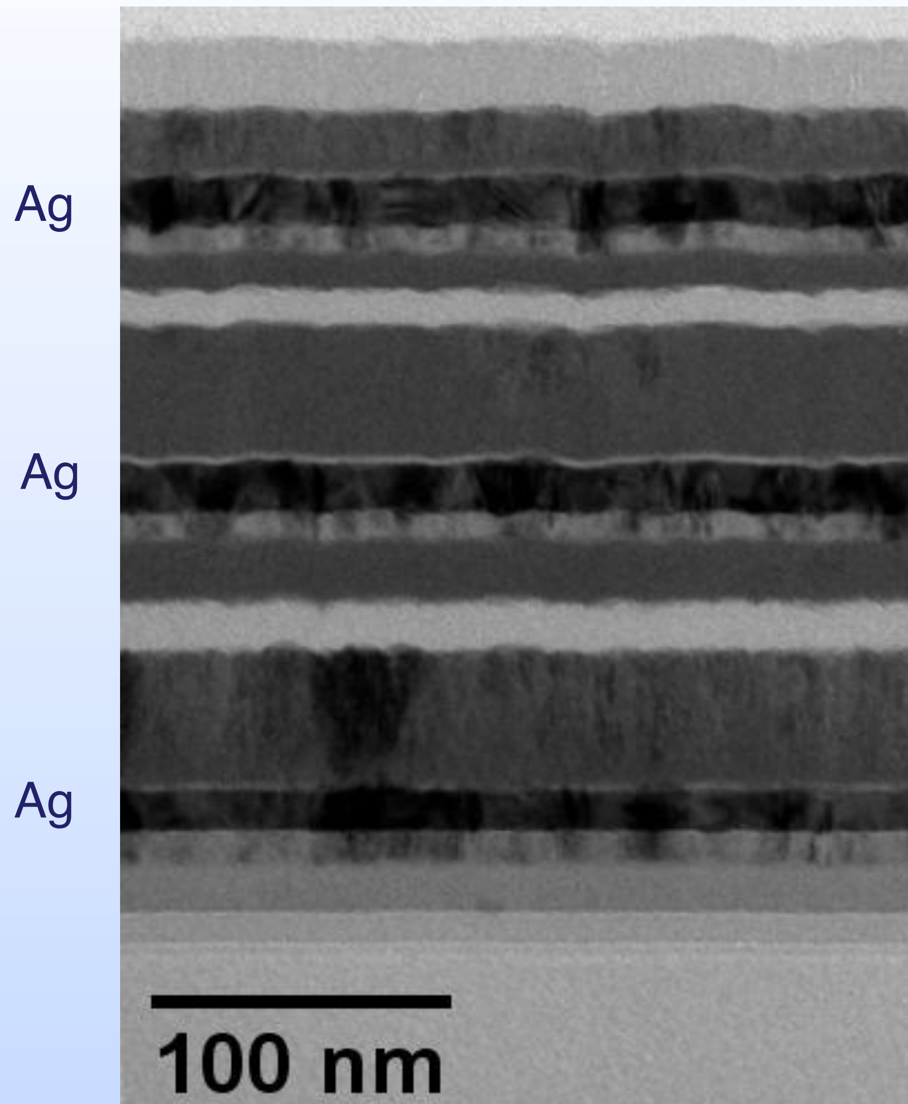
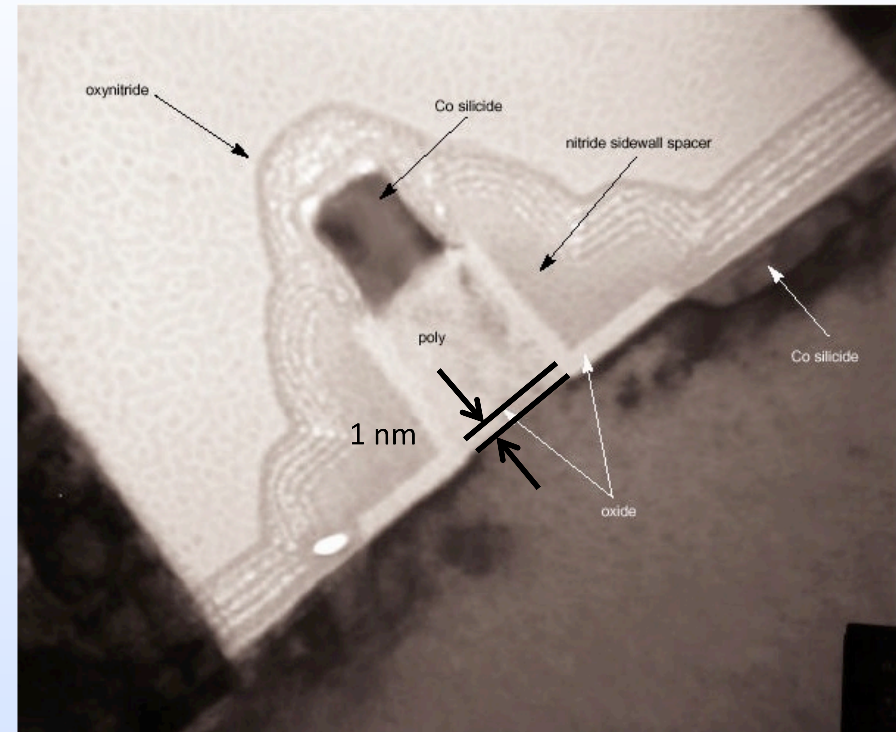
Thin Film Deposition

PD Dr. Andriy Romanyuk

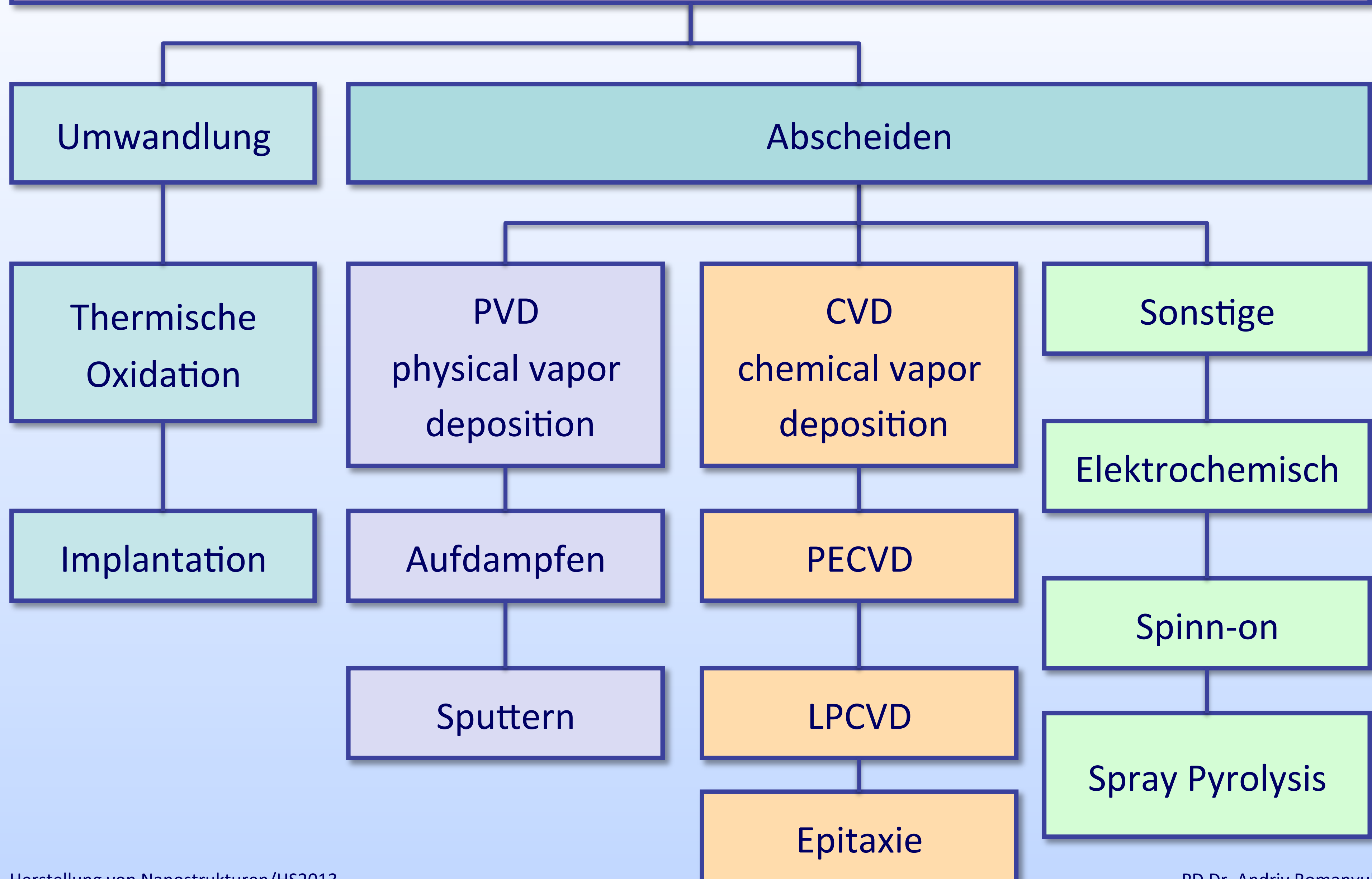
Wann spricht man von „dünnen Schichten“



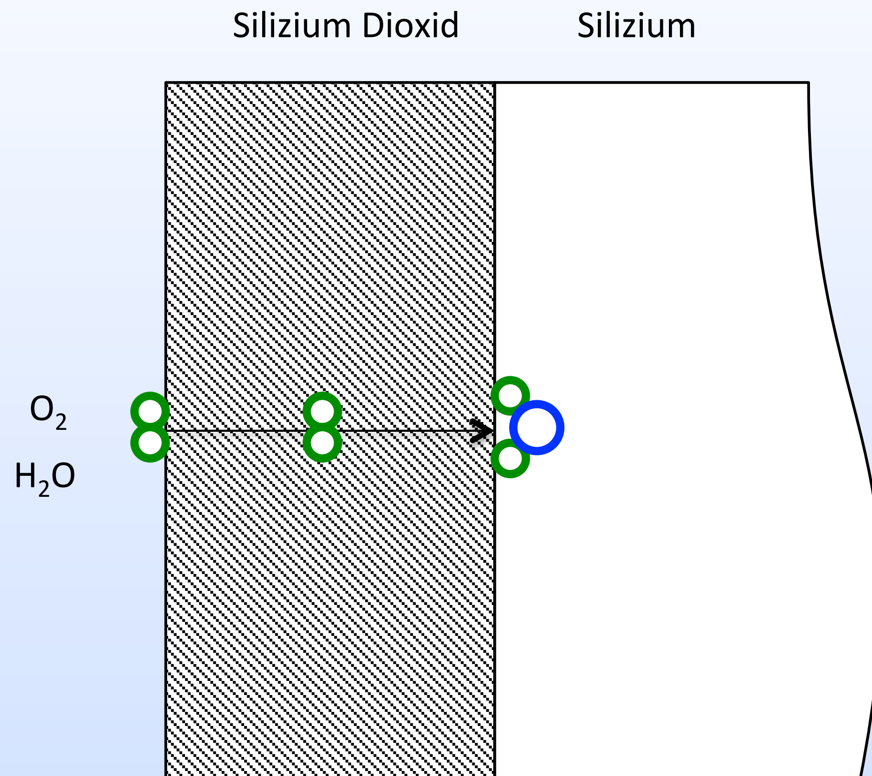


Typische Schichtdicken ...

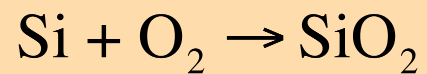
- von wenigen atomaren Lagen
- bis zu circa 20 µm


Erzeugung dünner Schichten
Umwandlung
Abscheiden
Thermische Oxidation
PVD physical vapor deposition
CVD chemical vapor deposition
Sonstige
Implantation
Aufdampfen
PECVD
Elektrochemisch
Sputtern
LPCVD
Spinn-on
Epitaxie
Spray Pyrolysis

Thermische Oxidation



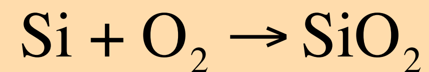
1. Diffusion des Sauerstoffes/ Wassers bis zur Oxidoberfläche
2. Diffusion des Sauerstoffes/ Wassers durch das bereits gebildete Oxid bis zur Grenzschicht
3. Chemische Reaktion an der Grenzschicht



$$Si + O_2 \rightarrow SiO_2$$

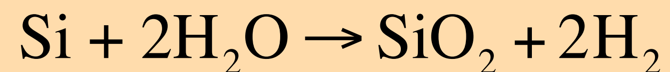
Thermische Oxidation

1. Prozessvariante: **trockene Oxidation** mit Sauerstoff



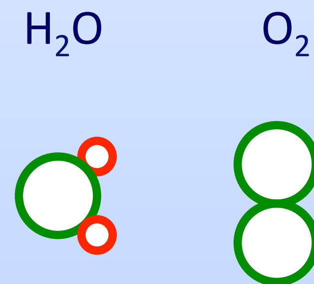
- T = 800°C – 1200°C
- sehr gute Qualität des Oxides
- geringe Aufwachstraten

2. Prozessvariante: **nasse Oxidation** mit Wasserdampf

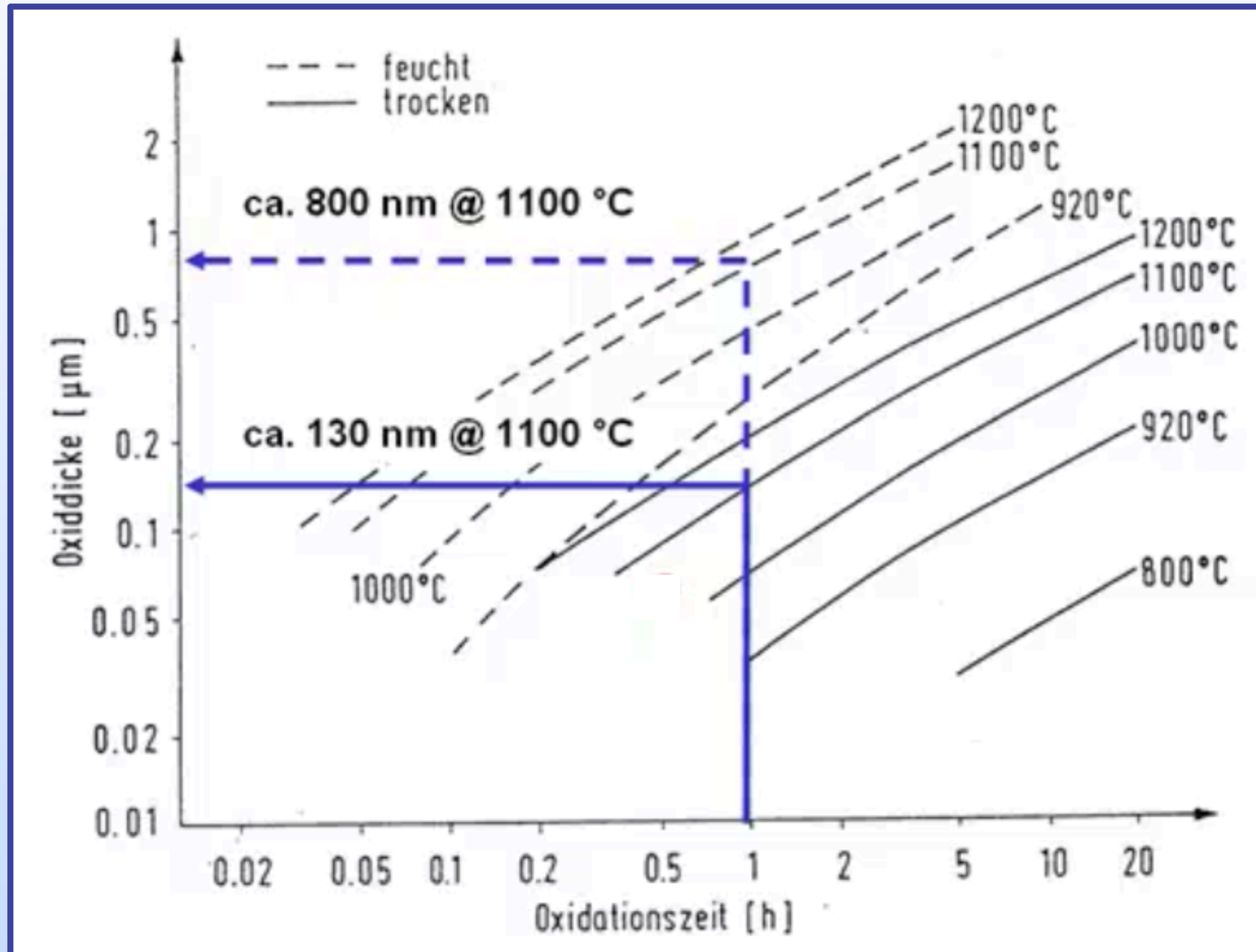


- T = 900°C – 1100°C
- höhere Reaktionsrate
- Verunreinigung des Oxides mit Wasser

H_2O O_2



Thermische Oxidation



- Diffusionskonstante

$$D = D(p,T)$$

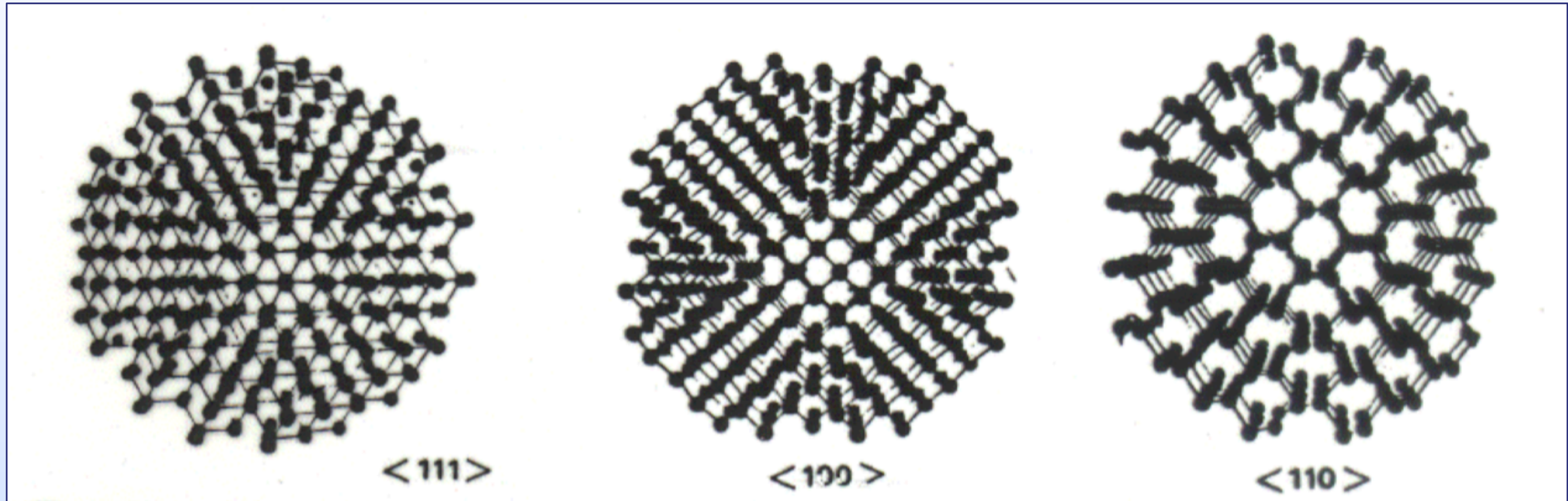
- Diffusionslänge

$$L = \sqrt{D\tau}$$

- Diffusionszeit

$$\tau = \frac{L^2}{D}$$

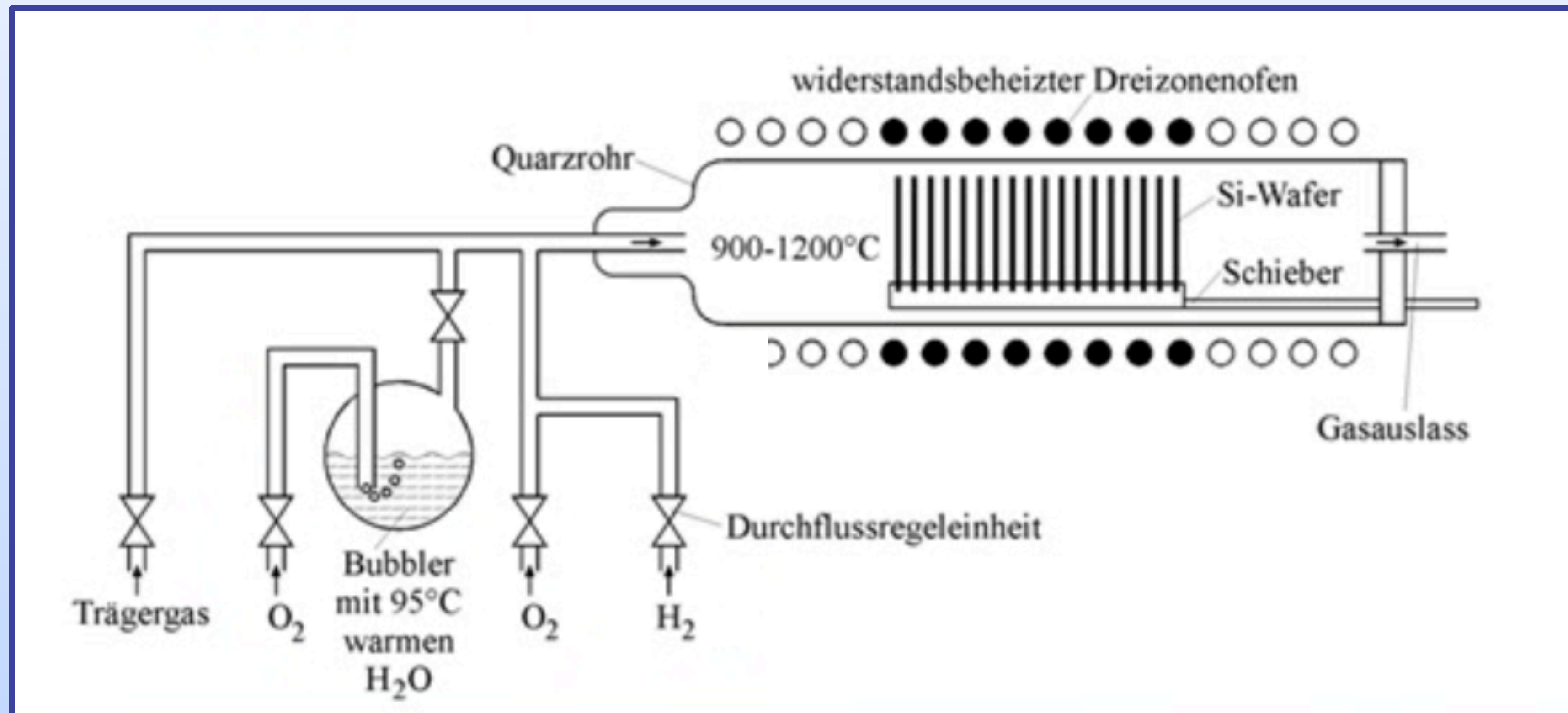
Thermische Oxidation



- Wachstumsrate ist auch abhängig von der Kristallorientierung
- (111) Silizium oxidiert 1.7 mal so schnell wie (100) Silizium
- Für die Diffusion ist die SiO_2 Schicht und nicht Si-Kristall relevant

Oxidationsofen

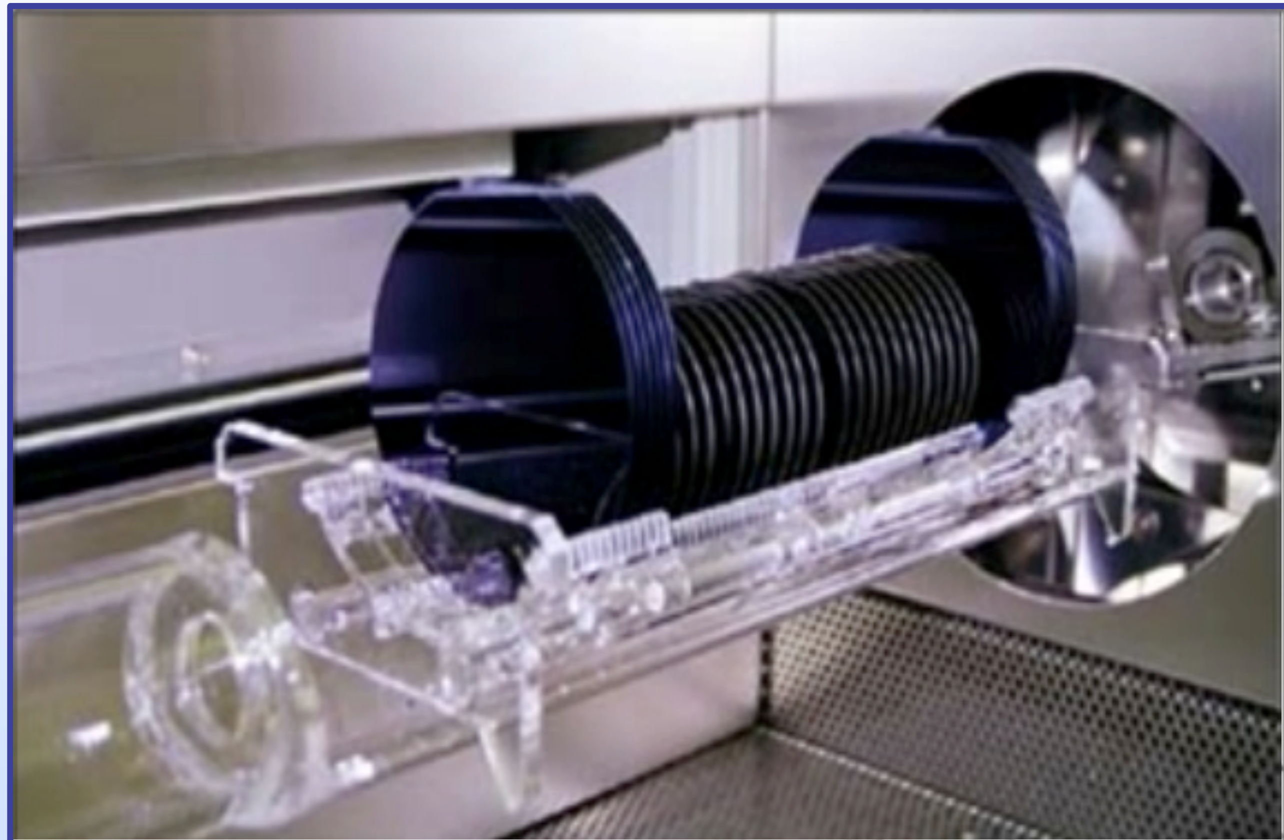
- Meist widerstandsbeheizte Dreizonenofen
- Gasregeleinheit und Bubbler
- Temperaturprofil mit ±0.5°C über eine Länge von einem Meter



Beispiel für einen Oxidationsofen

Prozesse:

- Oxidieren
- Tempern
- Dotieren
- LPCVD

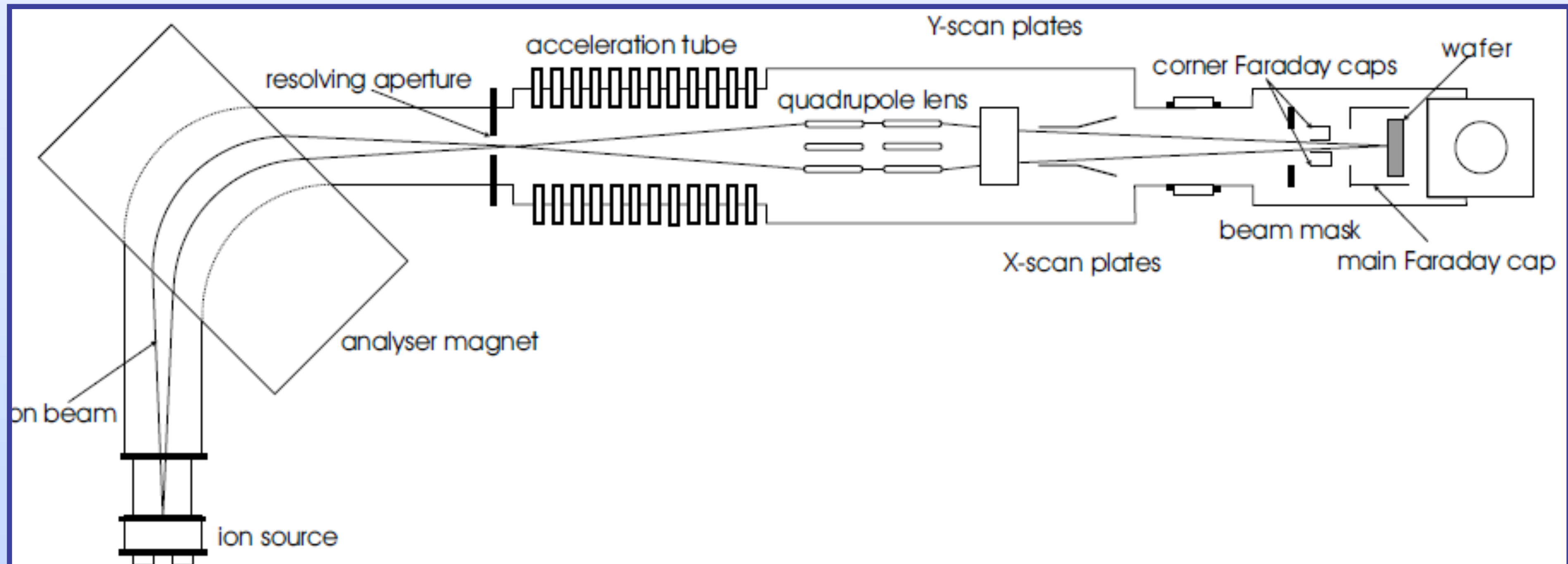


- Typische Batch-Grösse: 50 Wafers
- Hohe Anforderungen an Reinheit aufgrund hoher Temperaturen

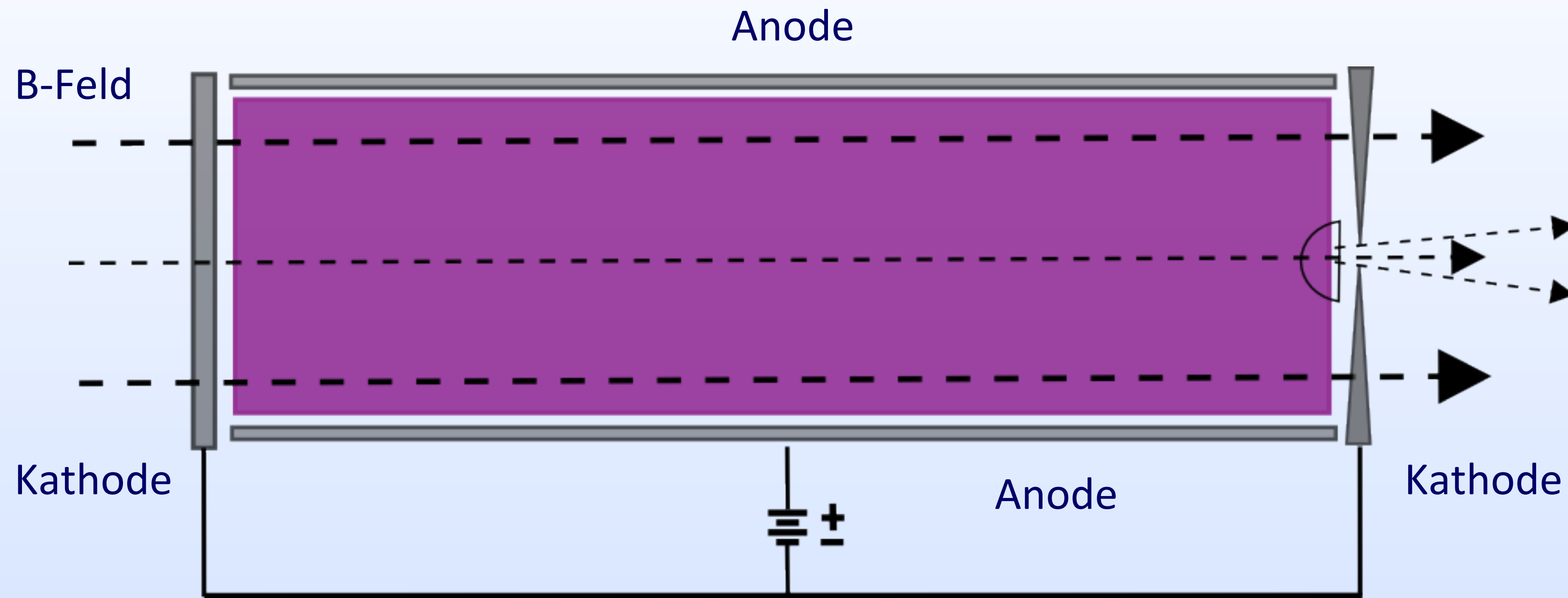
Ionenimplantation

Ionenimplantation

1. Ionisierung, Extraktion
2. Mass-Separation
3. Beschleunigen



Penning Ionenquelle



Typische Betriebsparameter:

P_{Ar} = 1 Torr

V = 500 V

I = 1.5 A

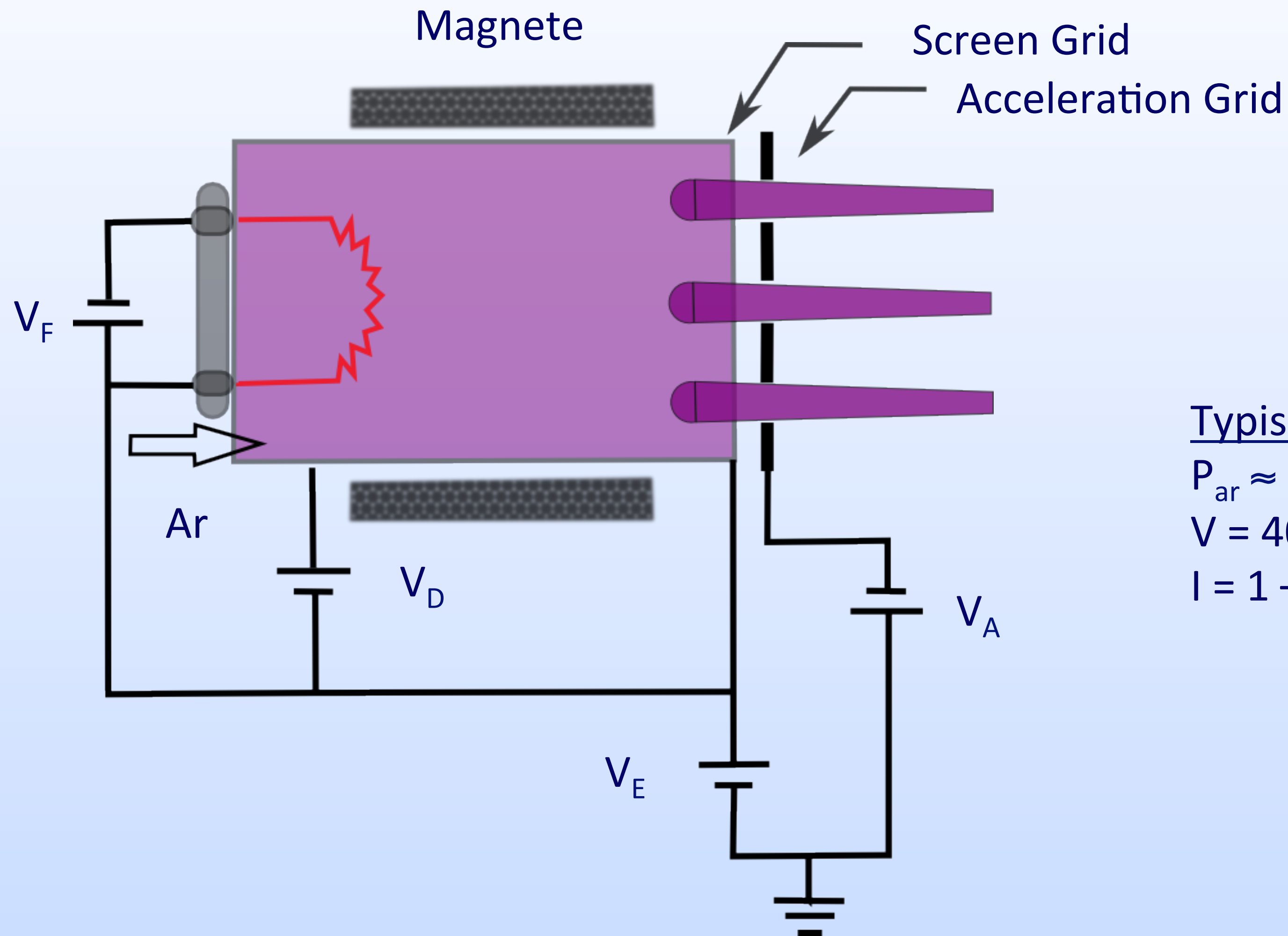
Vorteile:

- einfach
- billig

Nachteile:

- Strom und Spannung sind abhängig
- keine Fokussierung
- Kontaminationen

Kaufman Ionenquelle



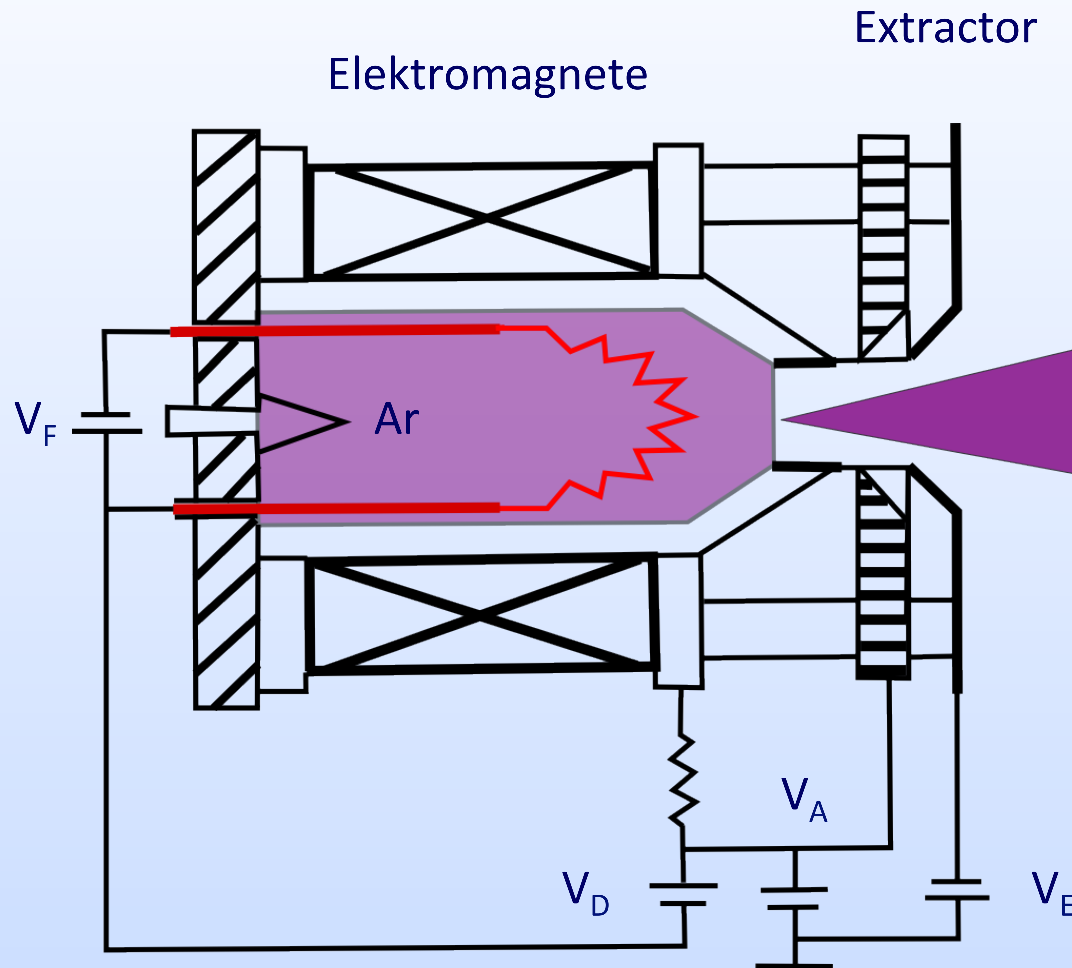
Typische Betriebsparameter:

$P_{ar} \approx 7$ mTorr

V = 40 V

I = 1 – 2 A

Duoplasmatron



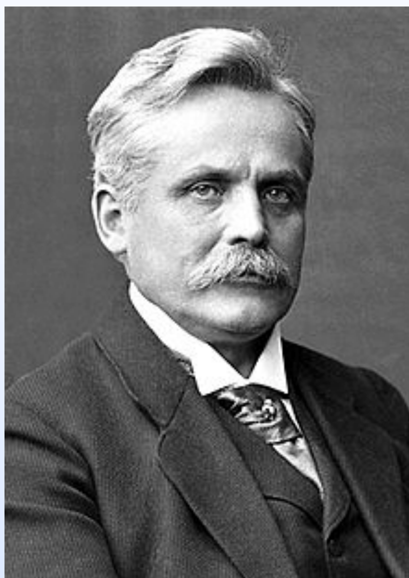
Typische Betriebsparameter:

P_{Ar} = 7 – 100 mTorr

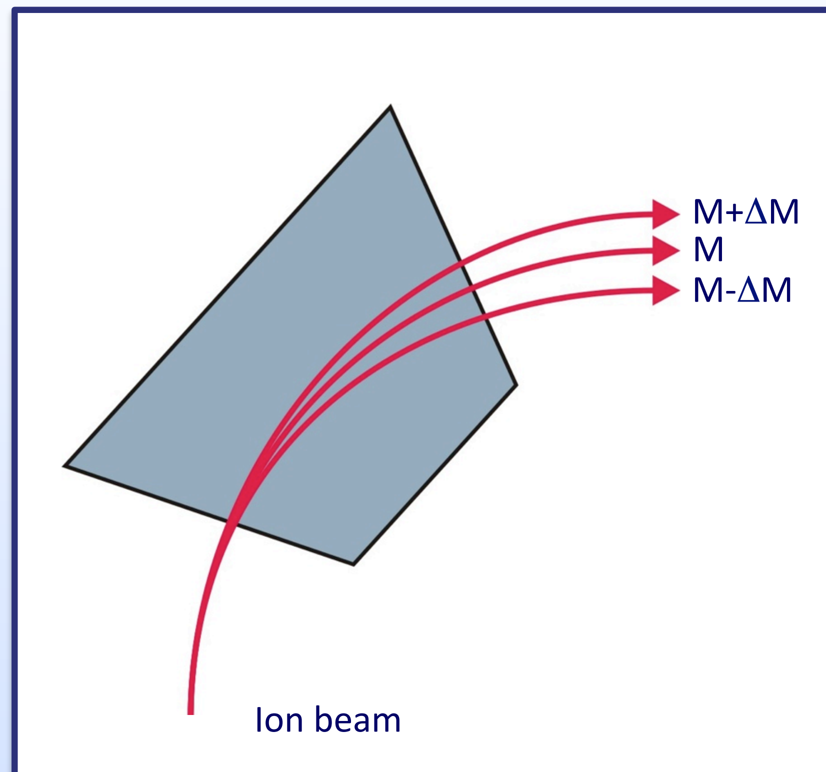
V = 80 V

I = 1 – 2 A

Sektor Mass Spectrometer



Wilhelm Carl Werner
Otto Fritz Franz Wien
(1864 – 1928)

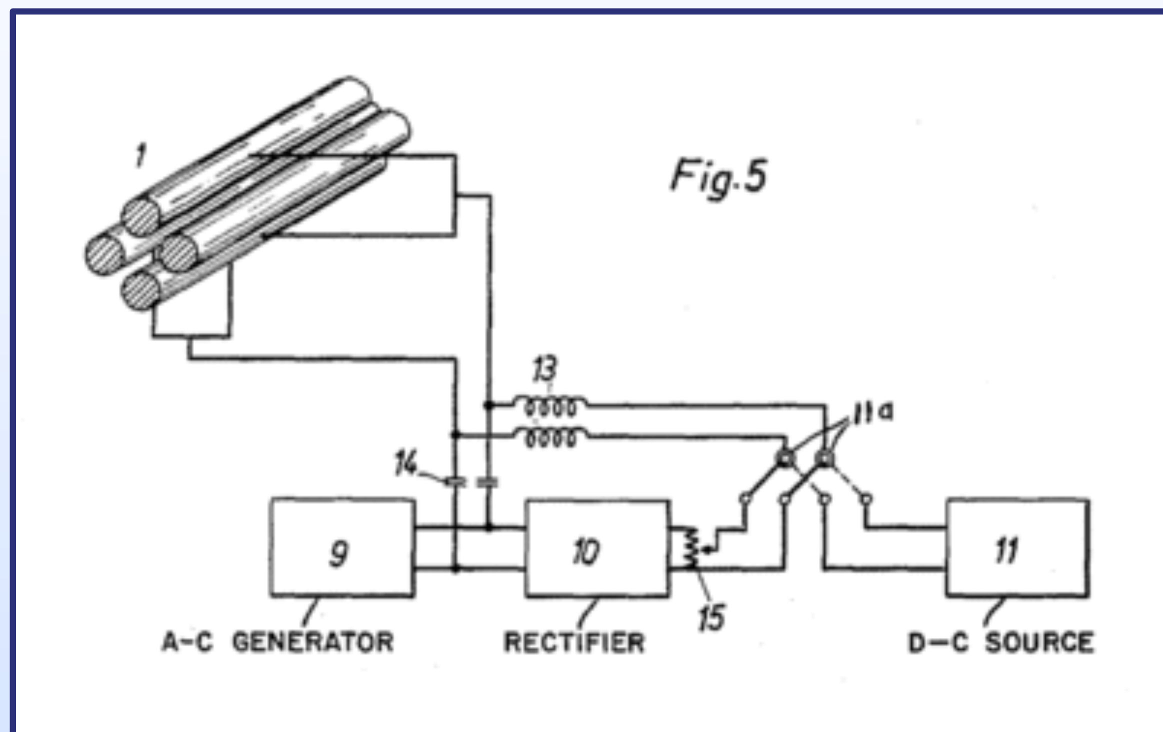


- High mass resolution
- High transmission
- Slow peak switching

$$\frac{m}{e} = \frac{B^2 r^2}{2V} \text{mit } V = \sqrt{\frac{2eU}{m}}$$

Quadrupole Mass Spectrometer

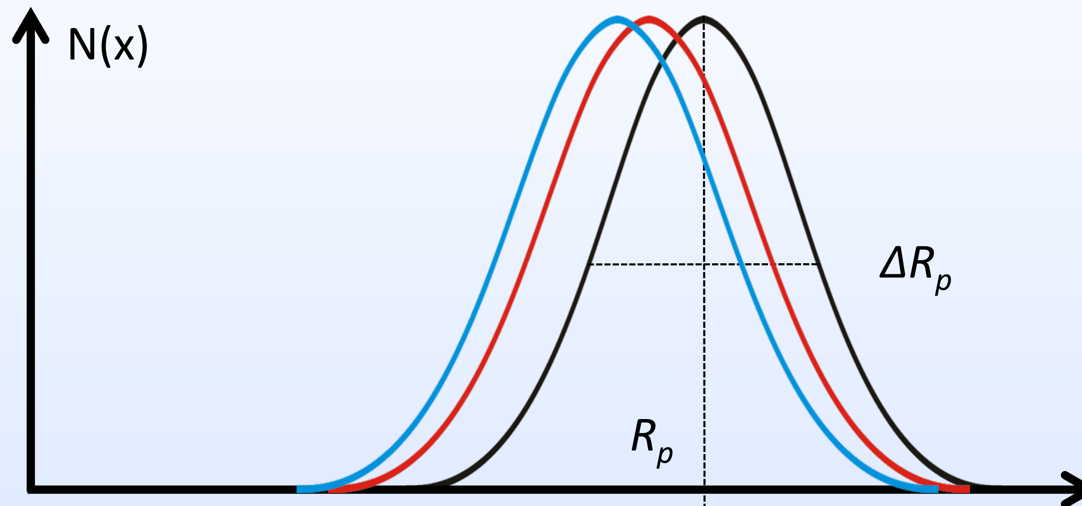
Wolfgang Paul
(1913 – 1993)



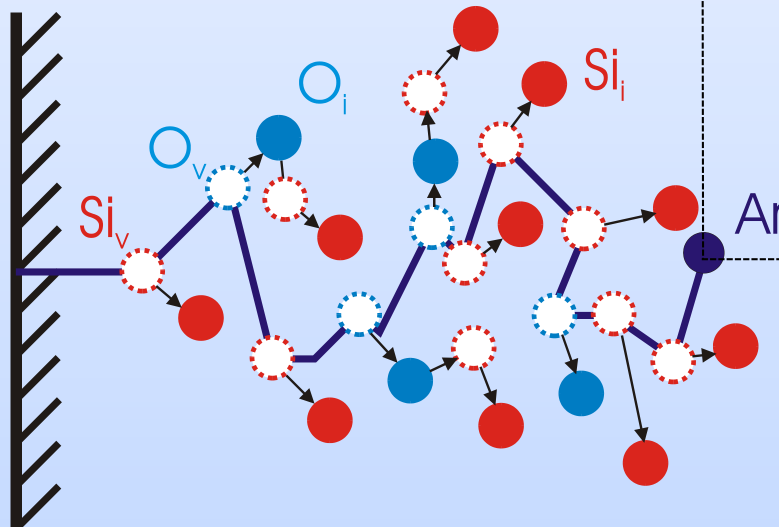
"Apparatus For Separating Charged Particles Of Different Specific Charges" Patent number: 2939952

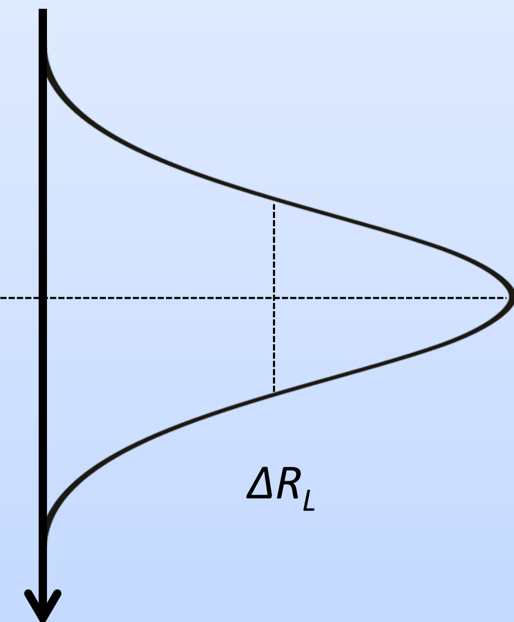
- Fast peak switching
- Low mass resolution
- Low transmission

Collision Cascade

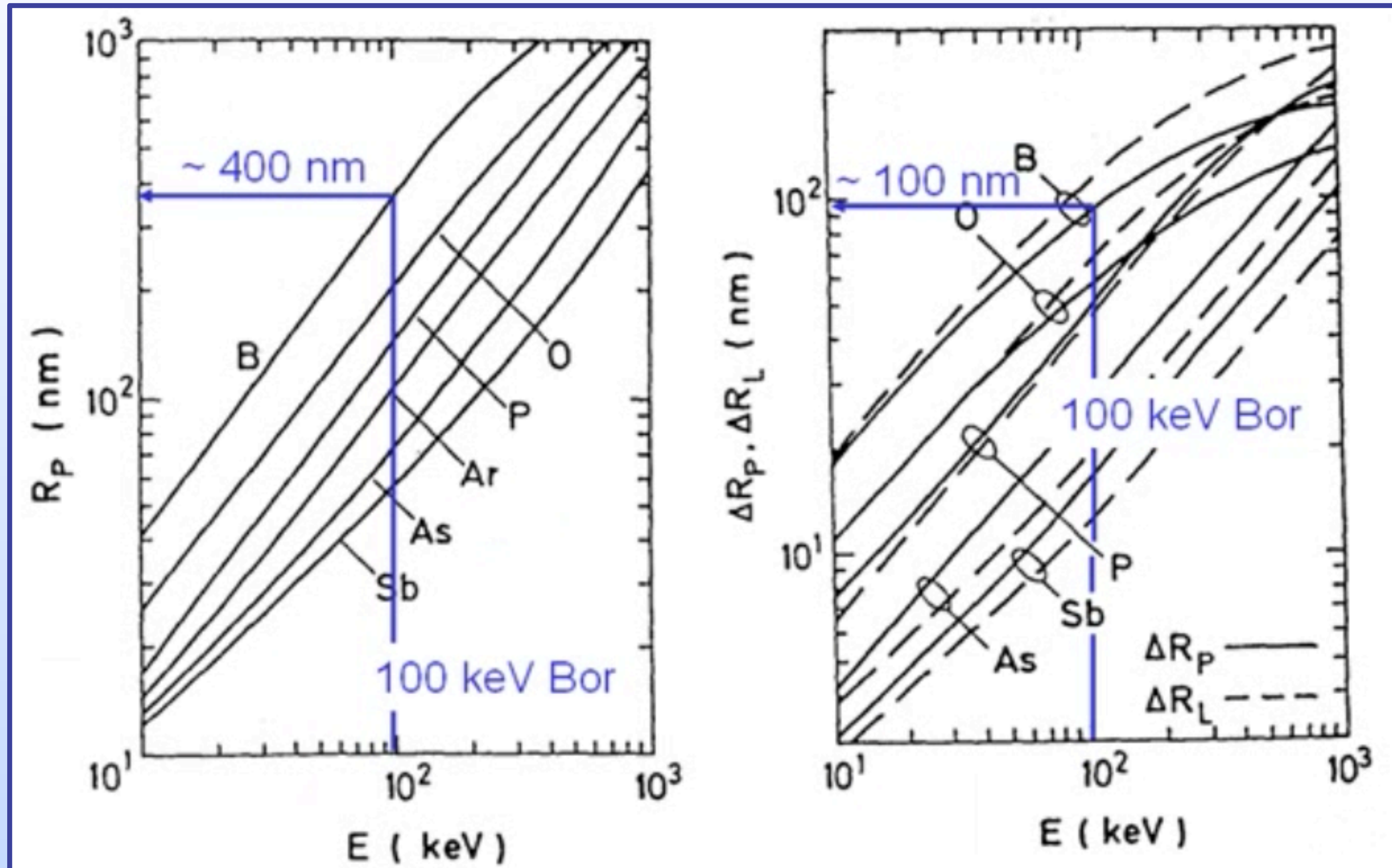


- Streuprozesse werden statistisch behandelt (Mittelung)
- Dotierprofil ist näherungsweise gaussförmig

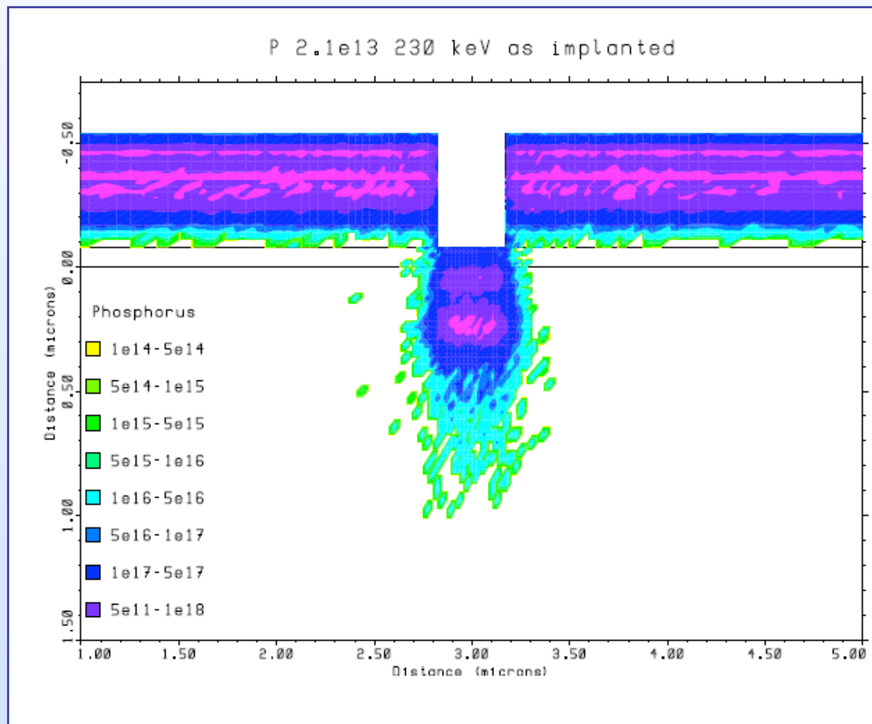


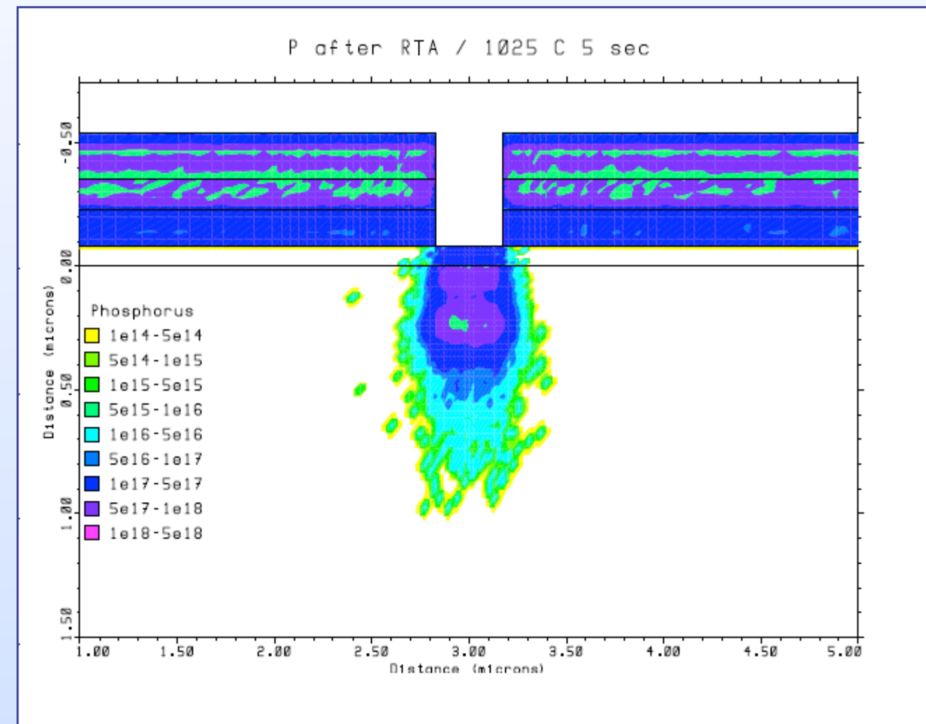


Reichweite, Streubreite & laterale Abweichung



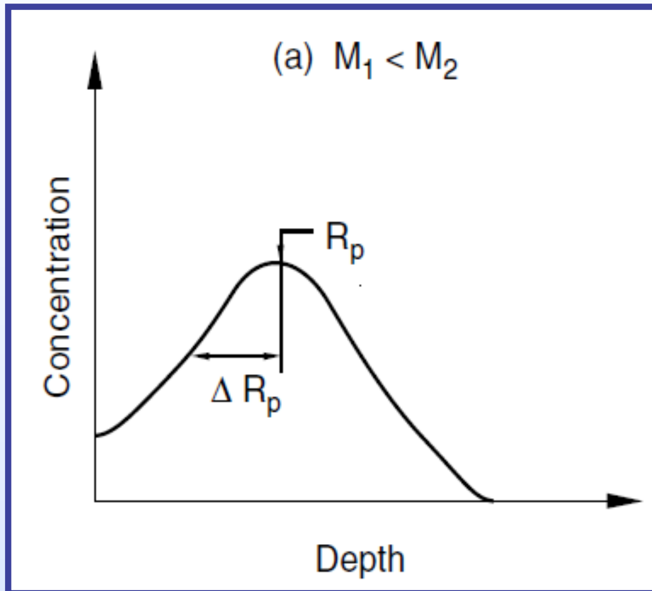
p-Well implantation

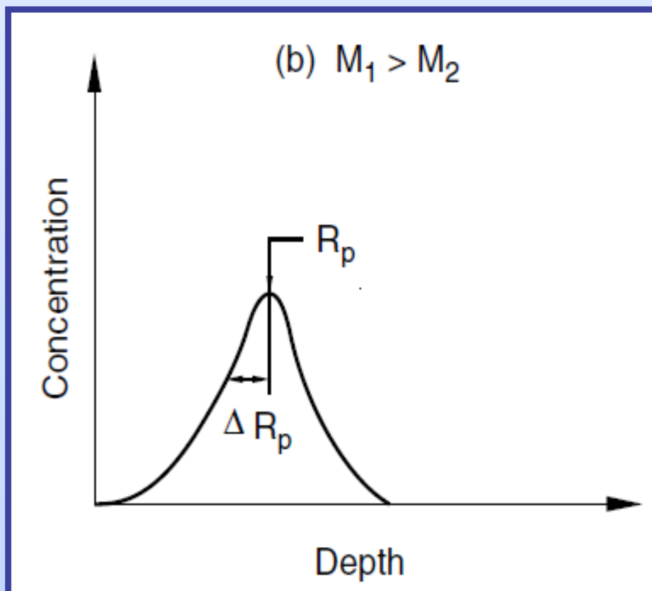




- **SRIM** (Stopping and Range of Ions in Matter): Monte Carlo simulation of transport properties of ions in matter
- **TSUPREM, TAURUS**: Monte Carlo simulation & diffusion processes

Profile parameters





Dose $$\phi = \int_0^\infty C(x)dx$$

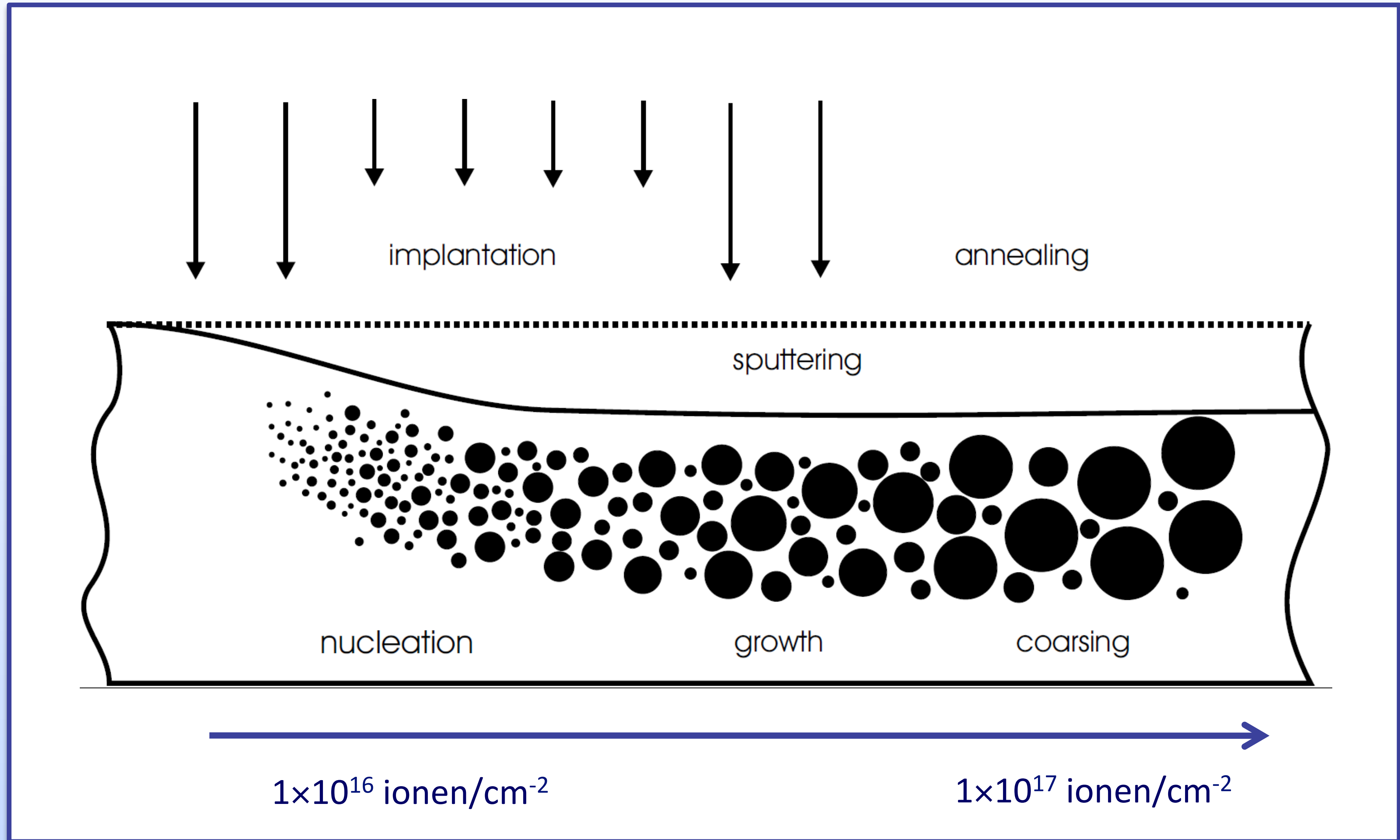
Projected Range $$R_P = \frac{1}{\phi}\int_0^\infty x \cdot C(x)dx$$

Longidutinal Straggle $$(\Delta R_P)^2 = \frac{1}{\phi}\int_0^\infty (x - R_R)^2 \cdot C(x)dx$$

Skewness $$\propto \frac{1}{\phi}\int_0^\infty (x - R_P)^3 \cdot C(x)dx$$

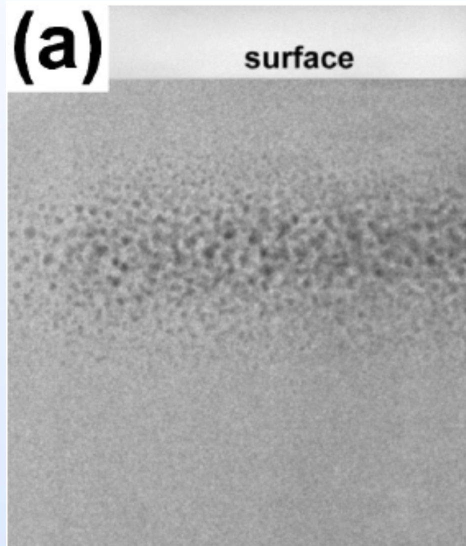
Kurtosis $$\propto \int_0^\infty (x - R_P)^4 \cdot C(x)dx$$

Ion implantation: Dose dependency

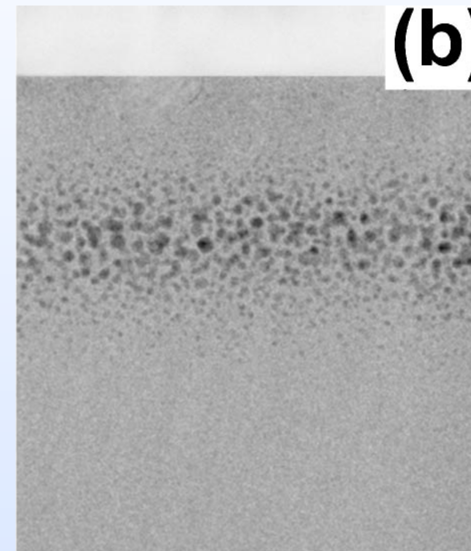


Nanoparticle formation

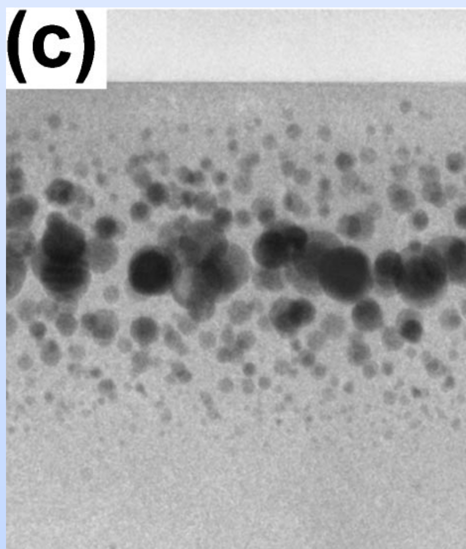
Implantation: 3×10^{16} cm^2 Au^+ into SiO_2 @ E = 190 keV



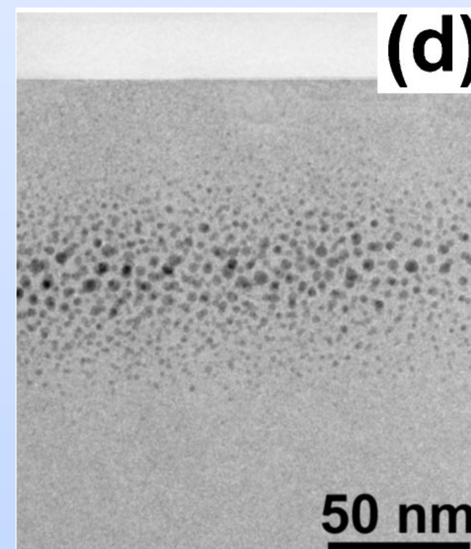
1h 400°C in air



1h 700°C in air



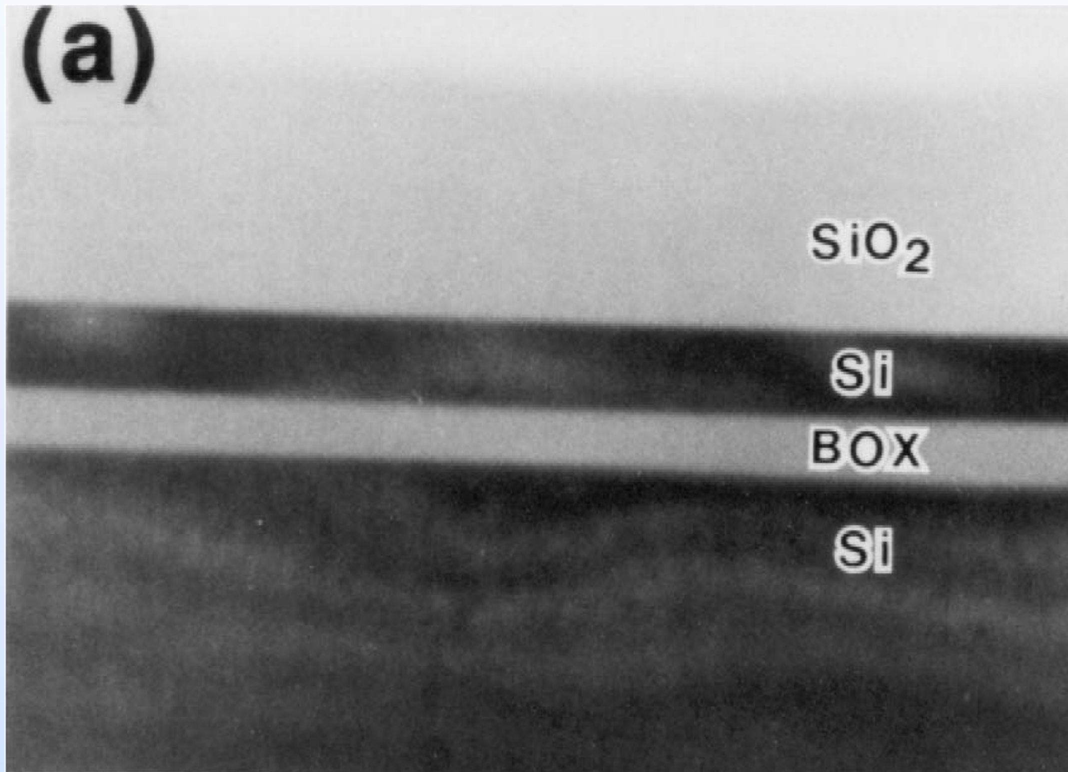
1h 900°C in air



1h 900°C in Ar

A. Miotello et al. in Phys. Rev. B 63 (2001) 075409.

Separation by Implanted Oxygen (SIMOX)



Implantation:

2×10^{17} cm^2 O^+ into Si @ E = 180 keV

Annealing

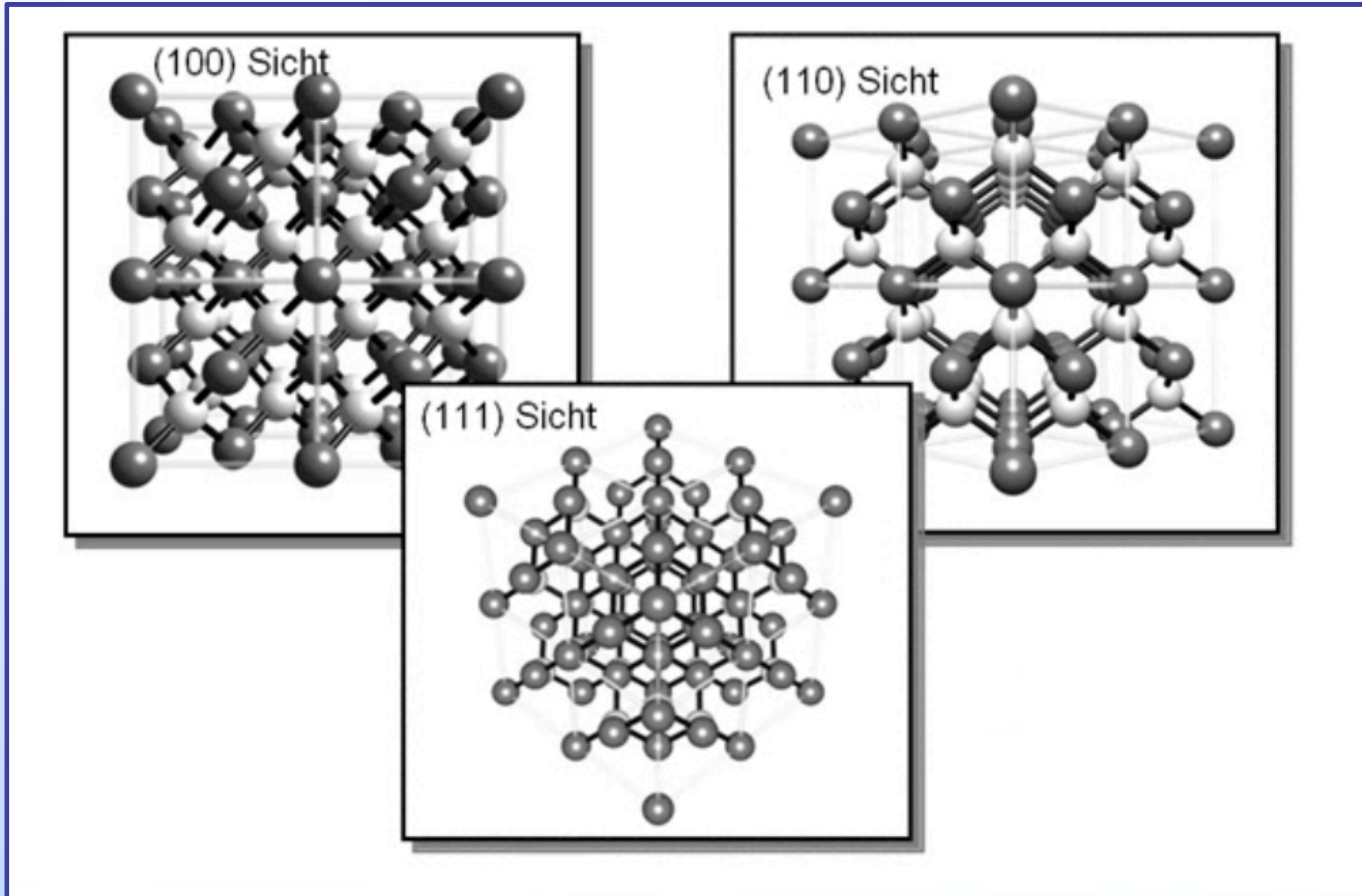
1340 °C in O_2/Ar atmosphere

O_2/Ar ration 0.5:100

——— R_P

A. Ogura, H. Onor, Applied Surface Science 159–160 (2000) 104–110

Channeling

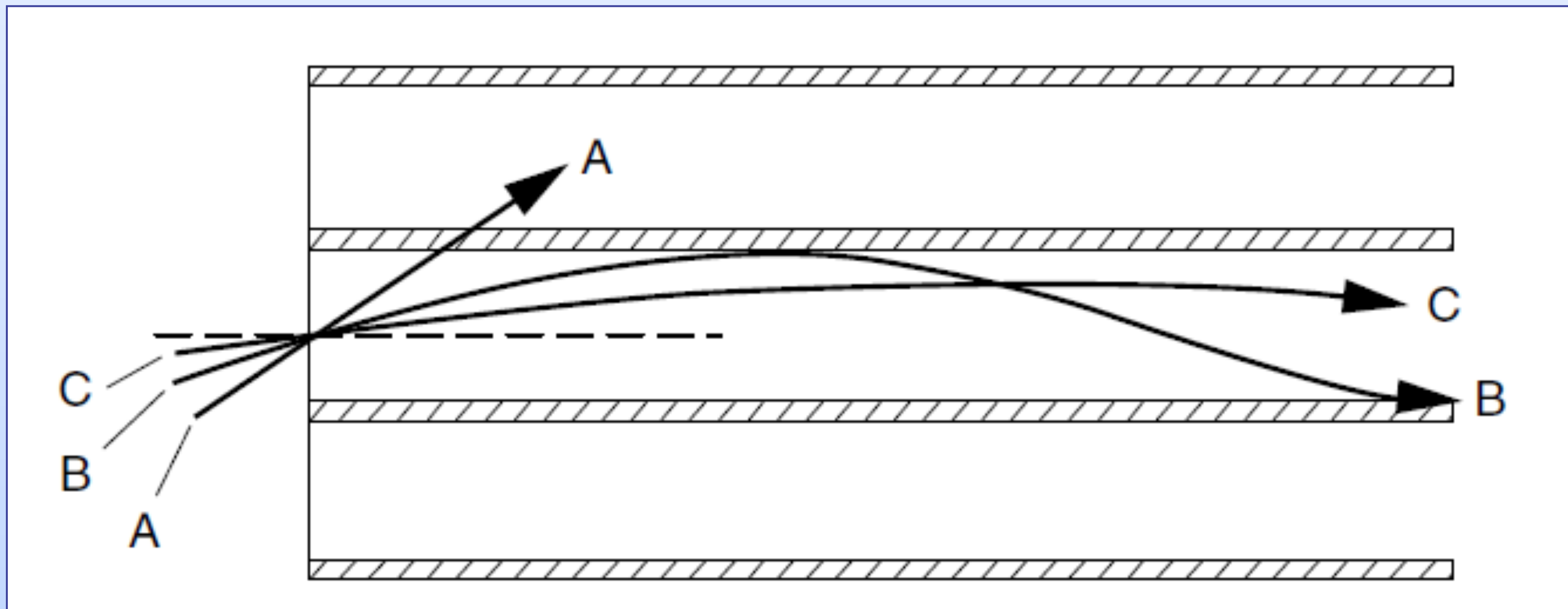


Channeling

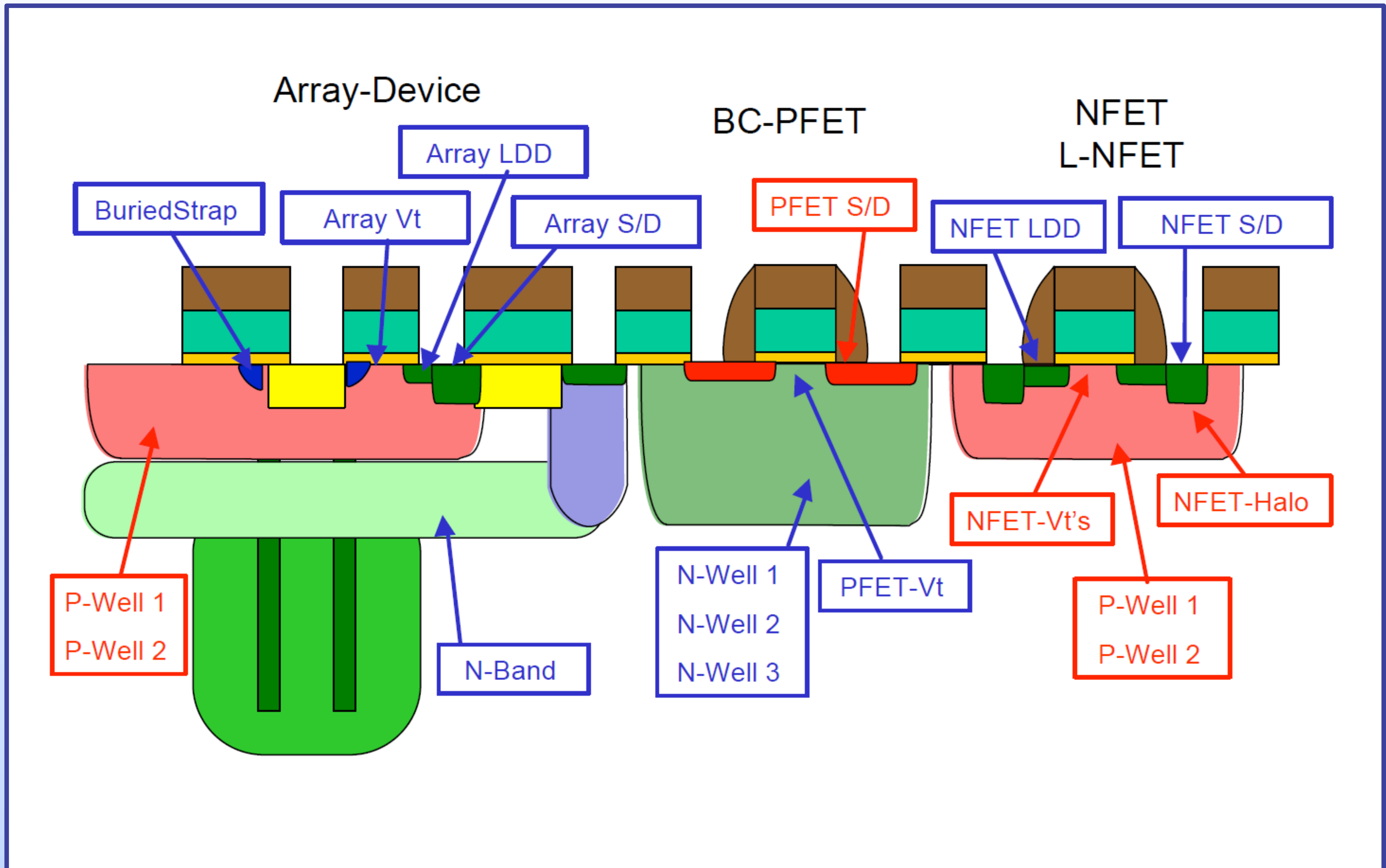
- Entlang bestimmter Kristallrichtungen („Kanäle“) können sich die Ionen mit wesentlich weniger Energieverlust ausbreiten
- Reichweite in solchen „Kanälen“ kann bis zu einer Grössenordnung grösser sein
- Kritischer Winkel liegt zwischen 3° und 7°

Unterbinden des Channeling

- Herausdrehen des Kristalls
- Abscheidung einer amorphen Oberflächenstreuschicht => diffuse Streuung



DRAM implants steps

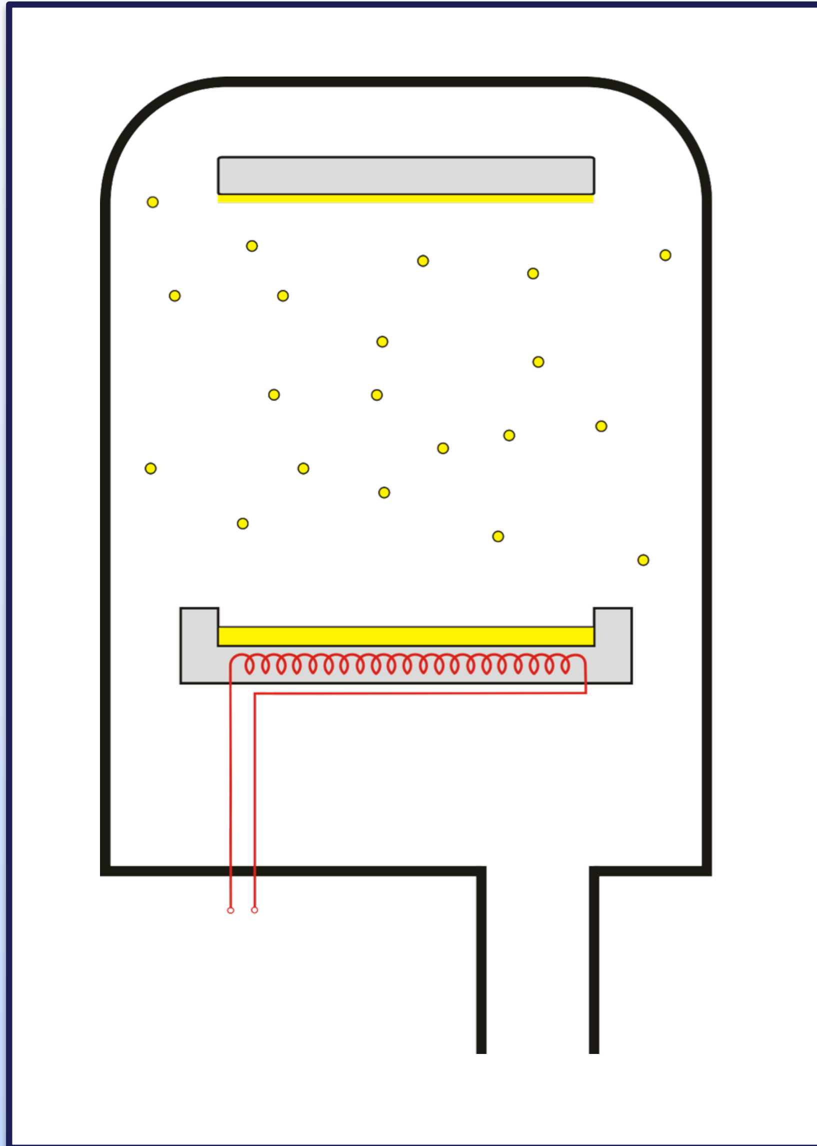


Ionenbeschleuniger

Uppsala University, The Ångström Laboratory

Aufdampfen

Aufdampfen



1. Thermisches Verdampfen von Material

2. Transfer der Dampfteilchen zum Substrat

3. Niederschlag (Kondensation auf kühlem Substrat und Wänden

Verdampfen

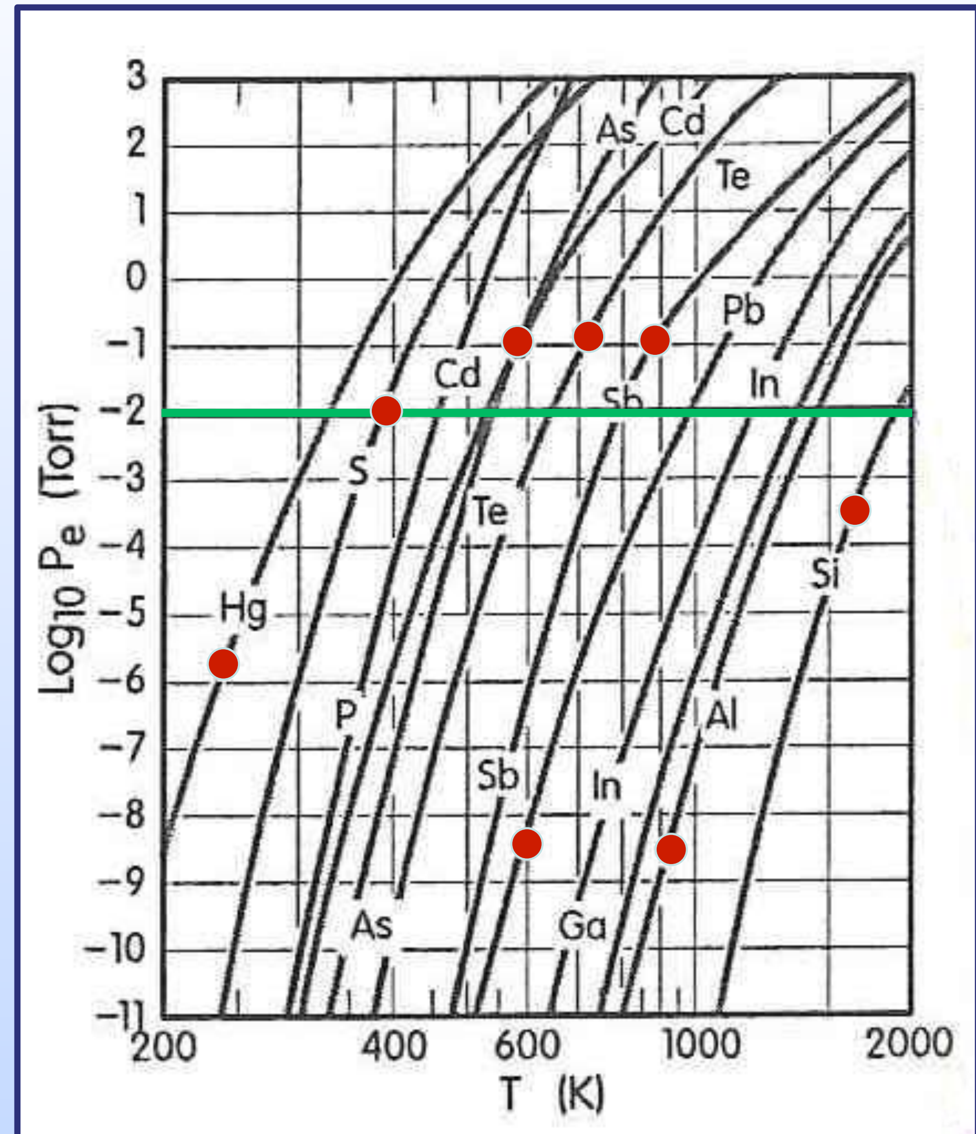
Die Quellematerial wird geheizt um die Dampfdruck zu erhören

$$P_e \sim \exp(-B/kT)$$

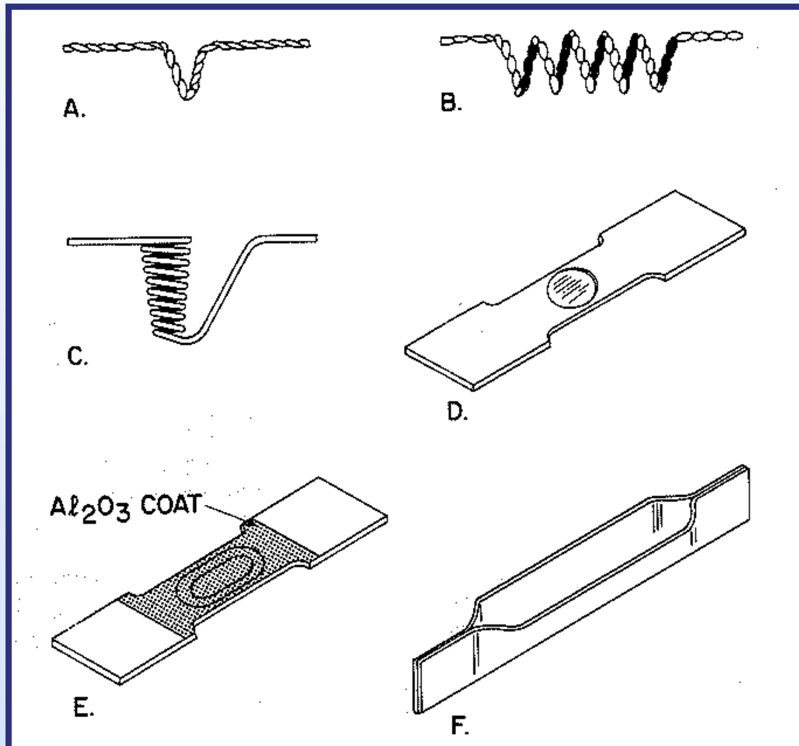
Allgemeiner Regel: $P_e > 10^{-2}$ Torr

Langmuirsche Gleichung:

$$W = 0.044 \cdot P_e \cdot \sqrt{\frac{M}{T}}$$



Verdampfungsquellen: Widerstandsheizung

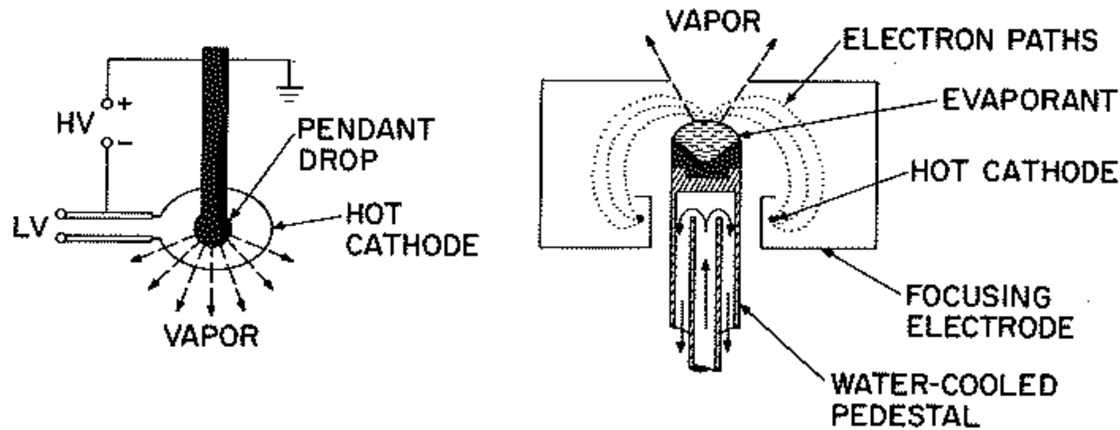


A	Hairpin source
B	Wire helix
C	Wire bascket
D	Dimpled foil
C	Dimpled foil with alumina
F	Canoe type

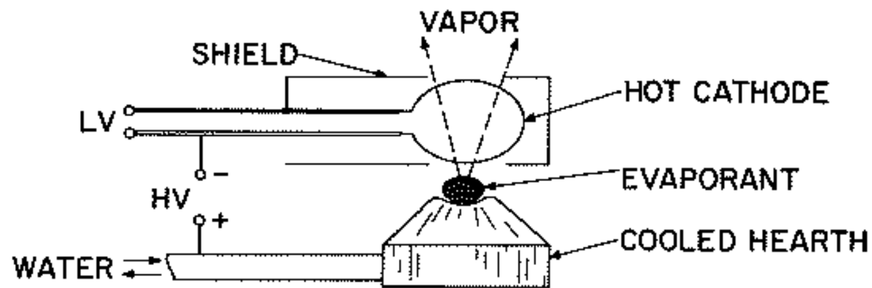
Materialien:

- Wolfram (3380°C)
- Tantale (3000°C)
- Molybdän (2610°C)

Verdampfungsquellen: Heizung mit Elektronenstrahl



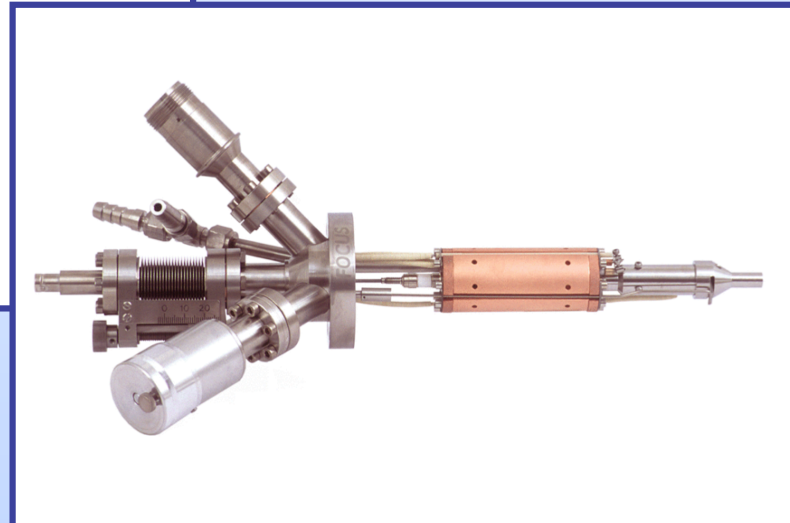
A. B.



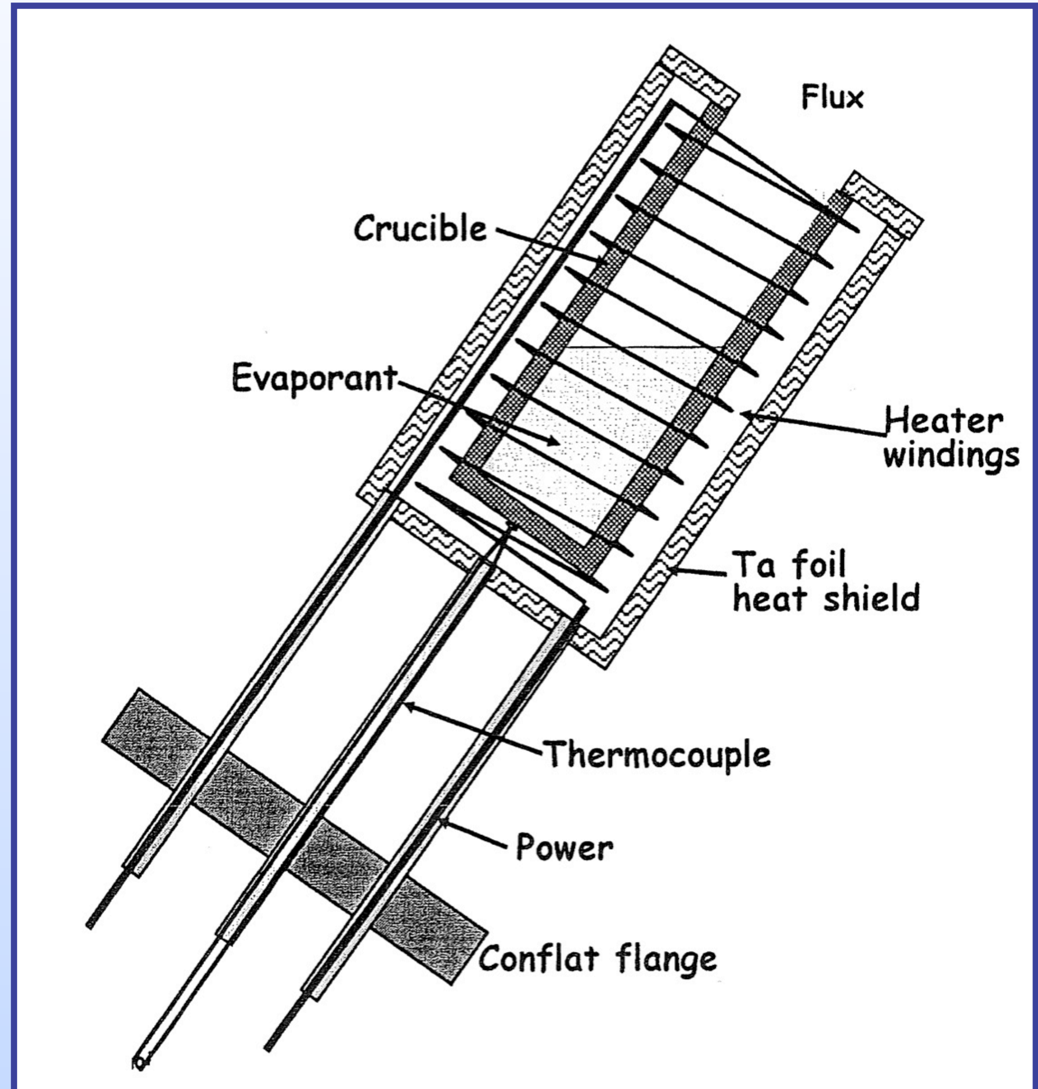
C.

$E_e = 5 – 10$ keV

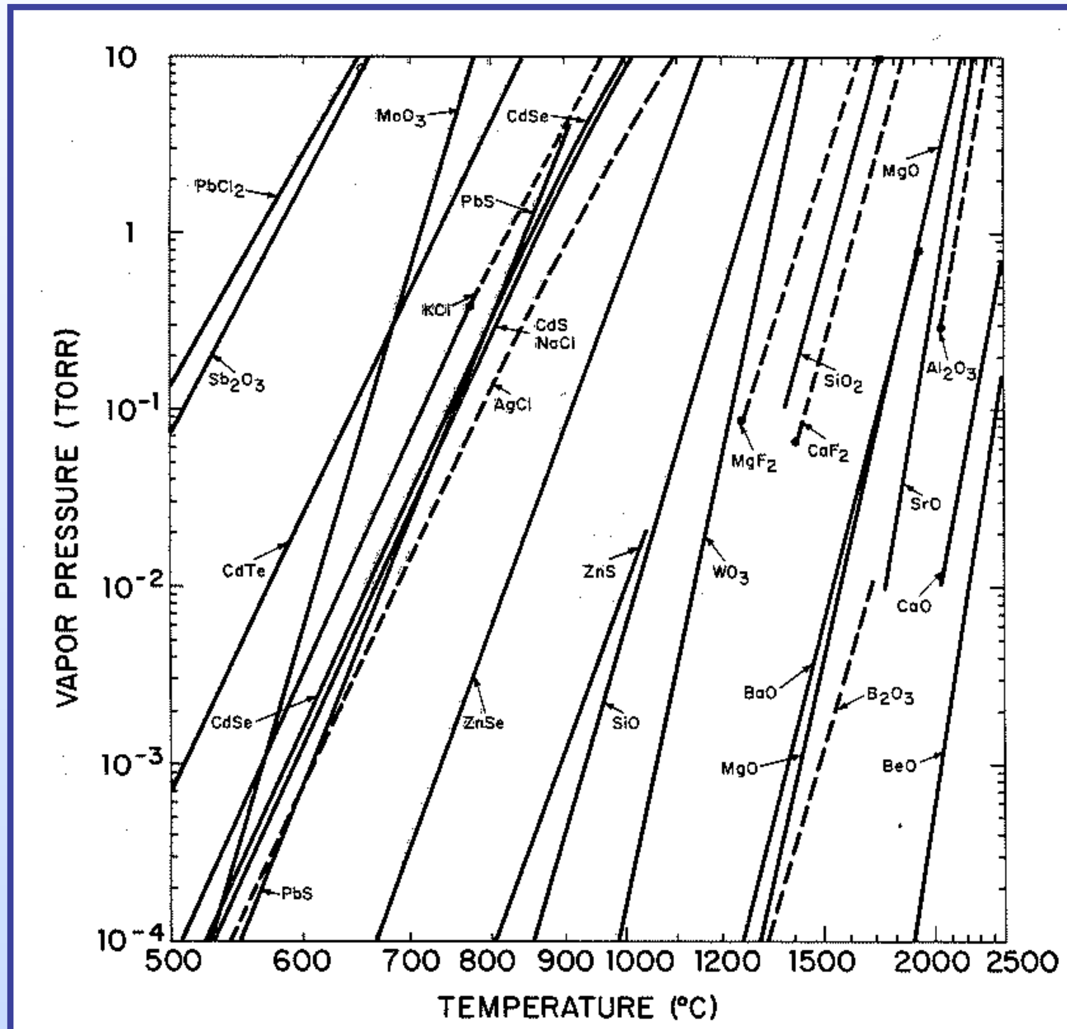
$T \approx 3000°C$

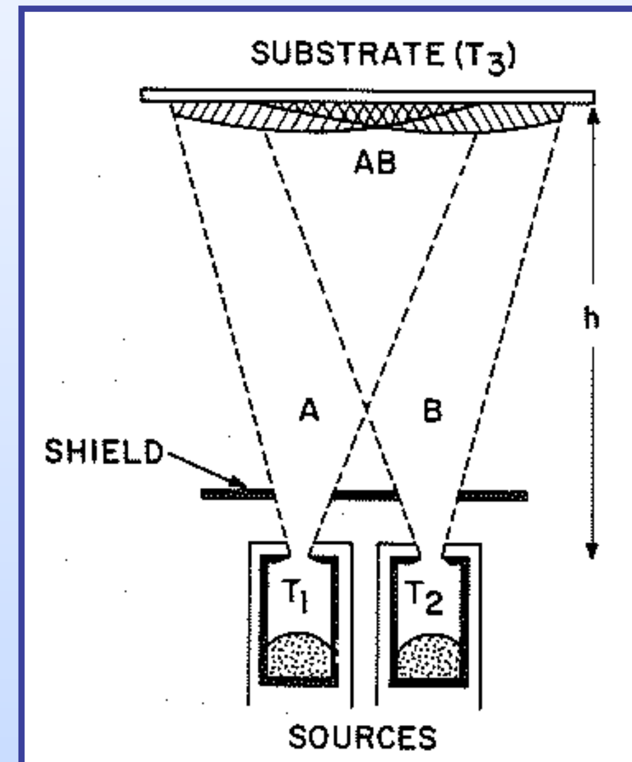


Effusionszelle (Knudsen Zelle)



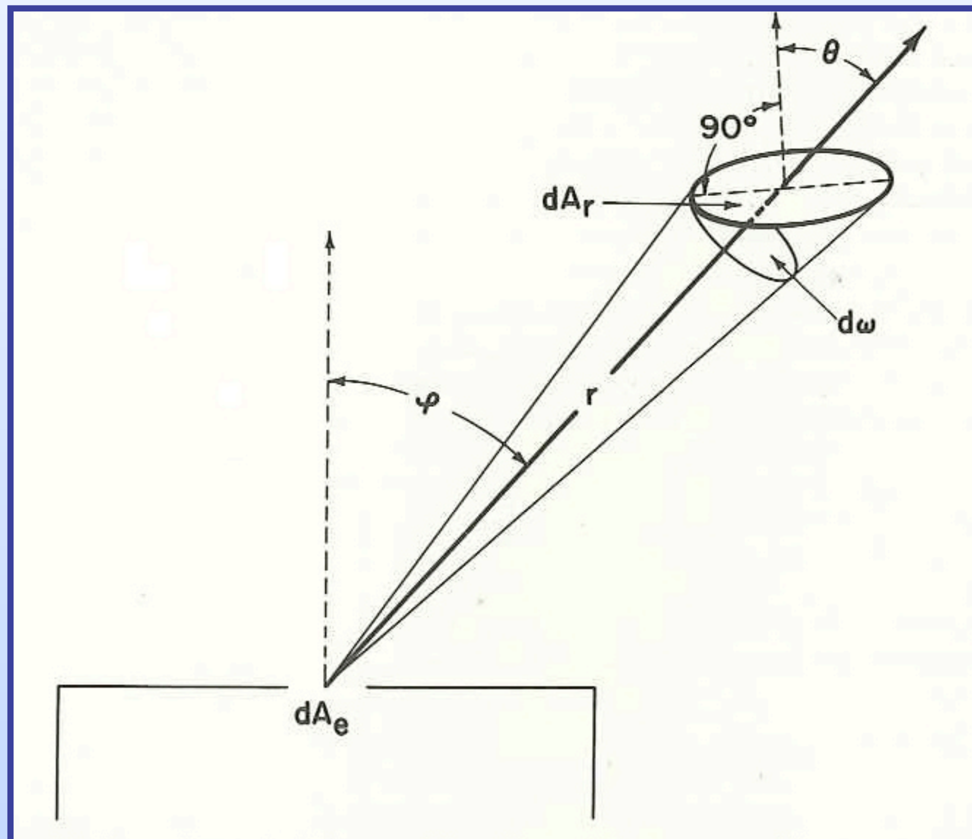
Aufdampfen von Mischungen





Verdampfen aus Punktquelle

- Energie der verdampften Teilchen ca. 0.2 eV
- Mittlere freie Weglänge typisch grösser als Dimension des Rezepinten
  - Streuung der Dampfteilchen sind selten

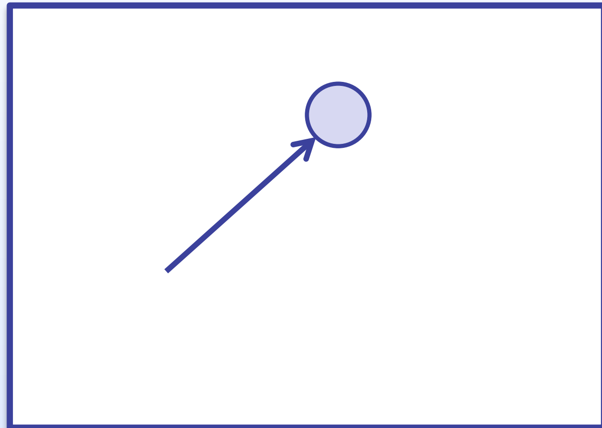


cos-Gesetz der Emission

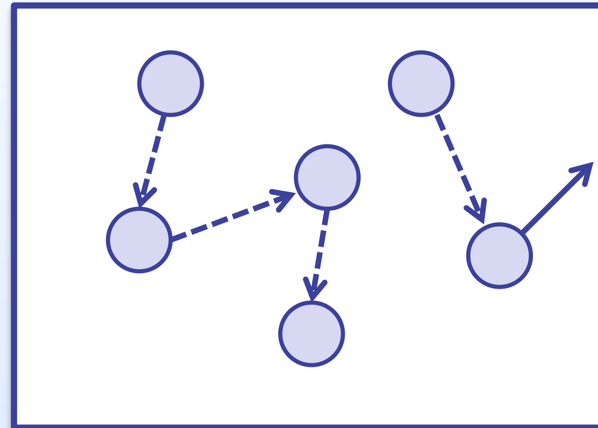
$$\frac{dm}{dt\,d\omega} = \frac{\Theta_0}{4\pi}\cos\varphi$$

$$d = \frac{1}{\rho}\frac{dm}{dA_r}$$

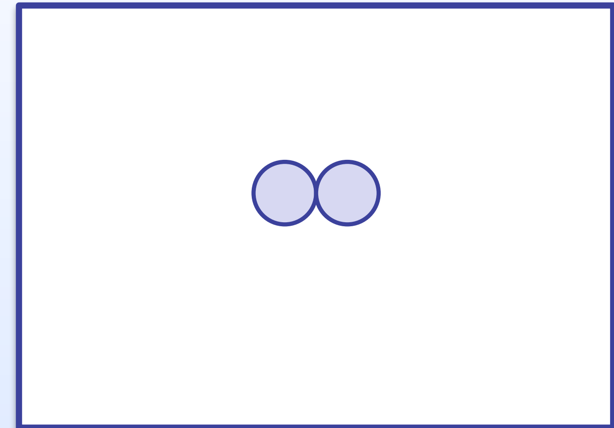
Growth steps



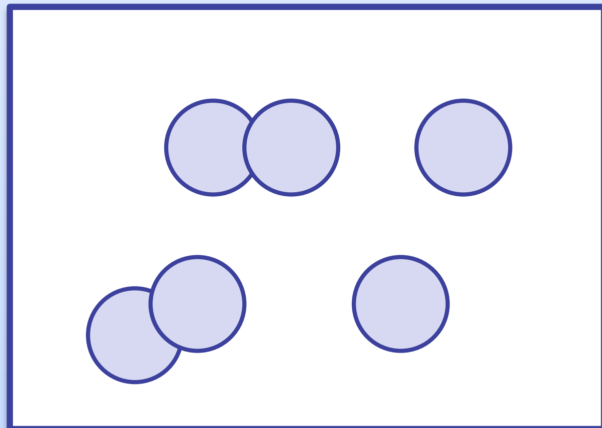
Single atom



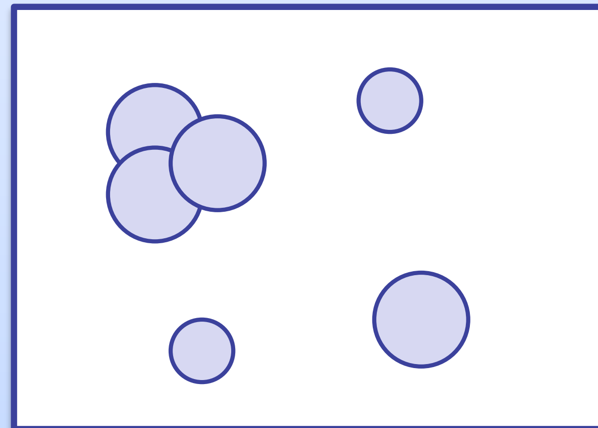
Migration/Re-Evaporation



Collision & Combination of single atoms



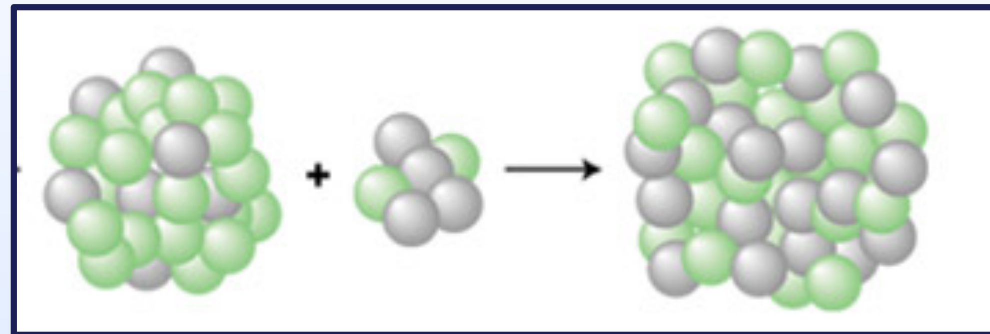
Coalescence



Coarsing (Ostwald ripening)

Ostwald ripening

Friedrich Wilhelm Ostwald
1853 – 1932

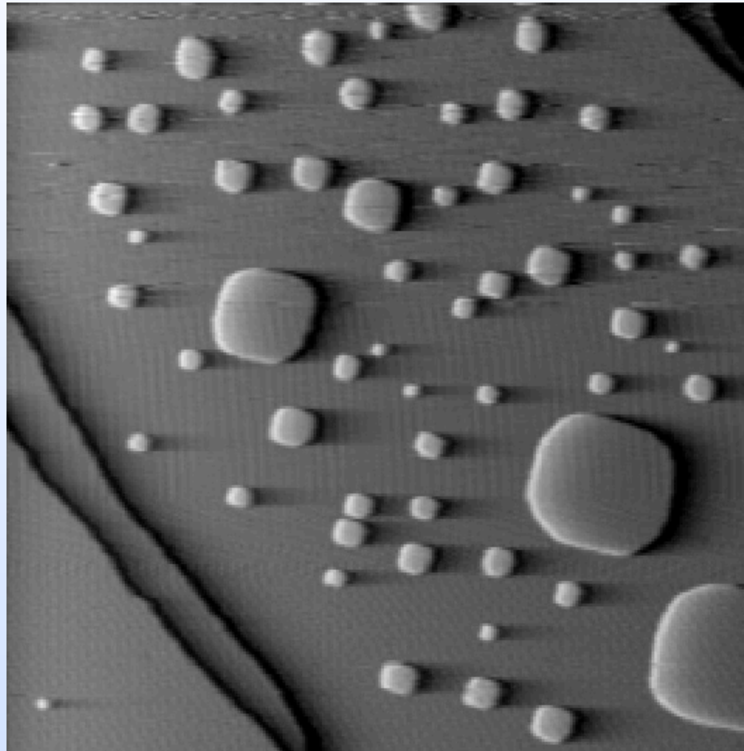


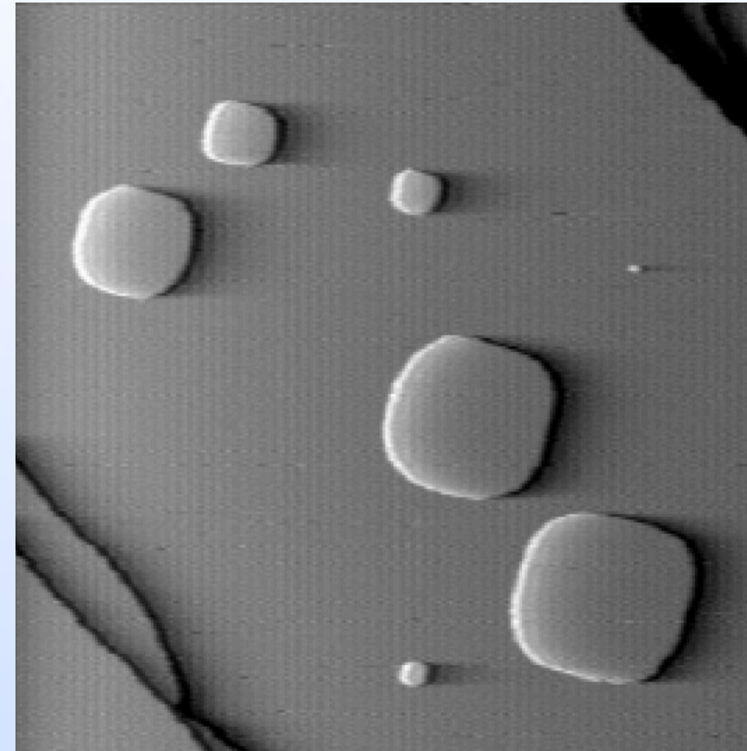
$$\frac{P}{P_e} = \exp\left(\frac{r_{\mathrm{crtical}}}{r}\right) = \exp\left(\frac{2\gamma V}{rkT}\right)$$

Gibbs-Thomson Gleichung

„da nach bekannten Prinzipien ein feines Pulver löslicher sein muss als ein grobes, ebenso wie kleine Tröpfchen einen größeren Dampfdruck haben als große"

Ostwald ripening

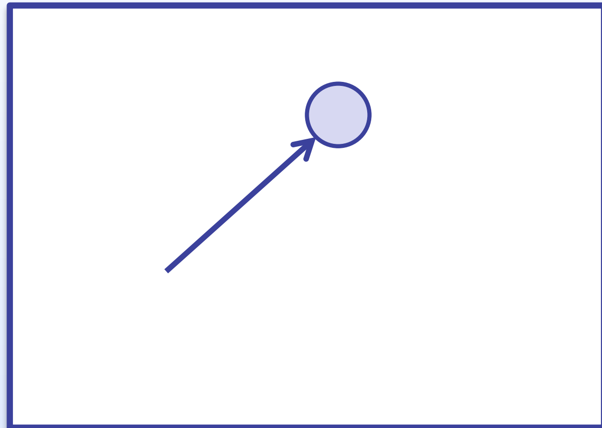




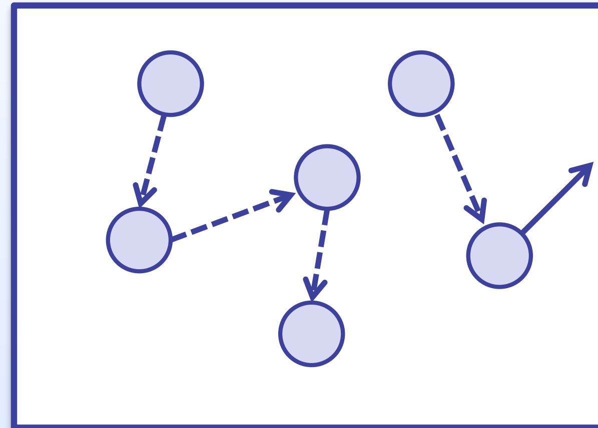
300 nm × 300 nm STM Cu/Cu (001), T_s = RT, t = 20‘000 sec

J. B. Hannon, C. Klünker, M. Giesen, H. Ibach, N. Bartelt, J. Hamilton, Phys. Rev. Lett. 79 (1997) 2506.

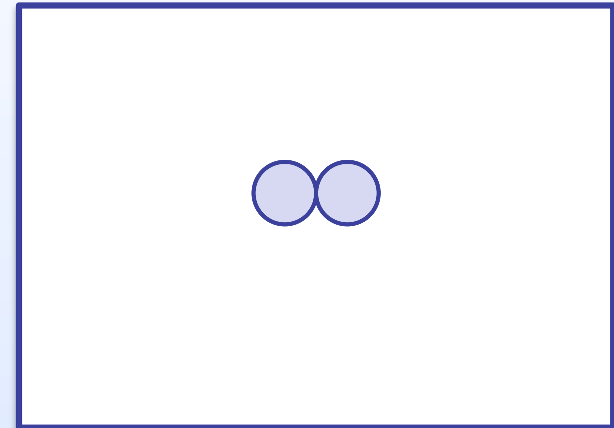
Growth steps



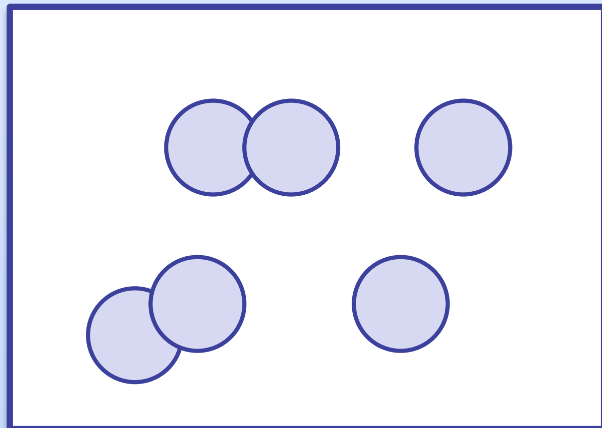
Single atom



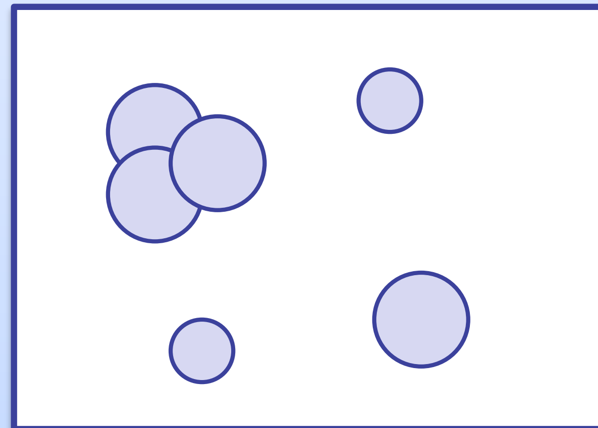
Migration/Re-Evaporation



Collision & Combination of single atoms



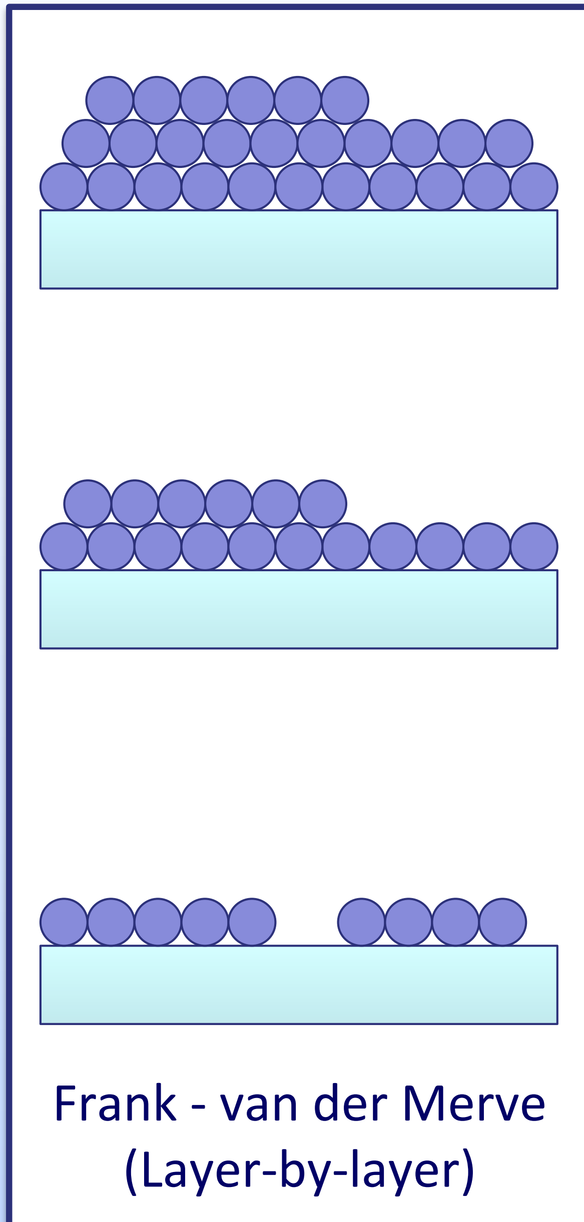
Coalescence

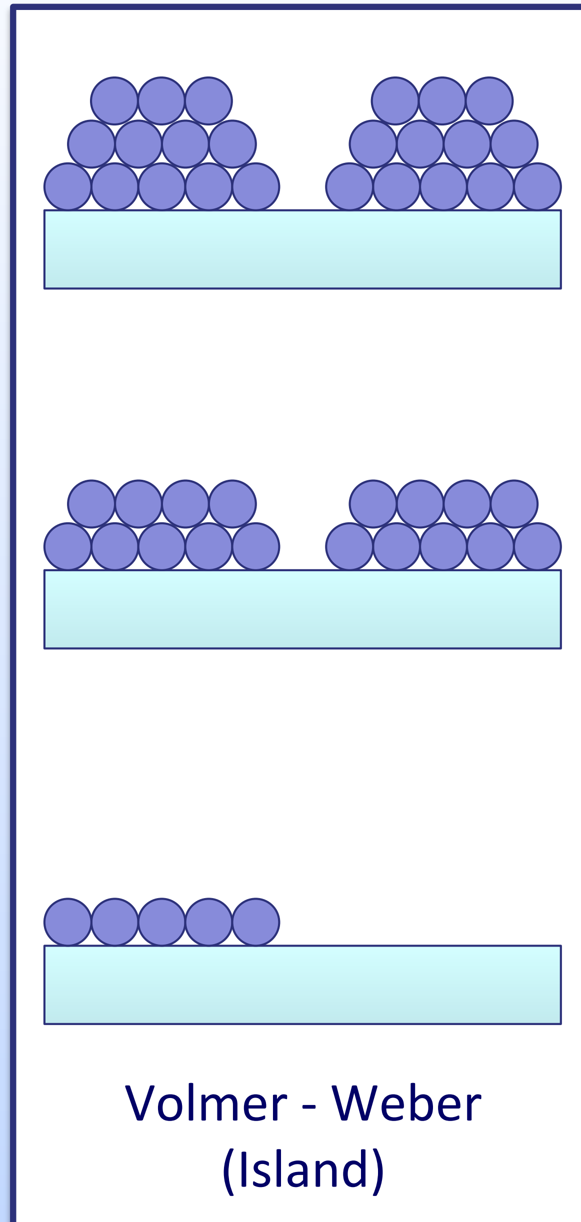


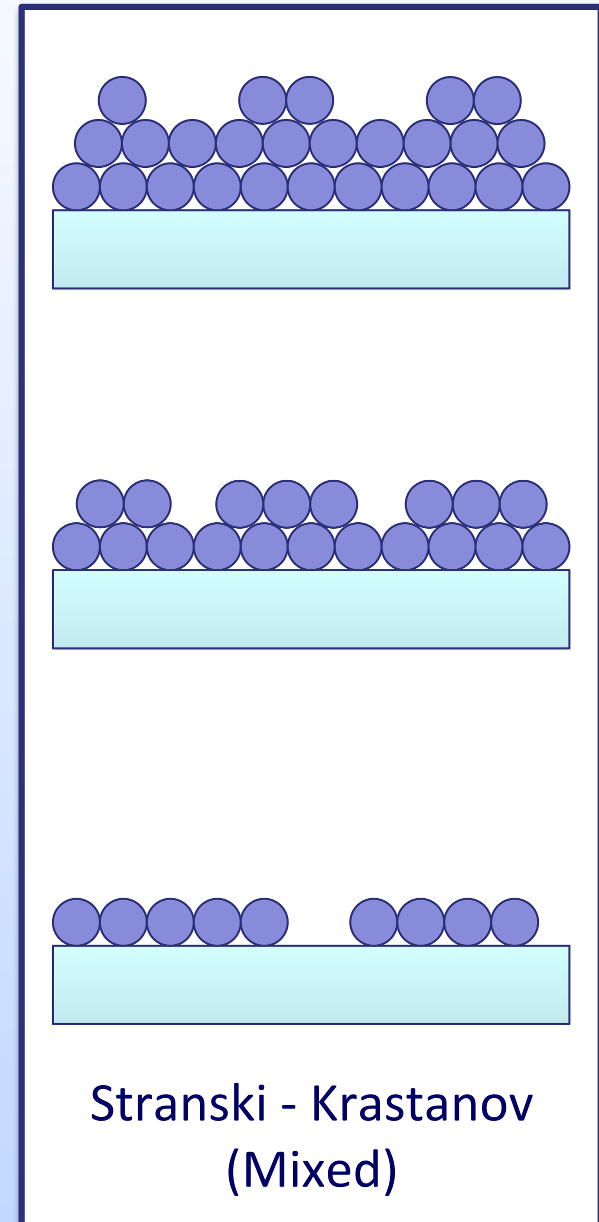
Coarsing (Ostwald ripening)

Continious film

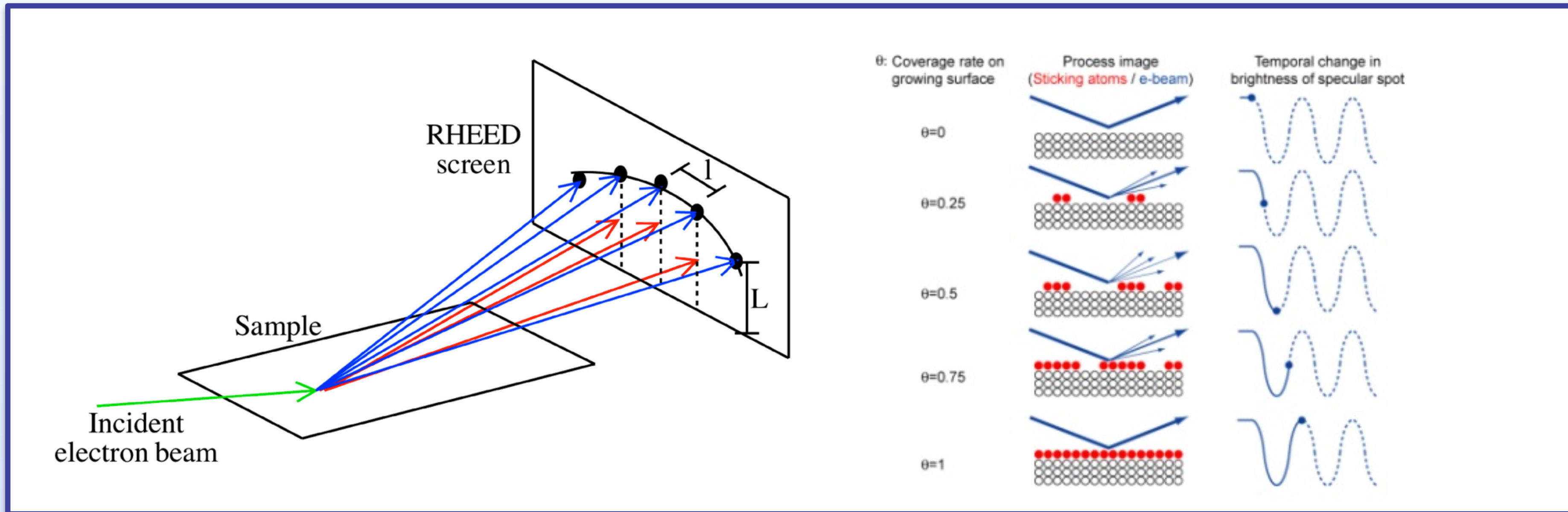
Growth modes

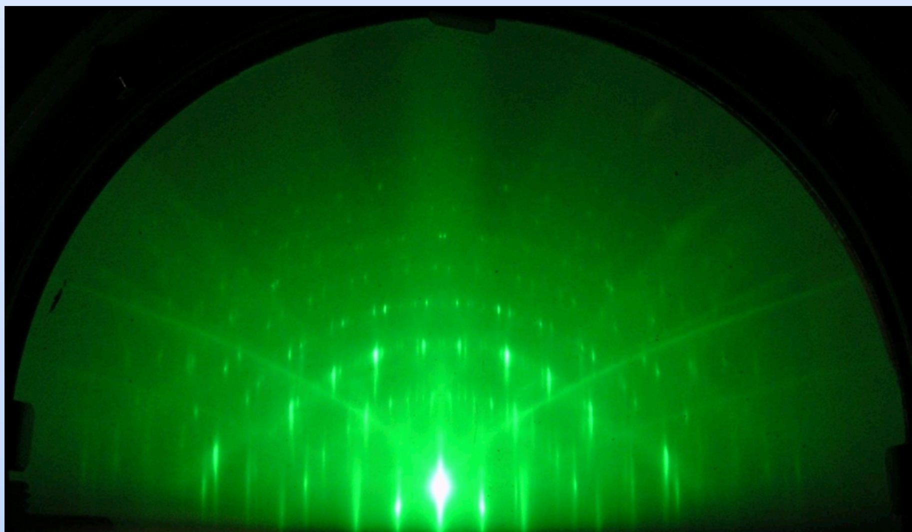


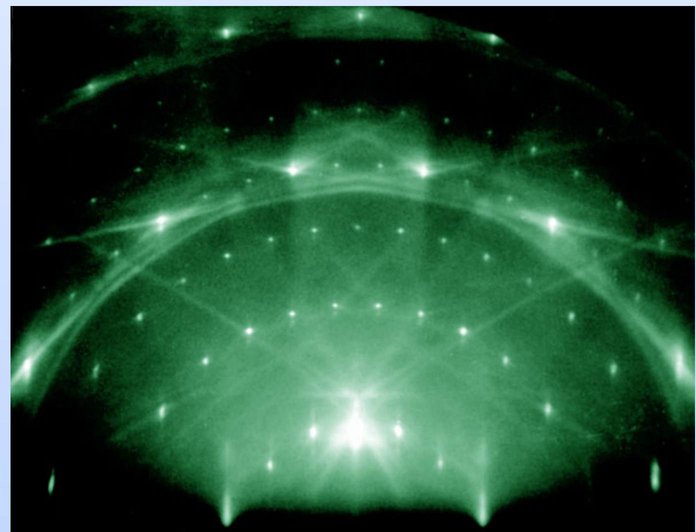




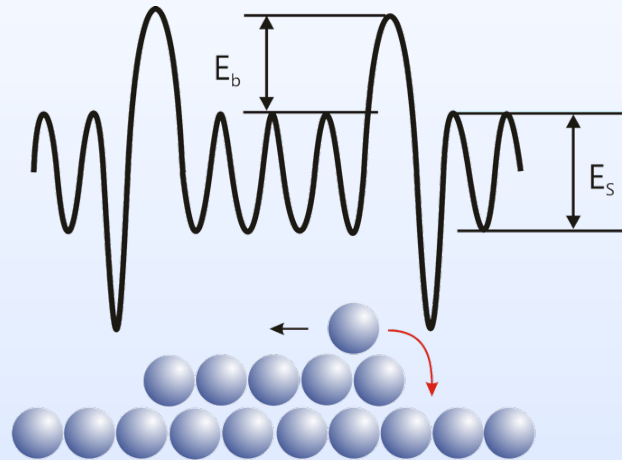
Reflection High Energy Electron Diffraction

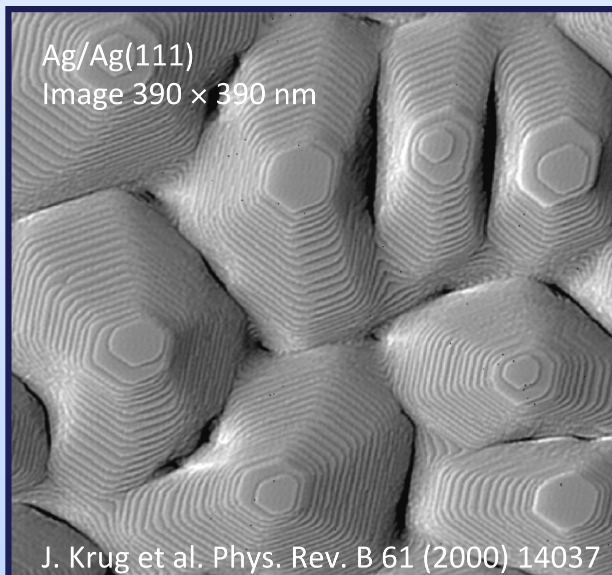


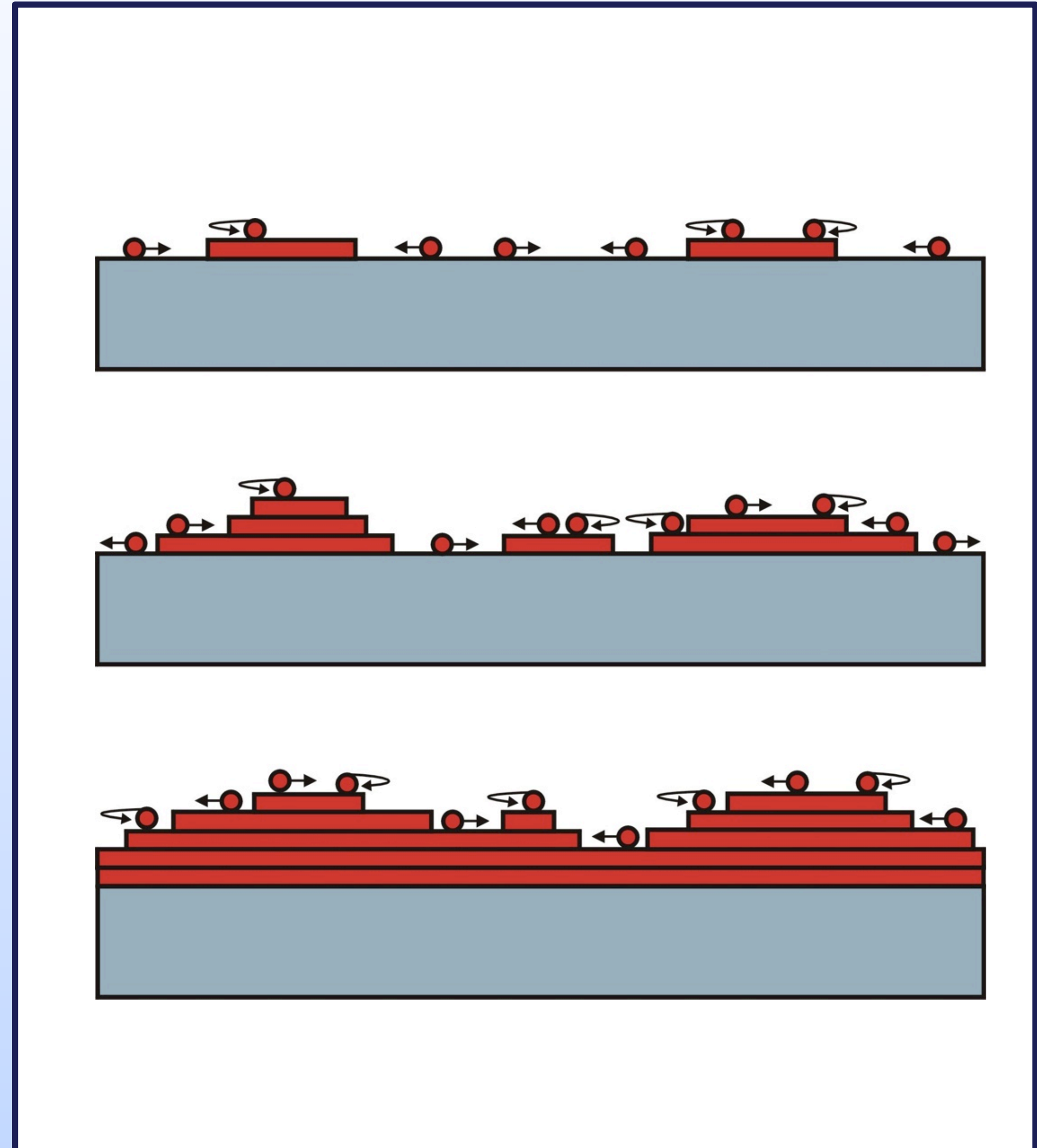




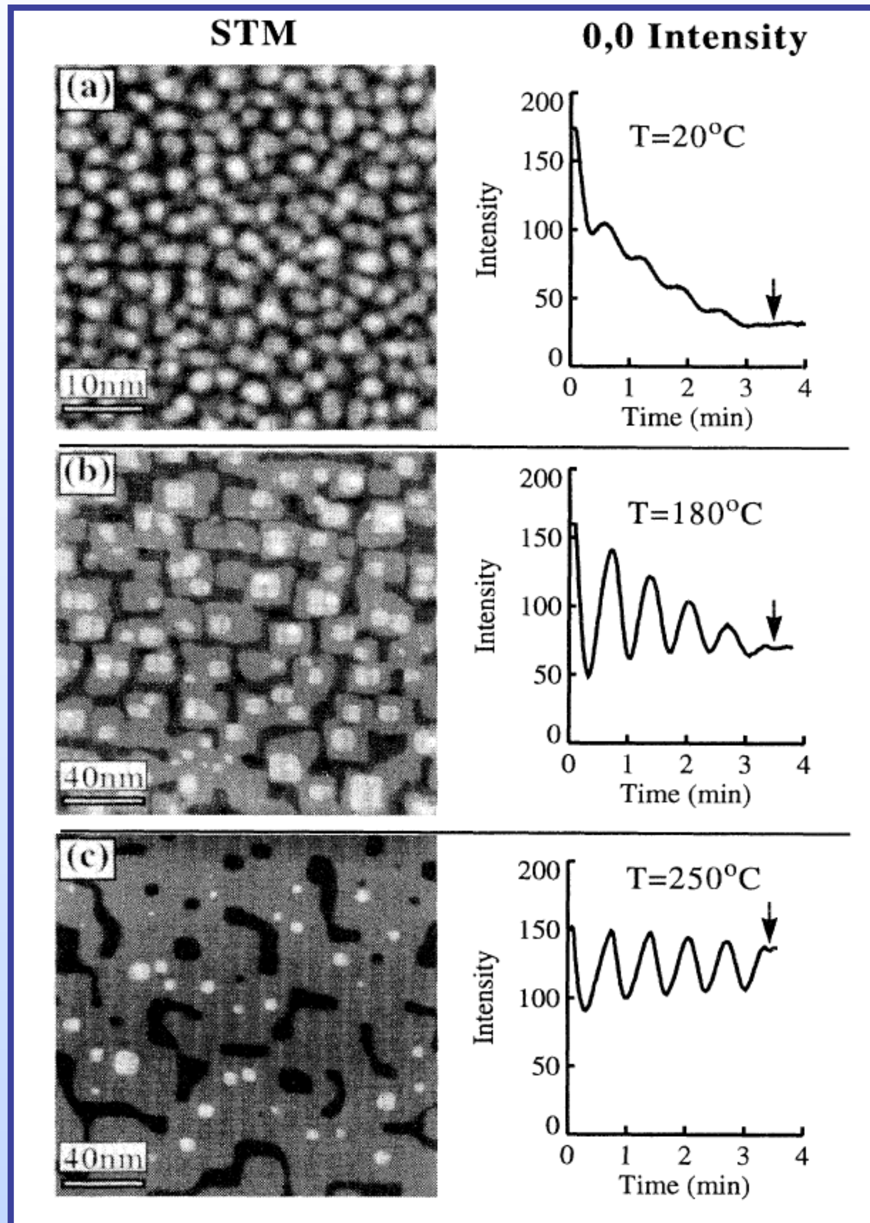
Ehrlich Barrier







Homoepitaxy Fe/Fe(100)



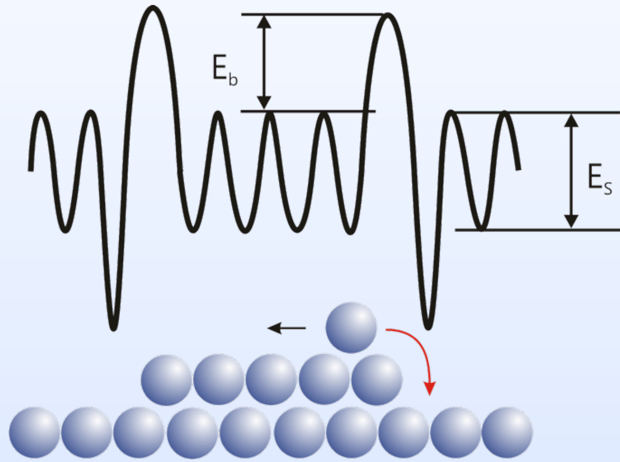
$\langle s \rangle = 1.74\ nm^{-1}$
$\langle w \rangle = 0.116\ nm$

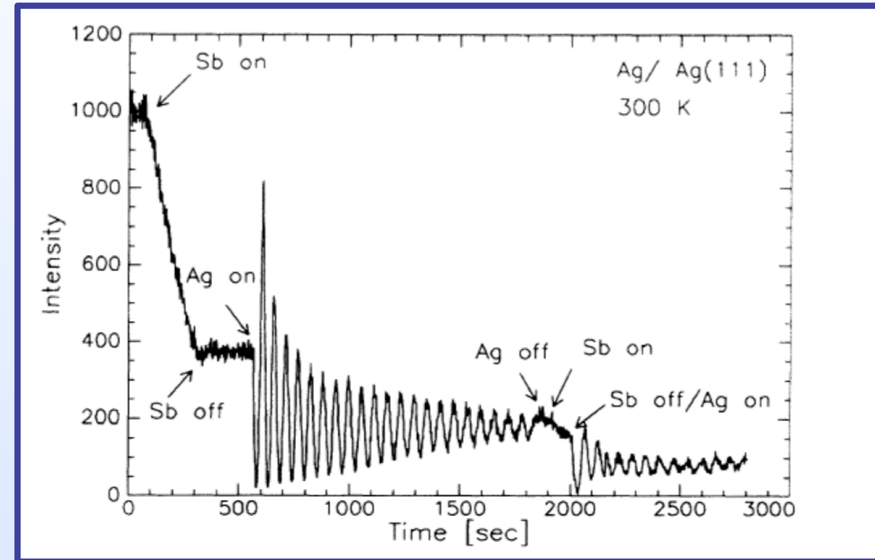
$\langle s \rangle = 0.23\ nm^{-1}$
$\langle w \rangle = 0.095\ nm$

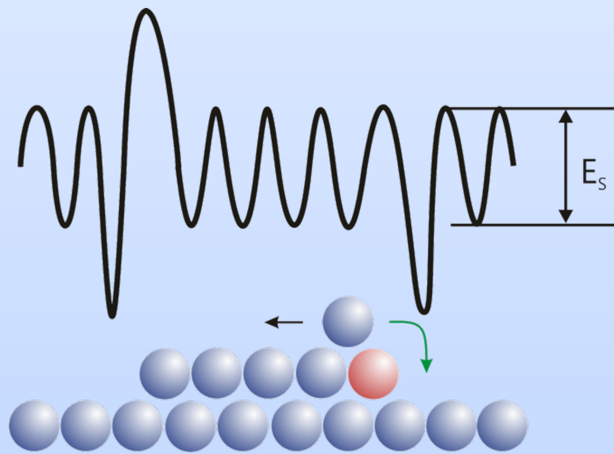
$\langle s \rangle = 0.09\ nm^{-1}$
$\langle w \rangle = 0.06\ nm$

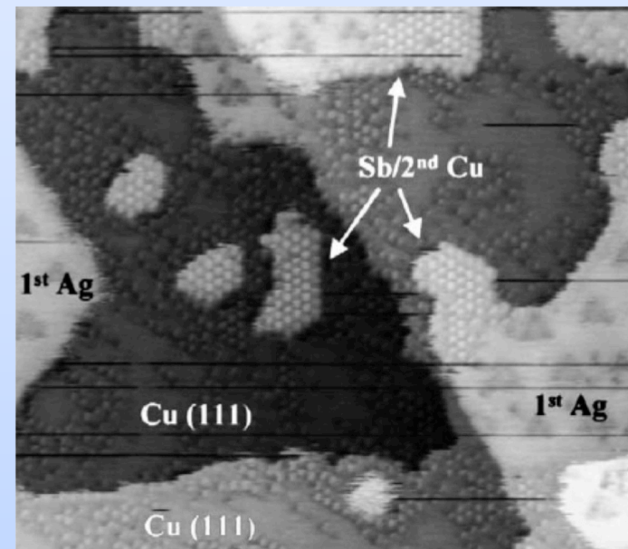
Stroscio et al., Phys. Rev. Lett. 70 (1993) 3615.

Surfactants



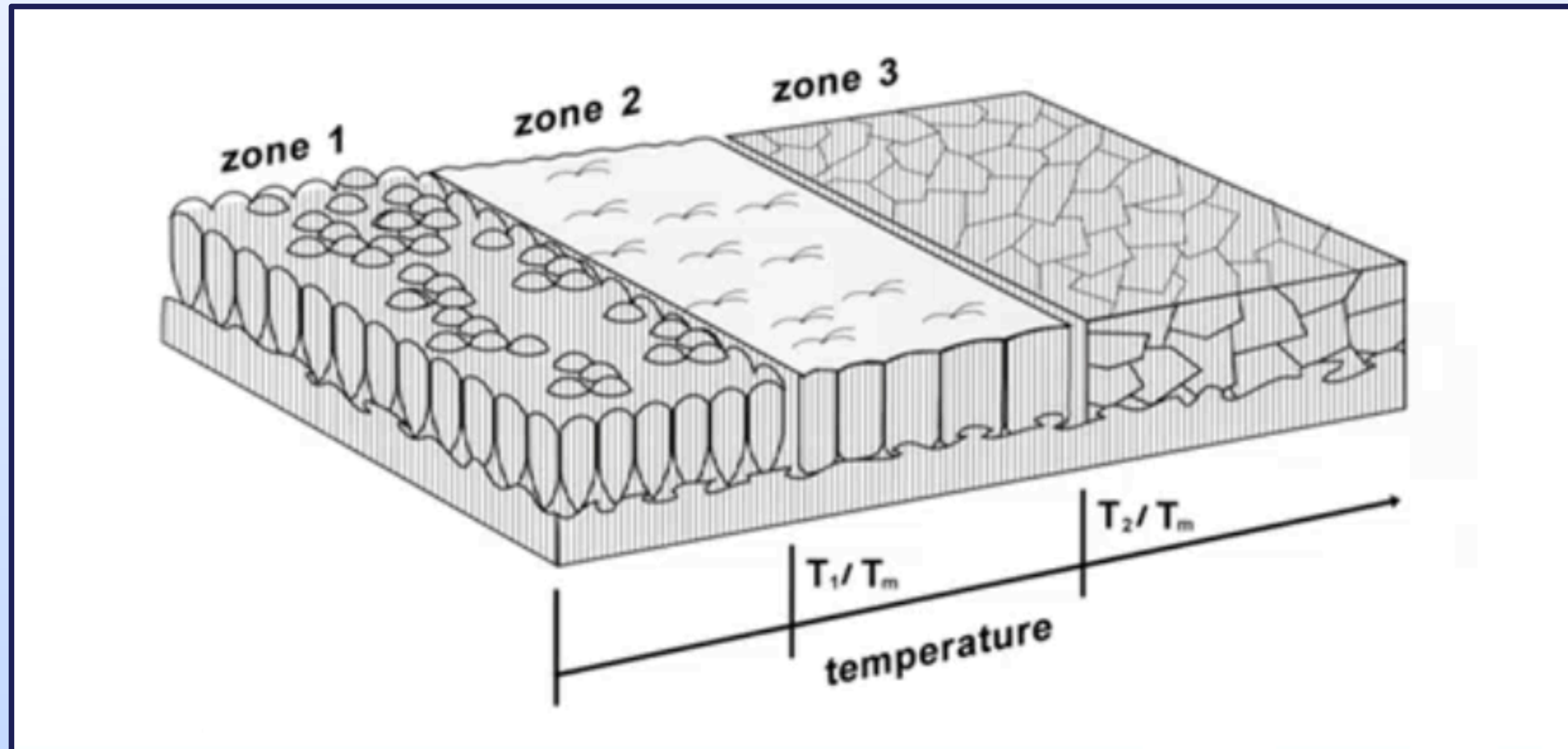






Morphologie: Movchan und Demchishin Modell

- Dreizonenmodell als Funktion des Temperaturkoeffizienten T/T_m (T_m = Schmelztemperatur)
- Untersuchung im Hochvakuum (10^{-6} – 10^{-7} mbar)



Literatur

Handbook of Thin Film Technhology
L. I. Maissel and R. Glang, McGraw-Hill, 1970

Handbook of nanostructured Materials and Technology
H. S. Nalwa, Academic Press, 2000

Deposition Technhologies for Films and Coatings
R. F. Bunshah, Noyes Publications, 1994

Introduction to Nanotechnology
C. P. Poole and F. J. Owens, J. Wiley, 2003

Quantum Dots
E. Borovitskaya and M. Shur, World Scientific, 2002

Nanostructures and Nanomaterials: Synthesis, Properties & Applications
G. Cao, Imperial College Press, 2004