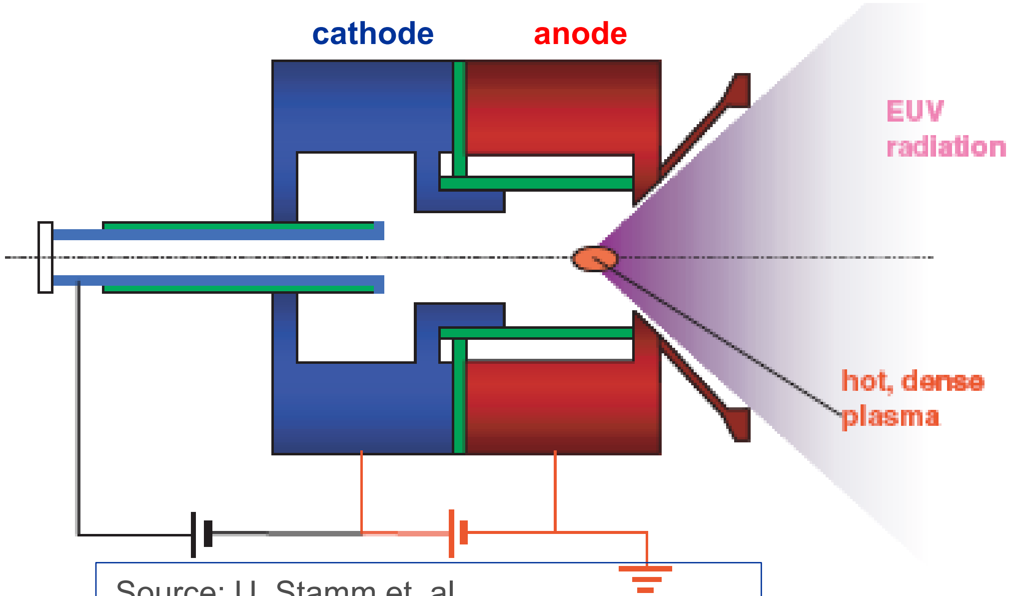
- radiation power ~1000 W
- source size 1 mm
- spatial and temporal stability 0.1 %
- lifetime 3000 hours

Source: U. Stamm et. al,
J. Phys. D: Appl. Phys 37 (2004) 3244



Generation of a hot dense plasma

1. laser generated plasma
   (e.g. Nd:YAG-laser pulse
   100 mJ, 1…15 ns,
   on Xe target)
2. z-pinch
3. hollow-cathode pinch



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Use of Pinch effect

$$\frac{B^2}{2\mu_0} = (Z+1)n_i kT$$

magnetic field $B = \frac{\mu_0 I}{2\pi r}$

ion density n_i

mean ionisation degree Z

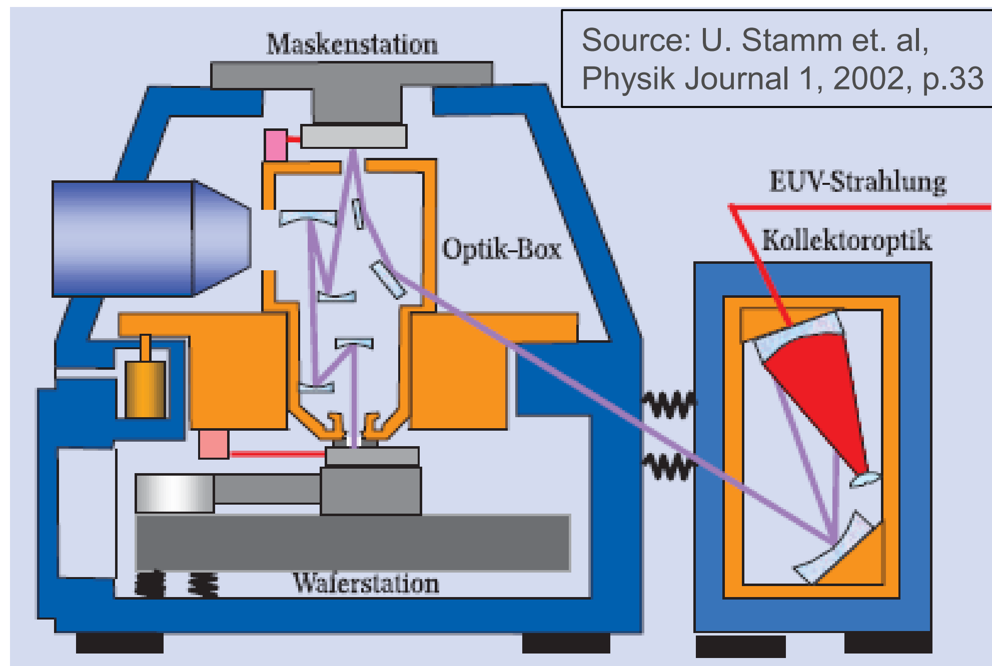
parameters:

- 2 … 30 J per pulse
- view kHz repetition
- 20 … 50 kA
- 1 mm plasma size,
- 40 W radiation intensity
- 0.5 % conversion (in 2π)

EUV lithography

Processes and devices

- protection against energetic particles from dense plasma (debris)
- no transparent materials for EUV →mirrors instead of lenses, masks as mirrors
- safety against all particles and organic contaminations

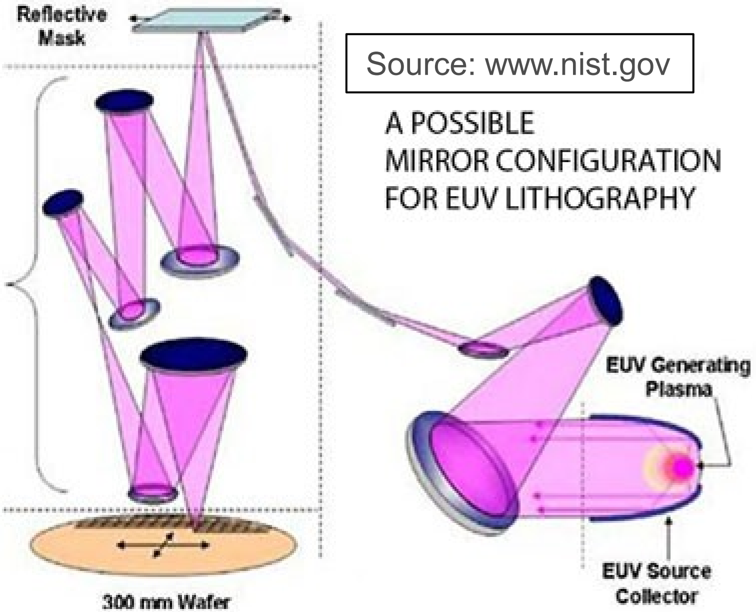


Source: U. Stamm et. al, Physik Journal 1, 2002, p.33

EUV mirrors and masks

multilayer mirror

- 50 to 100 Mo/Si layers as diffusion barrier
- capping layer
- 2 nm planarity required
- 72% reflectivity
  (86% losses for 6 mirrors)
- coating by PVD, CVD, ALD
  (most of them plasma assisted)



multilayer mask (also mirror)

- structured absorption layer
  made of Cr or TaN
- critical defects << 30 nm

photo resist

- organic polymer – increase of solubility due to radiation
- challenge: length of polymer chains defines edges

EUV lithography

Plasma phenomena

- Absorption of EUV radiation in chamber volumes (photoionization in low pressure)
- Electron yield by EUV adsorption at solid surfaces
- Plasma generation in chamber volumes
- Ion bombarding of solid surfaces (mirrors, masks)
- Cracking of contaminations at the surfaces (EUV, electrons, ions)

Who can plasma physics support?

- Plasma generation and sustainment in the volume
- Plasma impact on surfaces
- Behaviour of contaminations in the plasma
- Reduction of contaminations by the plasma

Plasma in the EUV chamber

Chamber

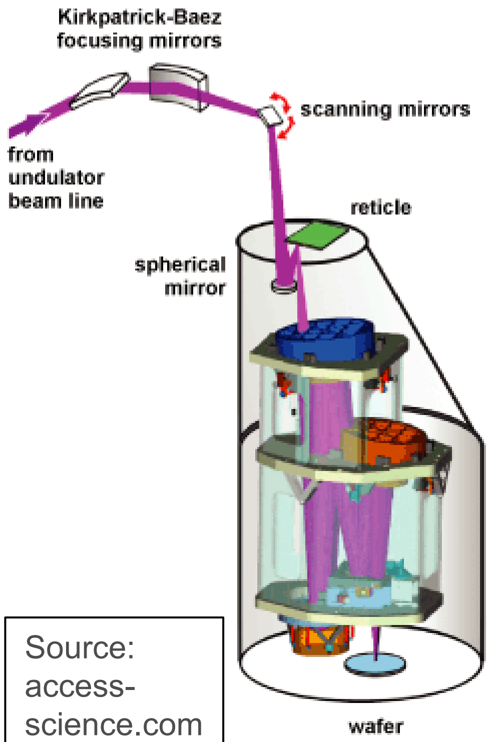
- typically large dimension (view m)
- low pressure (view Pa)

Problem of any contaminations
on the surfaces (mirrors, mask, resist)

self-cleaning of the chamber

- use of hydrogen filling
- small overpressure

Source: see e.g. US Patent 20110216298

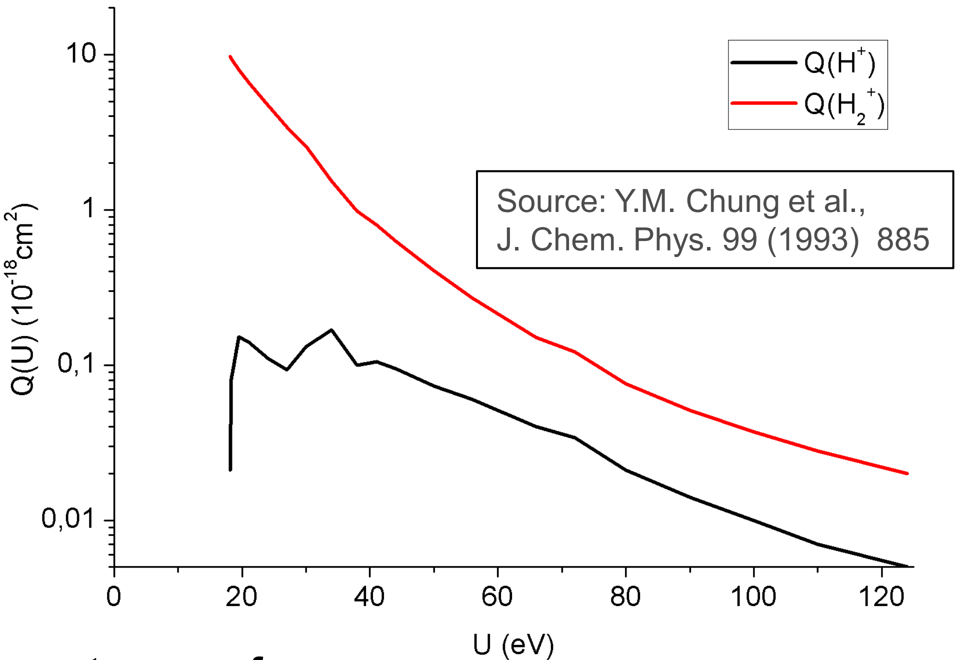


Source: access-science.com

Plasma in the EUV chamber

Plasma generation in the chamber

1. electron yield by photo-ionisation of the filling gas (e.g. containing hydrogen)



2. electron yield by EUV impact on surfaces
   - EUV photon generates up to 4 electrons in the solid
   - view % of them leave the solid
   - electron energy nearly 85 eV (EUV – work function)

Plasma in the EUV chamber

Plasma sustainment in the chamber

- ionisation of filling gas by electron impact
- space-charge confinement

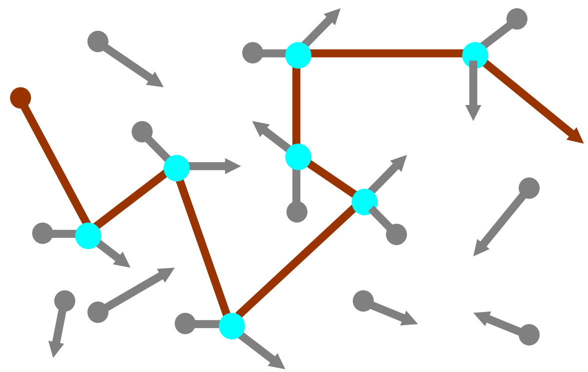
Importance of the plasma in the chamber

- generation of fast ions – potential degradation of surfaces ☹
- generation of H atoms – use for self-cleaning of the chamber ☺

►*Estimation of plasma state and ion fluxes on the surfaces required*

3. Excursus in plasma physics

Processes in a plasma



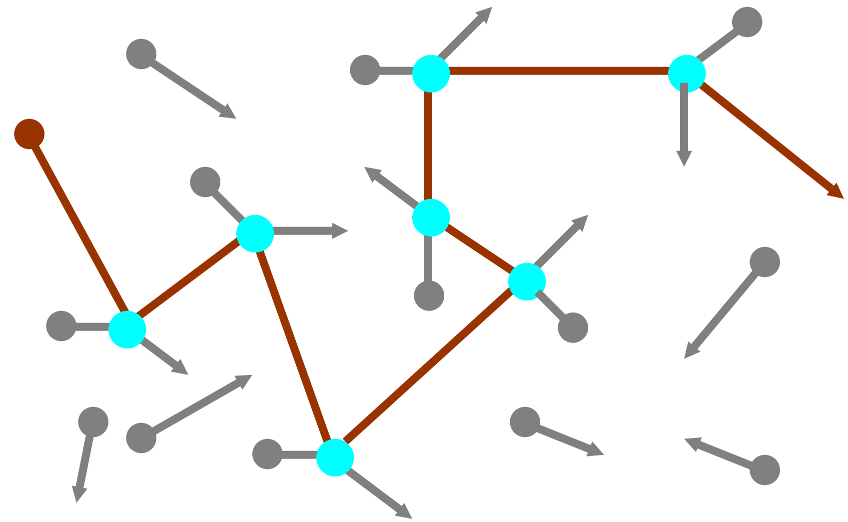
- conduction and Ohmic heating,
- flow, heat conduction and convection,
- radiation and plasma-chemical reactions,
- energy- and material transfer to walls

Microscopic processes in a plasma

- acceleration of charge carriers in electric fields (electrons)
- collision processes:
  - momentum and energy transfer to neutrals
  - electronic excitation, ionisation, dissociation
- species with local density, mean drift velocity and mean kinetic energy (specific temperatures)

Kinetic theory

ideal gas:
many particles
moving rapidly
and incidentally



particle trajectory
can be divided into

collision-free sections

- movement under the action of external fields

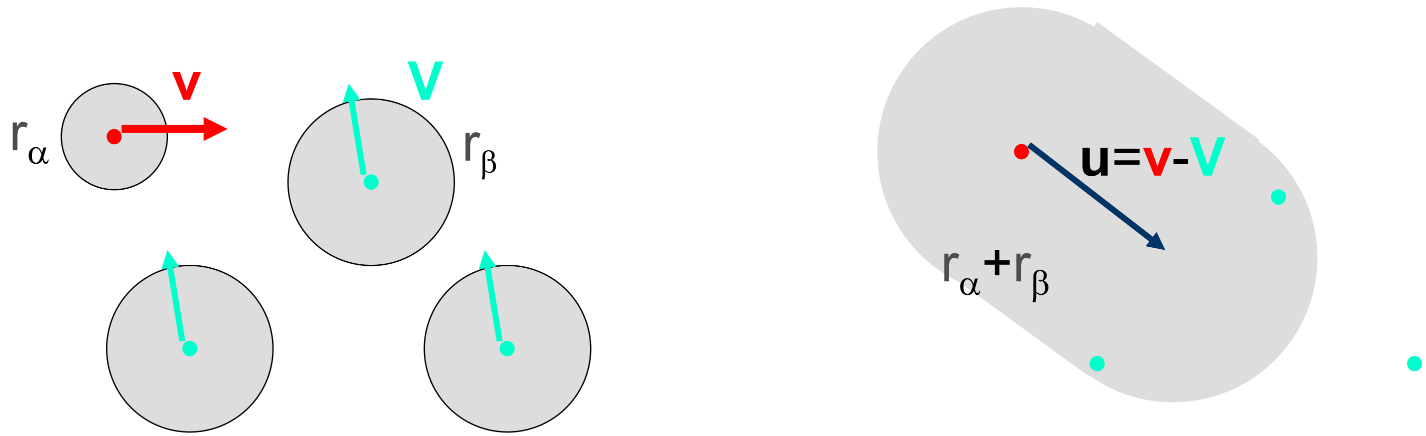
collision processes

- interaction radius << mean free path << vessel dimension
- collision time ≈ 0, particle radius ≈ 0
- binary collisions only
- no influence of external field

Particle interaction

Binary collisions

elementary treatment: particle α and particle β



Particle interaction

Binary collisions

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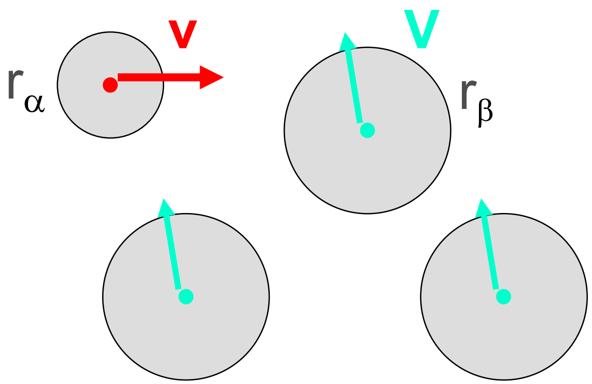
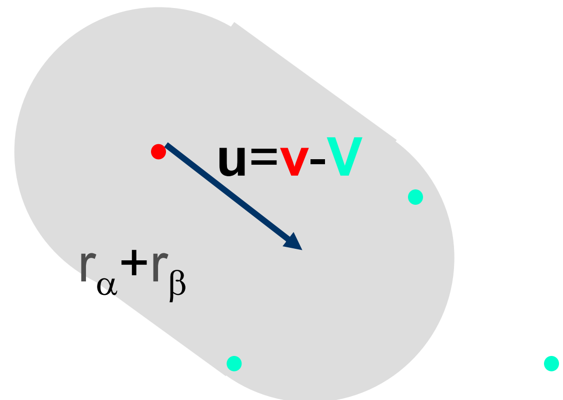




probability of a collision of particle α with one particle β in time step Δt:

density of species β x volume covered by particle α

$$W_{\alpha\beta} = N_\beta \, \pi(r_\alpha+r_\beta)^2 \, |\mathbf{v}-\mathbf{V}| \, \Delta t$$

collision cross section $Q_{\alpha\beta}$ x distance covered by particle α

collision frequency: $\upsilon = N_\beta \, Q_{\alpha\beta} \, |\mathbf{v}-\mathbf{V}|$ mean free path $\lambda = 1/ N_\beta \, Q_{\alpha\beta}$

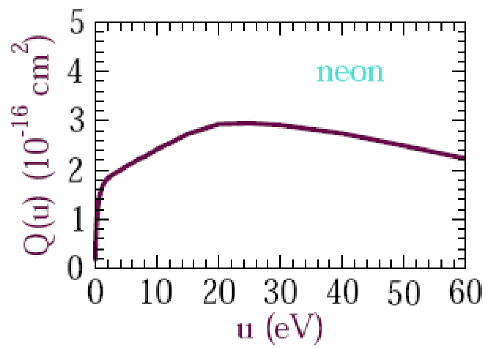
Particle interaction

Energy and momentum conservation

Example: collision of an electron (m_e, v_e) and an atom (m_a>>m_e, v_a<<v_e)

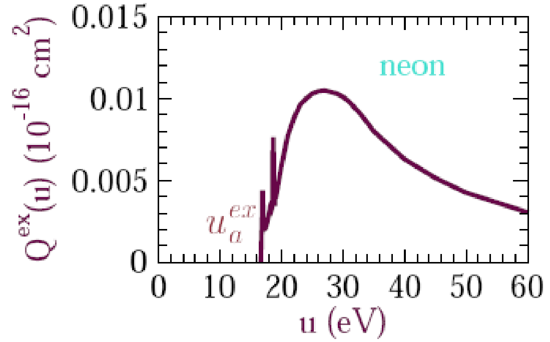
- elastic collision

$$m_e\vec{v}_e + m_a\vec{v}_a = m_e\vec{v}\,'_e + m_a\vec{v}\,'_a$$
$$\frac{m_e}{2}v_e^2 + \frac{m_a}{2}v_a^2 = \frac{m_e}{2}v_e'^2 + \frac{m_a}{2}v_a'^2$$



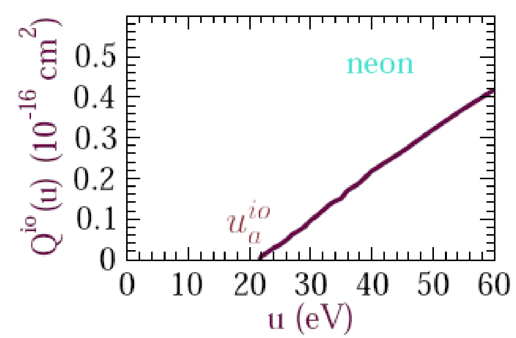
- exciting collision

$$m_e\vec{v}_e + m_a\vec{v}_a = m_e\vec{v}\,'_e + m_a\vec{v}\,'_a$$
$$\frac{m_e}{2}v_e^2 + \frac{m_a}{2}v_a^2 = \frac{m_e}{2}v_e'^2 + \frac{m_a}{2}v_a'^2 + u_a^{ex}$$



- ionizing collision

$$m_e\vec{v}_e + m_a\vec{v}_a = m_e(\vec{v}\,'_e + \vec{v}\,''_e) + m_a\vec{v}\,'_a$$
$$\frac{m_e}{2}v_e^2 + \frac{m_a}{2}v_a^2 = \frac{m_e}{2}(v_e'^2 + v_e''^2) + \frac{m_a}{2}v_a'^2 + u_a^{io}$$



Space charge potential

Plasma in front of isolated walls

- pairwise generation of electrons and positive ions
- almost no volume recombination at low pressure
- effective recombination at the wall surface
- movement of electrons and ions towards the walls

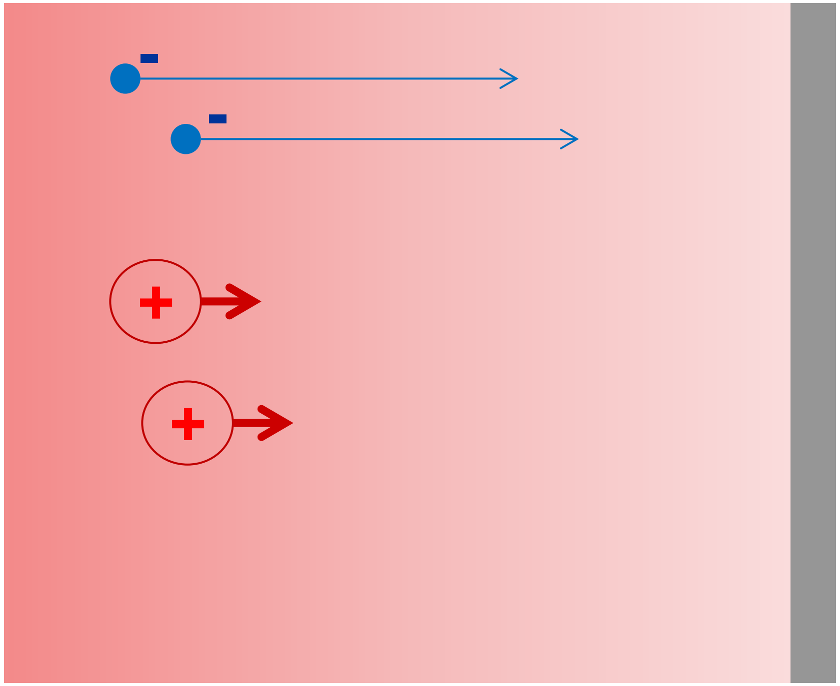
$$n_e \approx N_i << N$$
$$m_e << M_i$$
$$T_e >> T_i$$
$$v_e >> v_i$$

diffusion:

$$D_e = \frac{1}{3} v_e \lambda_e = \frac{1}{NQ_e} \sqrt{\frac{kT_e}{3m_e}}$$

$$D_i = \frac{1}{3} v_i \lambda_i = \frac{1}{NQ_i} \sqrt{\frac{kT_i}{3M_i}} << D_e$$

$$j_e^D = -D_e \nabla n_e >> j_i^D = -D_i \nabla N_i$$



Space charge potential

Plasma in front of isolated walls

- accumulation of positive charge in the volume
- negative charge at the wall

Poisson equation

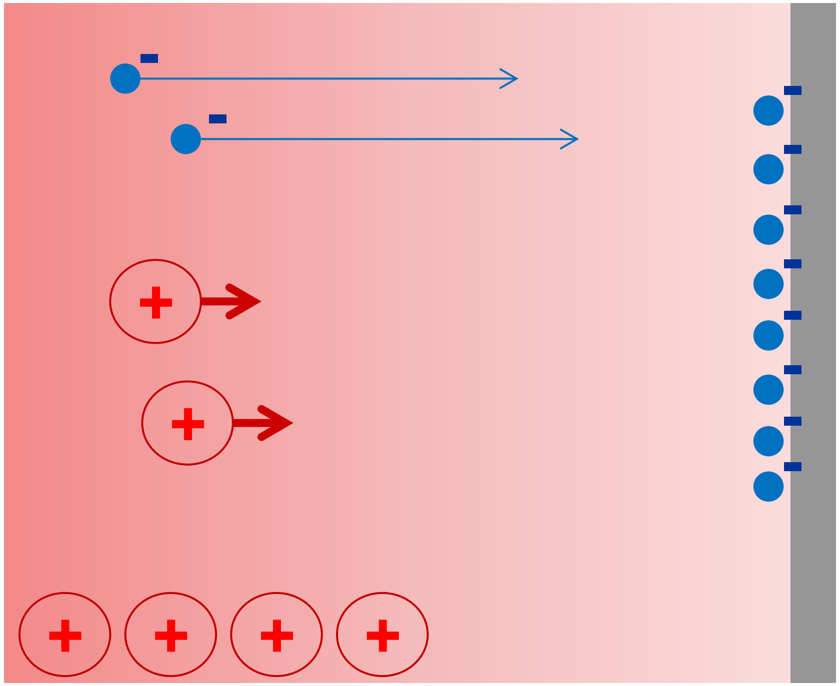
$$\Delta V = -\frac{e_0}{\varepsilon_0}(N_i - n_e)$$

drift in the electric field

$$b_e = \frac{e_0}{m_e}\frac{\lambda_e}{v_e} = \frac{1}{NQ_e}\sqrt{\frac{1}{3kT_e m_e}}$$

$$b_i = \frac{-e_0}{M_i}\frac{\lambda_i}{v_i} = \frac{1}{NQ_i}\sqrt{\frac{1}{3kT_i M_i}} << -b_e$$

$$j_e^E = n_e b_e E >> j_i^E = N_i b_i E$$



Space charge potential

Plasma in front of isolated walls

steady-state condition:

- equal volume production and loss at the wall
- charge carrier fluxes must be equal

ambipolar diffusion

$$j_e = j_i$$

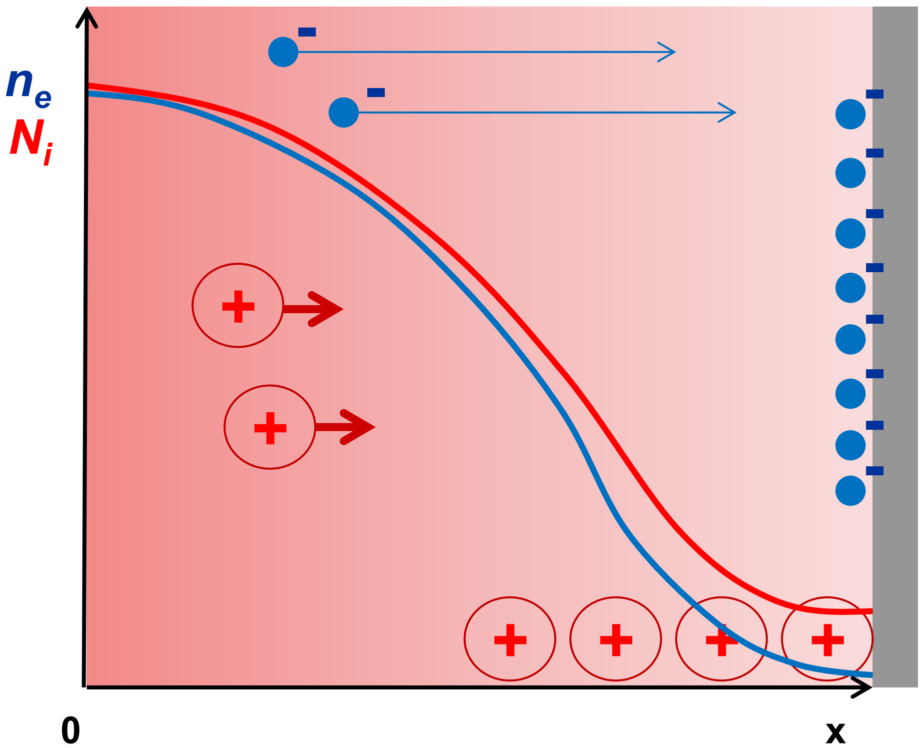
$$j_e^D + j_e^E = j_i^D + j_i^E$$

ambipolar potential

$$n_e \approx \frac{1}{E} \frac{D_e}{b_e} \frac{dn_e}{dx}$$

$$n_e \approx n_{e0} \exp\left(-\frac{b_e}{D_e} V \right)$$

$$j_e = j_i \approx \frac{b_i D_e}{b_e} \frac{dn_e}{dx}$$



Space charge potential

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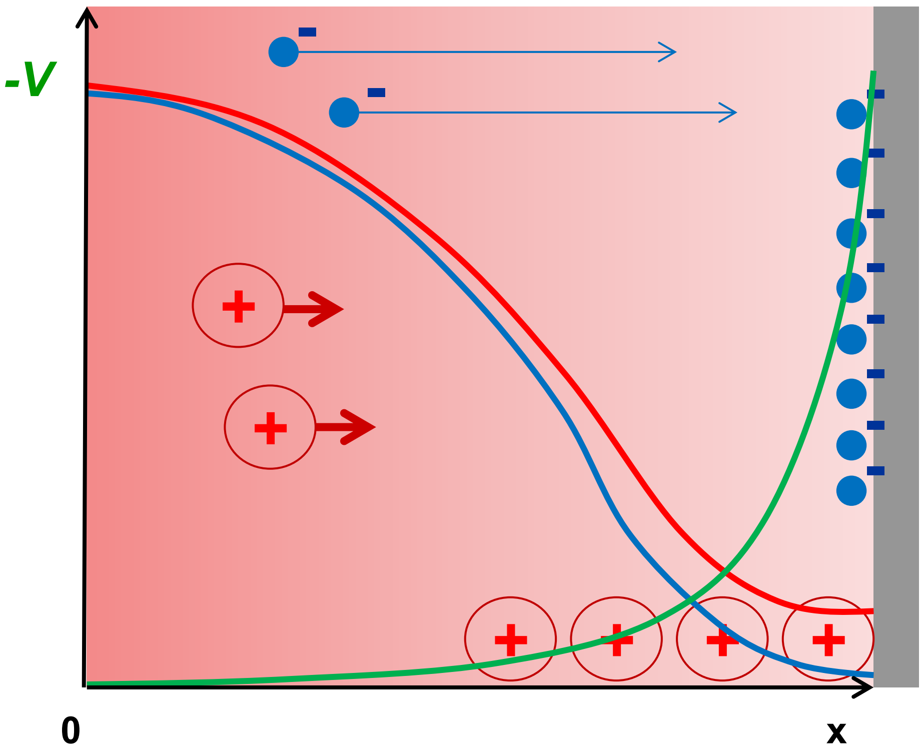
ambipolar potential

$$n_e \approx \frac{1}{E}\frac{D_e}{b_e}\frac{dn_e}{dx}$$

$$n_e \approx n_{e0}\exp\left(-\frac{b_e}{D_e}V\right)$$

$$j_e = j_i \approx \frac{b_i D_e}{b_e}\frac{dn_e}{dx}$$

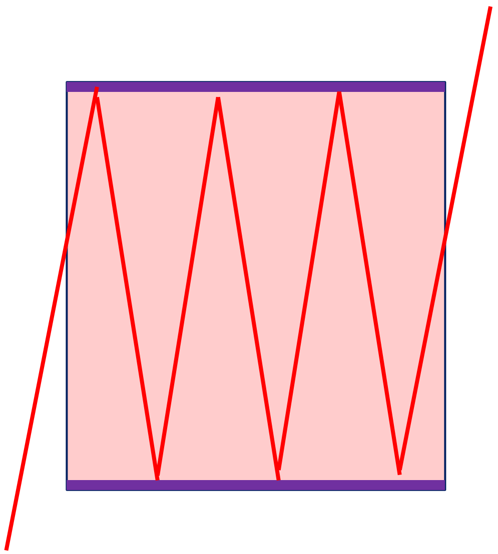


4. Conclusions for the plasma generation in chambers for EUV lithography

Plasma in the EUV chamber

How can the plasma generation be estimated?

Assumptions



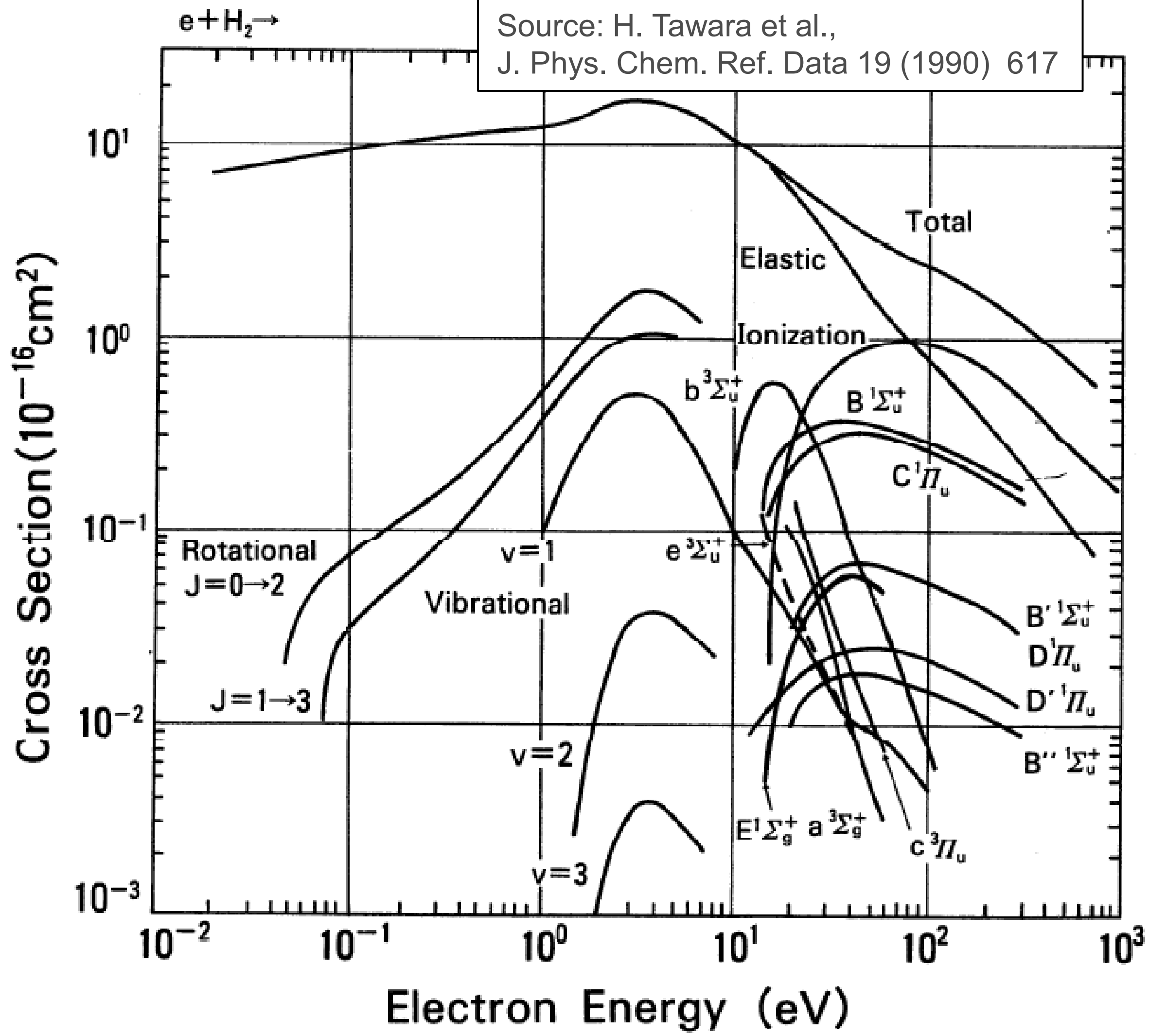
1. chamber dimension ~ 1 m,
2. walls ~ view m^2 mirrors
3. filling gas: H_2 at low pressure
   (~ view Pa, N ~ 10^{15} cm^{-3})
4. EUV radiation P_{EUV}: ~ 1 kW
   (~ 10^{16} photons/s)
5. view reflections at mirrors with 30% losses each
6. electron yield γ per photon at the surface
   (~ 10^{15}…10^{16} electrons/s, each with ~ 85 eV)
7. photo-ionisation due to EUV radiation (cross section)
8. plasma generation by electron collisions (cross sections)
9. plasma sustainment by space-charge confinement
   (very similar to low-pressure plasma process reactors)
10. impact of hydrogen ions on surfaces
    after acceleration in the space charge field

Hydrogen plasma

Electron collisions with hydrogen molecule

- momentum transfer
- rotational excitation
- vibrational excitation
- electronic excitation
- dissociation
- ionisation

Source: H. Tawara et al.,
J. Phys. Chem. Ref. Data 19 (1990) 617



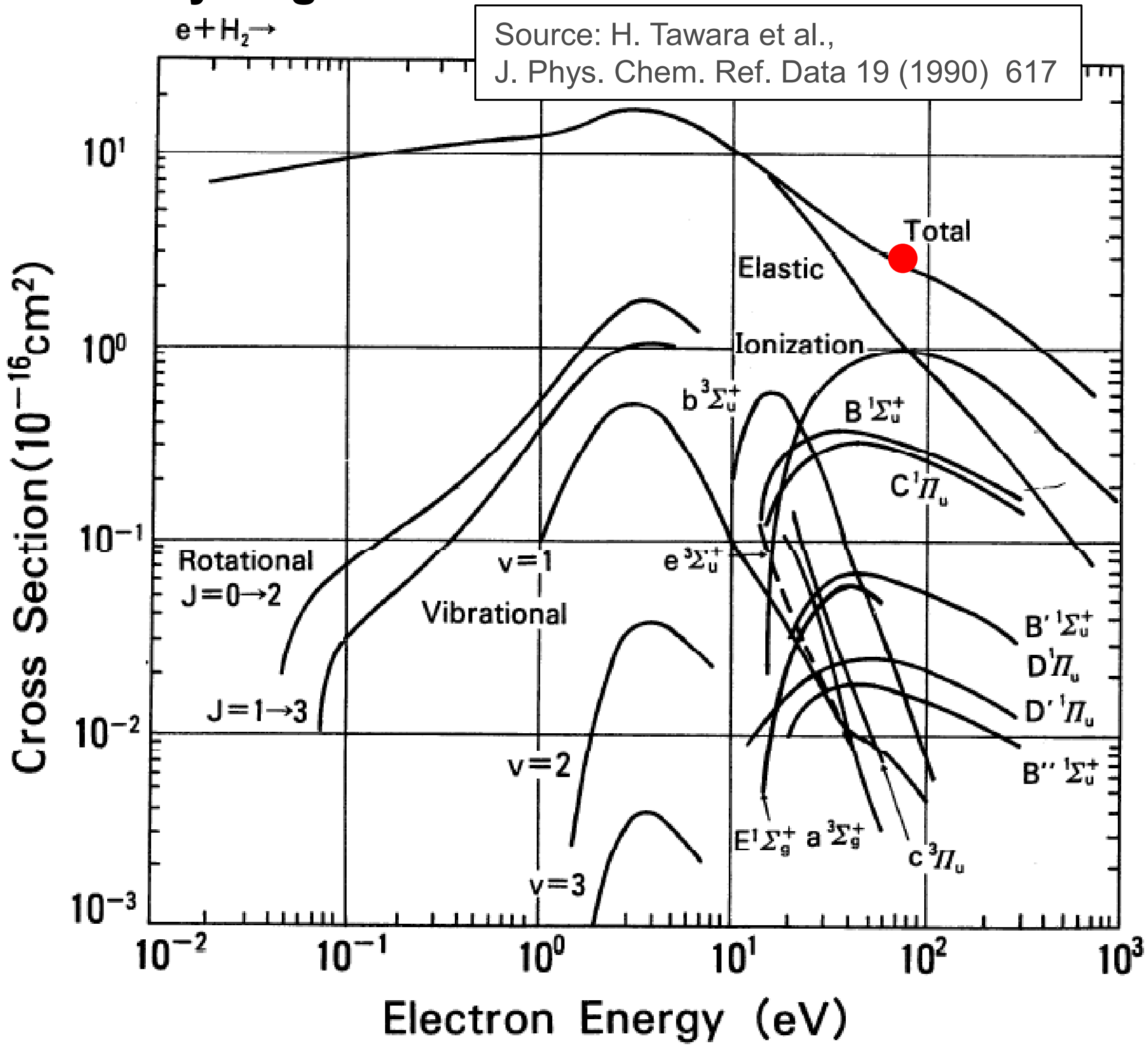
Hydrogen plasma

Electron collisions with hydrogen molecule

- momentum transfer
- rotational excitation
- vibrational excitation
- electronic excitation
- dissociation
- ionisation

mean free path

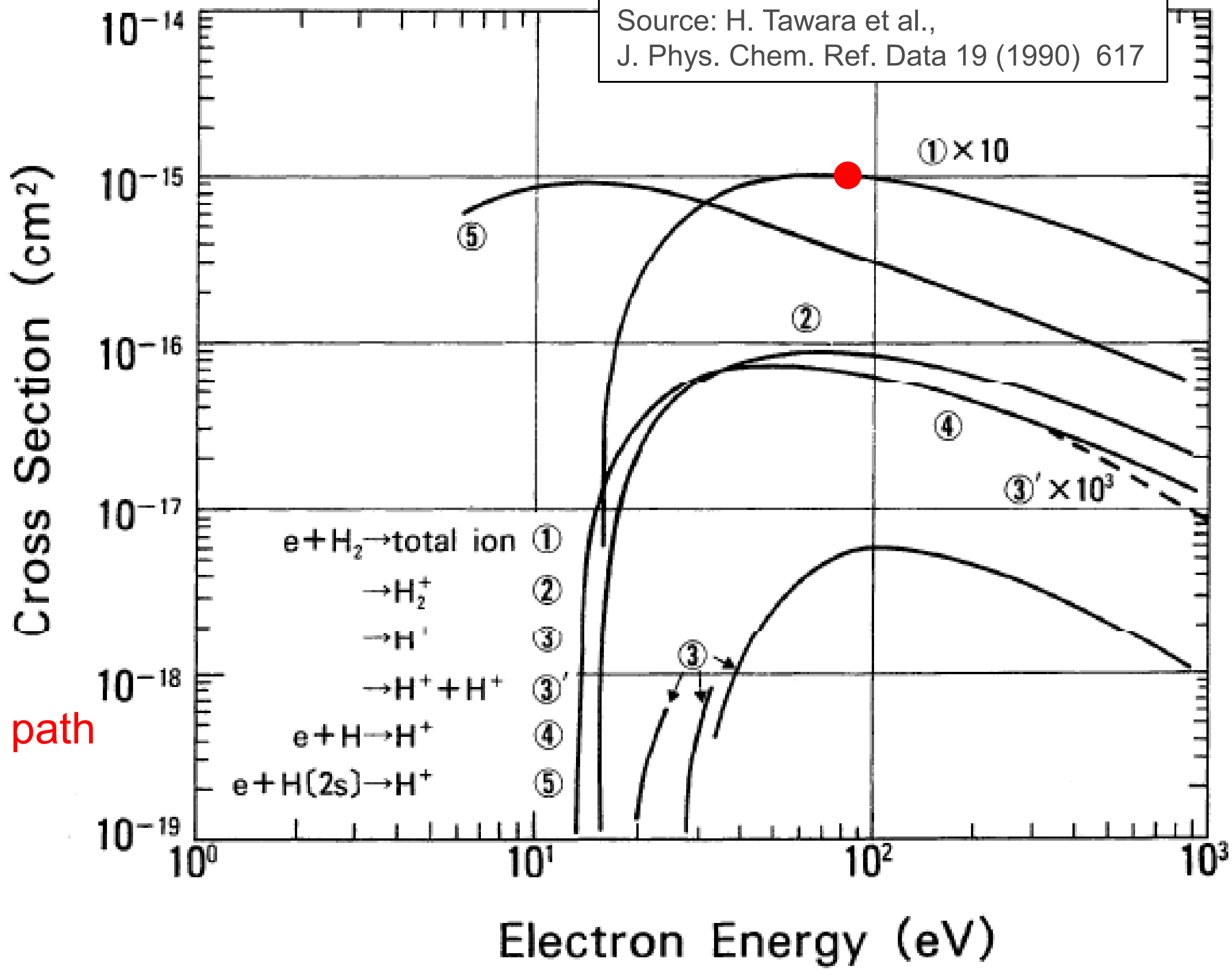
λ = 1/NQ ~ 3 cm



Hydrogen plasma

Electron impact ionisation of hydrogen

Source: H. Tawara et al.,
J. Phys. Chem. Ref. Data 19 (1990) 617



mean free path

$\lambda = 1/NQ$

~ 10 cm

Hydrogen plasma

Plasma chemistry in hydrogen

- molecule dissociation $H_2 + e^- \rightarrow 2\,H + e^-$
- molecule ionisation $H_2 + e^- \rightarrow H_2^+ + 2\,e^-$
- molecule ionisation $H_2 + e^- \rightarrow 2\,H^+ + 3\,e^-$
- attachment $H_2^+ + e^- \rightarrow 2\,H$
- excitation $H + e^- \rightarrow H^* + e^-$
- atom ionisation $H + e^- \rightarrow H^+ + 2\,e^-$
- atom ionisation $H^* + e^- \rightarrow H^+ + 2\,e^-$

surface impact:

- ion bombardment H_2^+ , H^+
- reduction of carbon layers $x\,C + y\,H \rightarrow C_xH_y$

Plasma in the EUV chamber

How can the plasma generation be estimated?

Power budget estimation

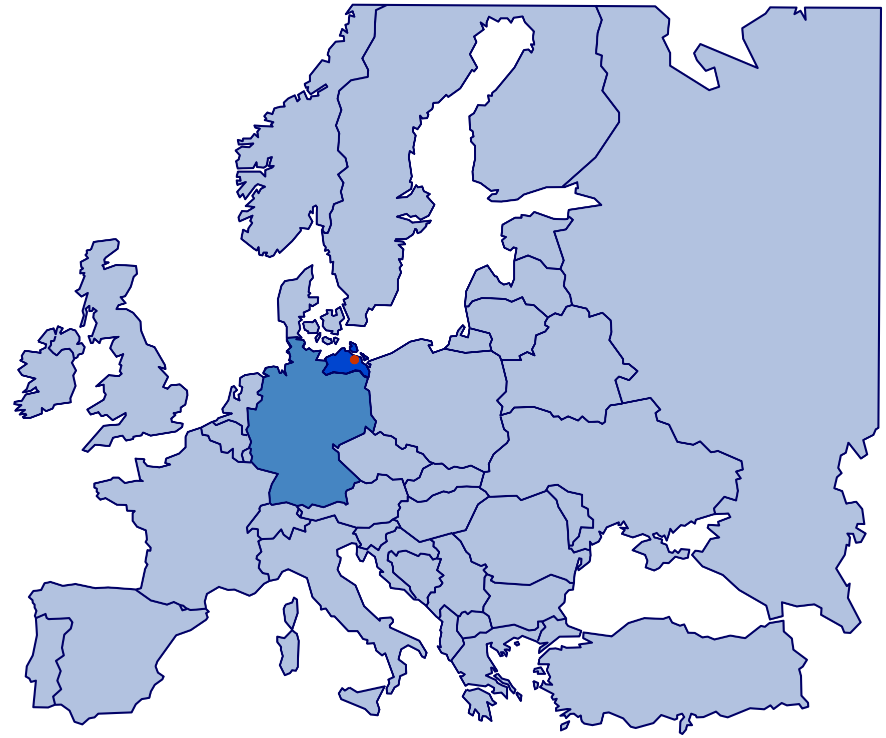
- EUV absorption and fast electron yield
- space-charge confinement
- estimation of ion densities according to ionisation thresholds and power budget
- ion fluxes to the walls according to the volume ionisation rate and acceleration in the space charge field

Plasma simulation

- non-local electron kinetic equation (at least 1D)
- collisions, balance equations of excited and ionized states
- space-charge field
- ion fluxes to the walls from balance equations

Thank you for the attention !

INP Greifswald



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