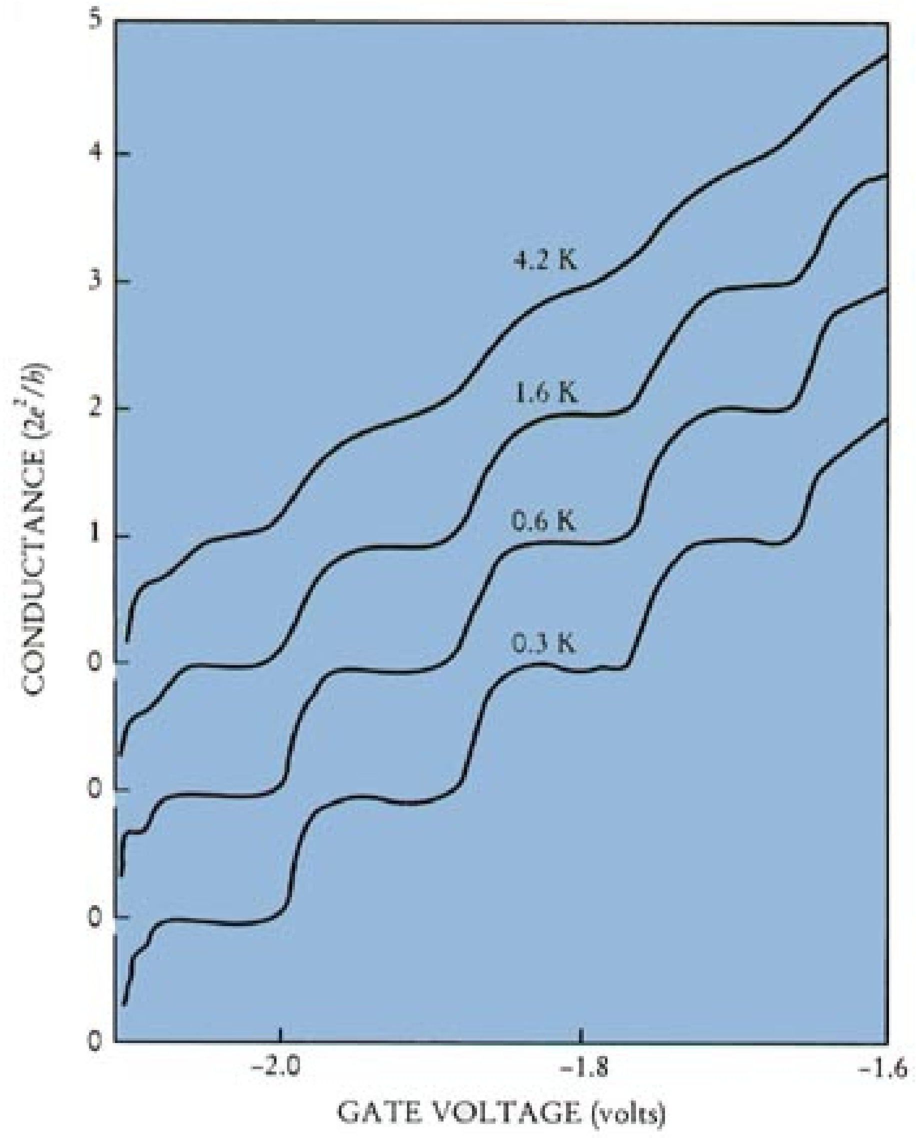
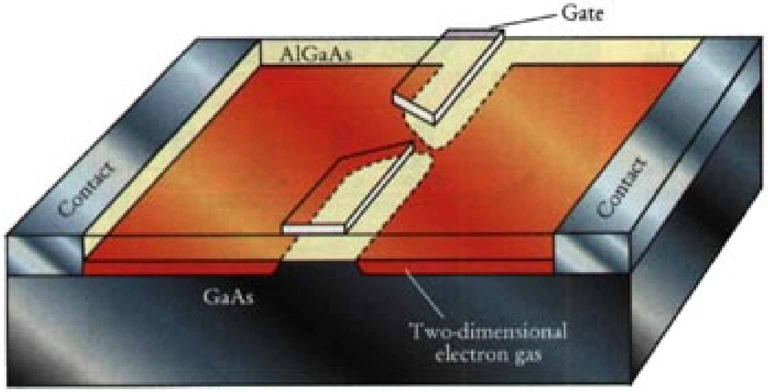
Conductance quantization in a 2DEG





$$G = \frac{2e^2}{h}\sum_n T_n$$

$$\text{Finite } V\text{: } G(V) = \frac{2e^2}{h}\frac{1}{eV}\sum_{n=1}^{N}\int_{E_F}^{E_F+eV} dE\,T_n(E)$$

$$\text{Finite } T\text{: } G(T) = \frac{2e^2}{h}\sum_{n=1}^{N}\int_0^{\infty} dE\left(-\frac{\partial f(E,T)}{\partial E}\right)T_n(E)$$

B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, C. T. Foxon, Phys. Rev. Lett. **60**, 848 (1988); Phys. Rev. B **43**, 12431 (1991).

D. A. Wharam, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J. E. F. Frost, D. G. Hasko, D. C. Peacock, D. A. Ritchie, G. A. C. Jones, J. Phys. C **21**, L209 (1988).

Chapter 4
Realization of reduced dimensions

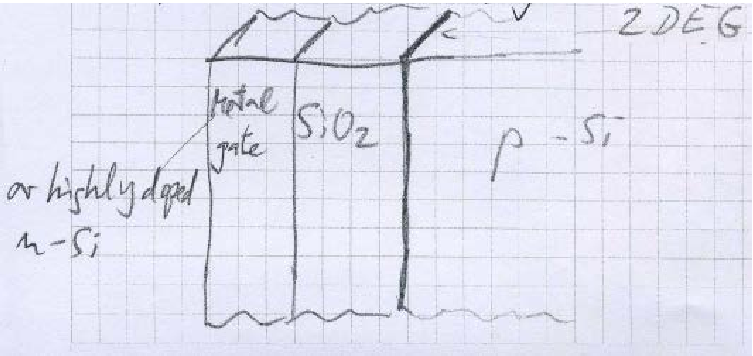
- Nanotechnology: Miniaturization + new functionalities
  Examples: Change of electronic structure, subbands etc.
  3D -> 2D: thin films
  2D -> 1D: wires
  1D -> 0D: nanoparticles, ...

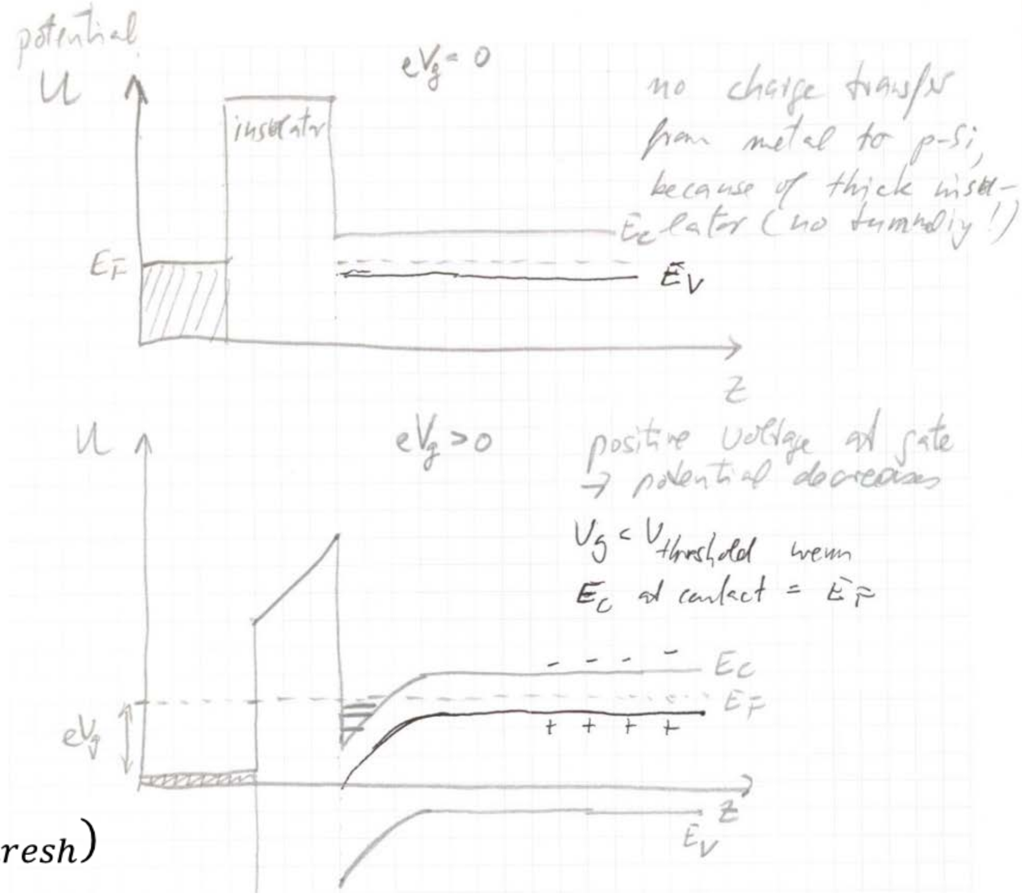
- Nanostructures often at surfaces because of fabrication, characterization, applications, addressability, ...
- Also free nanoparticles, but not of interest here.

- -> Here: Nanostructures on Surfaces

4.1 Two-dimensional Electron Gases (2DEG) (Quantum wells)

Silicon inversion layers





"Inversion" layer because surface of Si is negatively charged despite p-doping

Surface electron density n_s depends linearly on V_g ($\rho_2 = \text{const}$)
Assume planar capacitor with area A and capacitance C

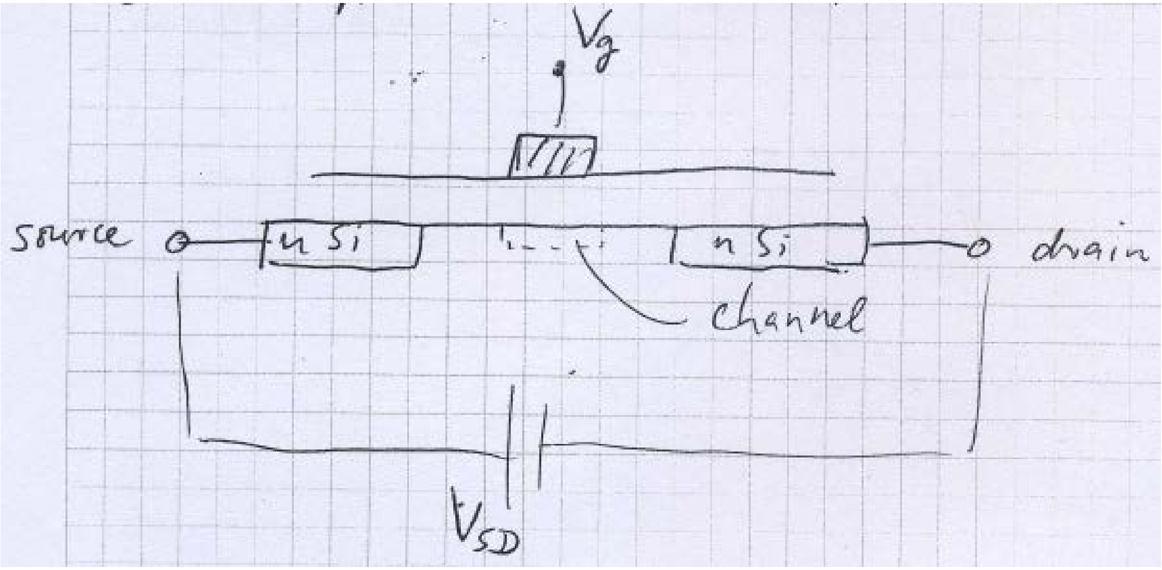
$$n_s \cdot e = \frac{Q}{A} = \frac{C}{A} \cdot U = \frac{\varepsilon_0 \varepsilon_{SiO2}}{d_{SiO2}} \cdot (V_g - V_{thresh})$$

V_{thresh}: needed to popuplate the first subband

4.1 Two-dimensional Electron Gases (2DEG)

Silicon inversion layers

Technical appliction MOSFET: Metal Oxide Semiconductor Field Effect Transistor

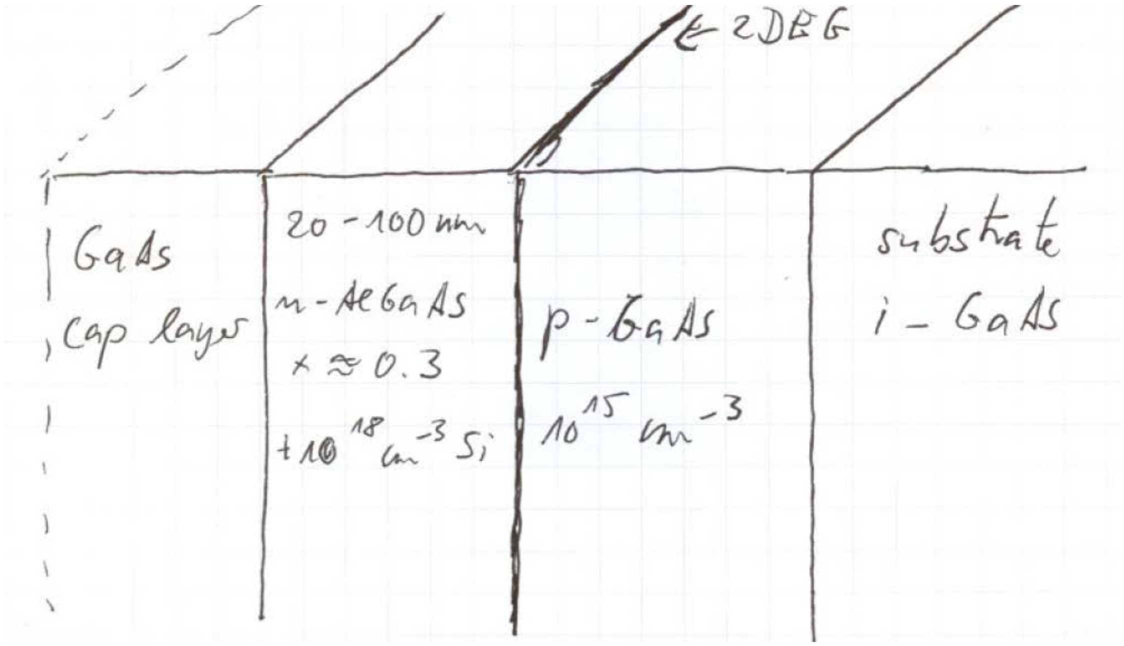


4.1 Two-dimensional Electron Gases (2DEG)

Semiconductor heterostructures

„Modulation doping“ Störmer et al, Nobel prize 1998

AlAs: Eg = 2.16 eV
Ga As: Ag = 1.424 eV, very similar lattice constant
AlxGa1-xAs: Eg variable, x < 0.4: direct Eg, x> 0.4 indirect Eg

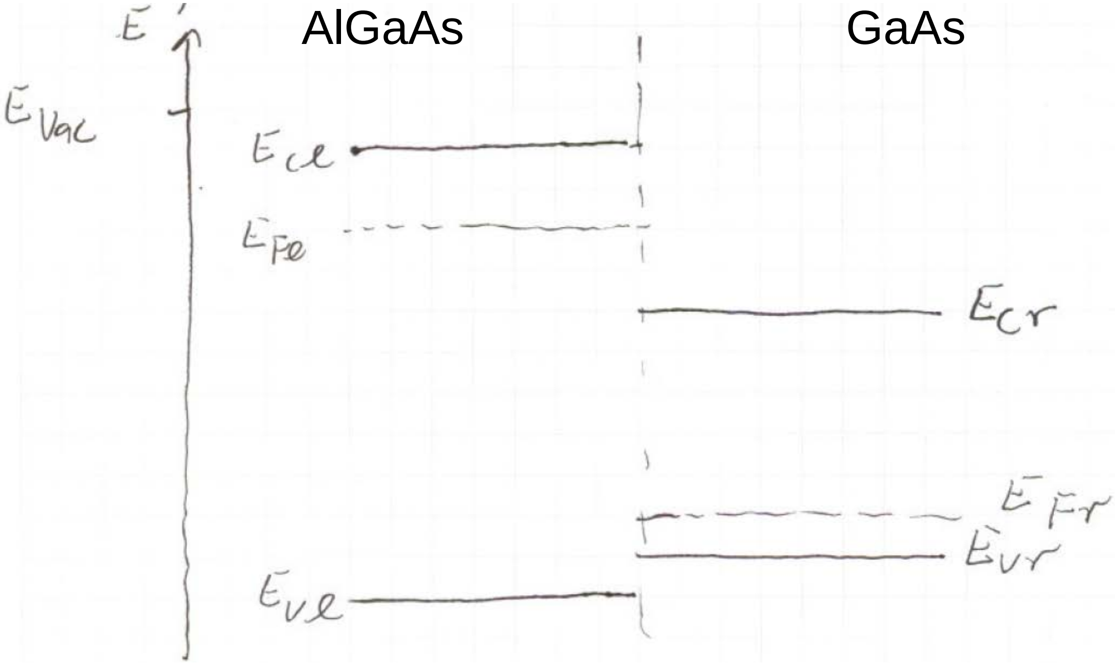


4.1 Two-dimensional Electron Gases (2DEG)

Semiconductor heterostructures

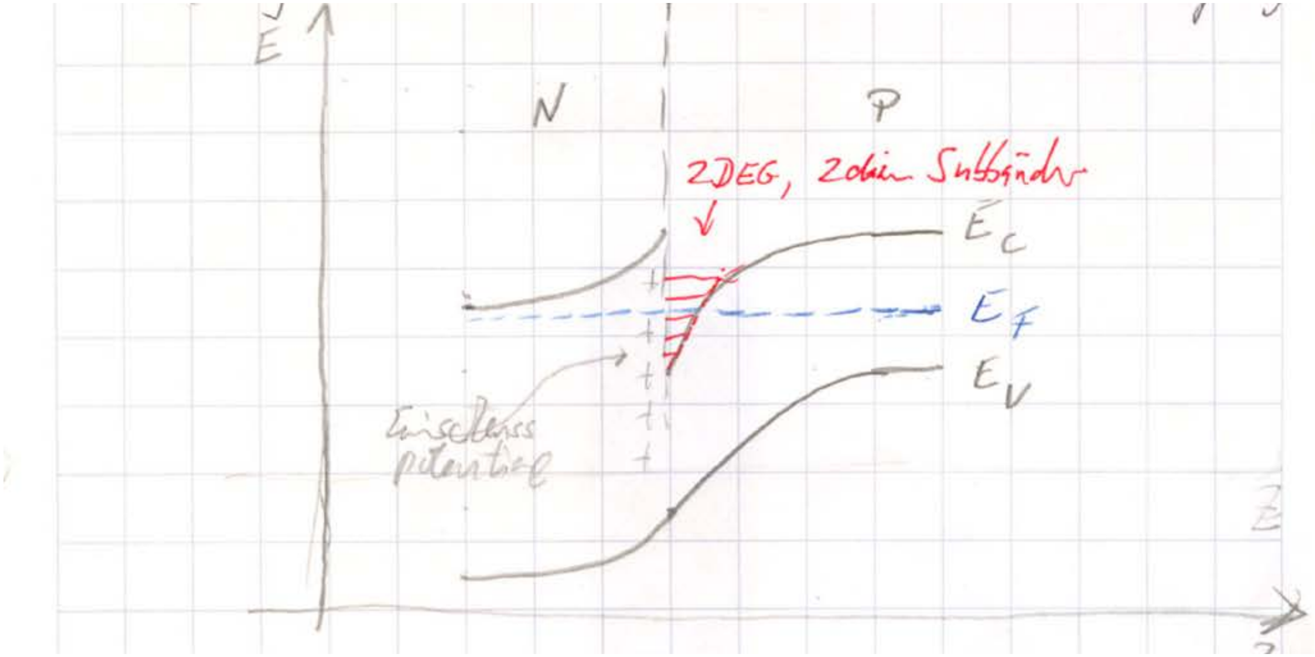
„Modulation doping“ Störmer et al, Nobel prize 1998

Schematic band diagram when layers are in contact, but no charge transfer occurred



4.1 Two-dimensional Electron Gases (2DEG)

$E_{Fl} > E_{Fr}$ and transparent interface:
-> Electron transfer from left to right
-> Positively charged donators are left behind
-> Space charge zone -> electrostat potential
-> band bending

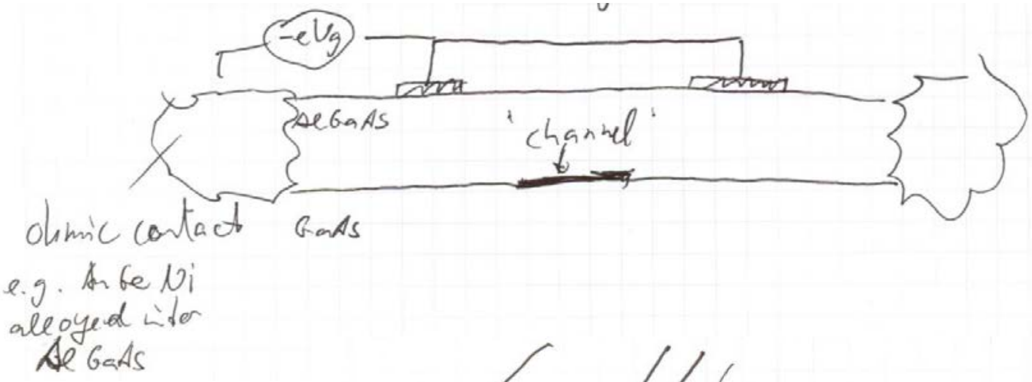


Main application: HEMT: High Electron Mobility Transistor
$\mu \sim 10^6 - 10^7$ cm²/Vs, $n = 10^{11}$ cm^{-2}
2DEG forms on the „clean side“ of the interface in the GaAs
-> few defects long elastic mean free path

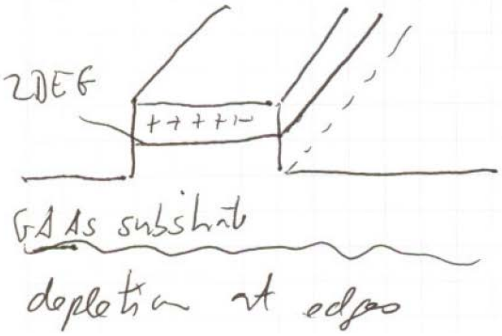
4.2 One-dimensional Electron Gases by Gates (Quantum wires)

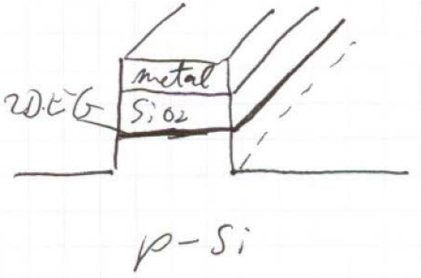
Gates at Si inversion layers: without V_g NO electrons in quantum well
-> gates necessary for creating the 2DEG
-> stripe-shaped gates: quasi-one-dimensional structures
Gates at heterostructures

- define conductive and non-conductve areas in the 2DEG
- without V_g 2DEG is filled with electrons
- negative V_g depletes electrons in 2DEG underneath – definition of channel



Other techniques:
etched channels





4.2 Other techniques for 1-dimensional electron systems

- Cleaved edge overgrowth: see script
- Carbon nanotubes: Chapter 5
- Atomic chains: Chapter 7
- Long molecules: Chapter 7

4.3 0-dimensional electron systems (quantum dots)

- Defined by gates onto 2DEGS
- Semiconductor nanoparticles, e.g. Cd Se
- Atomic clusters from gas phase
- Weakly coupled molecules: Chapter 87

Nanotechnology

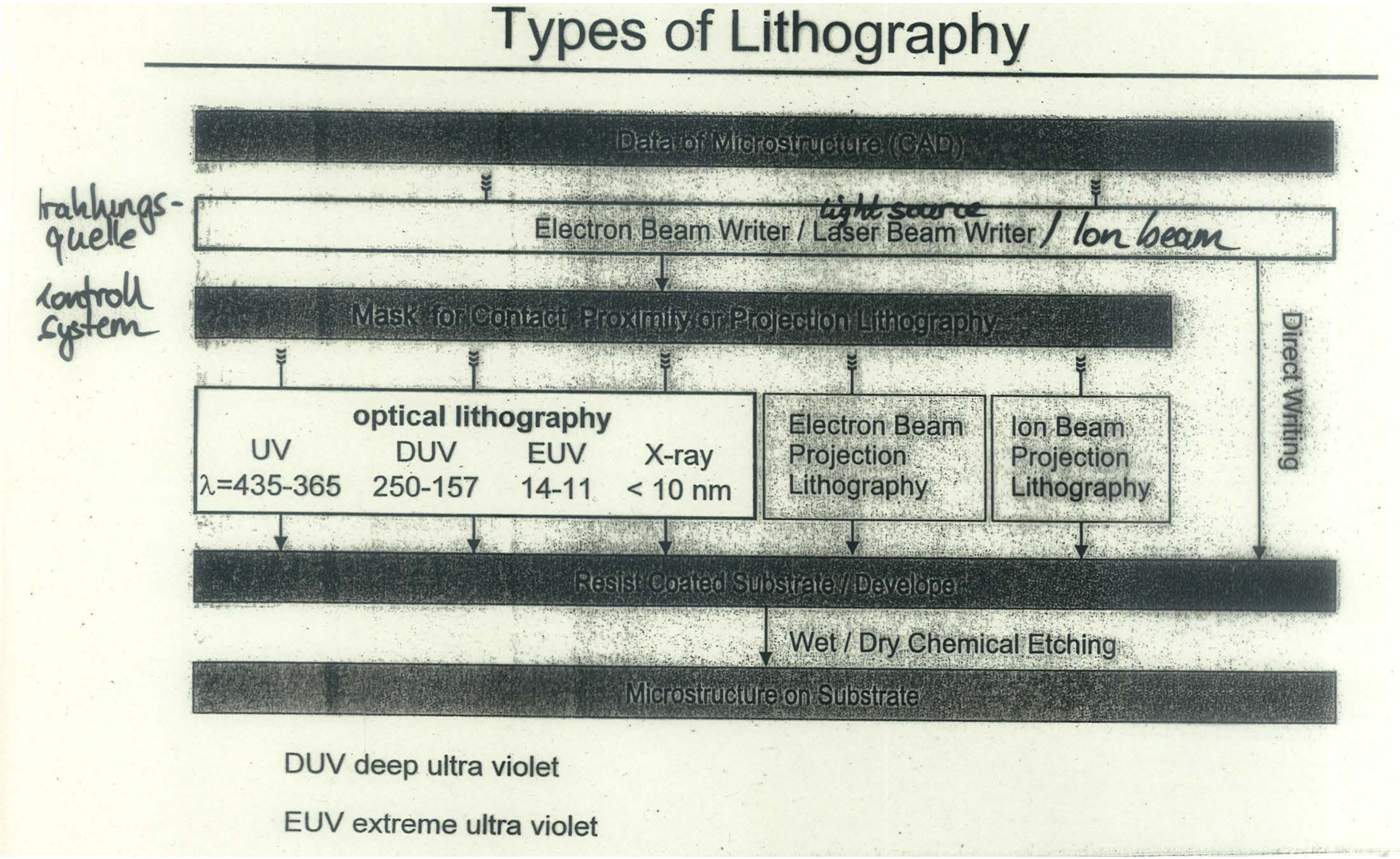
4.4 Lithography

4.5 Thin-film techniques
- Wet deposition techniques
- Vacuum techniques
- Thickness monitoring

4.4 Lithography

1. Overview over exposing techniques
2. Optical lithography
3. Electron Beam Lithography
4. Focussed ion beam (FIB)
5. Further processing: subtractive/additive/lift-off/shadow evaporation
6. Nano print techniqes: µCP/nCP, NIL, hot embossing

4.4.1 Overview



Types of Lithography

trahlungsquelle

controll system

Data of Microstructure (CAD)

light source

Electron Beam Writer / Laser Beam Writer / Ion beam

Mask for Contact, Proximity or Projection Lithography

optical lithography

UV	DUV	EUV	X-ray
λ=435-365	250-157	14-11	< 10 nm

Electron Beam Projection Lithography

Ion Beam Projection Lithography

Direct Writing

Resist Coated Substrate / Develope

Wet / Dry Chemical Etching

Microstructure on Substrate

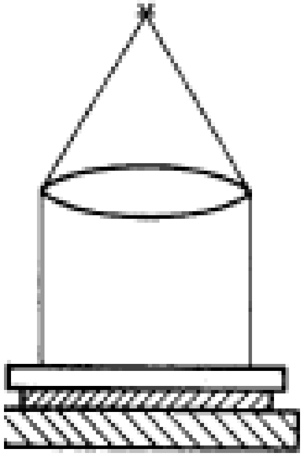
DUV deep ultra violet

EUV extreme ultra violet

4.4.2 Optical Lithography

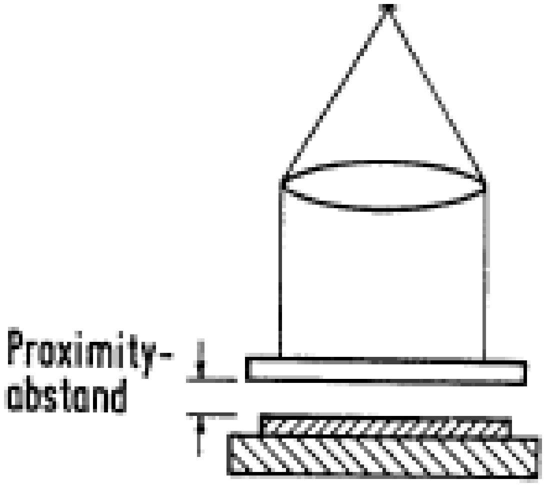
Schattenprojektion

Kontakt-Belichtung



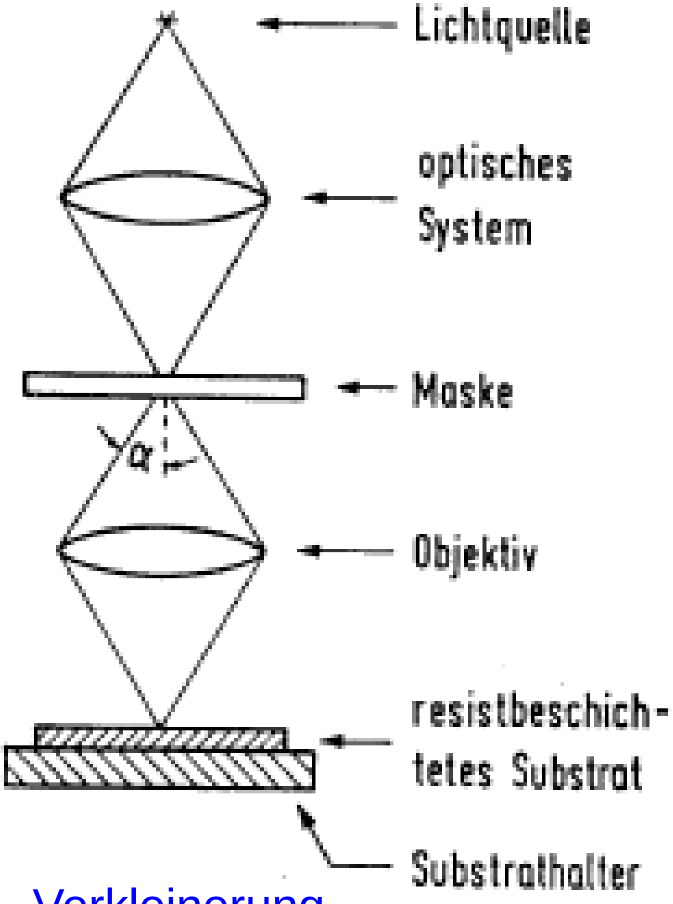
Beste Auflösung
Erfordert glattes Substrat
Starke Belastung der Maske

Proximity-Belichtung



Für Zuleitungen
(> 2 µm)

Abbildende Projektion



Verkleinerung
typischerweise 5:1

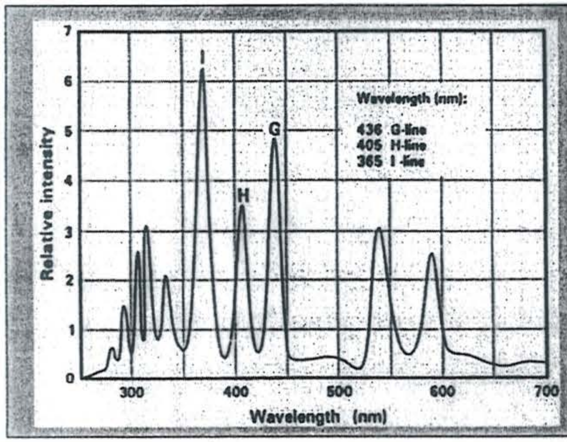
4.4.2 Optical Lithography

λ [nm]	Source	Range
436	Hg arc lamp	G-line
405	Hg arc lamp	H-line
365	Hg arc lamp	I-line
248	Hg/Xe arc lamp; KrF excimer laser	Deep UV (DUV)
193	ArF excimer laser	DUV
157	F_2 laser	Vacuum UV (VUV)
~10	Laser-produced plasma sources	Extreme UV (EUV)
~1	X-ray tube; synchrotron	X-ray

today

no transparent materials in this range, except ~ 13 nm

no optics



spectrum of high-pressure Hg lamp

Decay of excited halogen/noble-gas to the ground state,

electrically pumping of laser gas

4.4.2 Optical Lithography

- Verkleinerung der Maskenstruktur durch Objektiv
- abschnittsweise Projektion der Maske auf den Wafer

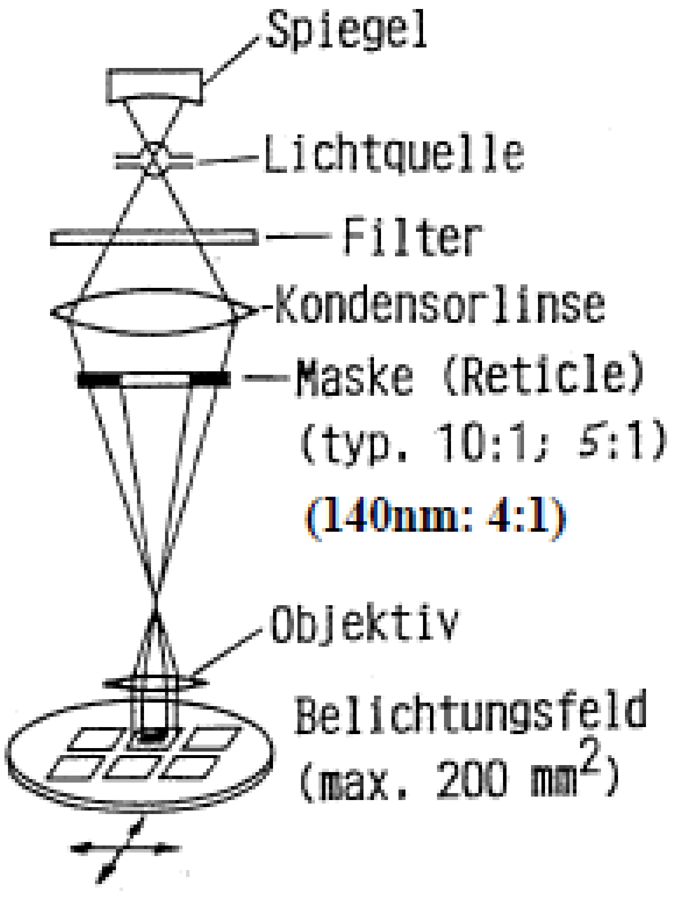
  → Maske enthält nur eine funktionelle Einheit z. B. einen Chip

  → „step and repeat"-Verfahren

- $b_{min} = 0.5 \cdot \lambda / NA$

  NA: numerische Apertur des Systems

- Tiefenschärfe $\Delta f = \lambda / NA^2$
- $\Delta f / b_{min} \sim 1 / NA$



verschiebbarer Probentisch
(step and repeat)

4.4.2 Optical Lithography

Abbildende Projektion

+ **Vorteile:**

- Vergrößerte Masken (Reticle) sind leichter herstellbar:
  → Bessere Kontrollierbarkeit.
  → Nur 1 Chip auf Maske: preiswertere Fertigung

- Einzelchipbelichtung ("Step and Repeat"):
  → Nichtlinearer Waferverzug ist korrigierbar

− **Nachteile:**

- Geräte sind sehr teuer (extrem korrigierte Optiken)
- Objektive haben NA < 0.6
- geringer Durchsatz → Justage für jeden einzelnen Chip
- Geringe Tiefenschärfe → geringes Aspektverhältnis

Status of EUV lithography

- First demonstration of wafer patterning with EUVL by IBM/AMD in 45nm node: 2008
- Expectation: market production > 2019 (in 16 nm node)

Problems with EUVL:

- Sufficiently strong light sources @ 13.5 nm difficult: xenon, plasma sources
- Strong absorption in air -> Vacuum Stepper
- Chromium is transparent: no absorbing material known -> Reflection optics (Bragg reflection Mo/Si)
- all possible mask materials with sufficient refractive and low absorption index are birefringent -> mirror optics
- Rayleigh scattering: surface smoothness important

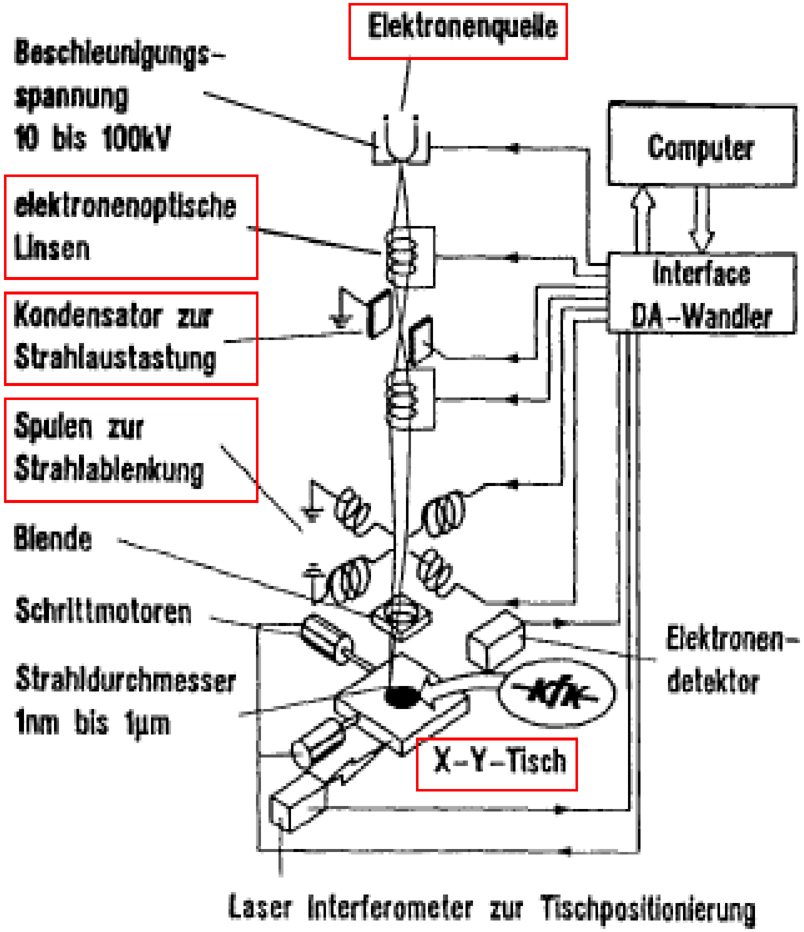
Source: Wikipedia

4.4.3 Electron beam lithography

Strukturierung von Resist mit Elektronenstrahlen (korpuskular-Strahlung)

- Resist: meist PMMA
- E-Strahlschreiber:
  → Vakuum
  → Strahlbreite < 2 nm,
  jedoch Streuung in Resist und Substrat
  → Strahlformen:
  „Gauß´scher Strahl" und „geformter Strahl"
  → ablenkbarer E-Strahl, keine Maske notwendig
  → serielles Verfahren, langsam

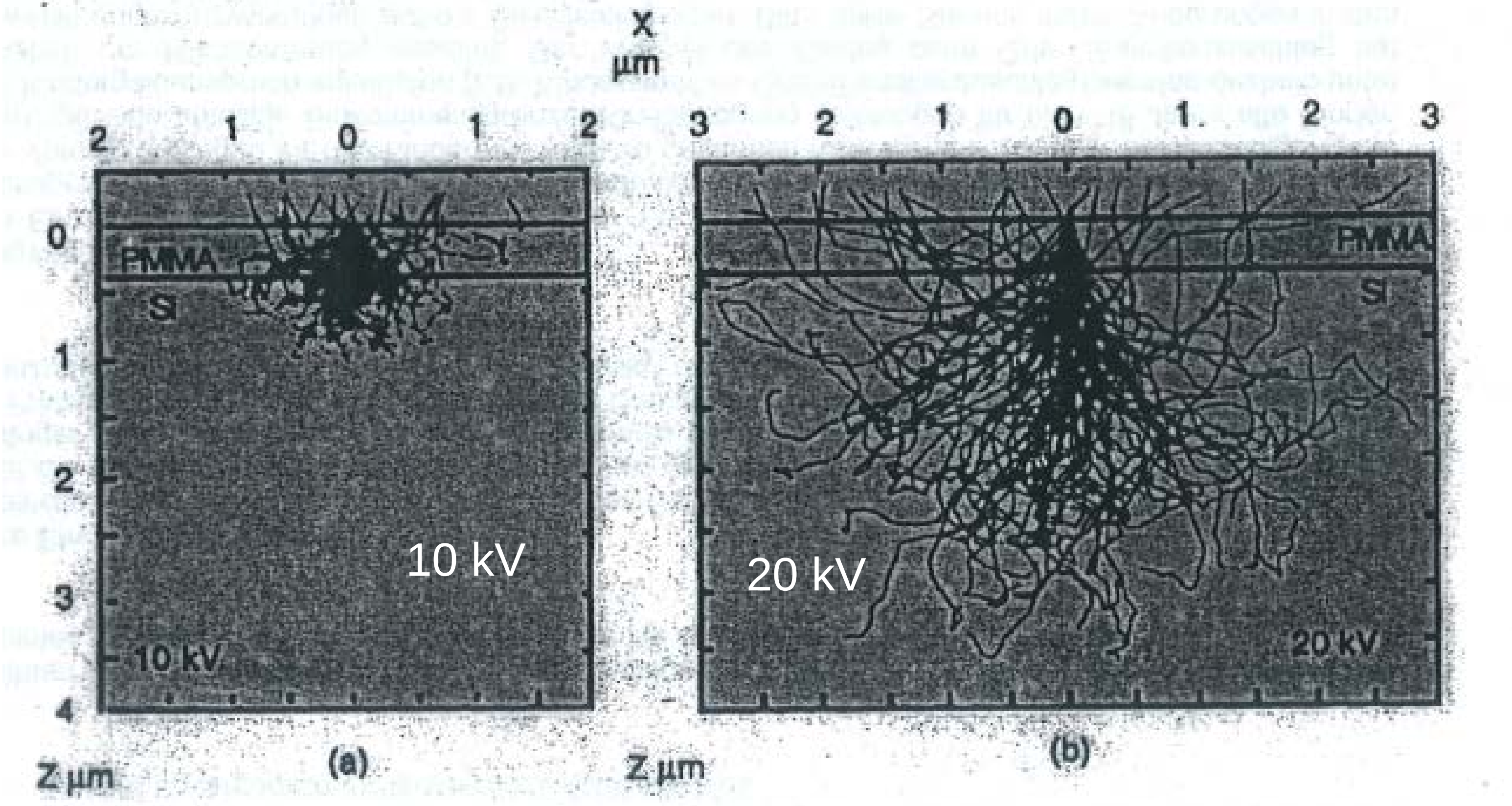
Anwendung: Maskenherstellung, Nanotechnologie



Resolution not limited by wavelength:
Old SEMS: beam diameter (Coulomb repulsion),
General: Resist, back scattering secondary electrons

Proximity Effect: Undesired exposure of neighboring areas due to beam profile

-> optimal dose depends on geometry and size of structure



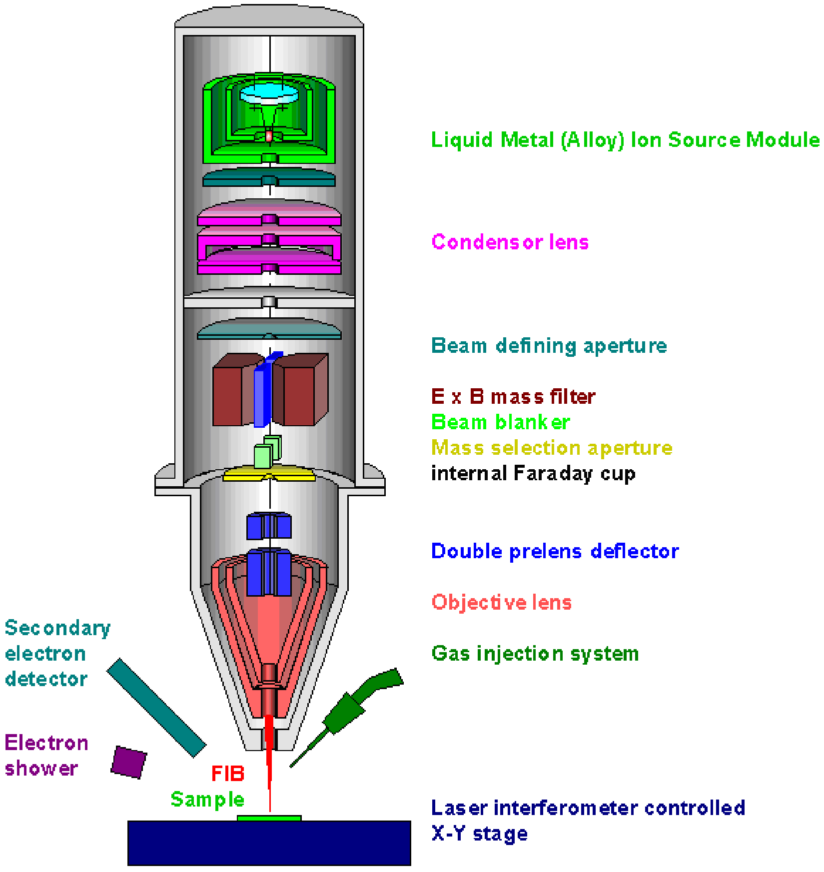
Modern pattern generators perform proximity corrections

4.4.4 Focussed Ion Beam (FIB)

- Similar to EBL (serial technique)
- Ion beam can remove material: etching
- Ion beam alters resists
- Ion beam can deposit material (with gas
-> gas injection system
- imaging by secondary electrons (alike SEM

Ion source: liquid metal (Ga)
Acceleration 10 kV
Electrostatic ion optics (Focussing)
Beam diameter 5-10 nm

Ion Optical Column
CANION 31Mplus



Sample contacting:
- in-situ tests
- heating
- cooling
- rotation

Quelle: HZDR

Pros:

- Stroing interactions -> small penetration depth
- Small Proximity Effect
- „Direct write“ w/o Resist possible

Cons:

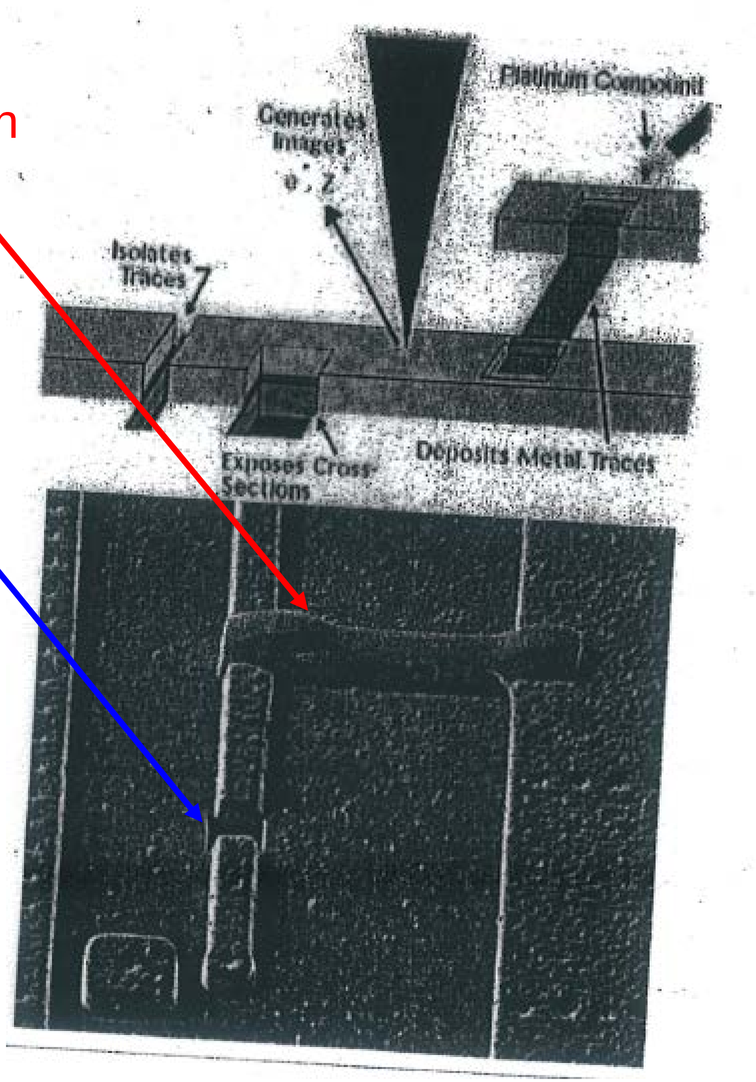
- slow
- Ga reactive -> formation chemical compounds
- Doping -> Alteration of electronic properties

Applications:

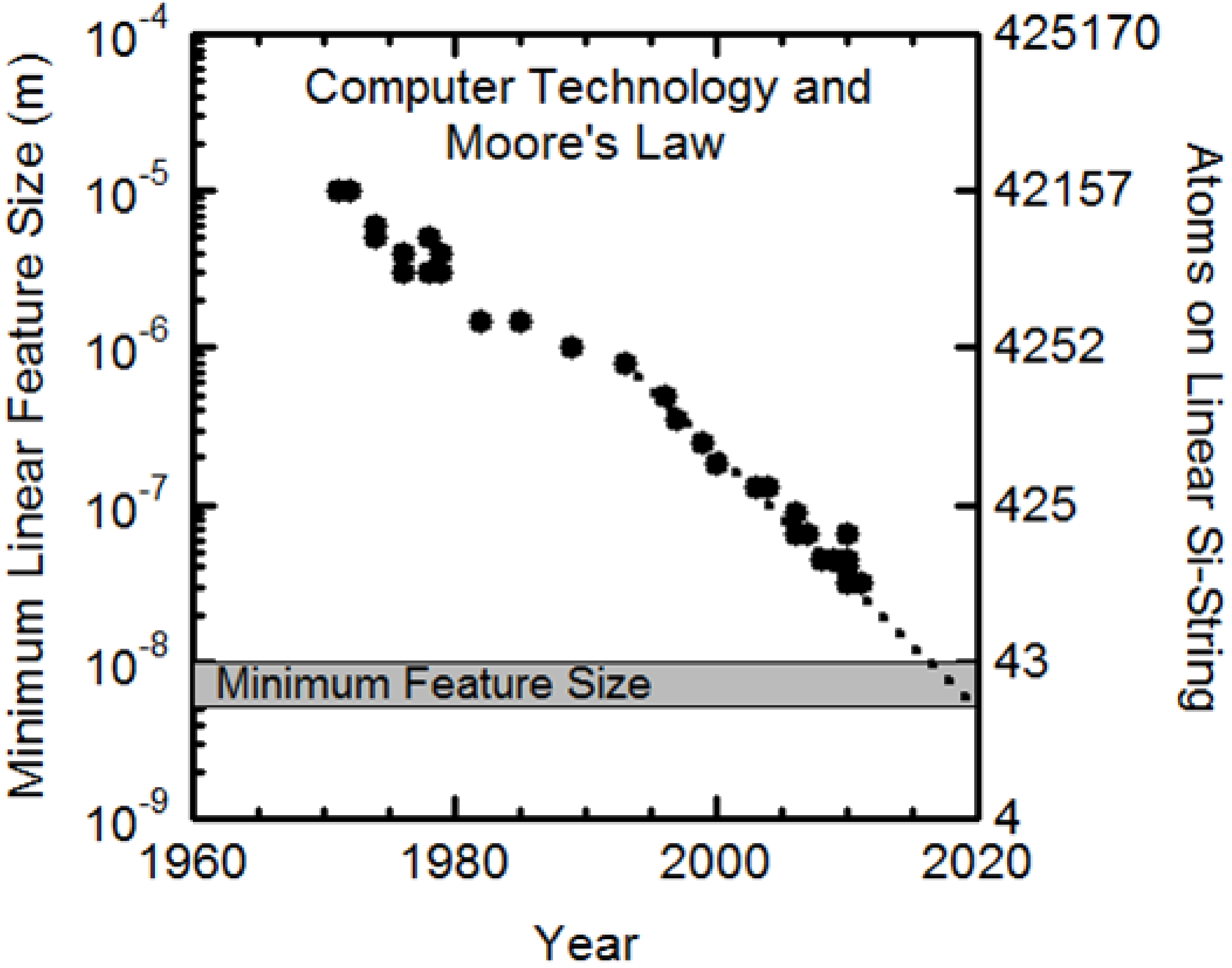
- Ionen Etching: 30 nm structure size @ 10 nm beam diameter
- Deposition with metal-organic gas (30-50 nm resolution)
  Problem: implemention of gas and Ga atoms
- Exposure of resists ≈ 20 nm resolution
- Reparating masks for Optical Lithography

FIB Examples

Etching and Deposition



Summary: What's next?



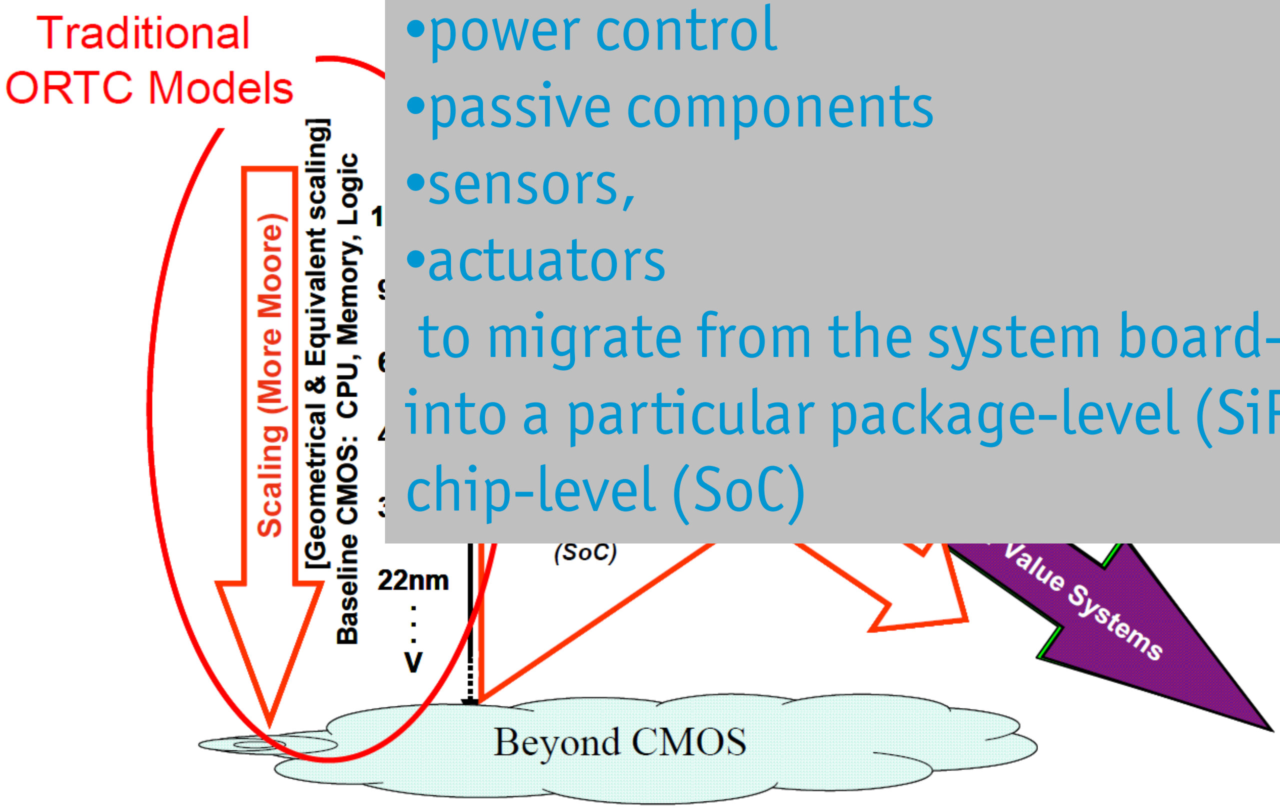
„More than Moore“

2011 white paper, MtM application:

Non-digital functionalities:

- RF communication
- power control
- passive components
- sensors,
- actuators

to migrate from the system board-level into a particular package-level (SiP) or chip-level (SoC)



ples for “Beyond
”

on-based nano-
ronics
-based devices
- ferromagnetic logic
- atomic switches
- nano-electro-mechanical-system (NEMS) switches

4.4.5 Further Processing/Pattern Transfer

Methods:

Wet Chemical Etching:

Mask protects sample areas not to be etched

- Mostly isotropic
- For some crystalline substrates anisotropic (e.g. Anisotropic etching of Si in KOH parallel to (111) crystal planes, see example next page)
- general problem: adhesion of mask might be insufficient -> limited precision of patterned geometry

Sputter cleaning:

- In non-reactive gas (Ar, N_2), similar to RF sputter deposition, but without target -> material removal, no deposition
- Removal by “bombardment“: very weak material selectivity
- Sputter rates slightly different because of varying hardness of materials
- mostly isotropic because of high gas pressure
- Application: cleaning between subsequent metal deposition steps
- Improvement of adhesion by surface roughening

Dry Etching methods

Plasma Etching (PE)/Plasma-Ätzen/Plasma-Veraschen:

- In reactive gas (O2)
- Etching of organic resists
- Material selective
- Isotropic (high pressure, and electric field distribution)
- Application: stripping of resists, masks, surface oxidation, activation of surfaces
- Cleaning

Reactive Ion Etching (RIE)/Reaktives Ionenätzen:

- Similar to PE but sample plate acts as RF electrode , low pressure

-> electric field distribution such that voltage drop between plasma (reactive species) and sample -> directed/anisotropic etching,

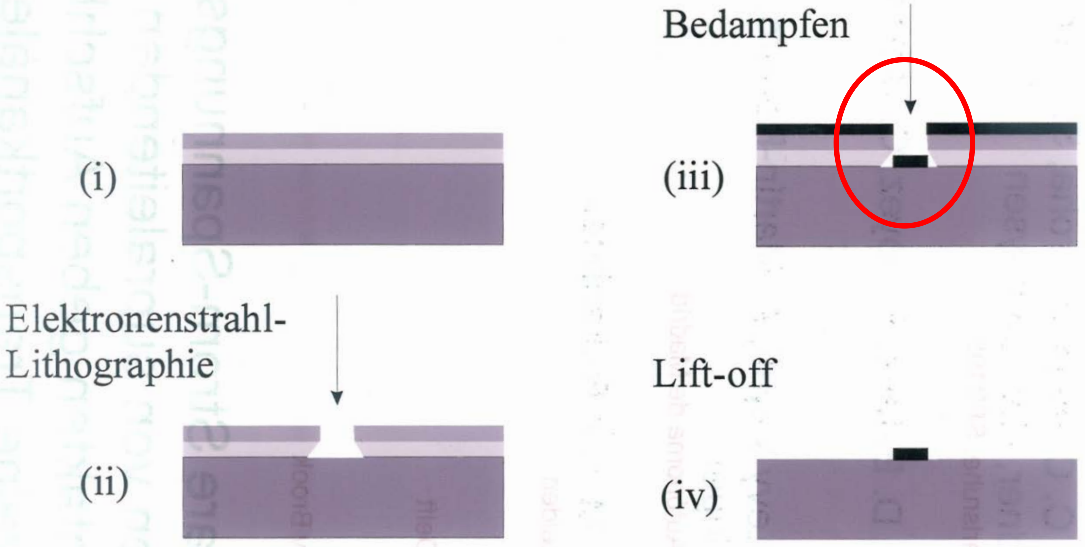
- Manifold gases: Fluoridic (SF6, CHF3, CF4), mainly for metal etching and Si
- Chloridic gases : GaAs and some metals
- Application: pattern transfer, e.g. trilevel lithography

4.4.5 Further Processing

Process types

1) Additive: deposition, lift-off process
2) Subtractive: Etching
3) Material modification

1) **Lift-off-Technik**



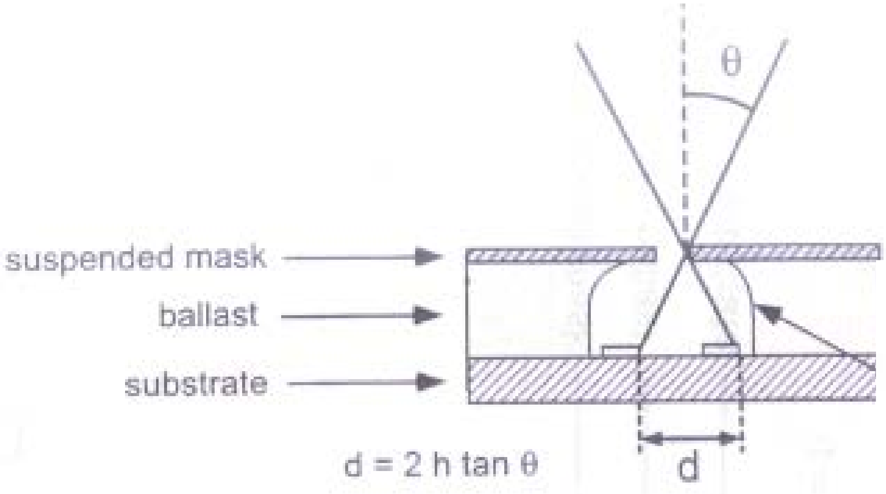
Strukturbreiten bis ca 40 nm

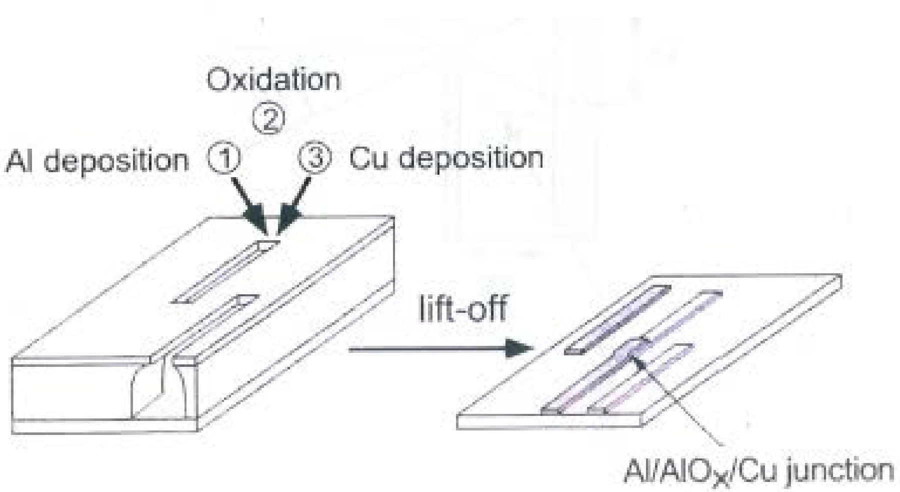
Important : Undercut

Can be adjusted by:
- Exposure dose
- Acceleration voltage
- Substrate
- Resistsystem (bilayer, trilevel)

4.4.5 Further Processing

Application of multilevel resists: Shadow evaporation





- Reduction of lateral structure size
- Subsequent evaporation of two or several metals without breaking vacuum
  -> Controlled, clean contacts between metals/parts of a device
- Contact area adjustable by evaporation angle
- Self-aligned patterning: two or more layers with one lithography mask: no complex alignment procedure necessary
- Drawback: limited versatility of sample design

Images Courtesy S. Gueron

4.4.5 Subtractive Postprocessing

Process for easy-to-etch material

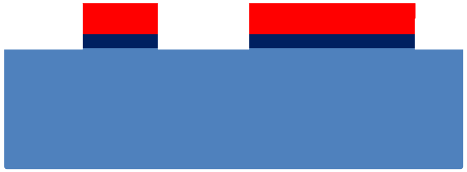
Dry etching (Reactive Ion Etching)

Wet etching

Resist

Metall, sacrificial layer, substrate surface

Substrate



After RIE

After stripping of resist
(O_2 plasma or wet)

Requirement:
Resist is more resistant than material to be etched

4.4.5 Subtractive Postprocessing

Process for etch-resistant material

Resist
Metall, sacrificial layer, substrate surface
Substrate

Deposition of mask material
(etch resistant)

After resist stripping

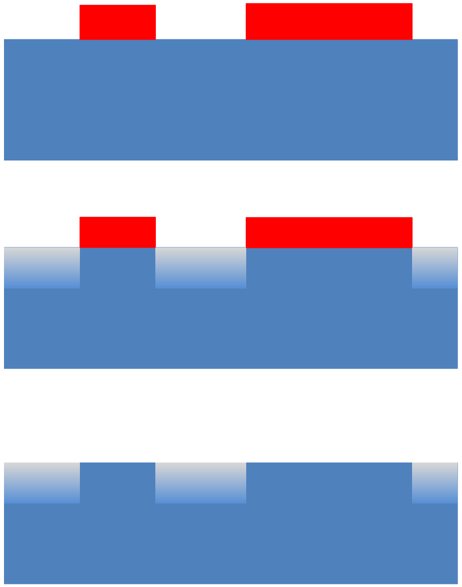
After RIE

Attention:
Pattern inversion

After mask removal
(wet or dry)

4.4.5 Material Modification

Example: Doping



After Ion implantation

After stripping of resist
(O_2 plasma or wet)

4.4.5 Material Modification

Example: Doping with trilevel resist for high impact dopants

Resist
Metal mask
Buffer resist
Substrate

After lithography (patterning of top resist)

After RIE of mask and resist stripping

After wet etching of buffer

After Ion implantation

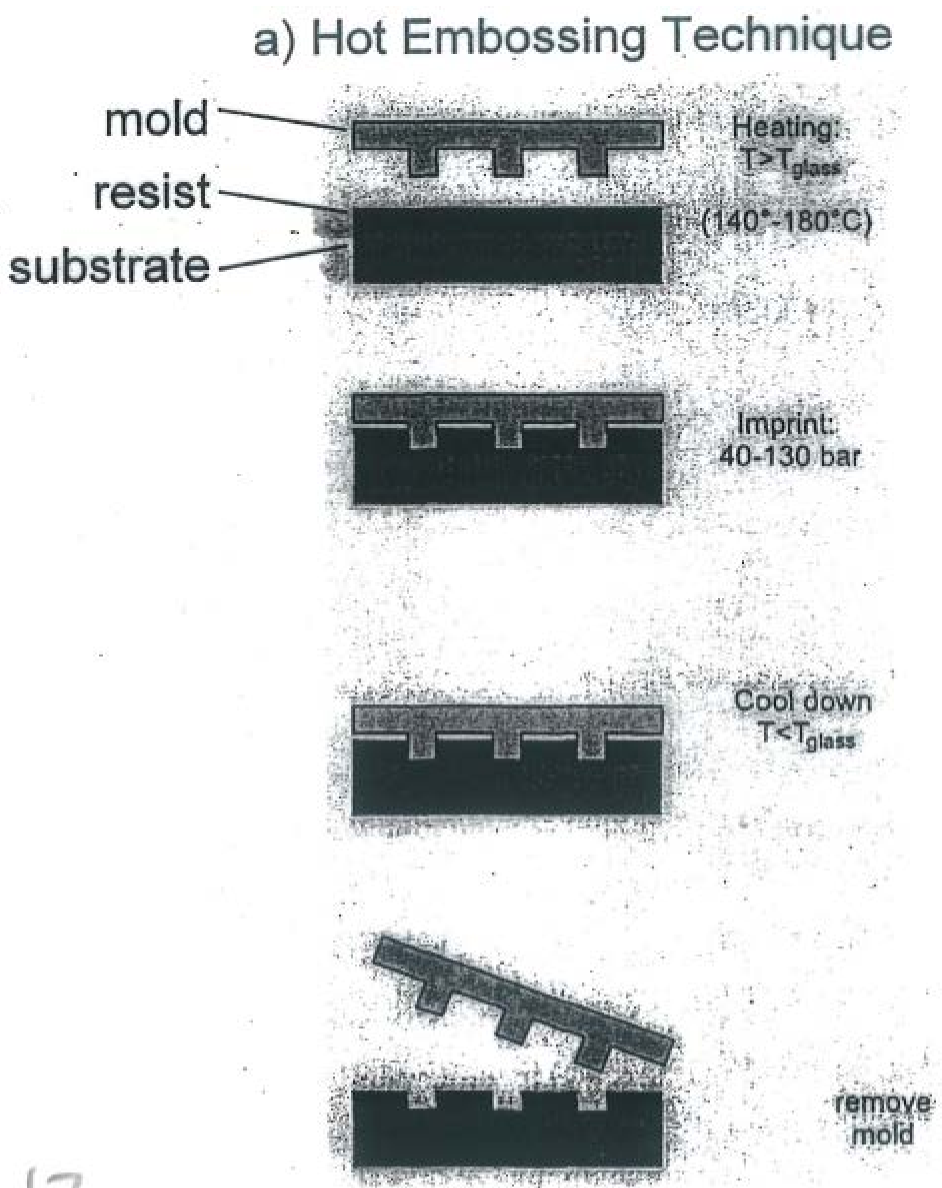
After stripping of buffer (O_2 plasma or wet)

4.4.6 Nano Print Techniques

a) Hot embossing / Heißprägen
b) Nanoimprint lithography (NIL)
c) Micro-/Nano contact printing

a) Hot Embossing

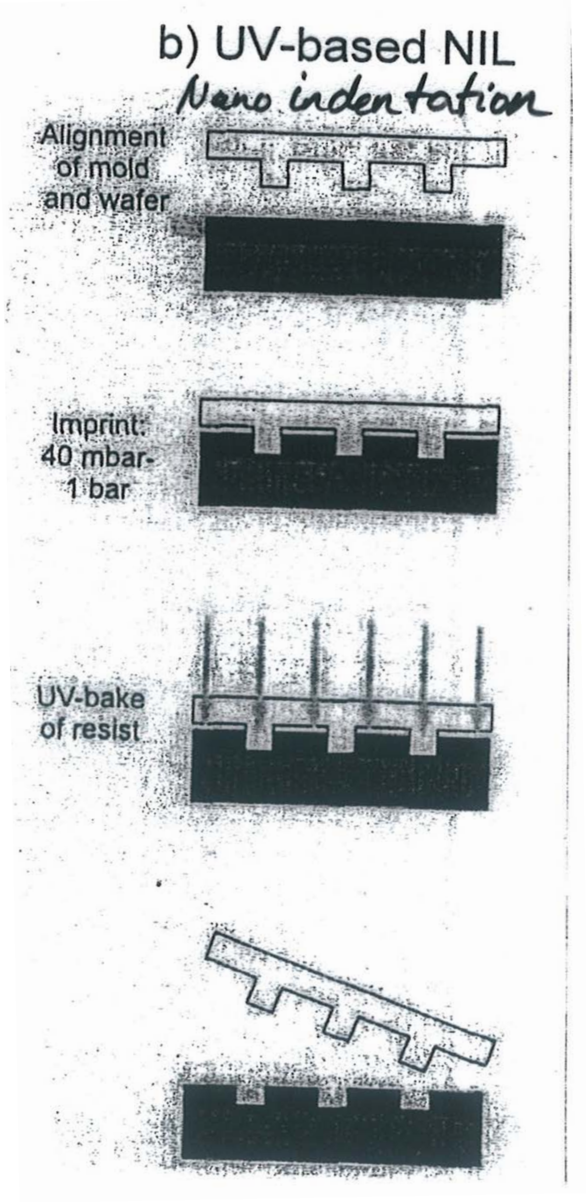
- Hard stamp/mold (Si oder SiO2 structured by EBL)
- Indentation into thermoplasti polymer: liquifies at elevated temperature & pressure
- Problems: thermal expansion/shrinking
- Further processing with other methods, e.g. RIE
- Lateral Resolution 10 nm holes
- 45 nm grooves



4.4.6 Nano Print Techniques

b) UV-based nanoimprint lithography / UV-Nanodruck-Lithographie (NIL) Alike a) but UV hardening of resist when in contact with sample

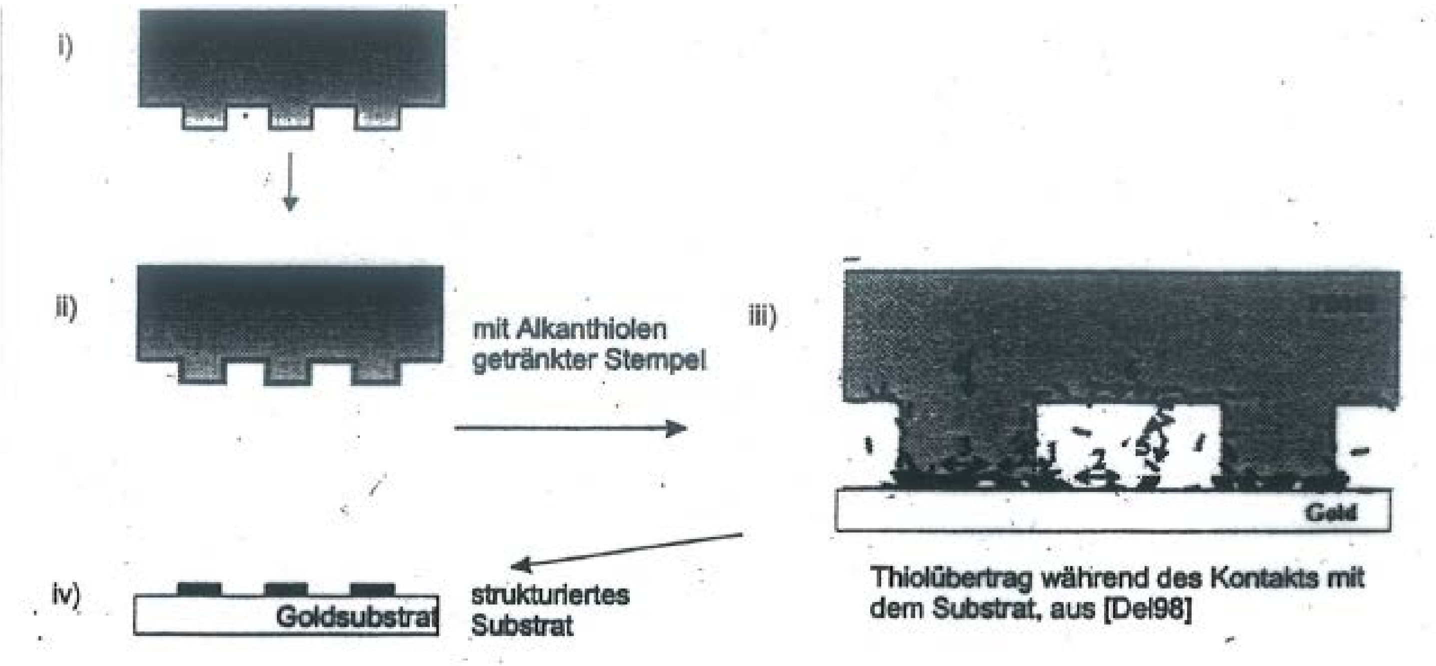
- Requires transparent mold
- Lower thermal impact of resist
- Less shrinking, more precise structure transfer



4.4.6 Nano Print Techniques

b) Micro-/Nanocontacts printing (µCP, nCP)

- Many variations
- Additive or subtractive
- Application in Molecular Electronics



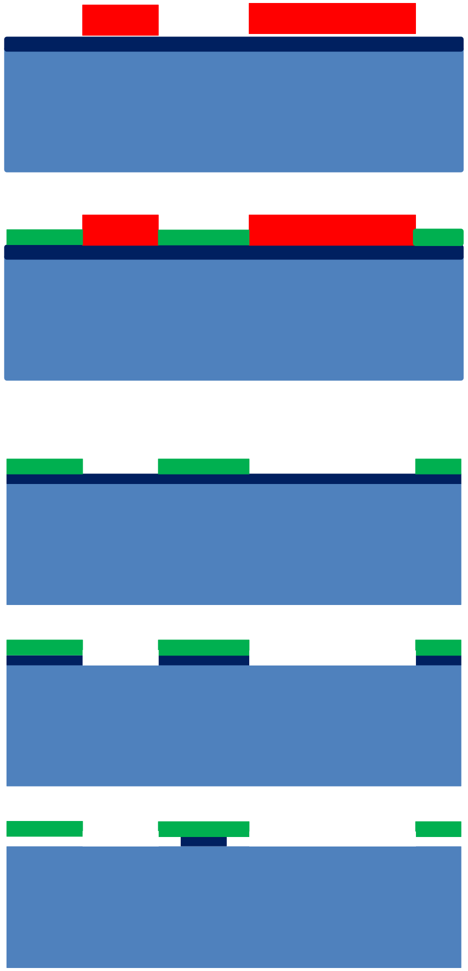
Further Patterning techniques

(a) 3D laser lithography
(b) Laser interference lithography
(c) Nano-ink techniques: dip-pen lithography
(d) Scanning probe techniques: STM, AFM, SNOM
(e) ……..

4.5 Thin film deposition techniques for electrodes

4.5.1 Electro deposition

- Here: for metals
- Also works on patterned surfaces (optional steps: grey)



a) - Deposition of seed layer (electrical conductive)
- Patterning with photo resist

b) - Electrical contacting
- Immersion in electrolyte: metal ions are reduced on seed layer surface e.g. $Cu^{2+} + 2e^{-} \rightarrow Cu$
- Film thickness controlled by charge (current x time)

c) Removal of photo resist (wet or dry etching)

d) Removal of seed layer

e) Special version: isotropic removal of seed layer
“sacrificial layer“ underneath film for defining suspended structures.
Application: mechanically controlled break junctions
LIGA process: Lithographie + Galvanisieren + Abformen

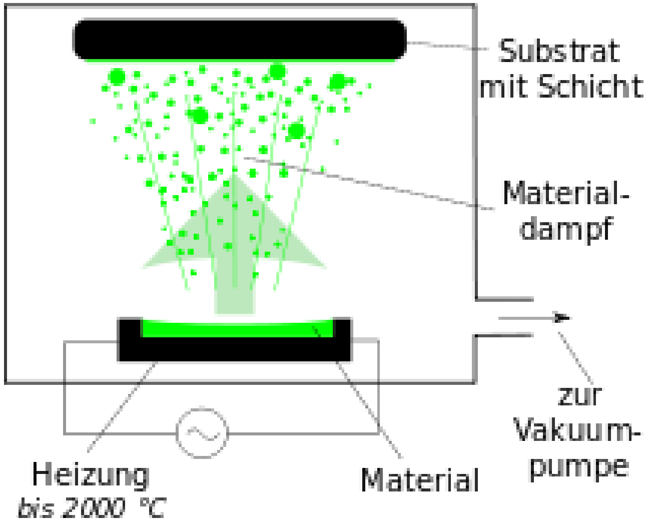
4.5.2 Vacuum generation

- Vacuum necessary for - directed deposition through masks
  - clean (low contamination) films
- Vacuum generated by pumping system consisting of several pumps
- Pump type chosen according to vacuum regime

Regime	Pressure hPa (mbar)	Molecule density cm^{-3}	Mean free path	Typical application/ realization
Ambient vacuum	1013.25	$2.7 \cdot 10^{19}$	68 nm	Average air pressure @ sea level
Rough vacuum	1013 - 1	10^{19} - 10^{16}	10 nm – 100 µm	Vacuum cleaner, vac. packaging
Fine vacuum (FV)	1 – 10^{-3}	10^{16} - 10^{13}	100 µm – 10 cm	Light bulbs, discharge tubes
High vacuum (HV)	10^{-3} – 10^{-7}	10^{13} - 10^{9}	10 cm – 1 km	Electron tubes
Ultrahochvakuum (UHV)	10^{-7} – 10^{-12}	10^{9} -10^{4}	1 – 10^{5} km	Aero space
Extreme high vacuum (XHV)	< 10^{-12}	< 10^{4}	> 10^{5} km	Free space, cryogenic vacuum

4.5.3 Thermal evaporation

- Heating metal to/above melting point (~ 1000 °C to 3500 °C)
- Condensation onto substrate and surfaces of vacuum chamber
- Main technique for metals, also in use for semiconductors, rarely for organic (molecular) materials, for alloys with restrictions (differences in vapor pressure results in distillation)
- Anisotropic (directed) deposition (ballistic motion)
- Clean films
- Pressure has to be lower than vapor pressure of metal
- Pressure ~ 10^{-6} hPa



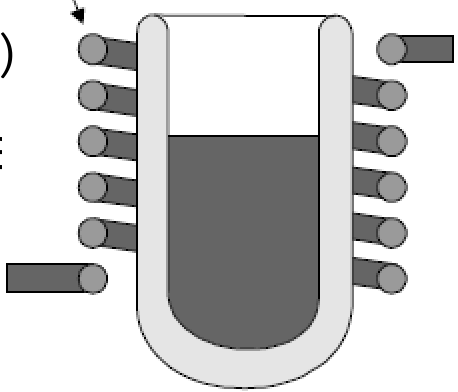
Evaporation sources

a) W, Mo or Ta boat (Schiffchen)
- typical thickness 100 µm width 5 mm, length, some mm to cm
- Heated by electrical current („Joule heating“)
- typical kinetic energy of evaporated particles: 0.1 eV

b) W spiral

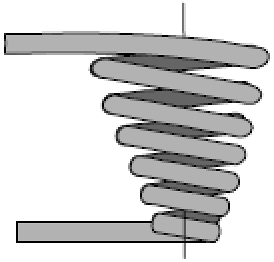
c) inductively heated BN crucible

c)



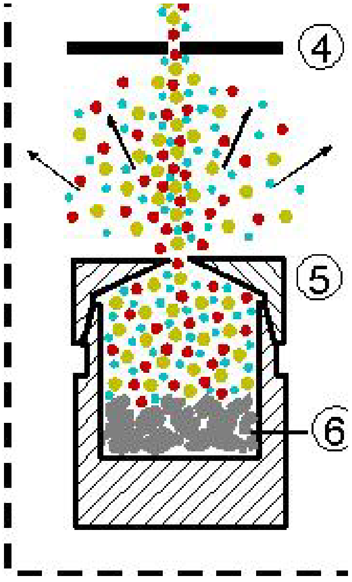
For all: - rate depends exponentially on temperature
-> difficult to control

b)



a)

Evaporation sources (continued)



d) Knudsen cell (Effusion cell)

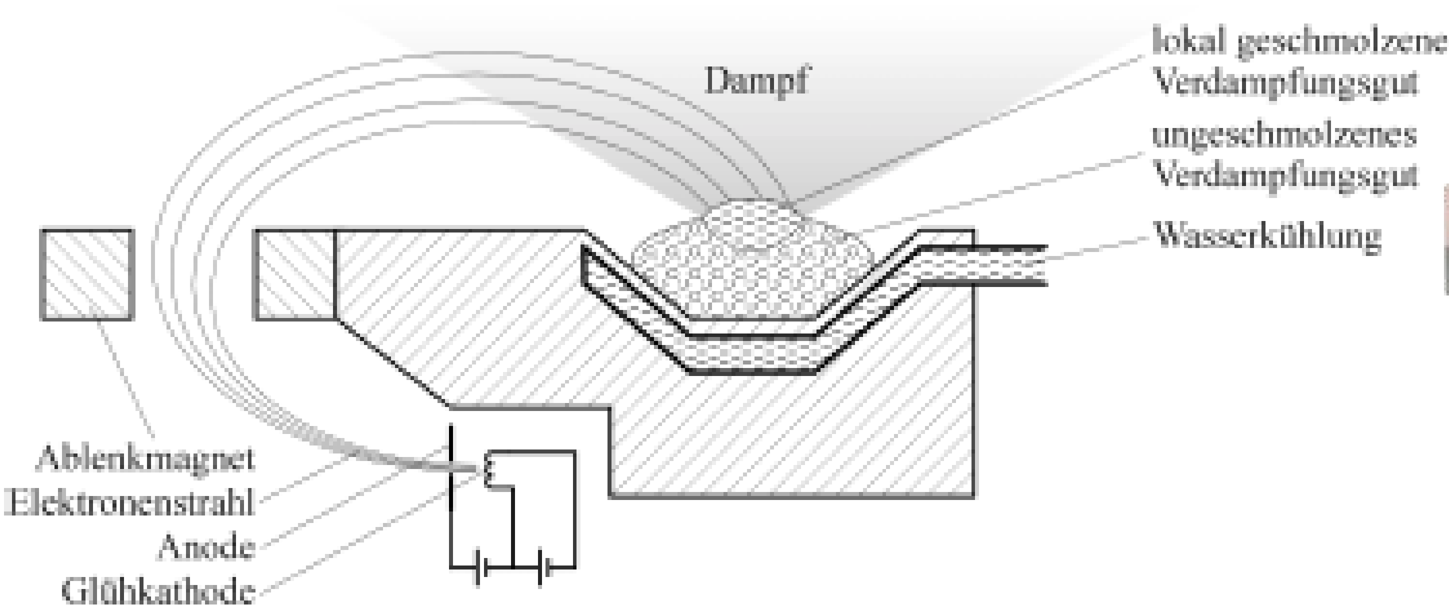
- crucible (Tiegel) surrounded by wire used for Joule heating
- cover (Deckel) with small bore with diameter < mfp -> ballistic motion of evaporated particles
- advantage: flux and angular distribution can be calculated exactly
- typical kinetic energy of evaporated particles: 0.1 eV – 1 eV
- Evaporation rate r: $r = \dfrac{pA_0\sqrt{N_A}}{\sqrt{2\pi m k_B T}}$

(m particle mass, A_0 bore surface,
p pressure, k_B Boltzmann constant
N_A Avogadro's constant, T temperature)

Evaporation sources (continued)

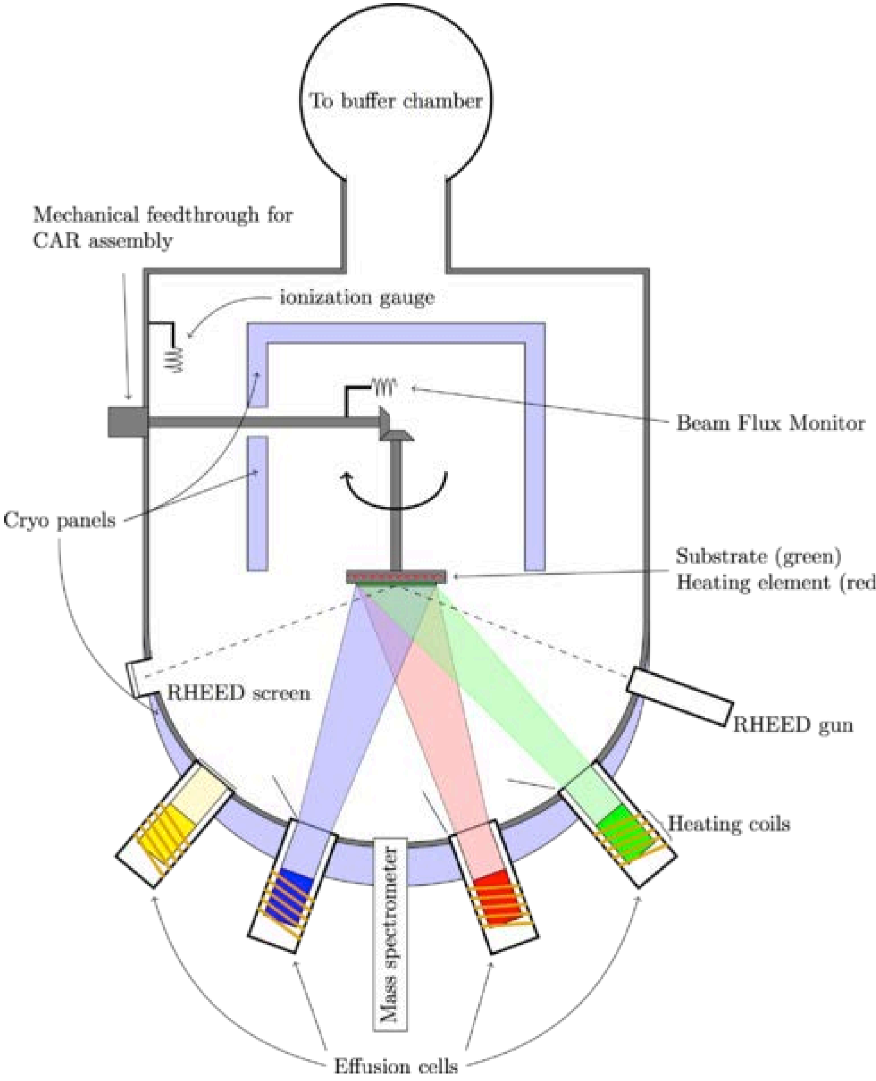
e) Electron gun (Elektronenstrahlverdampfer)

- heating by electron bombardment
- electrons emitted from glow filament (Glühwendel)
- acceleration in electric field (~ 10 keV)
- e-beam guided and focused by magnetic field onto metallic charge in a cooled copper crucible -> local melting -> better defined beam shape
- typical kinetic energy of evaporated particles: 0.1 to 1 eV



4.5.4 Molecular beam epitaxy (MBE)

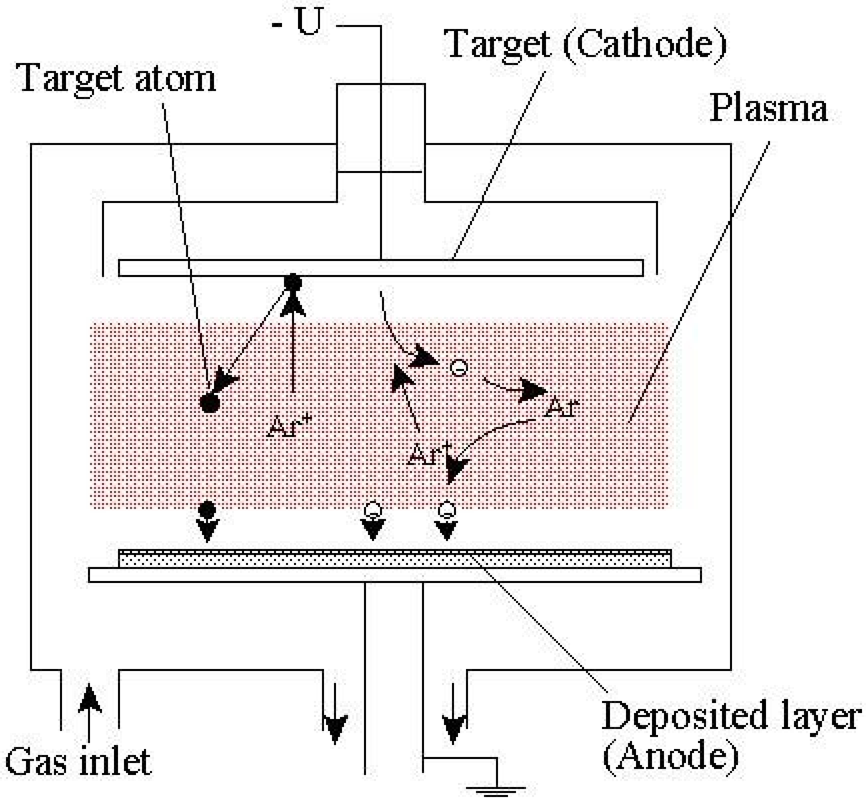
- Co-deposition from several sources with controlled rates for deposition of stoichiometric alloys (e.g. GaAs) or other high-quality films
- Graham's law: $\frac{r_1}{r_2} = \sqrt{\frac{m_2}{m_1}}$
- Rotating substrate for enhancing homogeneity
- Heatable substrate to ~ 500 – 800 °C for increasing surface diffusion (film quality)



4.5.6 Sputter deposition (Zerstäubungsbeschichtung)

a) DC-Sputtering (Gleichfeld)

- Carrier gas is ionized by high voltage (~10 kV)
  -> Plasma excitation
- Positive ions move to target and scatter particles (atoms) off the target
- Diffusion of particles to substrate -> deposition



Sputter process requires threshold ion energy of ~ 50 eV

4.1.7 Sputter deposition (Zerstäubungsbeschichtung)

b) Magnetron Sputtering

- Additional magnetic field -> screw motion

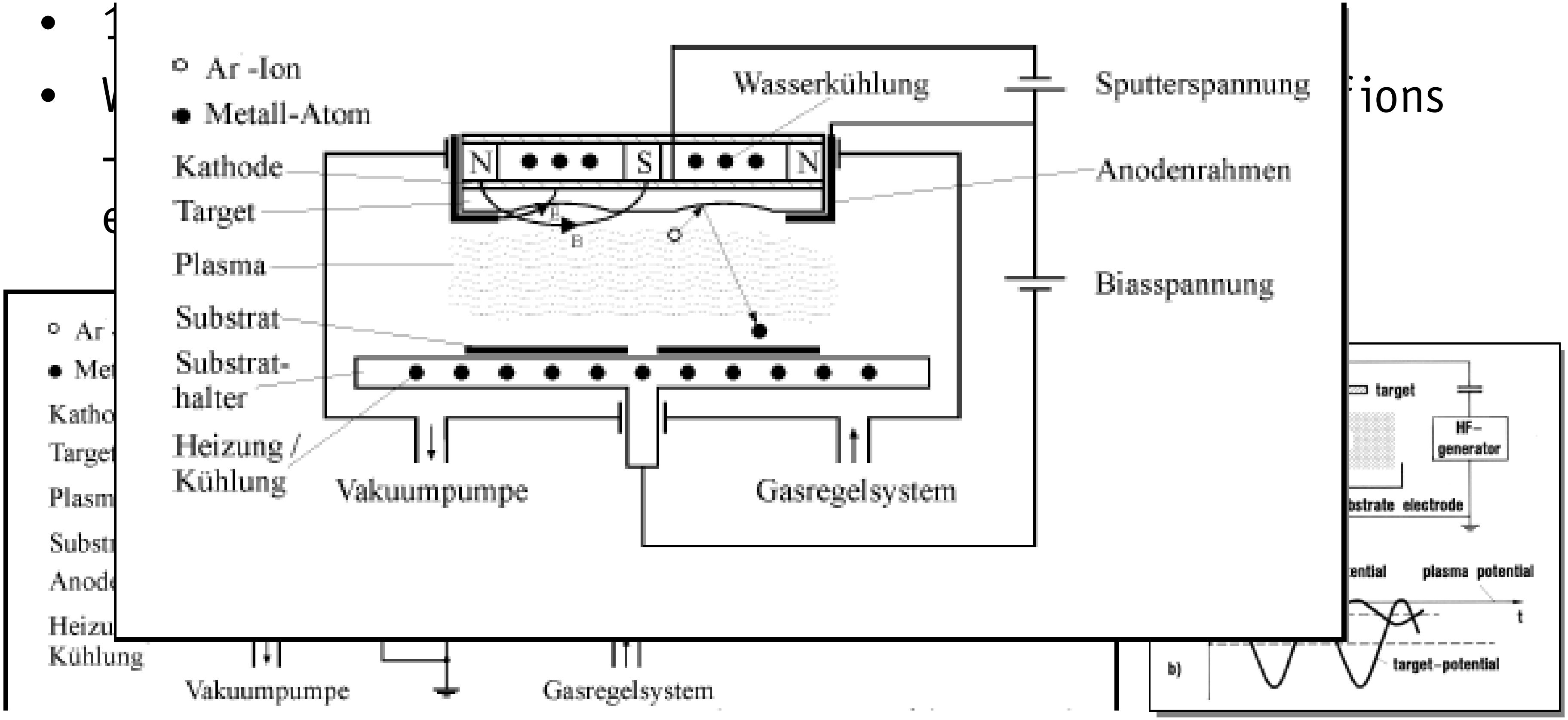
  -> more collisions, more ionization -> higher deposition rate

c) RF (Radio Frequency) sputtering

- 1
- W ions

  –

  e



4.1.7 Sputter deposition (Zerstäubungsbeschichtung)

- Typical kinetic energies of sputtered particles: 10-50 eV

-> indentation into substrate surface possible

-> increased adhesion possible

- Higher rates than thermal evaporation
- Isotropic deposition due to scattering with gas ions
- Lower purity due to incorporation of gas atoms

4.1.9 Thickness/Rate Monitoring

Quartz crystal micro balance (QCM, Quarzmikrowaage, Schwingquarz)

- Thin quartz plate excited to oscillate in resonance frequency f_R ~ 5 MHz (piezoelectric effect)
- Additional mass reduces f_R
- Density and acoustical impedance of deposited material have to be known to determine the thickness
- Resolution 0.01 nm – 0.1 nm

$$\Delta f = -\frac{2 f_0^2}{\sqrt{\rho_q \mu_q}} \frac{\Delta m}{A}$$