

“Nanotechnologie I“

Wintersemester 2017/2018

A. Nanoanalytik

1. Elektronenmikroskopie
 - 1.1 Einführung: Lichtmikroskopie vs. Elektronenmikroskopie
 - 1.2 Prinzipieller Aufbau eines Elektronenmikroskops
 - 1.2.1 Elektronenquellen
 - 1.2.2 Elektronenlinsen
 - 1.2.3 Detektoren
 - 1.3 Wechselwirkung des Elektronenstrahls mit Materie
 - 1.4 Rasterelektronenmikroskopie (SEM)
 - 1.4.1 Abbildung mittels Sekundärelektronen
 - 1.4.2 Abbildung mittels Rückstreuelektronen
 - 1.5 Transmissionselektronenmikroskopie (TEM)
 - 1.6 Weitere analytische Verfahren
2. Rastersondenmikroskopie
 - 2.1 Allgemeines
 - 2.2 Piezoelektrischer Effekt
 - 2.3 Raster-Tunnelmikroskopie
 - 2.3.1 Zur Quantenmechanik des Tunnelns
 - 2.3.2 Messmodi des RTM
 - 2.3.3 Manipulation mit dem RTM
 - 2.4 Rasterkraftmikroskopie
 - 2.4.1 Cantilever
 - 2.4.2 Relevante Kräfte zwischen Spitze und Probe
 - 2.4.3 Kontakt-Modus
 - 2.4.4 Dynamische Kraftmikroskopie
 - 2.5 Optische Nahfeld-Rastermikroskopie

B. Nanolithografie

3. Optische Lithografie
 - 3.1 Grundprinzipien, Belichten
 - 3.1.1 Maskaligning, Jusistierung
 - 3.1.2 Projektion
 - 3.1.3 Phasenschieberteknik
 - 3.1.4 Off-Axis-Beleuchtung
 - 3.1.5 optische Proximity-Korrektur
 - 3.2 Graustufen-Fotolithografie
 - 3.3 direktschreibende (maskenfreie) optische Lithografie

- 4. Fotolacke
 - 4.1 Charakteristische Eigenschaften und Beispiele
 - 4.1.1 Fotolacke für optische Lithografie
 - 4.1.2 Hochauflösende Fotolacke für Elektronenstrahlolithografie
 - 4.1.3 Fotolacke für Dickschicht-Lithografie
 - 4.2 Belackungstechniken
- 5. Ätzverfahren
 - 5.1 Nassätzverfahren
 - 5.1.1 Anisotropes Ätzen von Si
 - 5.1.2 Isotropes Ätzen von Si
 - 5.2 Trockenätzverfahren
 - 5.2.1 Plasma-Erzeugung
 - 5.2.2 Reaktortypen
 - 5.2.3 Grundlegende Methoden
 - (i) RIE
 - (ii) ICP-RIE
 - (iii) Ionensputtern
 - (iv) Reaktivgas-Ätzen
 - 5.2.4 Anwendungsbeispiele
 - (i) Ätzen von Si
 - (ii) Ätzen von Dielektrika
 - (iii) Ätzen von Metallen
 - (iv) Ätzen von Verbindungshalbleiter
 - (v) Fotoresist-Veraschung
 - (vi) Ätzen metall. Multilagen
 - (vii) Ätzen komplexer Oxid-Verbindungen
- 6. Abscheidetechniken
 - 6.1 Grundlagen des Aufdampfens
 - 6.1.1 Kinetik der Gasatome
 - 6.1.2 Filmwachstum
 - 6.1.3 Thermodynamik/Phasendiagramm
 - 6.2 Physikalische Abscheidetechniken
 - 6.2.1 Thermisches Verdampfen/MBE
 - 6.2.2 Pulsed Laser Deposition
 - 6.2.3 Sputtern
 - 6.3 Chemische Abscheidetechniken
 - 6.3.1 CVD
 - 6.3.2 CSD

Literatur zur Vorlesung ”Nanotechnologie I”

Zur Vorbereitung der Vorlesung wurde verwendet:

- Christian Colliex
Elektronenmikroskopie
Wissenschaftl. Verlagsgesellschaft Stuttgart 2008
ISBN 978-3-8047-2399-3
(Standort UB: nat 2.12, 2008 A 700e)
- Ian M. Watt
The principles and practice of electron microscopy
Cambridge University Press, 2nd edition 1997
ISBN 0-521-43456-4
(Standort FBP: nat 2.12, 98 E 86 (2))
- E. Meyer, H. J. Hug, R. Bennewitz
Scanning Probe Microscopy
Springer Heidelberg 2004
ISBN 3-540-43180-2
(Standort UB: nat 1.12, 2004 A 15016)
- Zheng Cui
Micro-Nanofabrication
Springer/Higher Education Press 2005
ISBN 7-04-017663-7
(Standort UB: nach 8.23, 2007 A 447)
- Rainer Waser (Ed.)
Nanoelectronics and Information Technology
2th edition, John Wiley & Sons Ltd 2005
ISBN 3-527-40363-9 (Standort UB: nach 8.20, 2003 E 201(2)f)
oder 3th edition, John Wiley & Sons Ltd 2012 (Standort UB: nach 8.20, 2003 E 201(3))

Das in der Vorlesung verwendete Bildmaterial wurde im Wesentlichen diesen Büchern entnommen und steht daher unter Copyright.

Weiterführende Literatur:

- Harry J. Levinson
Principles of Lithography
SPIE Press 2001, ISBN 0-8194-4045-0 (Standort PI Bibliothek: 10 Lev Pi)
oder SPIE Press 2010, ISBN 978-0-8194-8324-9
(Standort KIT-Bibliothek Nord: nach 8.23, 2001 E 643(3))
- Ludwig Reimer
Scanning Electron Microscopy
Springer-Verlag 1998
ISBN 3-540-63976-4
(Standort UB: phys 4.8, 86 A 202(2))

Modul: Nanotechnologie I

Lehrveranstaltungsnummer: 4021041

Modulverantwortliche: Gernot Goll

Einordnung in Studiengang: Master Physik, Themenfeld/er:
Kondensierte Materie, Nano-Physik

Level: Master (4)

Leistungspunkte: 4

Semesterwochenstunden: 2

Arbeitsaufwand: 120 Stunden bestehend aus Präsenzzeiten (30), Nachbereitung der Vorlesung inkl. Prüfungsvorbereitung. (90)

Modulturnus: WS

Moduldauer: Ein Semester

Lehr- und Lernformen:

4021041 Vorlesung 2 SWS; G Goll

Voraussetzungen: keine

Bedingungen: keine

Empfehlungen: Grundlagenkenntnisse der Festkörperphysik und der Quantenmechanik werden erwartet.

Qualifikationsziele:

Der Studierende vertieft sein Wissen auf einem Gebiet der Nano-Physik, beherrscht die relevanten theoretischen Konzepte und ist mit grundlegenden Techniken und Messmethoden der Nano-Analytik und der Lithographie vertraut.

Inhalt:

Einführung in zentrale Gebiete der Nanotechnologie:

Der Studierende vertieft sein Wissen auf einem Gebiet der Nano-Physik, beherrscht die relevanten theoretischen Konzepte und ist mit grundlegenden Techniken und Messmethoden der Nano-Analytik und der Lithographie vertraut.

Inhalt:

Einführung in zentrale Gebiete der Nanotechnologie;

Vermittlung der konzeptionellen, theoretischen und insbesondere methodischen Grundlagen:

1. Methoden der Abbildung und Charakterisierung (Nanoanalytik)

Grundlegende Konzepte der Elektronenmikroskopie und der damit verbundenen analytischen Möglichkeiten werden einführend behandelt. Rastersondenverfahren wie die Tunnel- und die Kraftmikroskopie zur Untersuchung und Abbildung leitfähiger bzw. isolierender Probenoberflächen werden diskutiert. Ergänzend werden spektroskopische Möglichkeiten der Rastersondenverfahren erläutert.

2. Methoden der Herstellung von Nanostrukturen (Lithographie und Selbstorganisation)

Entlang der einzelnen Prozessschritte von der Belackung über die Belichtung bis hin zur Strukturübertragung durch Ätzen und Bedampfen werden die eingesetzten Methoden erläutert, deren Einsatzgrenzen diskutiert und aktuelle Entwicklungen aufgezeigt.

Die Vorlesung „Nanotechnologie II“ behandelt im Sommersemester Anwendungsgebiete und aktuelle Forschungsthemen.

Literatur:

Zur Nachbereitung und Vertiefung des Vorlesungsstoffes wird auf verschiedene Lehrbücher sowie Original- und Übersichtsartikel verwiesen. Eine ausführliche Liste wird in der Vorlesung genannt.

Leistungsnachweis:

Je nach Teilnehmerzahl in Form einer Klausur, eines Referates oder einer mündlichen Einzelprüfung.

Notenbildung:

Entsprechend den Regeln der Prüfungsordnung und des Studienplans je nach Verwendung als Schwerpunkt-, Ergänzungs- oder Nebenfach.

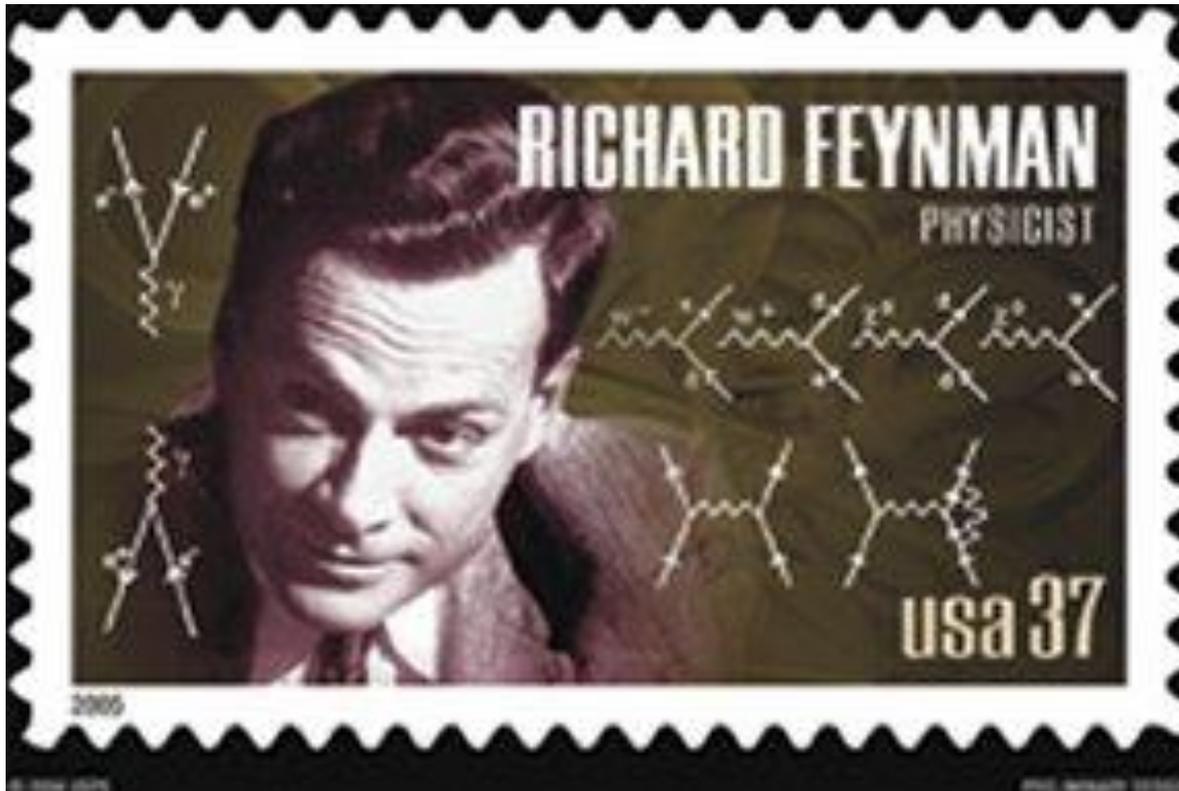
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Zugangspasswort: Nano1WS

Feynman's 1959

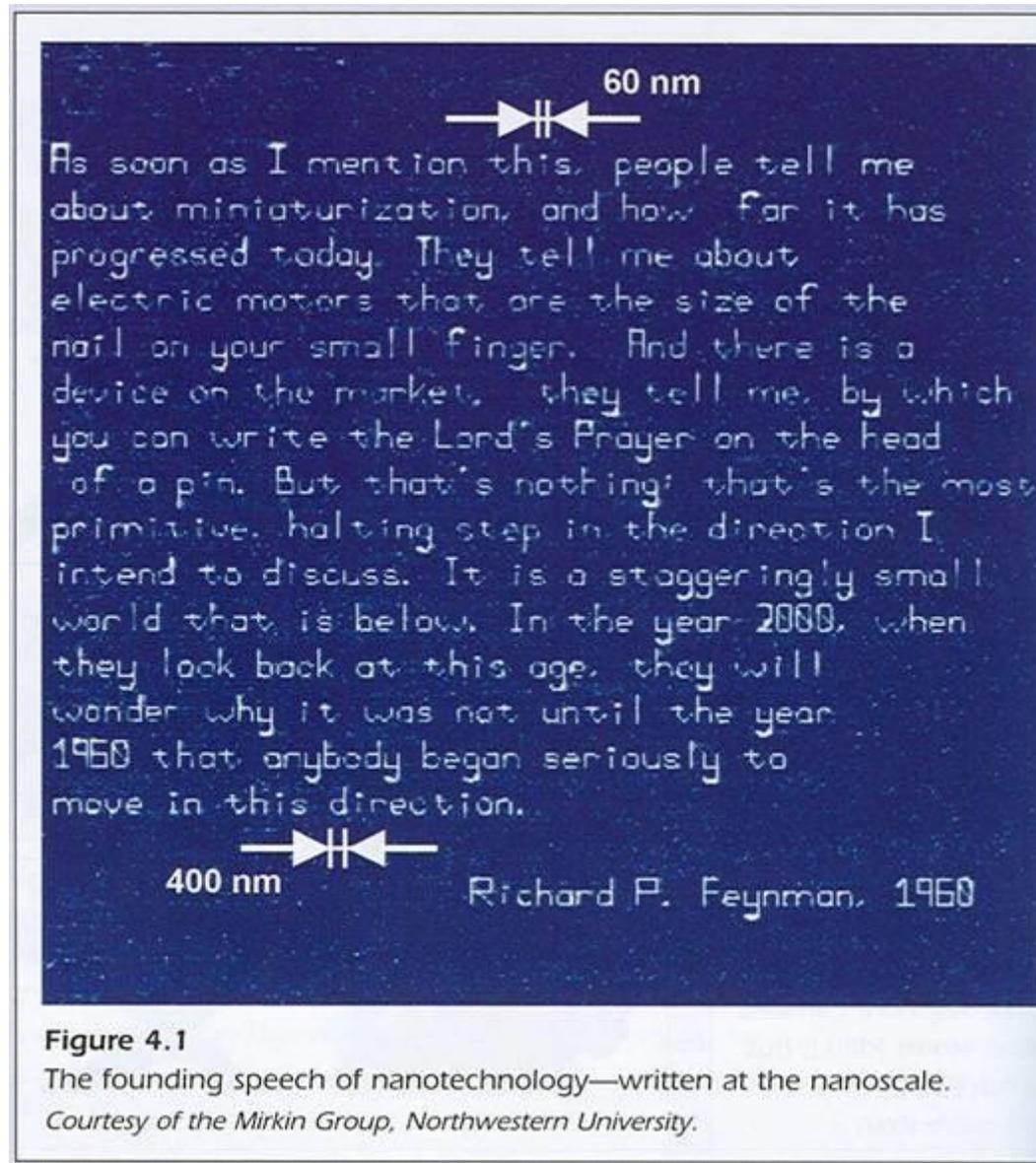
“There's Plenty of Room at the bottom”.

<http://www.zyvex.com/nanotech/feynman.html>



aus "Nanotechnology", Ratner and Ratner.

hergestellt durch dip-pen Nanolithographie und dargestellt durch ein AFM



Micro- und Nanoprocessing Technologies

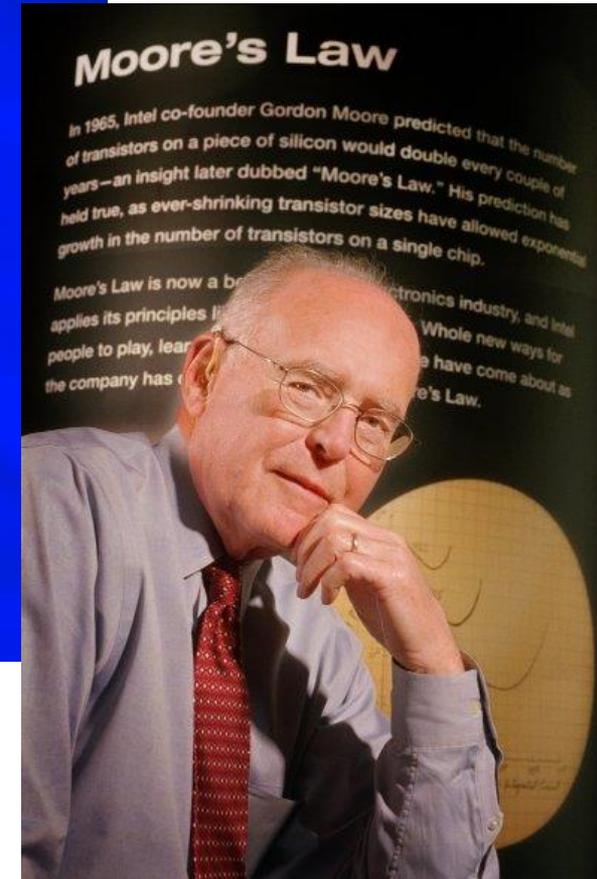
A New Process Every 2 Years

Intel.

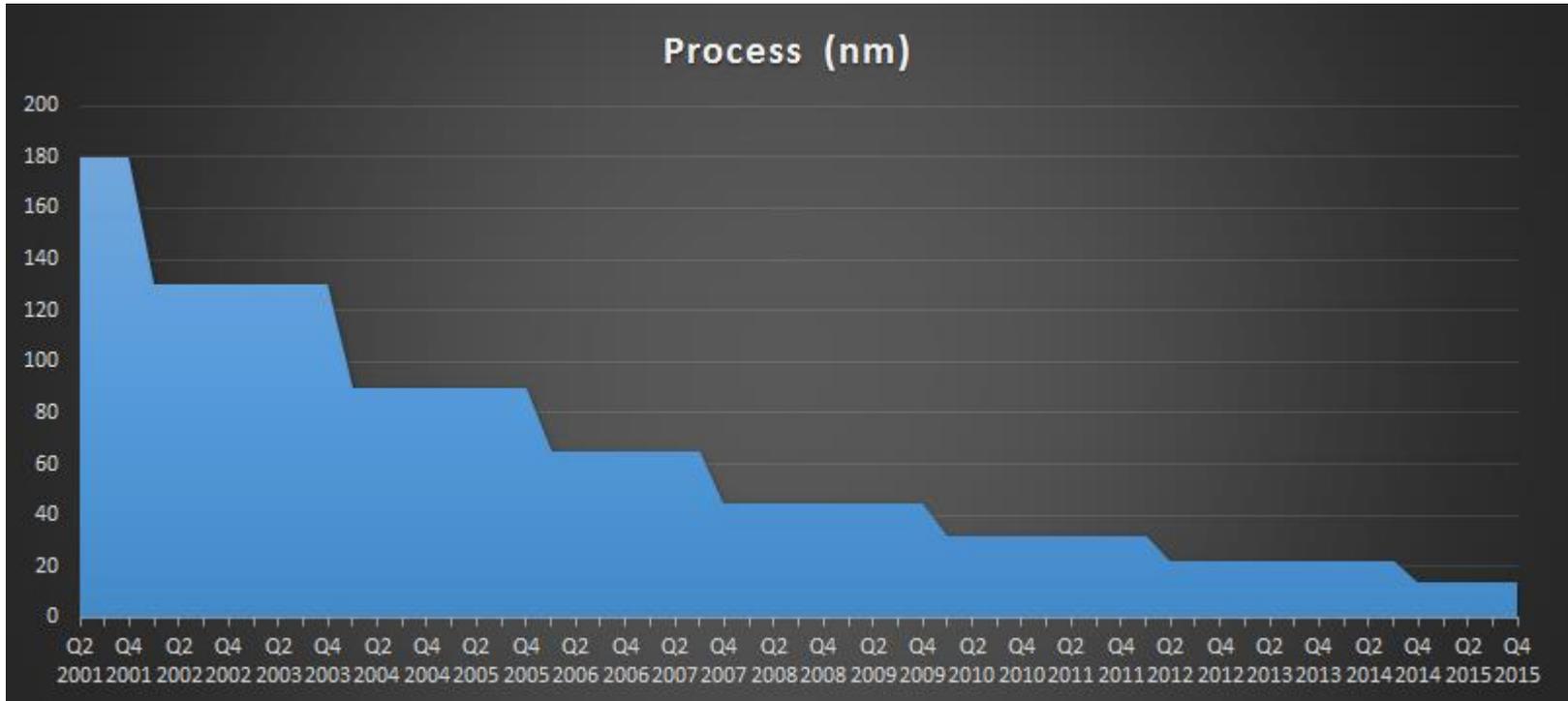
Process Name	<u>P856</u>	<u>P858</u>	<u>Px60</u>	<u>P1262</u>	<u>P1264</u>	<u>P1266</u>
1 st Production	1997	1999	2001	2003	2005	2007
Lithography	0.25 μ m	0.18 μ m	0.13 μ m	90nm	65nm	45nm
Gate Length	0.20 μ m	0.13 μ m	<70nm	<50nm	<35nm	<25nm
Wafer (mm)	200	200	200/300	300	300	300

Moore's Law continues!

- Intel has been introducing new technology generations on a faster 2 year interval since 1989
- We have technologies in Intel's R&D laboratories that will drive this pace of innovation into the next decade

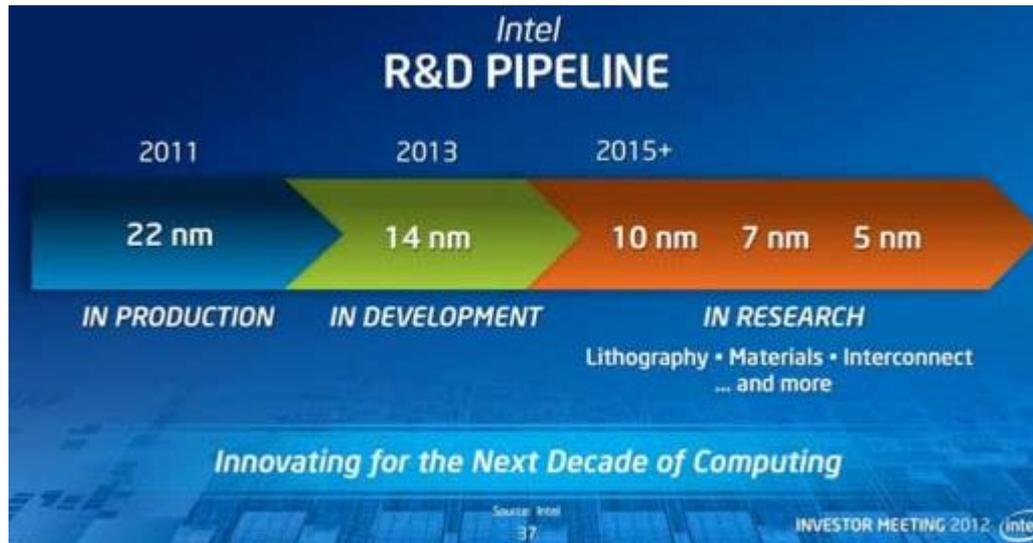


Micro- und Nanoprocessing Technologies



Quelle: Intel

Micro- und Nanoprocessing Technologies



Intel's FAB 32: 300mm Wafer, 45/32 nm Strukturgröße (in Betrieb seit 2007)

Micro- und Nanoprocessing Technologies

MIT technology review:

Moore's Law Is Dead. Now What?

Shrinking transistors have powered 50 years of advances in computing—but now other ways must be found to make computers more capable.

by Tom Simonite May 13, 2016

WELT N24

WEBWELT & TECHNIK MOORE'S LAW

Das fundamentale Computer-Gesetz gilt nicht mehr

Physikalische Grenze der Chip-Entwicklung

Kleiner geht's nicht

Spiegel Online

Fünfzig Jahre lang wurden Computerchips stetig kleiner, günstiger und leistungsfähiger. Doch Ende dieses mooreschen Gesetzes. Stockt die digitale Revolution, weil das Schrumpfen ein En

Frankfurter Allgemeine

Moore's Law

Das wichtigste Computerchip-Gesetz gilt nicht mehr

Bisher stieg die Leistung von Computerchips exponentiell. Das ändert sich jetzt, Moore's Law läuft aus. Na und?

12.08.2016, von CARSTEN KNOP

Wie geht es weiter? Nanotechnologie?

Micro- und Nanoprocessing Technologies



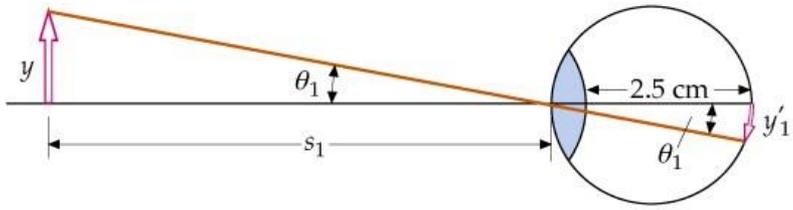
Quelle: Nature **530**, 144 | 11 FEBRUARY 2016

**THE SEMICONDUCTOR INDUSTRY
WILL SOON ABANDON ITS PURSUIT
OF MOORE'S LAW.
NOW THINGS COULD GET A LOT
MORE INTERESTING.**

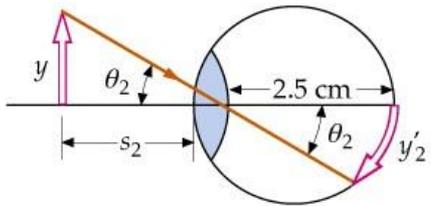
Next month, the worldwide semiconductor industry will formally acknowledge what has become increasingly obvious to everyone involved: Moore's law, the principle that has powered the information-technology revolution since the 1960s, is nearing its end.

neue Materialien; carbon nanotubes,
Graphene, InSb, Organic

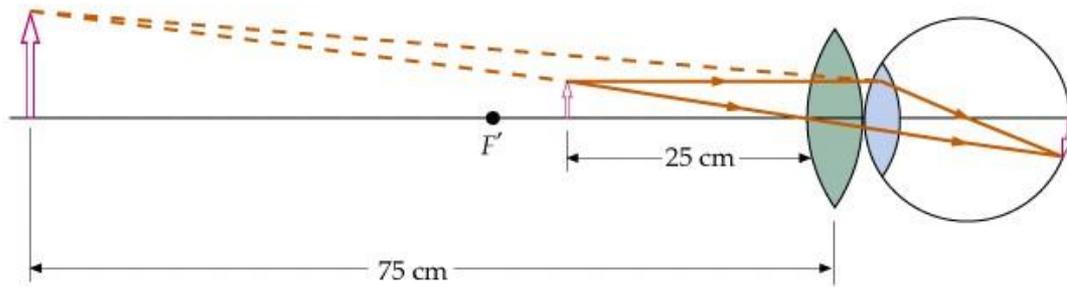
neue Anwendungen; biochips, MEMS,
microfluidics, Quantum devices(SQUID),
spintronic, high frequency devices,
Microwave and terahertz

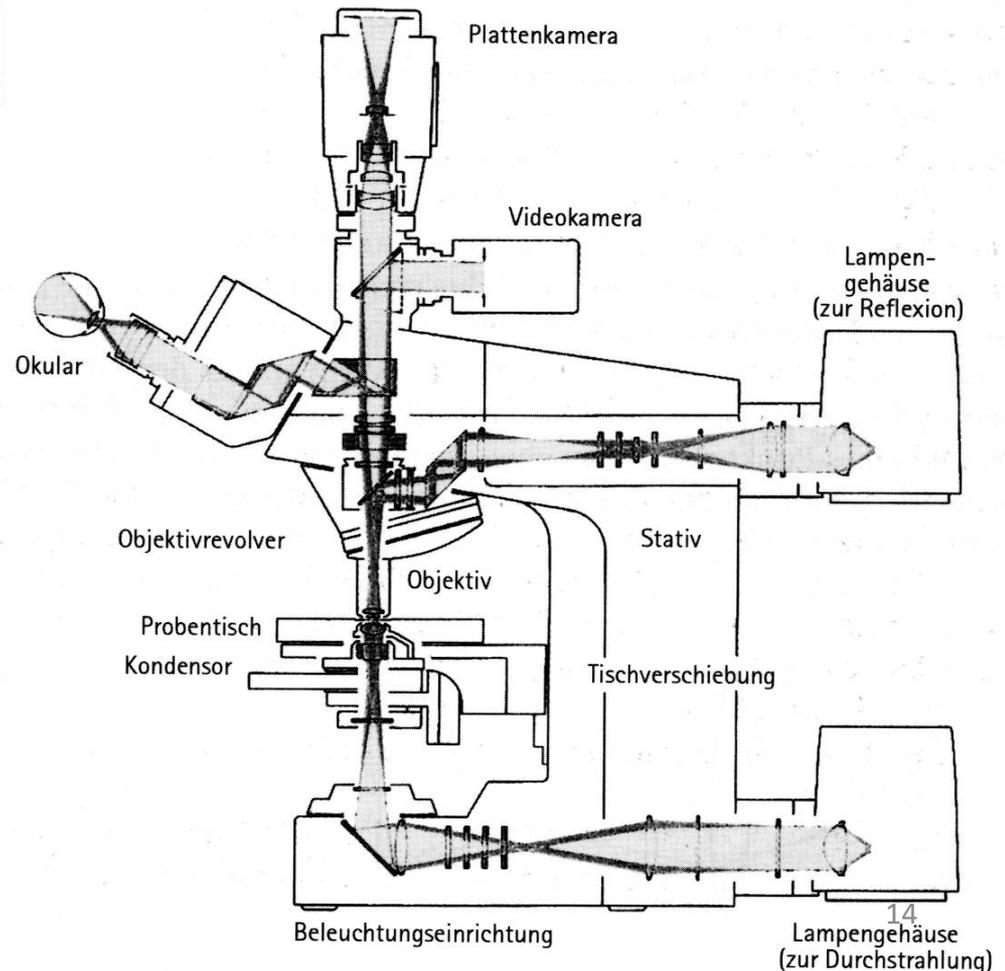
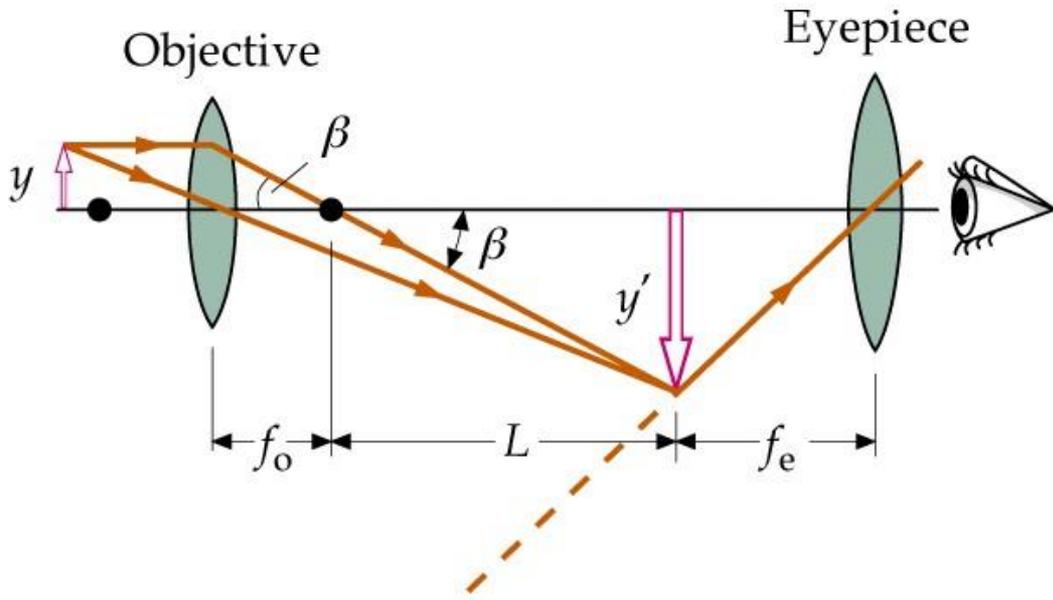


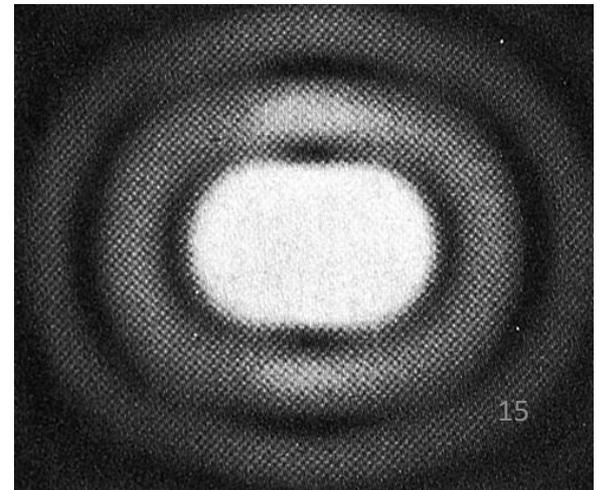
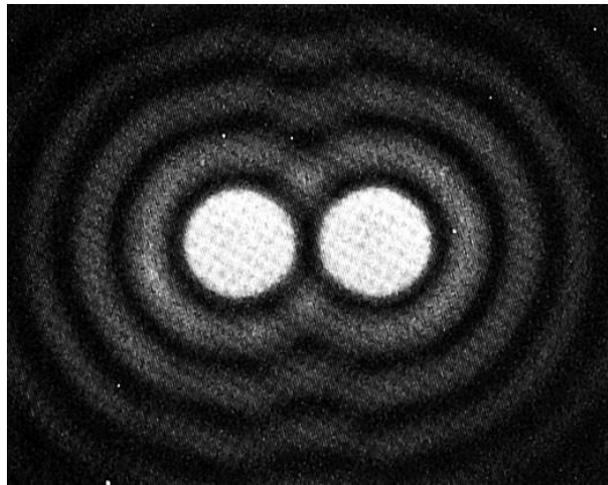
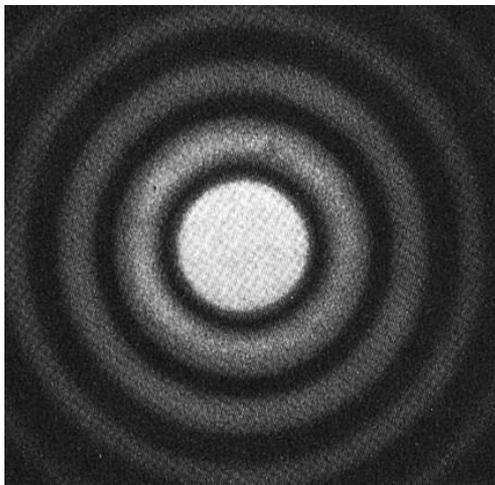
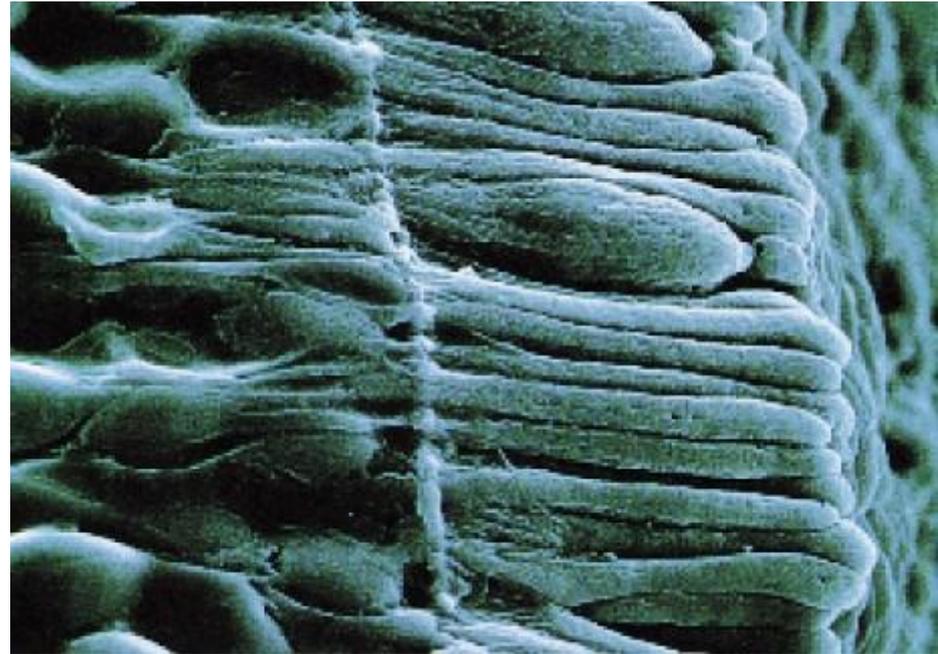
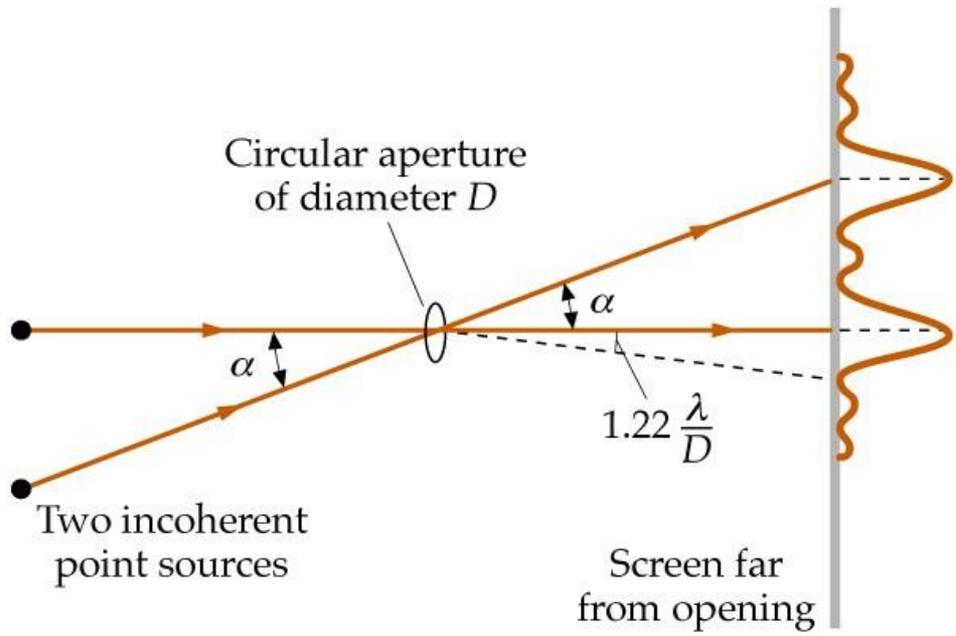
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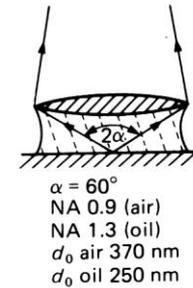
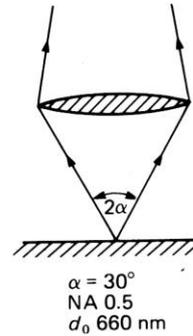
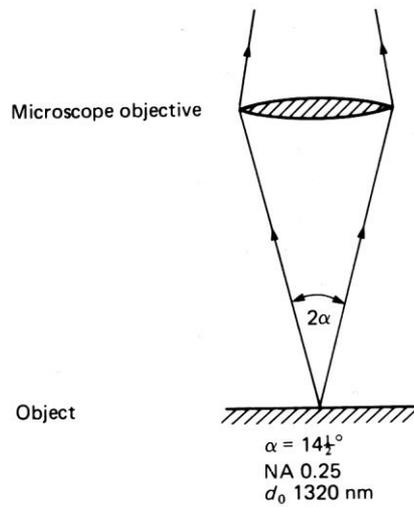
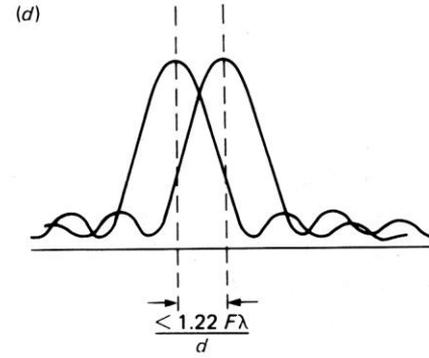
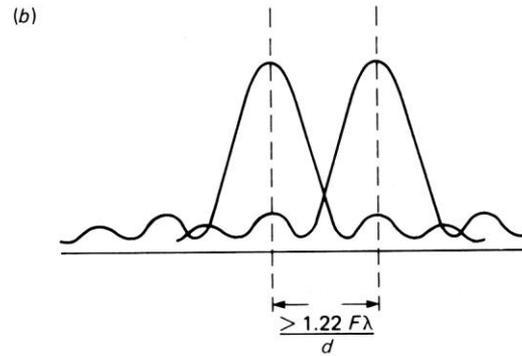
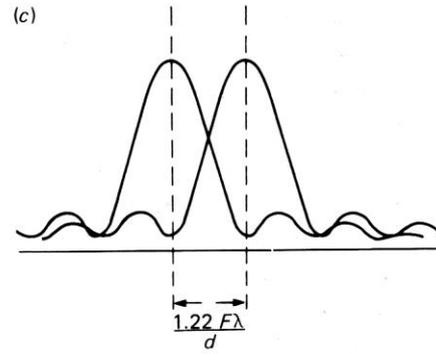
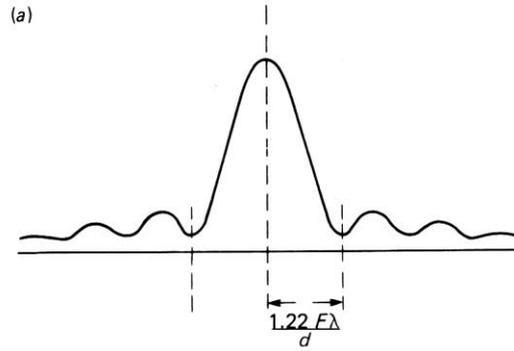


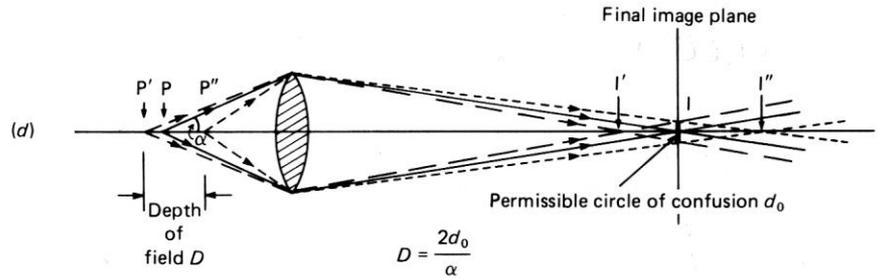
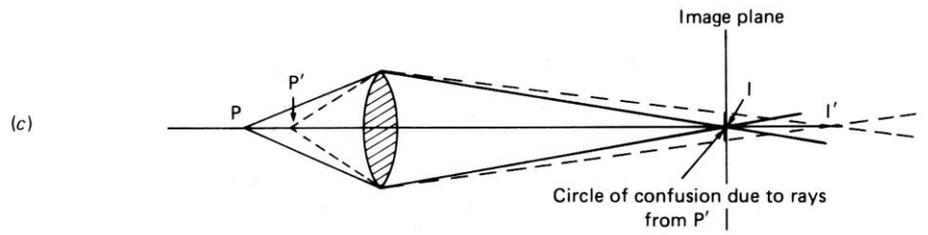
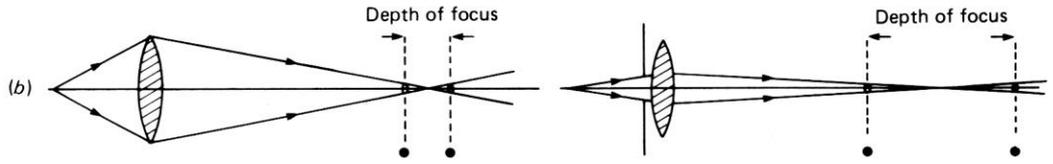
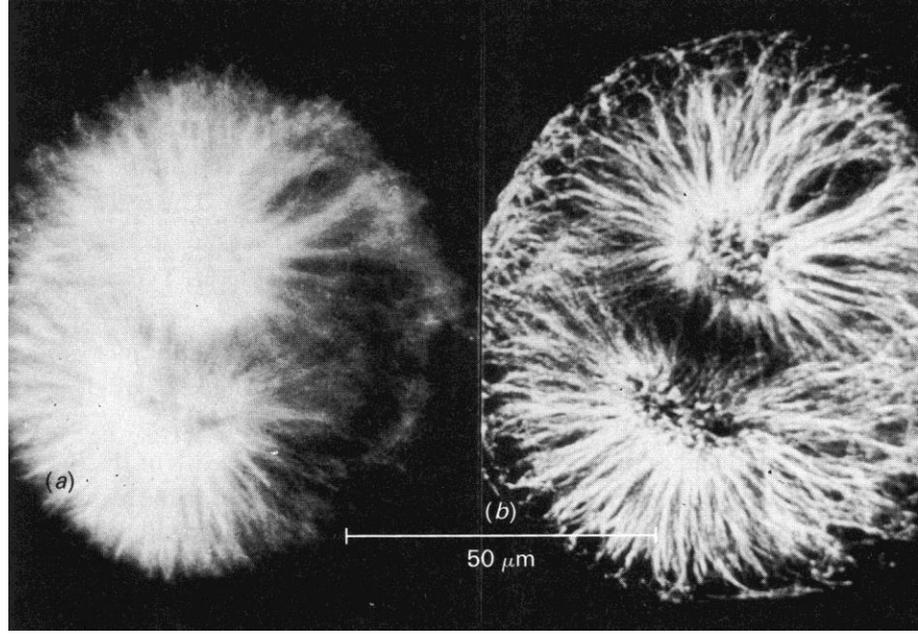
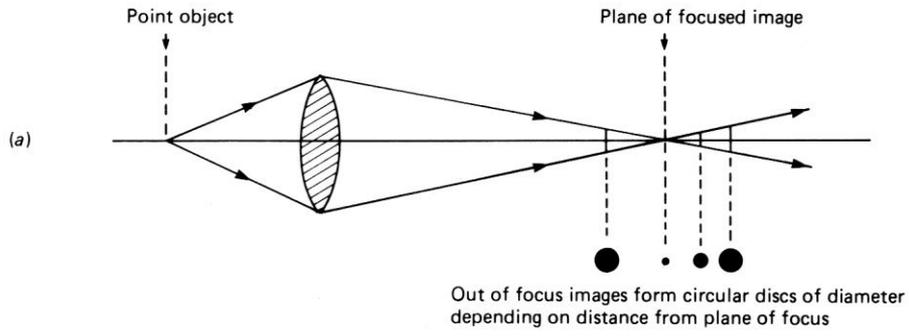
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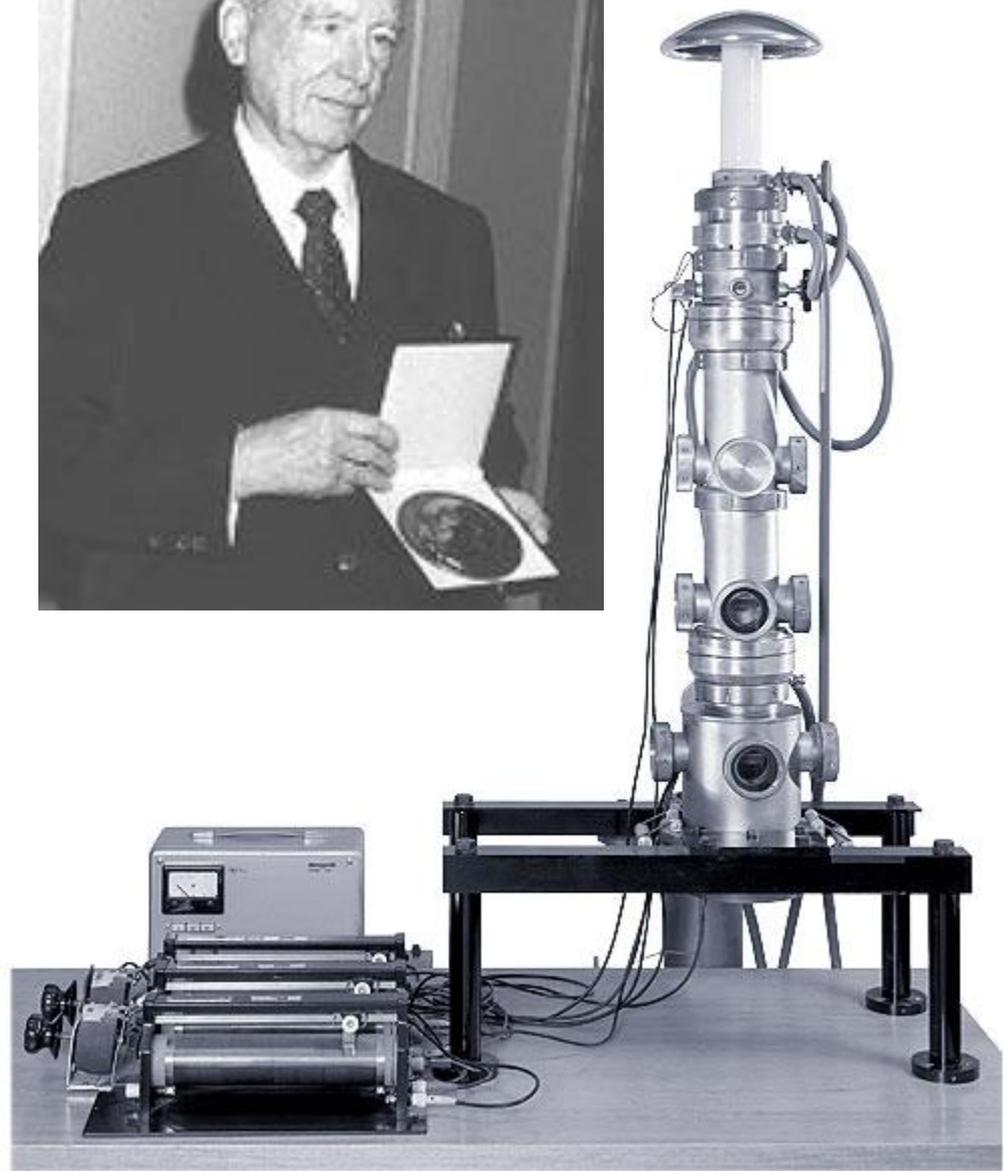
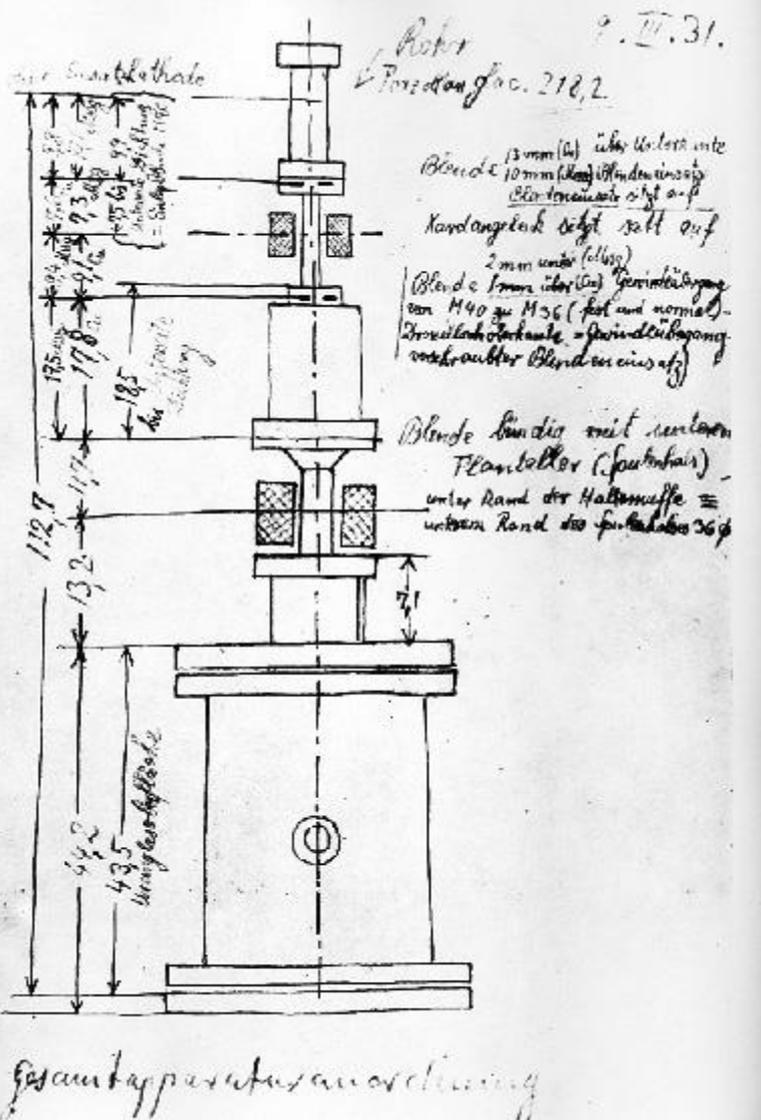








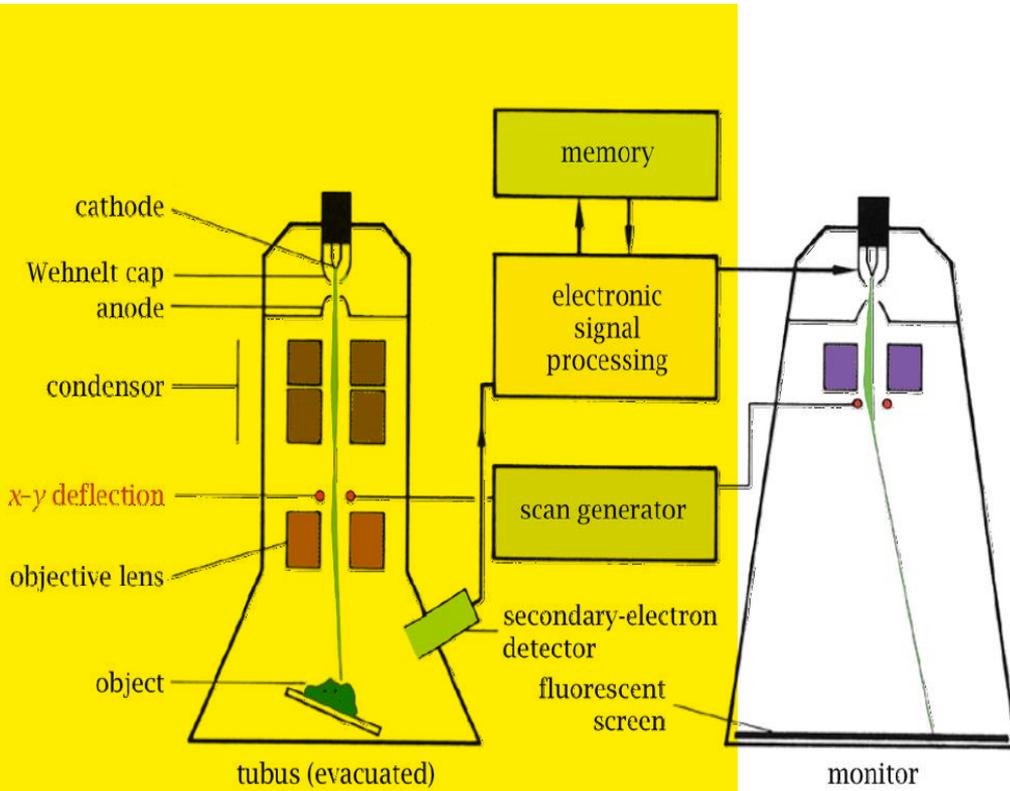




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Zugangspasswort: Nano1WS

Prinzipieller Aufbau

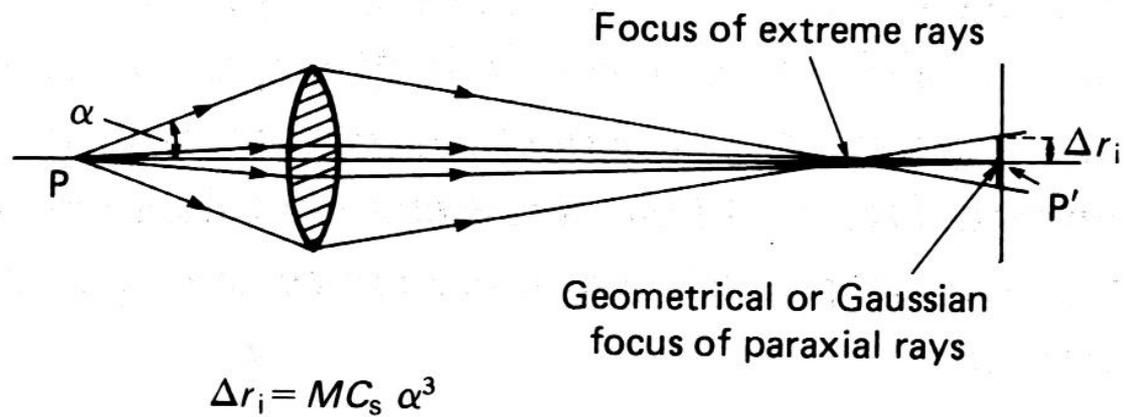


F. Ernst, „Scanning Electron Microscopy“, EMSE 515

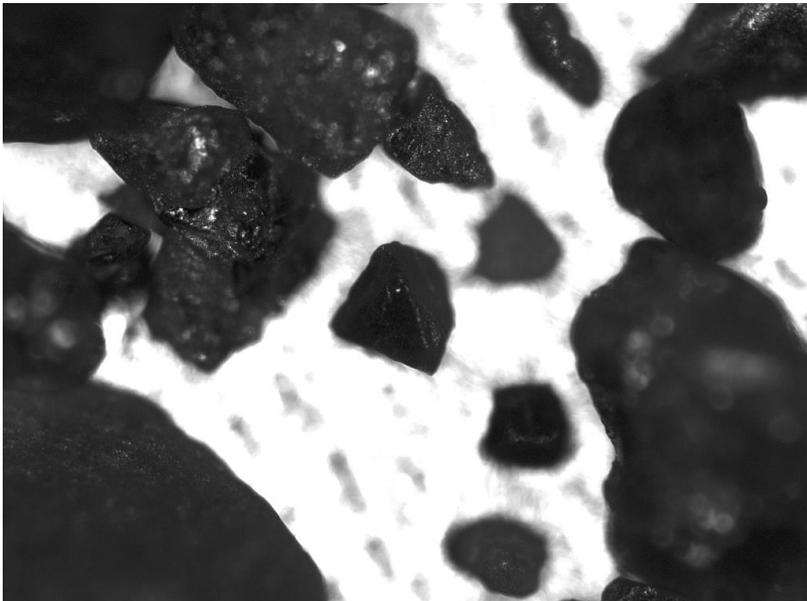
Source type	brightness [A/cm ² /sr]	source size [μm]	energy spread [eV]	Operating vacuum [mbar]	operating temperature [K]	life time [h]
tungsten filament	10 ⁵	25	2..3	10 ⁻⁶	2700	100
LaB ₆ tip	10 ⁶	10	2..3	10 ⁻⁸	1700	500
Schottky emitter	10 ⁸	0.02	1.0	10 ⁻⁹	1800	> 1000
cold field emitter	10 ⁹	0.005	0.2	10 ⁻¹⁰	300	> 1000

Table 2: Properties of electron sources commonly used in electron beam tools.

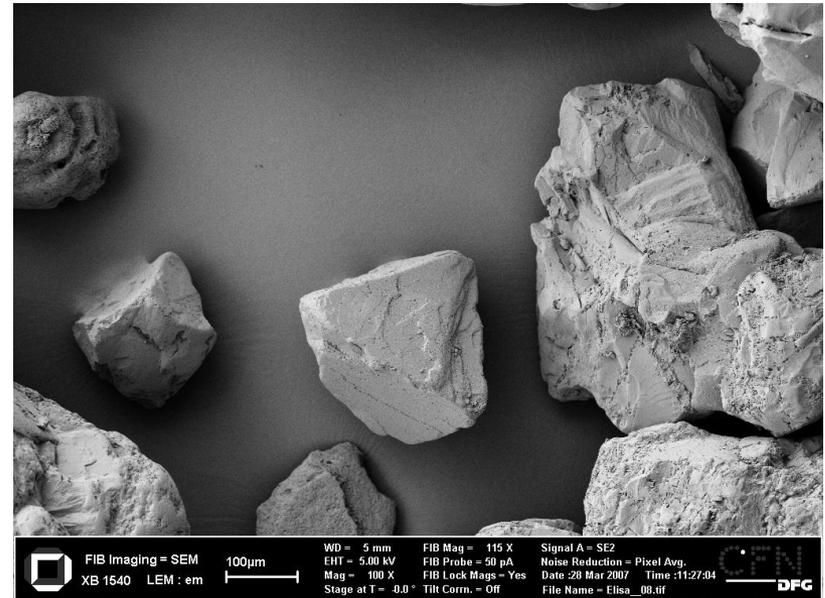
Linsenfehler: sphärische Aberration



Vergleich der Tiefenschärfe eines Lichtmikroskops mit der eines Elektronenmikroskops

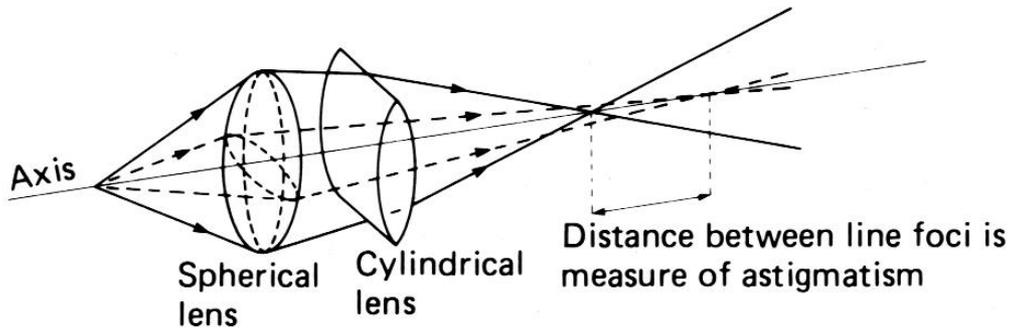


Lichtmikroskopaufnahme von Sandkörnern

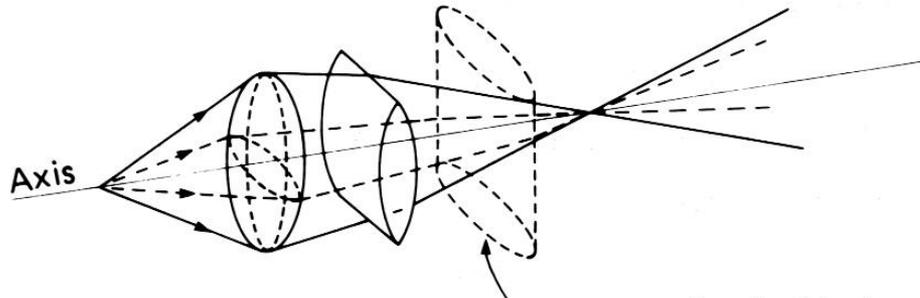


Rasterelektronenmikroskopaufnahme von Sandkörnern

Linsenfehler: Astigmatismus

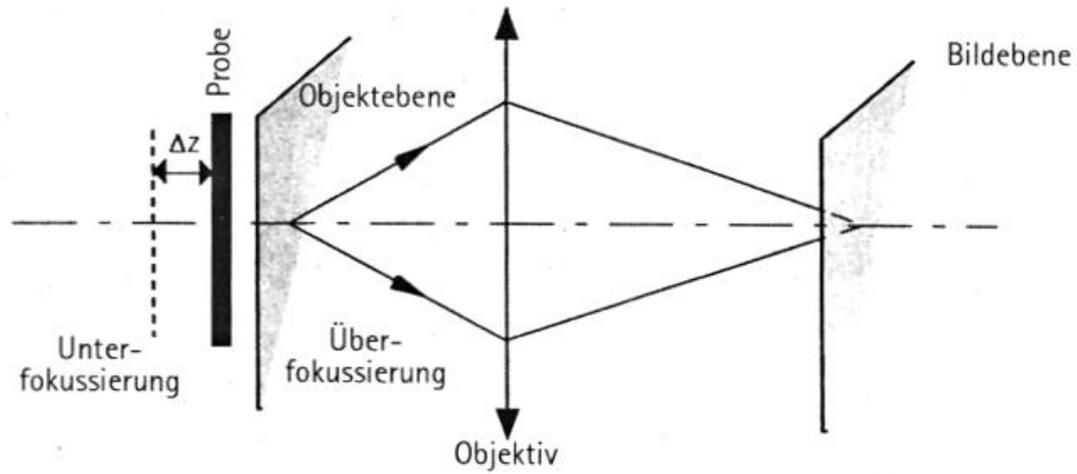


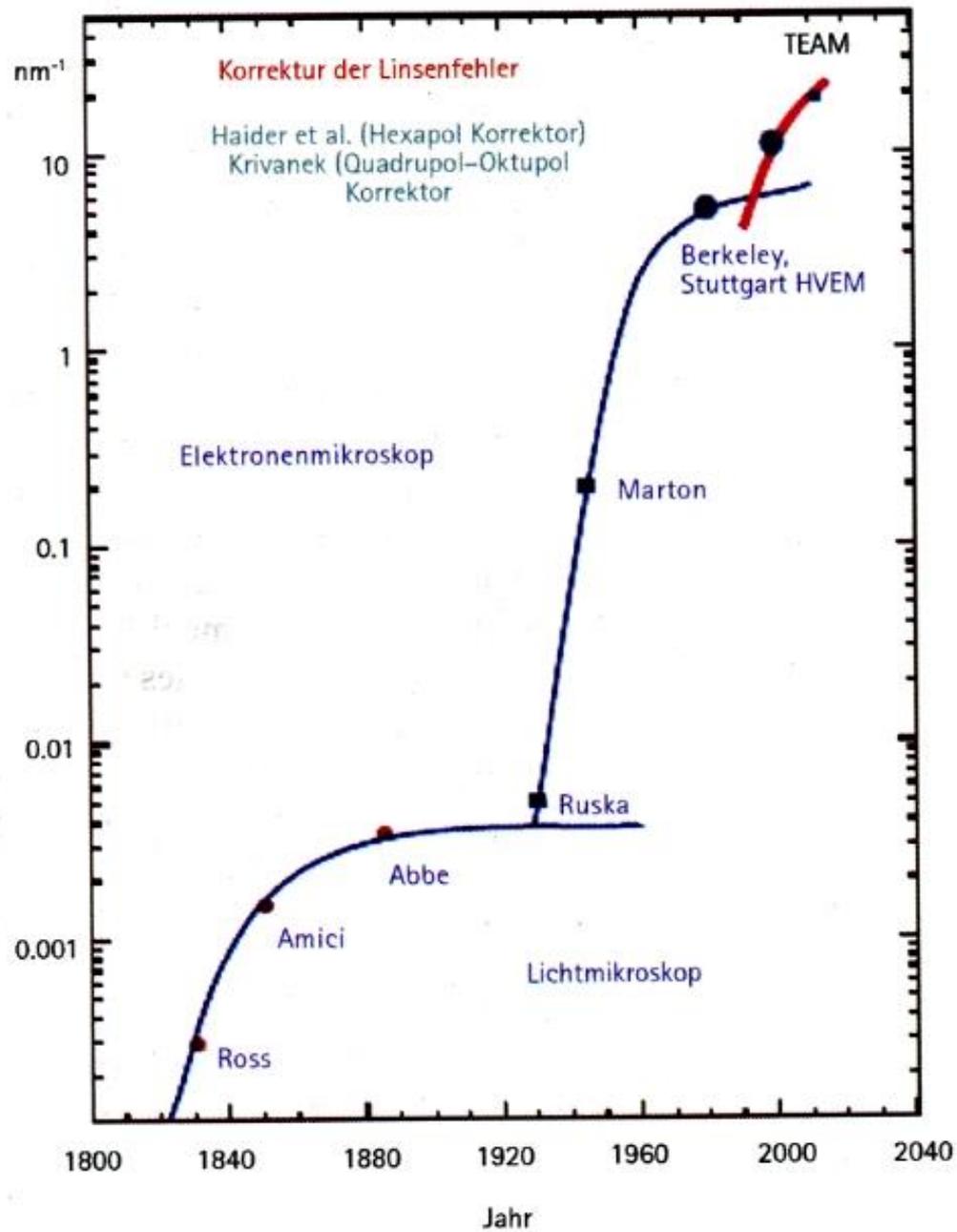
Astigmatic lens is equivalent to combination of spherical and cylindrical lenses. Instead of a point focus, forms two line foci at right angles



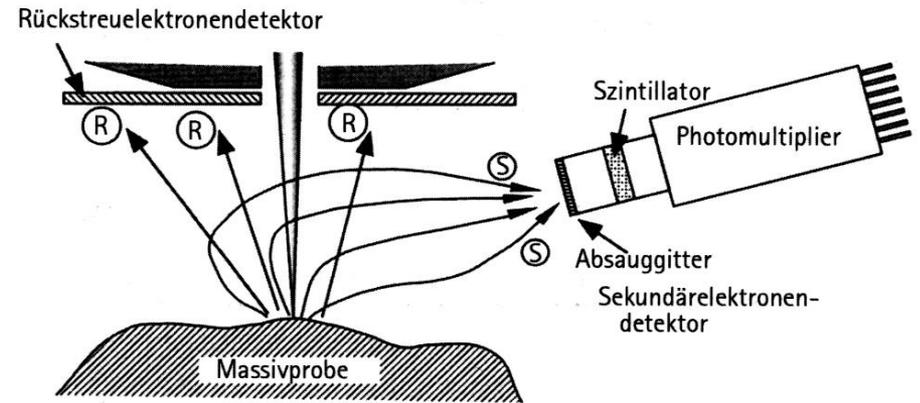
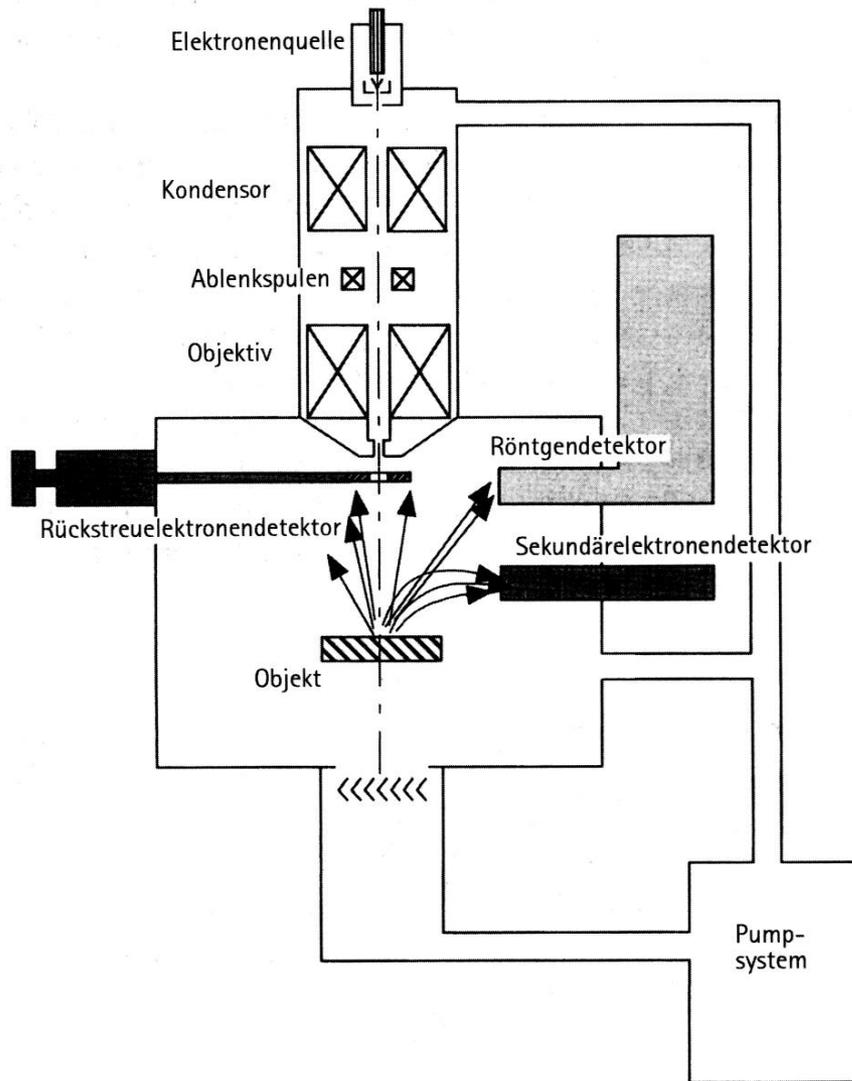
Astigmatism corrector acts as second cylindrical lens with axis at right angle to inherent defect and brings rays to common focus

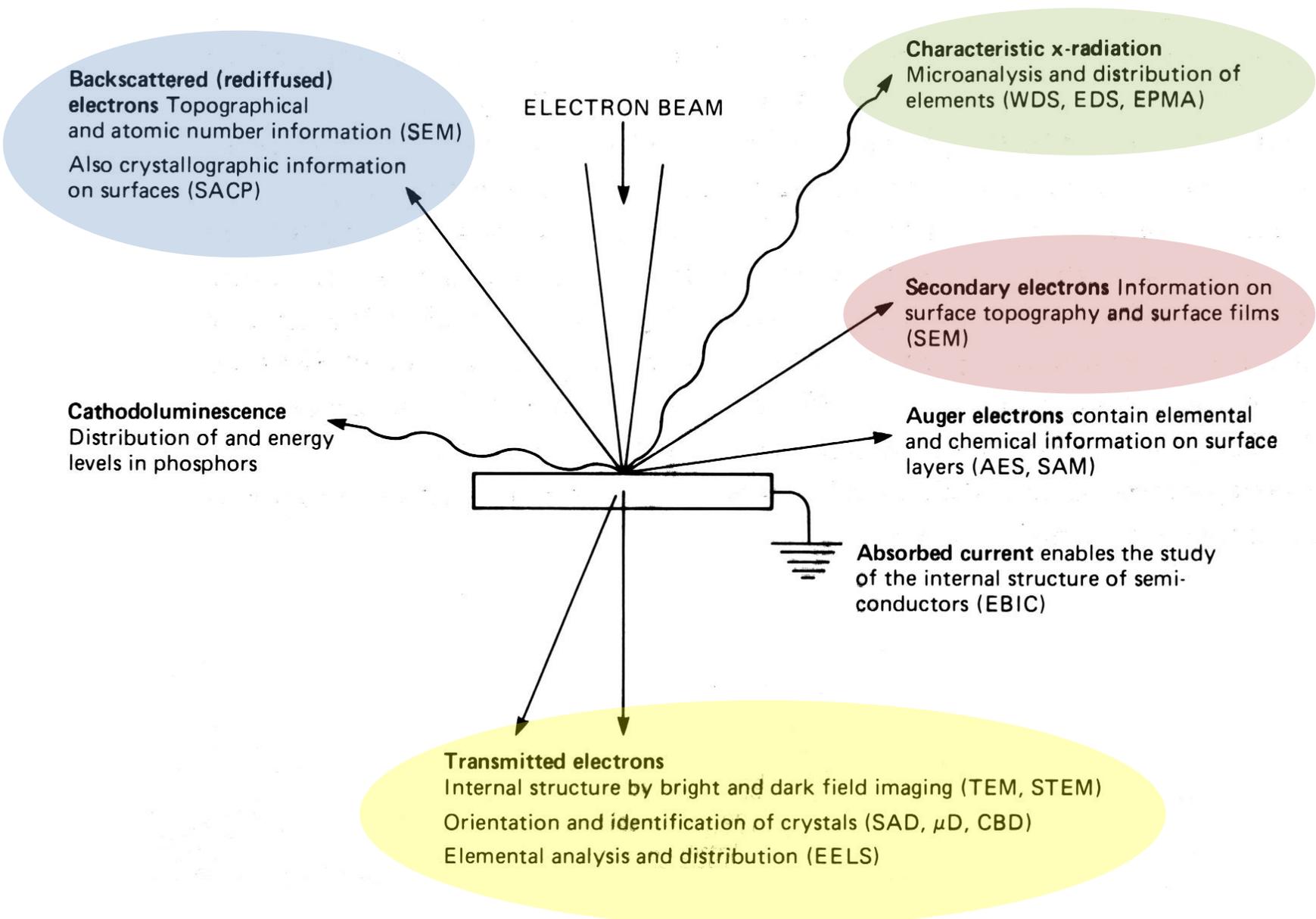
Kompensation von Linsenfehlern durch Defokussierung

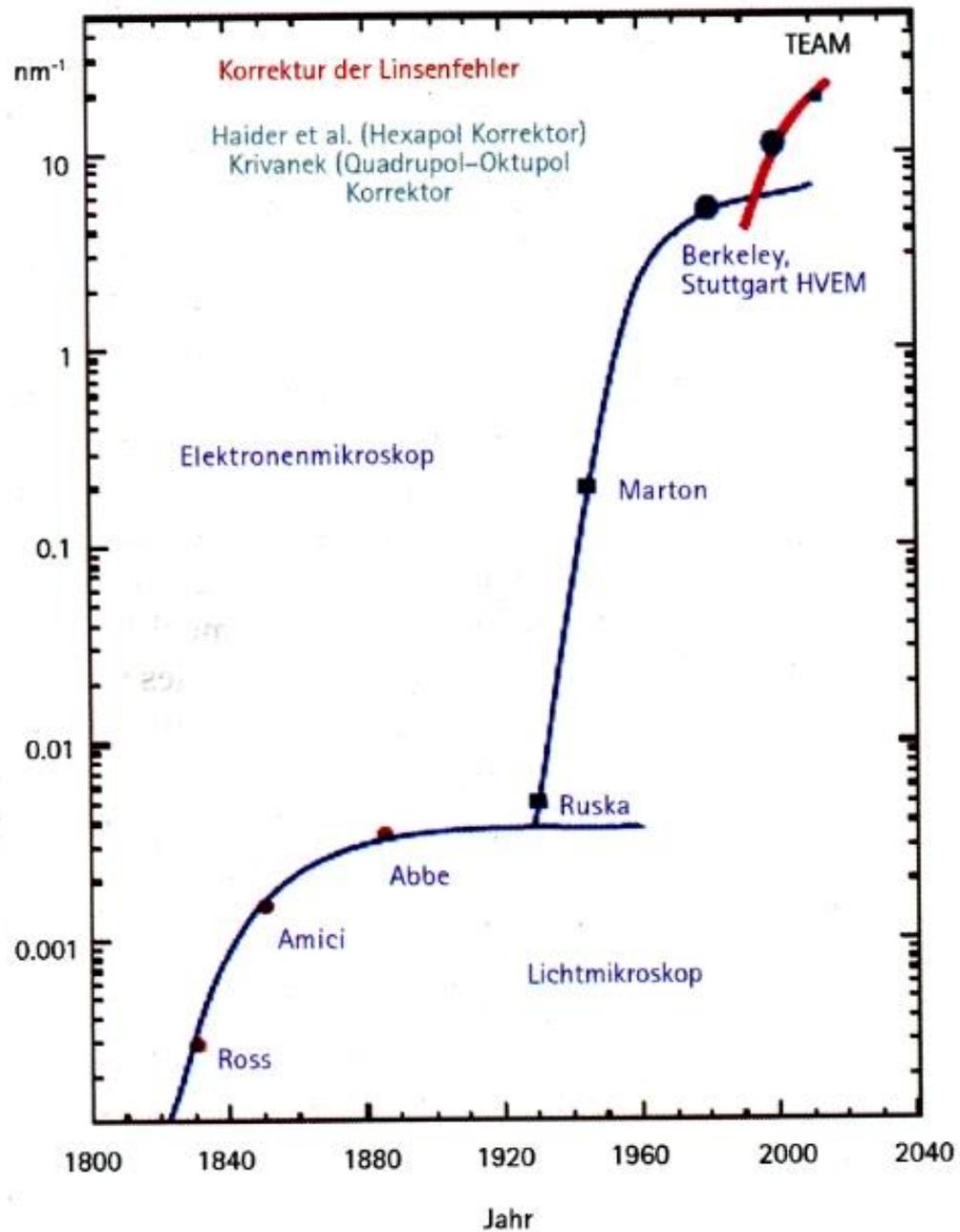




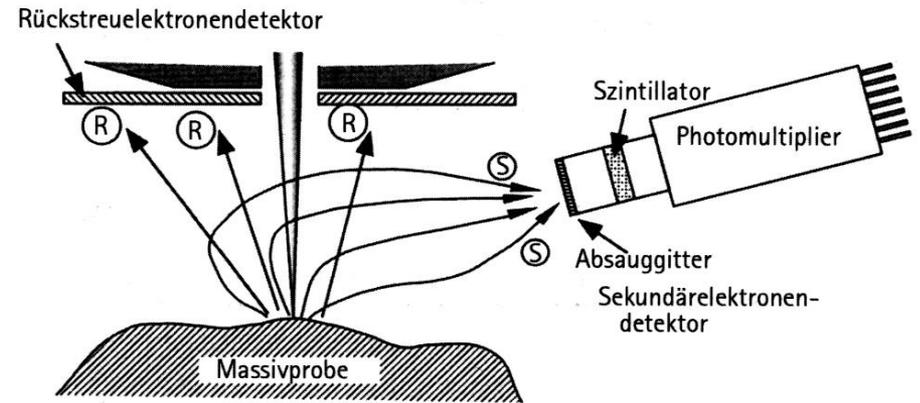
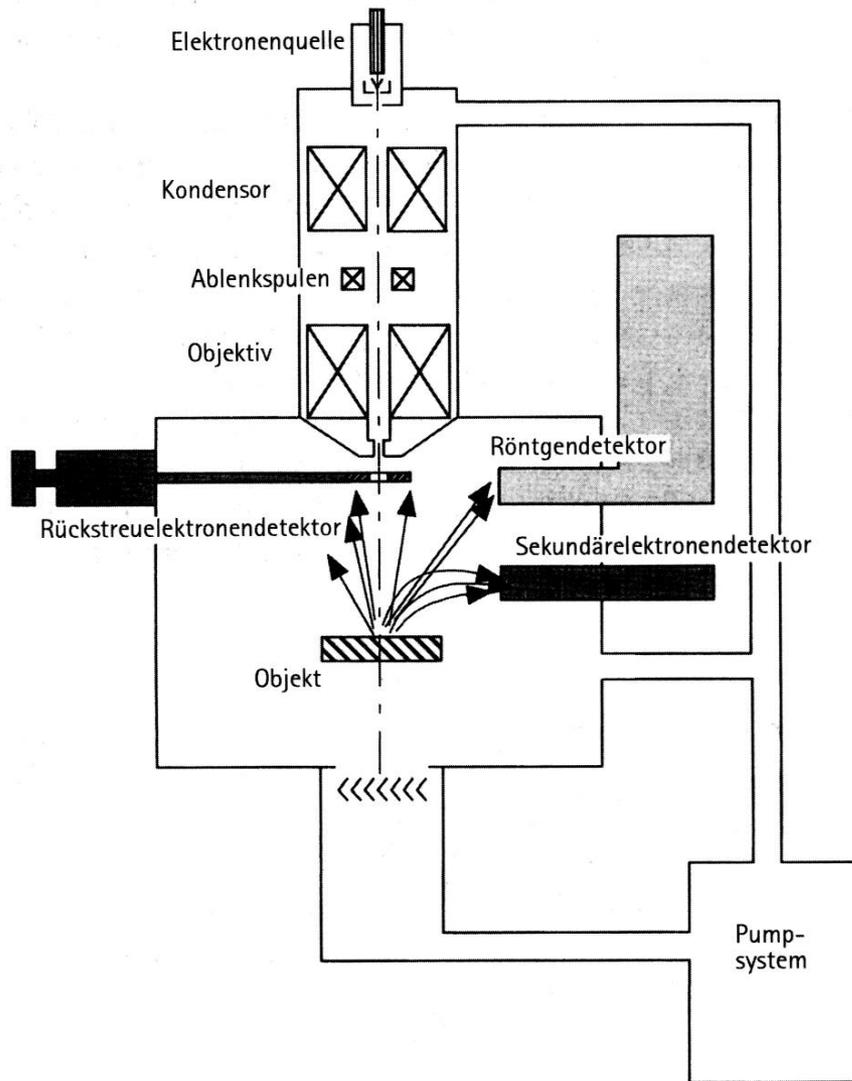
Aufbau eines Rasterelektronenmikroskops







Aufbau eines Rasterelektronenmikroskops



Backscattered (rediffused) electrons Topographical and atomic number information (SEM)
Also crystallographic information on surfaces (SACP)

ELECTRON BEAM

Characteristic x-radiation
Microanalysis and distribution of elements (WDS, EDS, EPMA)

Secondary electrons Information on surface topography and surface films (SEM)

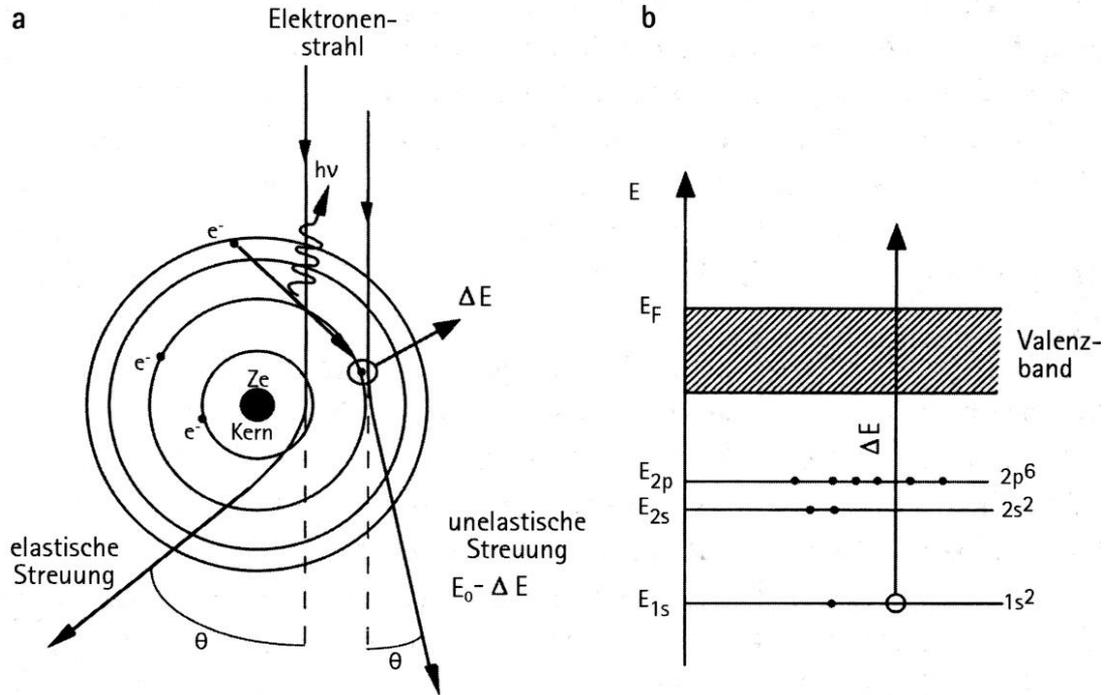
Cathodoluminescence
Distribution of and energy levels in phosphors

Auger electrons contain elemental and chemical information on surface layers (AES, SAM)

Absorbed current enables the study of the internal structure of semi-conductors (EBIC)

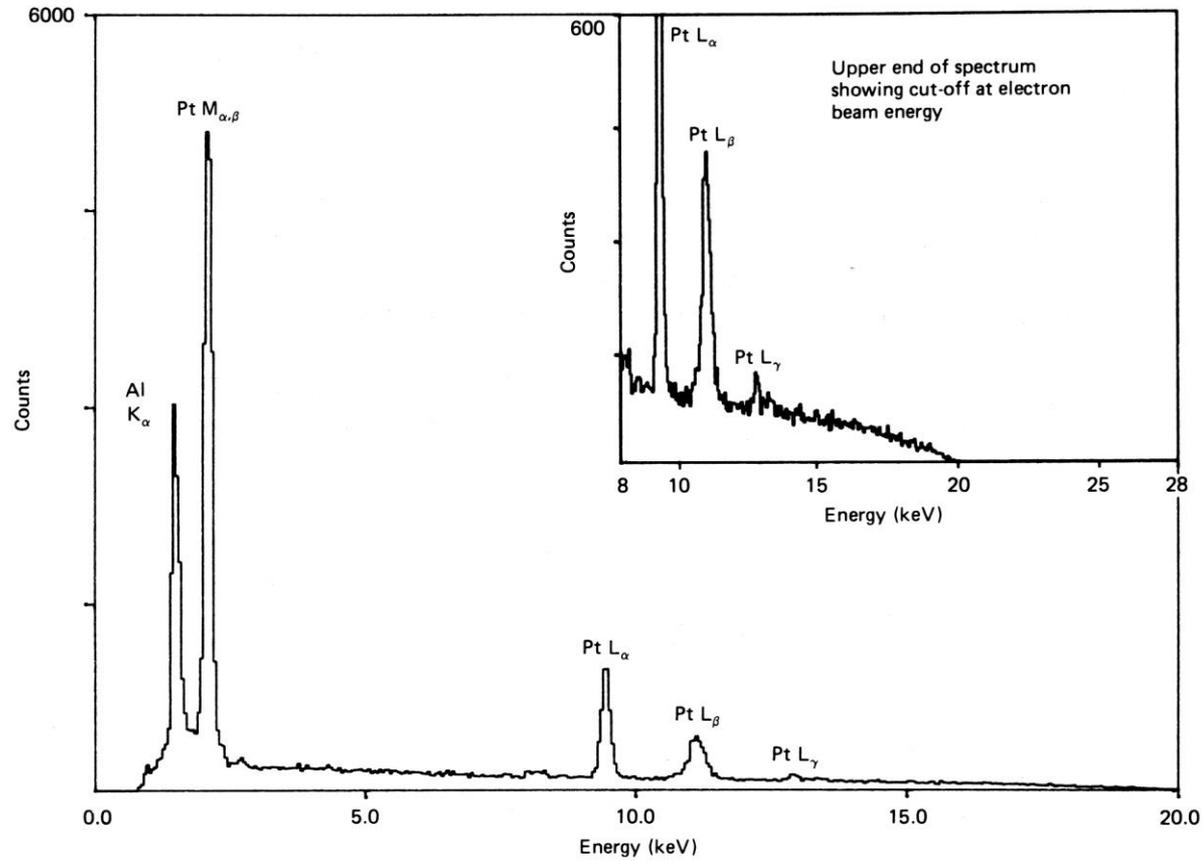
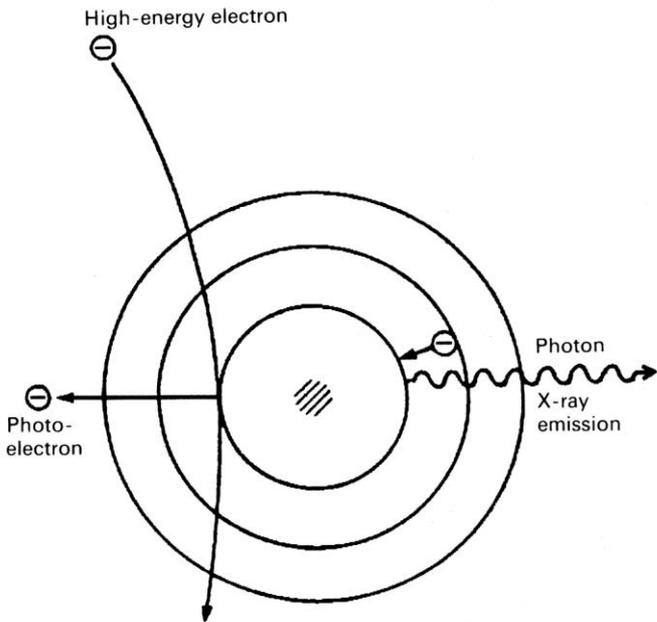
Transmitted electrons
Internal structure by bright and dark field imaging (TEM, STEM)
Orientation and identification of crystals (SAD, μ D, CBD)
Elemental analysis and distribution (EELS)

Wechselwirkung der Elektronen mit Materie

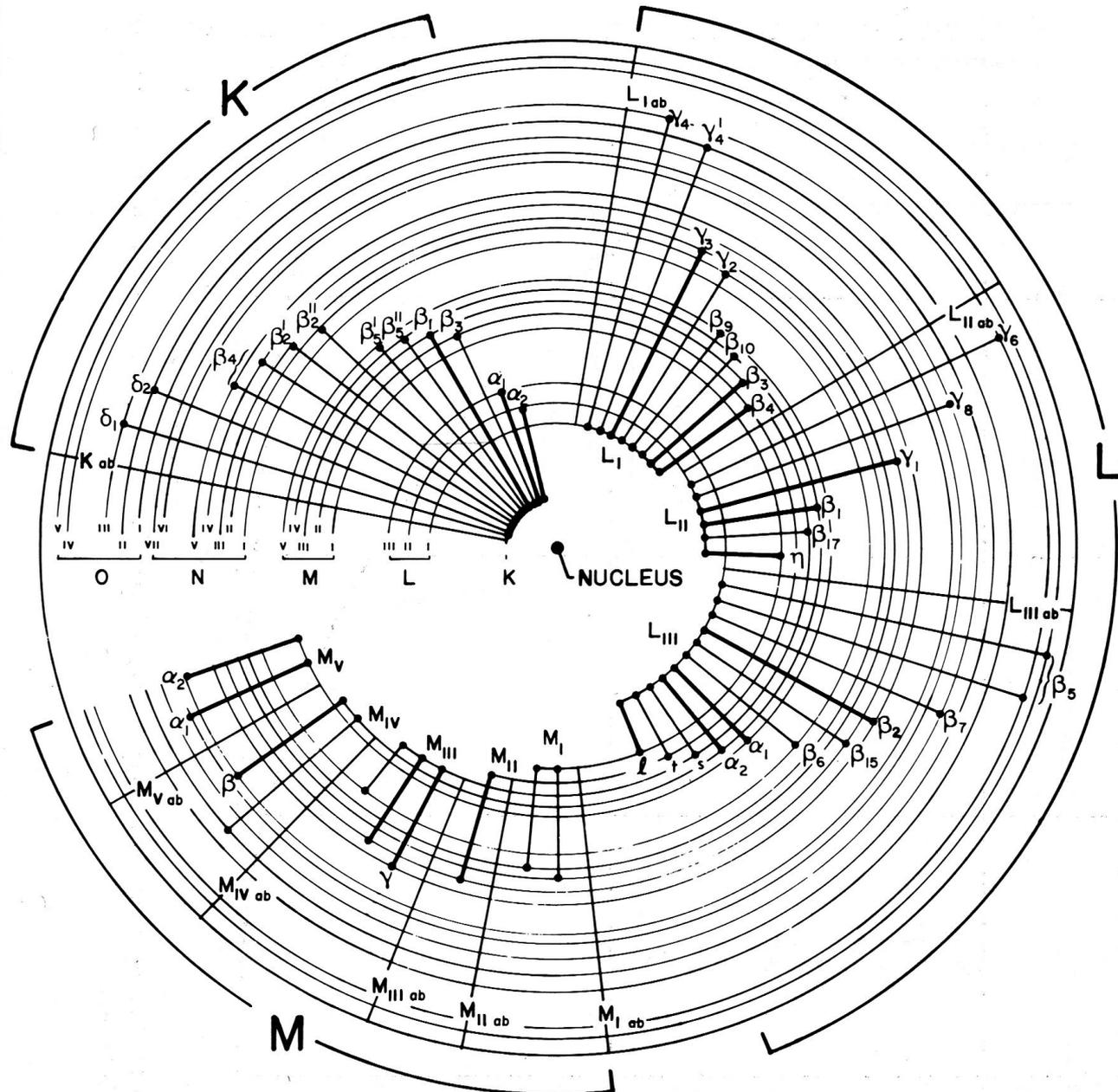


Charakteristische Röntgenstrahlung

Pt on alumina fibre

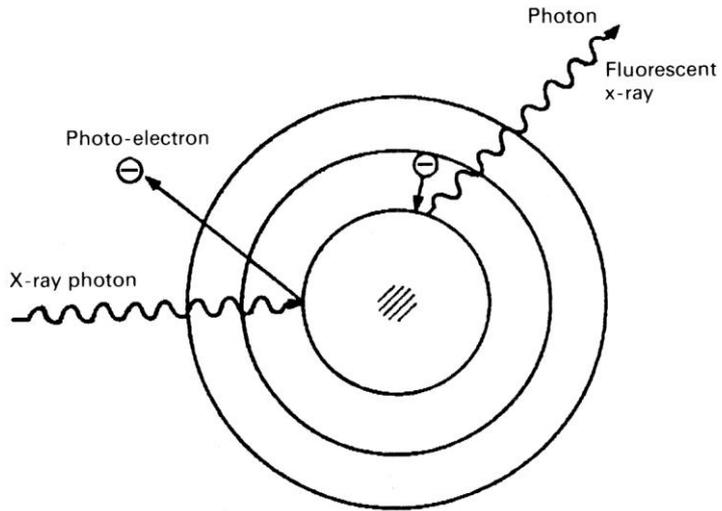


Charakteristische Röntgenstrahlung

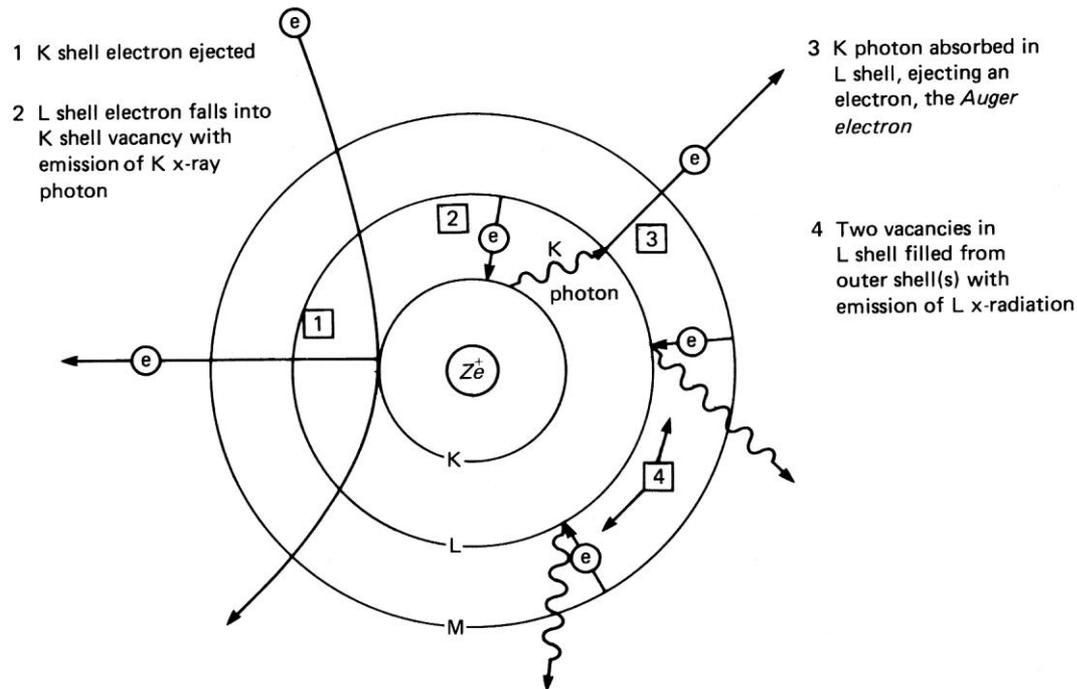


Sekundärprozesse:

Fluoreszenz



Auger-Elektronen



Emission von Elektronen und Photonen, Primärelektronenenergie E_0

- Sekundärelektronen (SE): $E < 50 \text{ eV}$
- Rückstreuerelektronen (BSE): $50 \text{ eV} \leq E \leq E_0$
- charakteristische Röntgenstrahlung (EDX)
- Auger-Elektronen (AE)

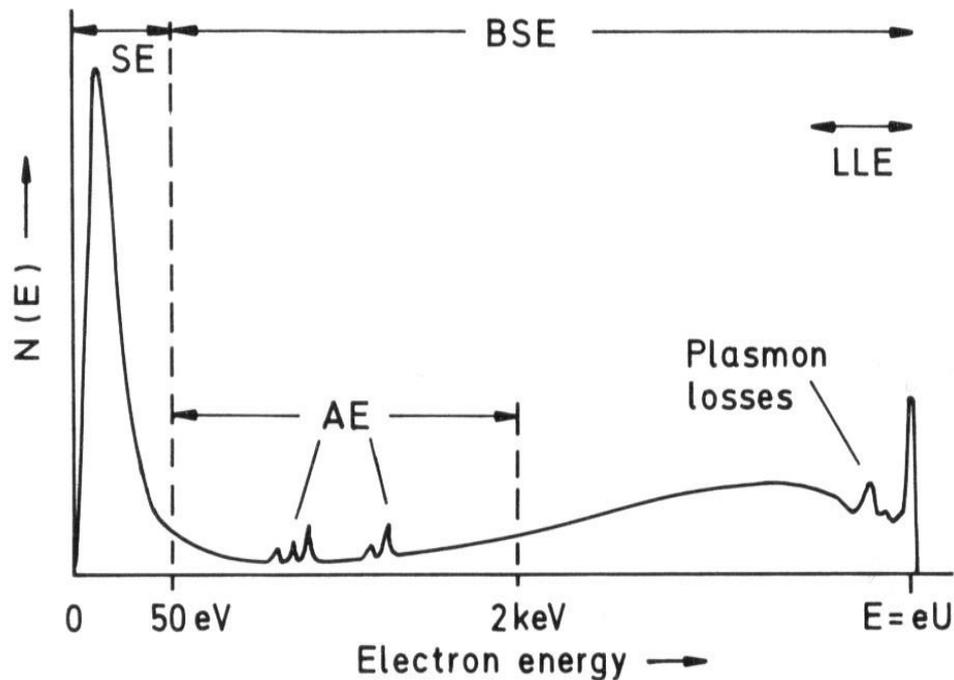
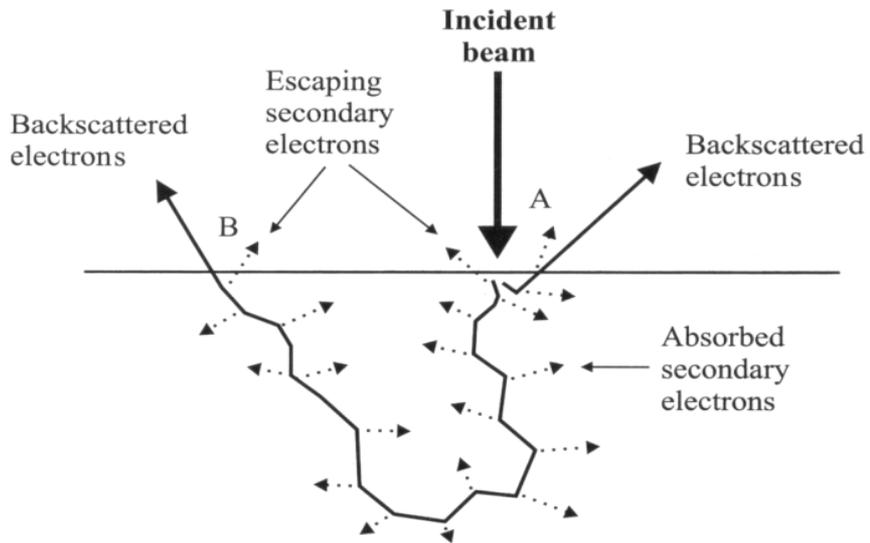


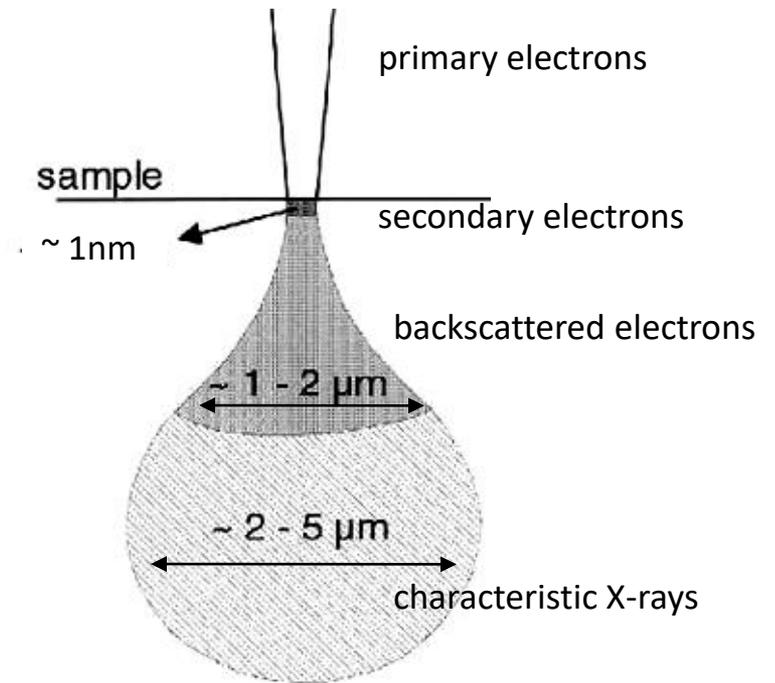
Fig. 1.6

Wechselwirkung zwischen Elektron und Probe

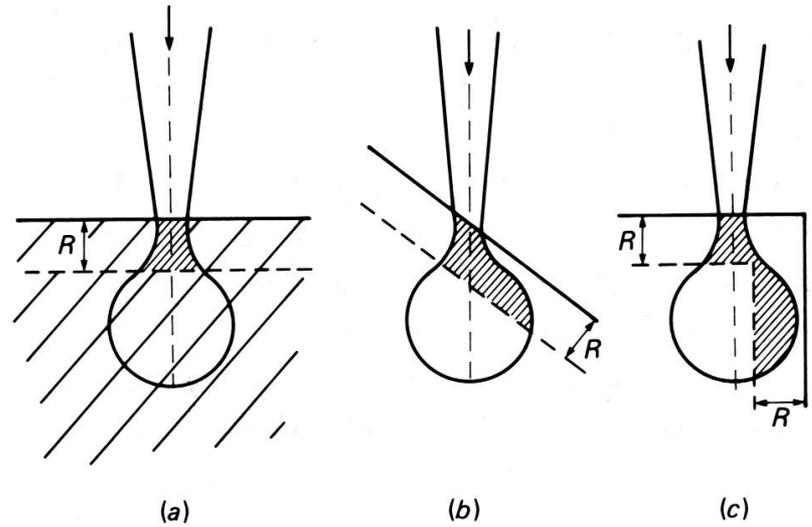
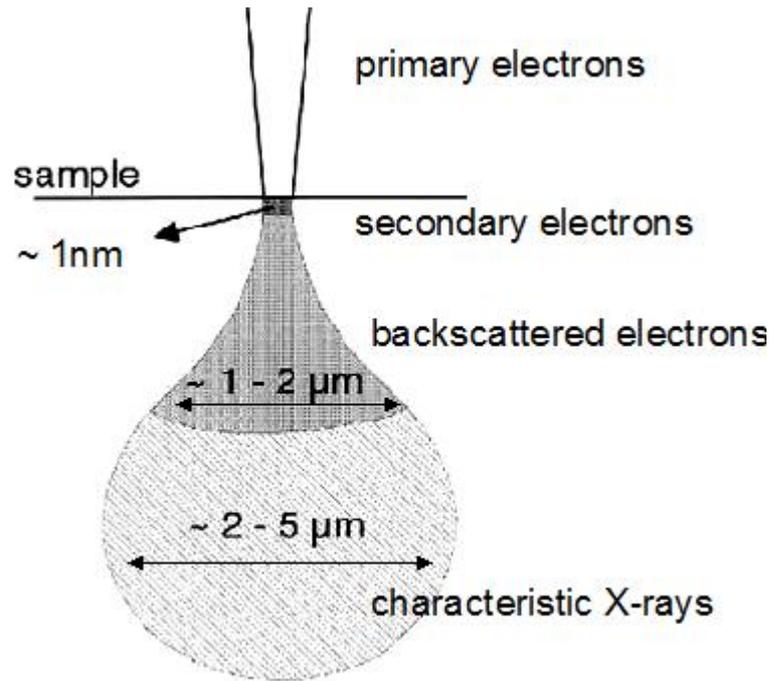


(a)

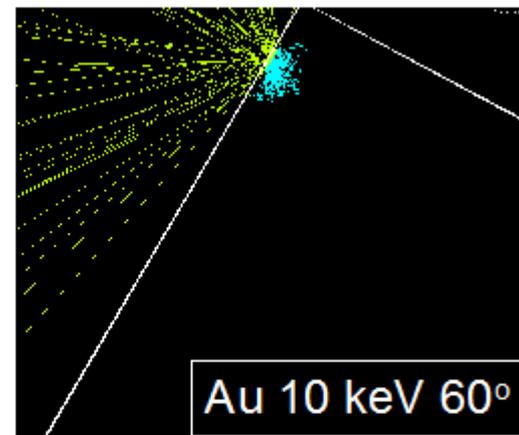
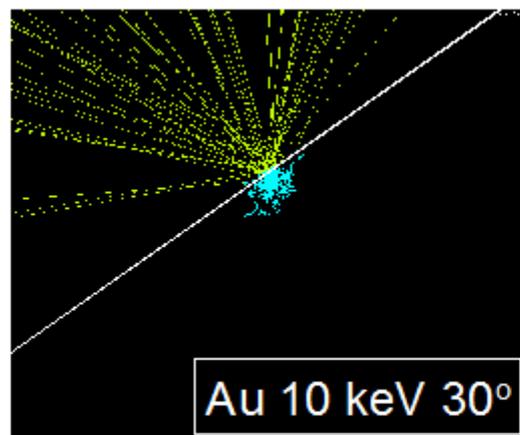
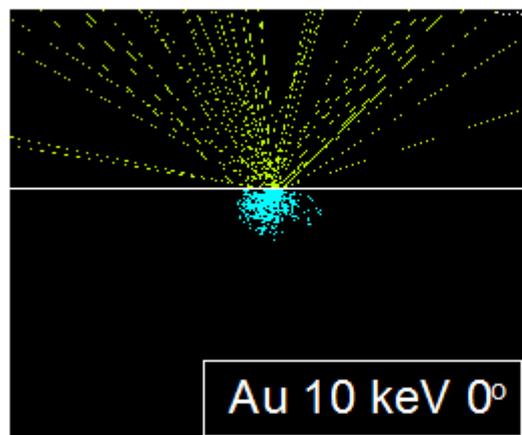
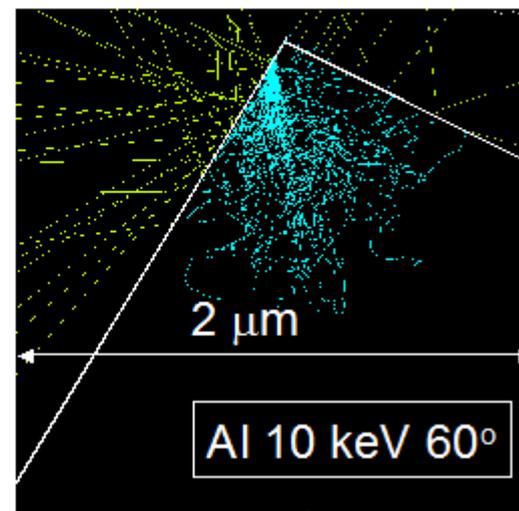
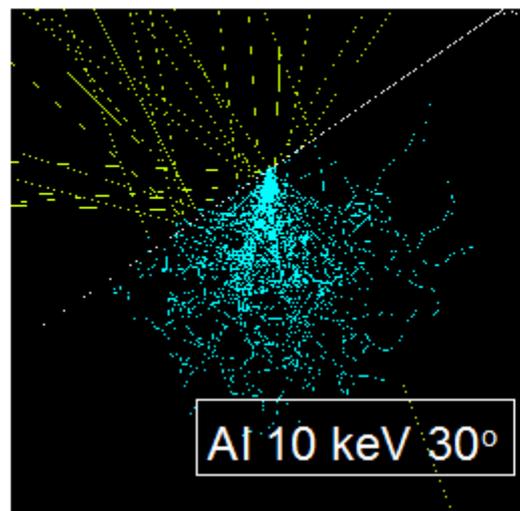
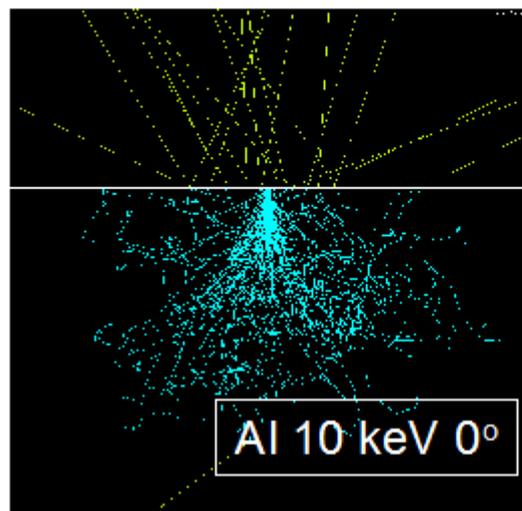
Goodhews, Humphreys, Beanland,
„Electron Microscopy and Analysis“, Fig. 5.7a

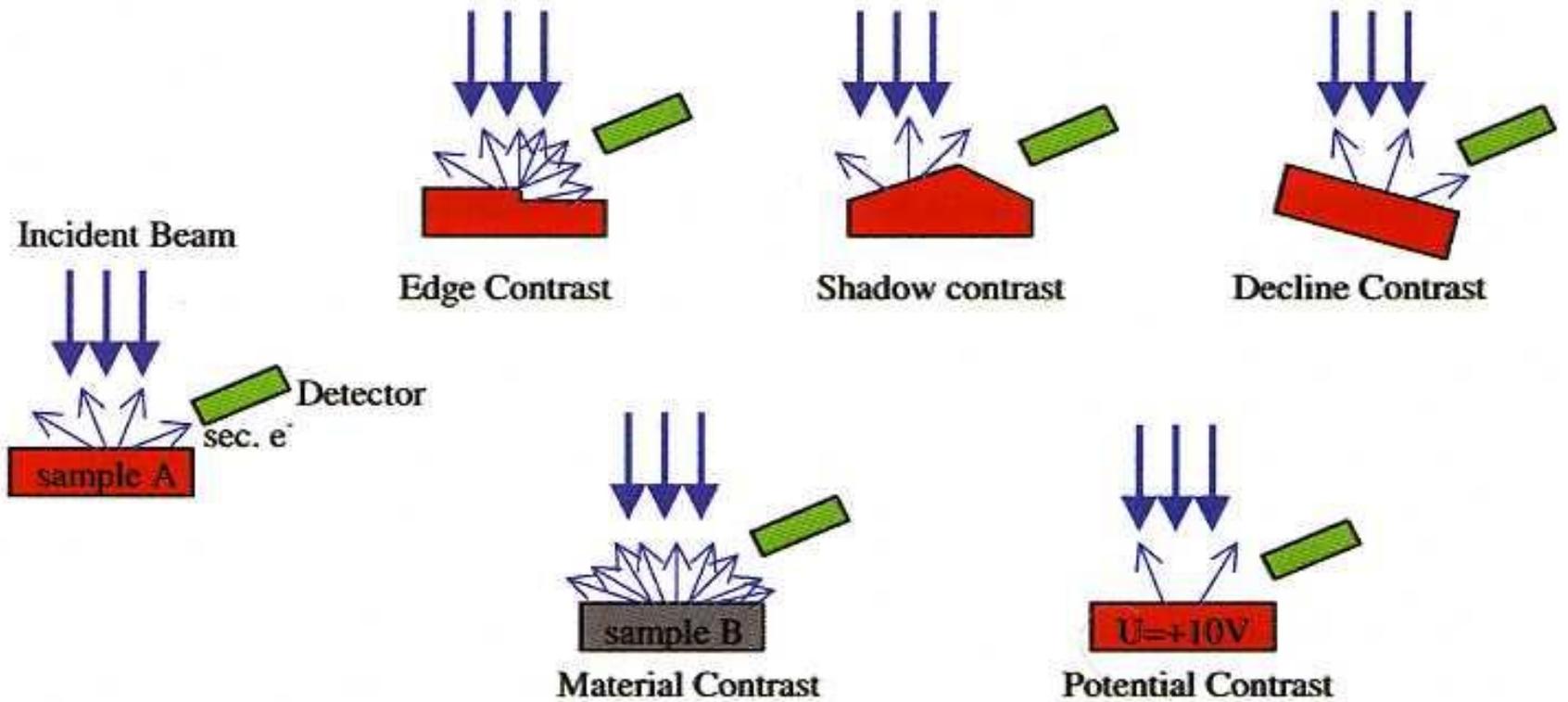


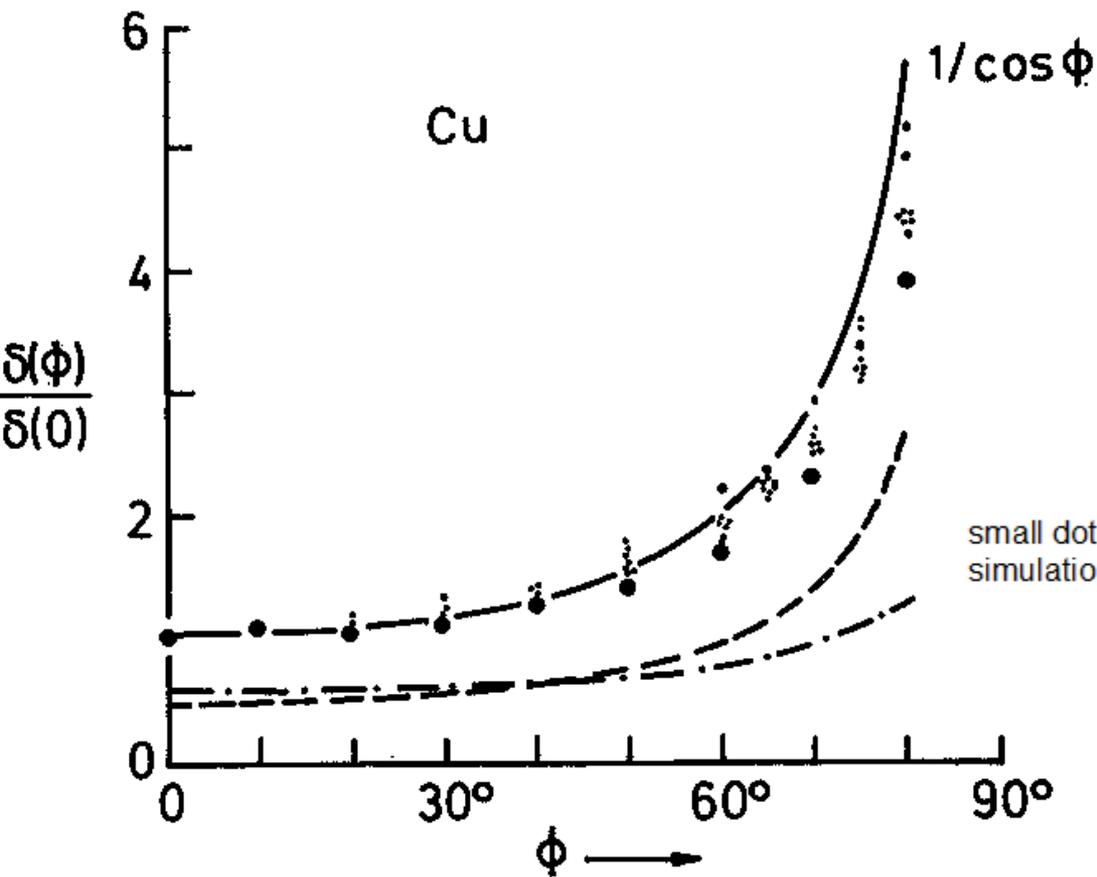
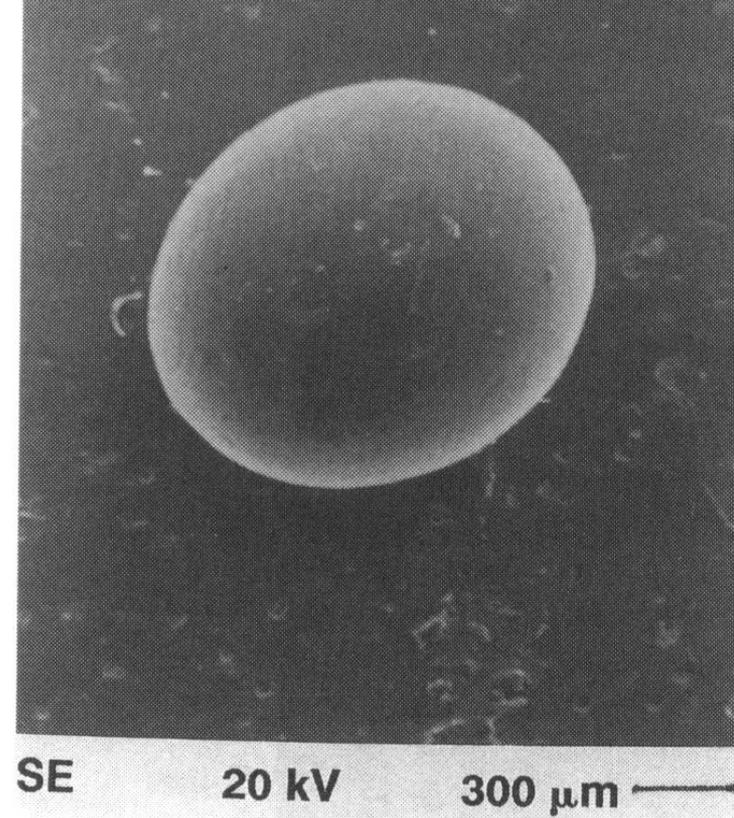
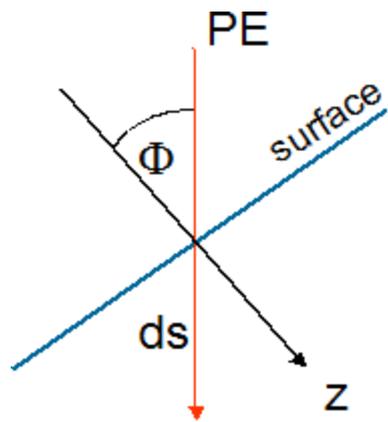
electron range in $\mu\text{g}/\text{cm}^2$: $R = aE^n$
 $a = 7 - 14$, $n = 1.3 - 1.7$, $E[\text{kV}]$



Monte Carlo Simulation der Rückstreuelektronen







small dots: measurements; large dots: Monte Carlo (MC) simulations

- : $1/\cos \phi$
- : contribution of the primary electrons
- : contribution of the backscattered electrons

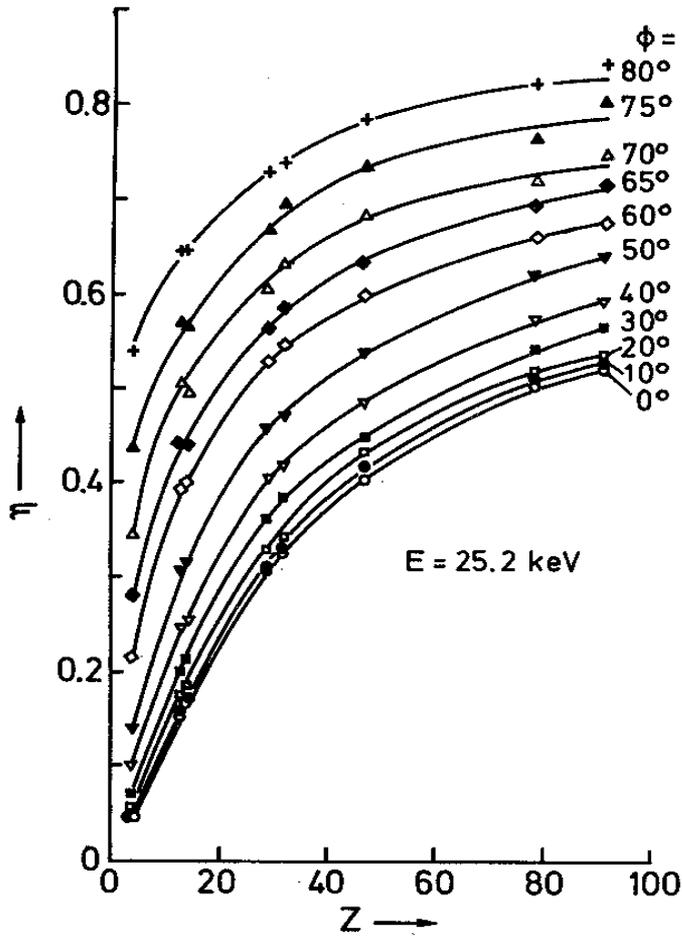


Fig. 4.7. Increase of the backscattering coefficient η of 25.2 keV electrons with increasing atomic number Z for different tilt angles ϕ ($\phi = 0$: normal incidence) [4.1]

$$\eta(Z, \Phi) = (1 + \cos \Phi) \frac{9}{\sqrt{Z}}$$

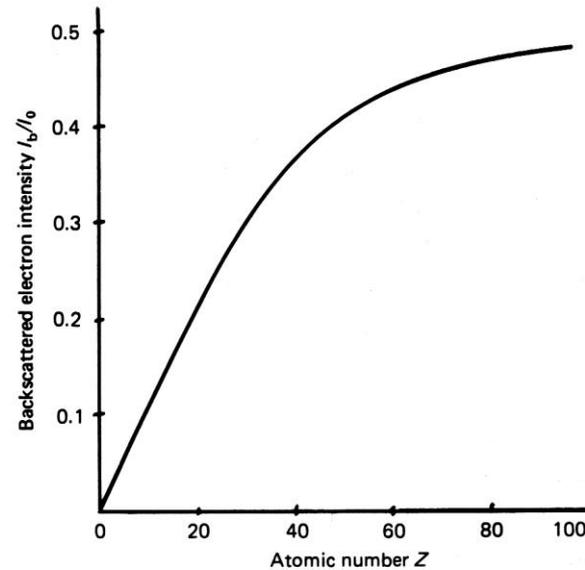


Abbildung mittels BSE: Auflösung

Table 5.1 Atomic number contrast

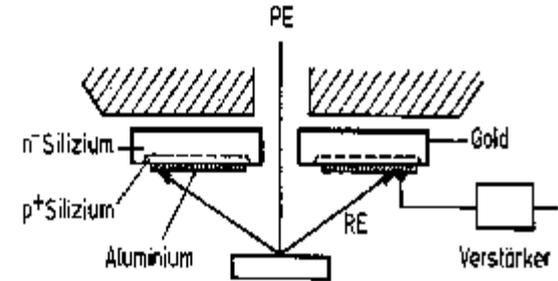
Phase <i>1</i>	Z_1	Phase <i>2</i>	Z_2	η_1	η_2	Contrast %	Resolution Degradation (nm)
Al	13	Mg	12	0.153	0.141	7.6	19
Al	13	Cu	29	0.153	0.304	49.4	5
Al	13	Pt	78	0.153	0.485	68.4	4
Cu	29	Zn	30	0.304	0.310	2.3	47
α -brass	29.4	β -brass	29.5	0.305	0.306	0.2	264

P.J. Goodhew, J. Humphreys, R. Beanland,
Electron Microscopy and Analysis, Tabelle 5.1

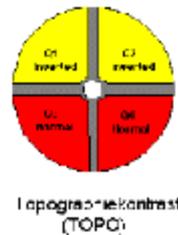
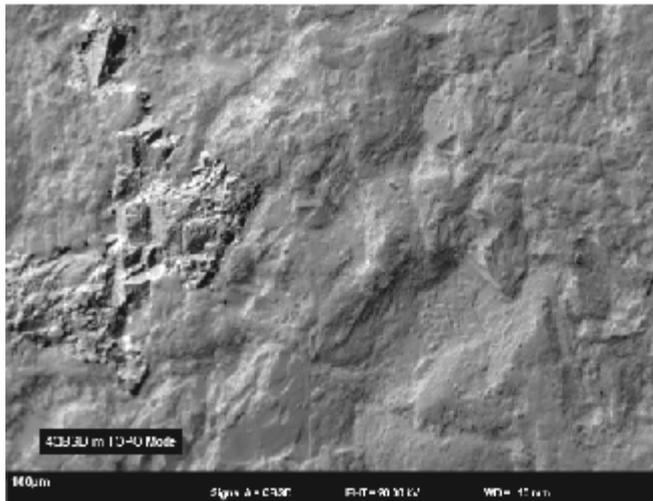
Atomzahl-Kontrast

$$C = \frac{\eta_1 - \eta_2}{\eta_1}$$

Abbildung mittels BSE: Zusammensetzung und Topographie



BSD detector



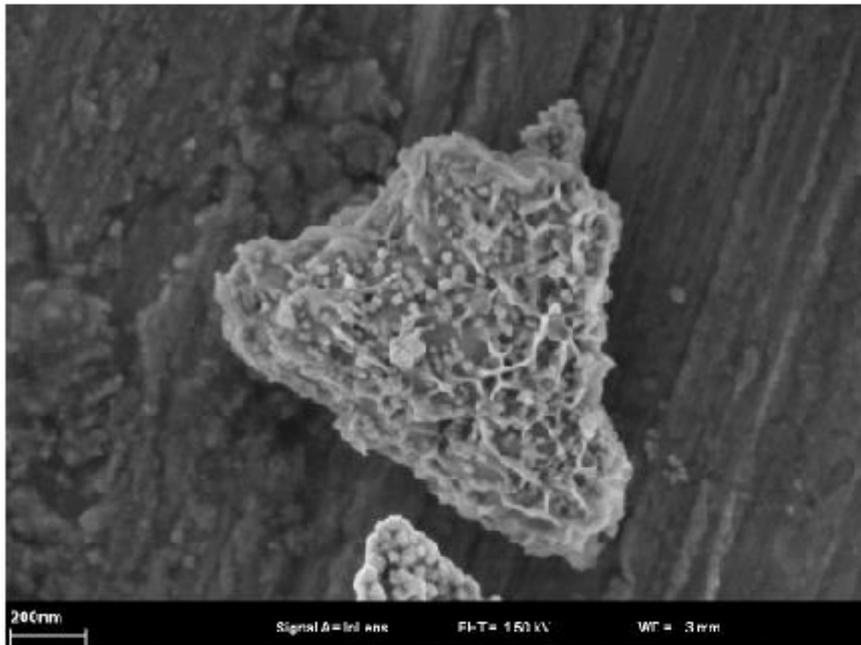
Topographischer Kontrast entsteht durch Subtraktion der Signale gegenüberliegender Teile des Detektors

Handbuch ZEISS Rasterelektronenmikroskop SUPRA, S.54 - 55

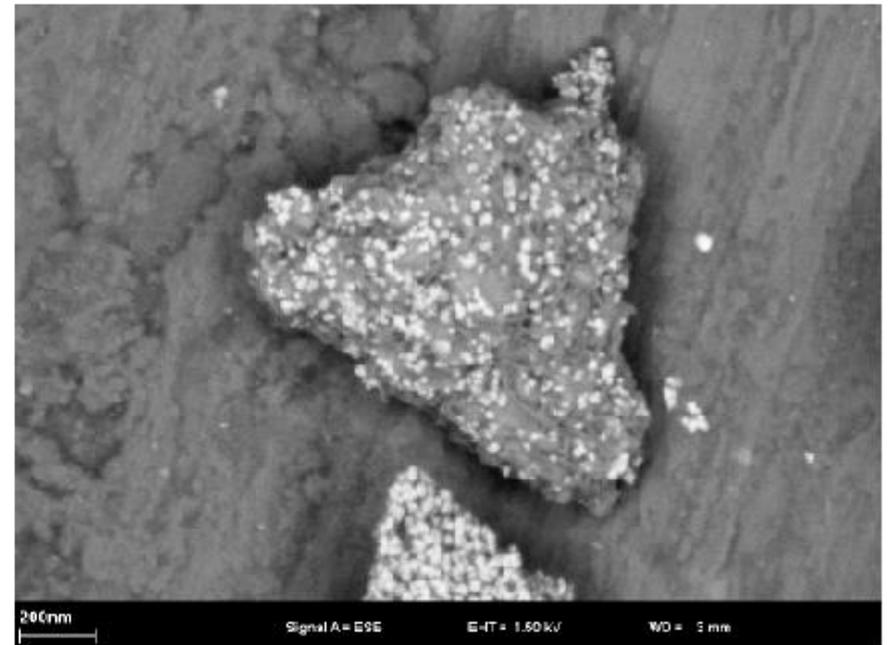
Abbildung mittels BSE

Unterschiede zw. topographischem and material- (Z-)abhängigem Kontrast in SE/BSE-Abbildungen

In-lens SE Detector



In-lens BSD Detector



Handbuch ZEISS Rasterelektronenmikroskop SUPRA, S. 44

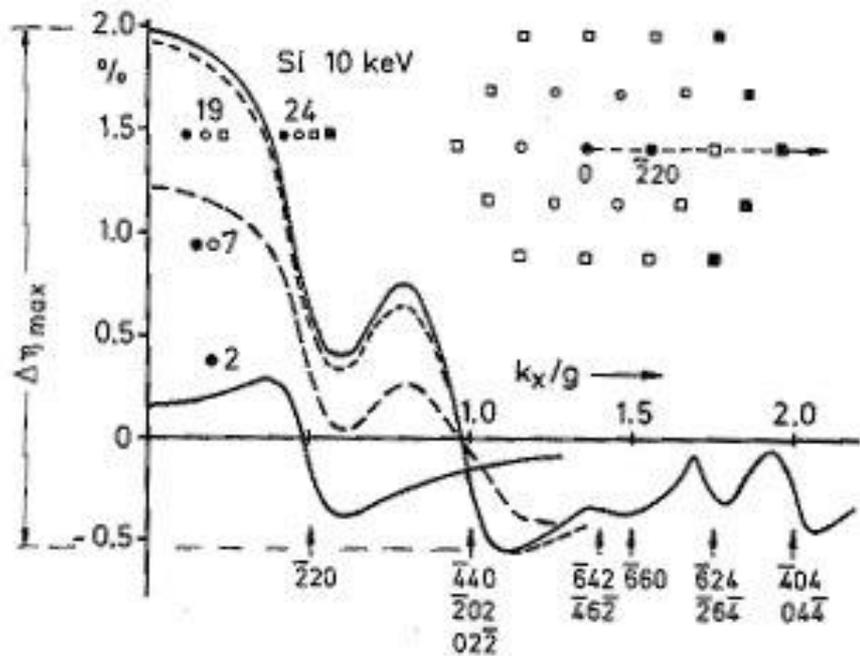


Fig. 8.16. Calculated variation $\Delta\eta$ of the backscattering coefficient from the centre of the 111 pole along the indicated line normal to the $\bar{2}20$ Kikuchi band and parallel to $g = \bar{2}20$ (see also Fig. 8.26a) for an increasing number n of beams in the dynamical theory

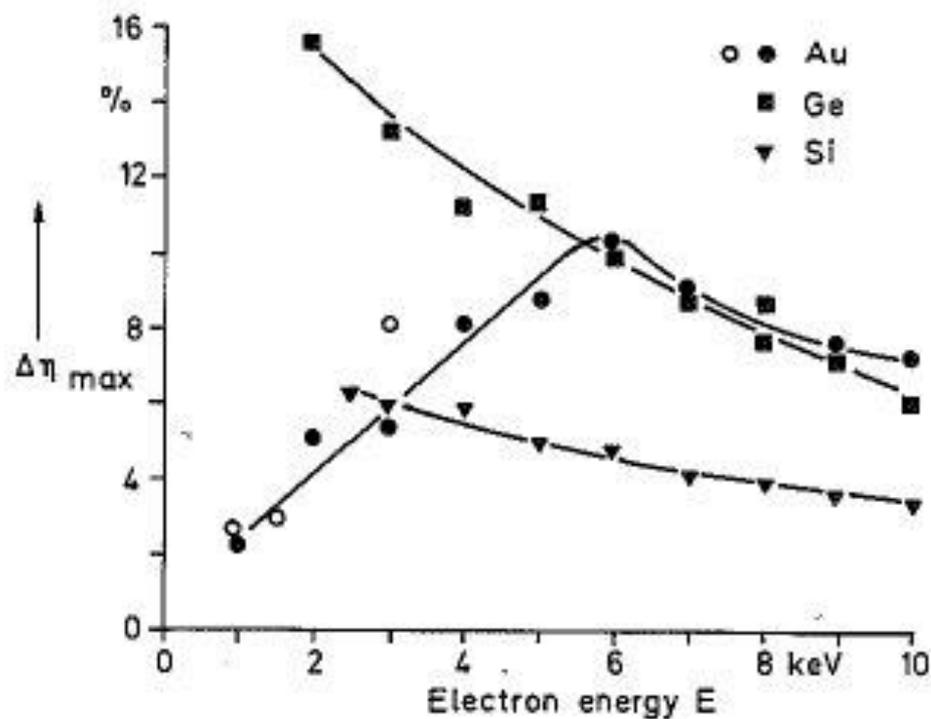


Fig. 8.17. Dependence of $\Delta\eta_{max}$ (Fig. 8.16) at the 111 pole of Si, Ge and Au on electron energy E

Abbildung mittels BSE: Orientierungskontrast (Channelling)

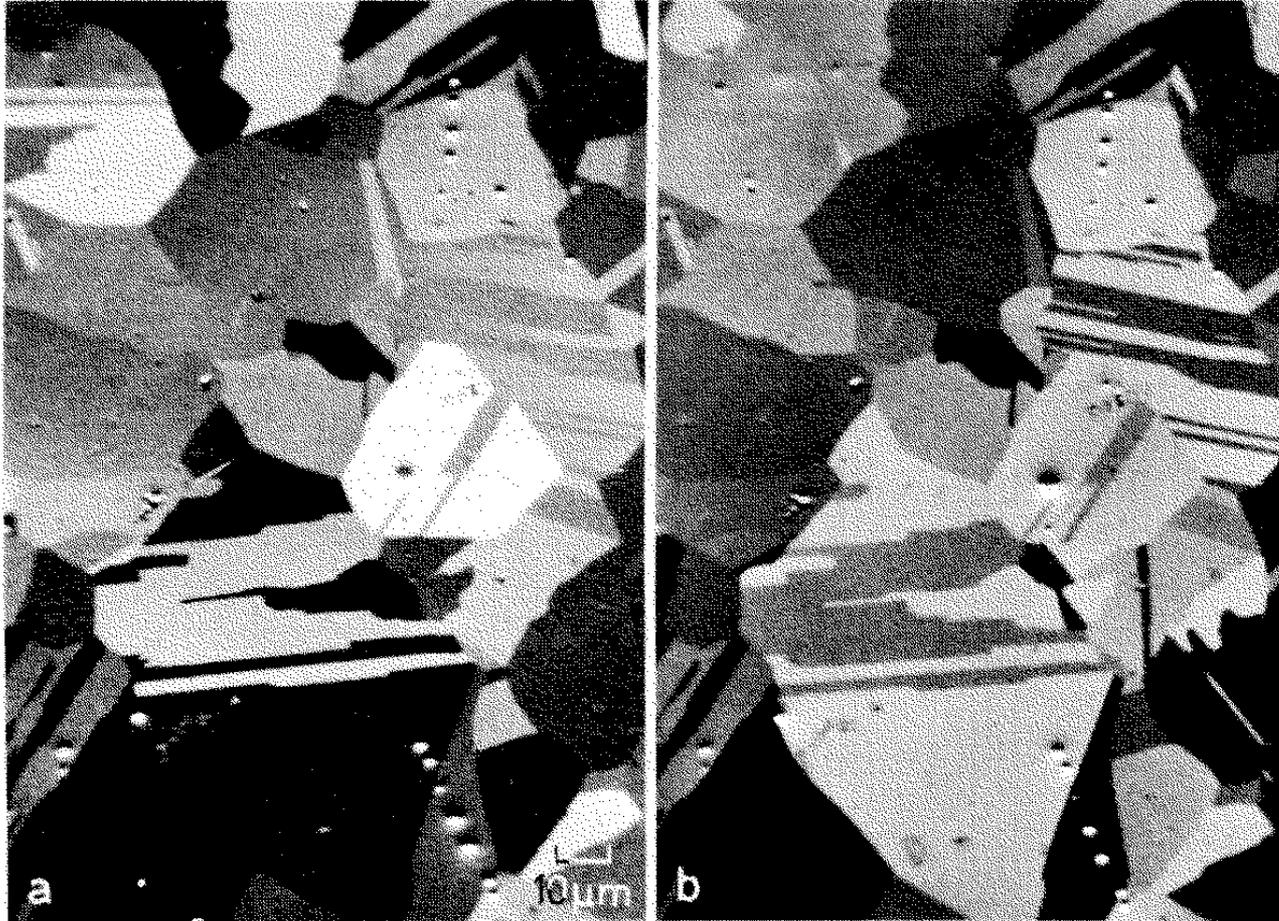
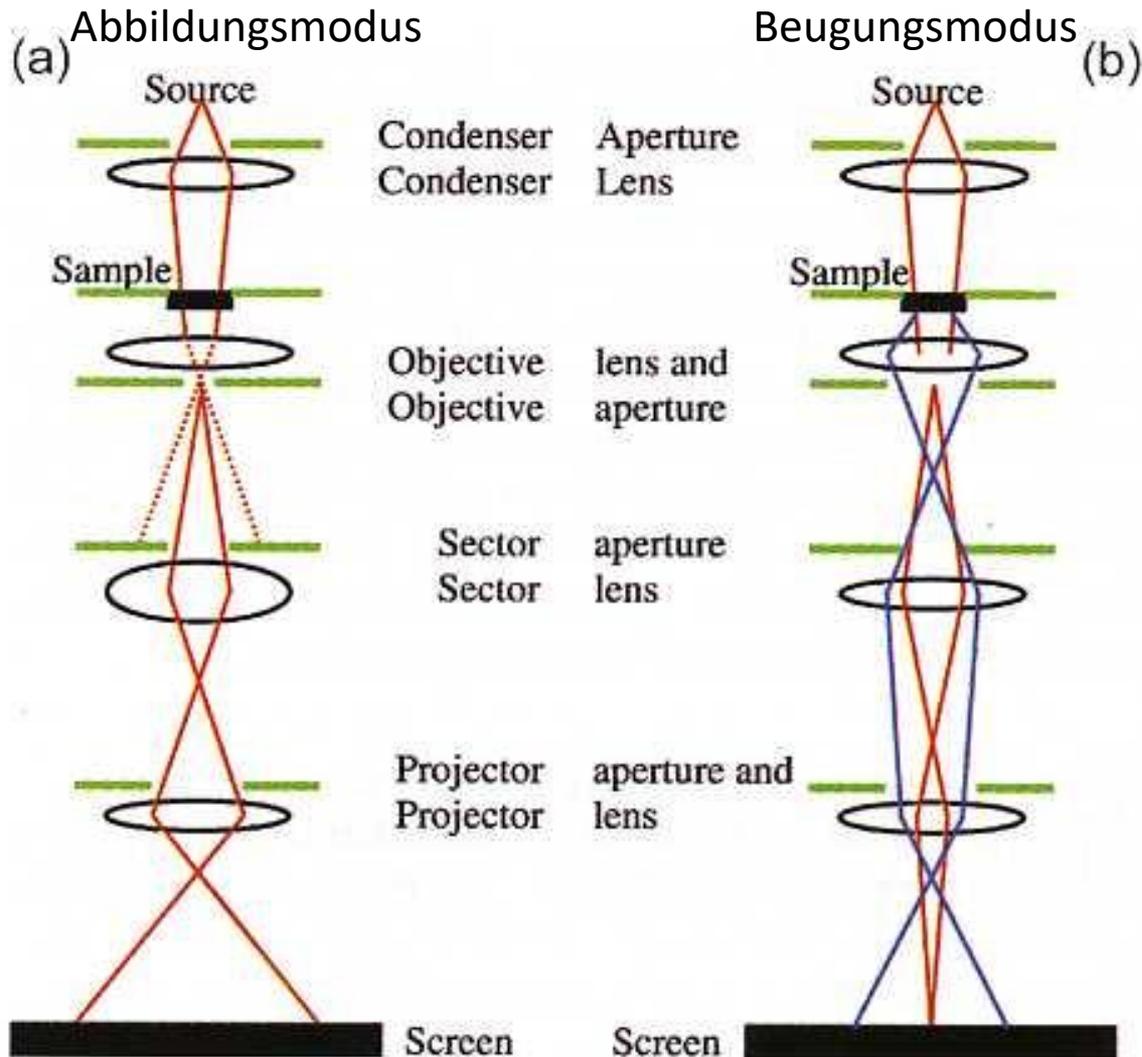
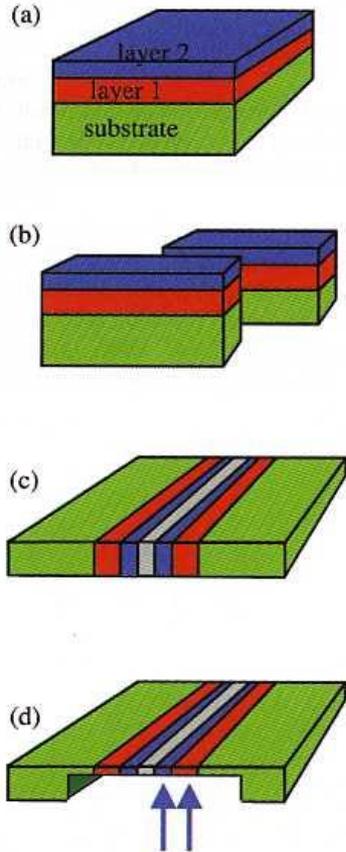


Fig. 6.17 a, b. Crystal orientation contrast in a BSE micrograph of an electrolytically polished, polycrystalline copper specimen. Note the change of contrast of single grains when the specimen is tilted through 1° between (a) and (b) [6.35]

Das Transmissionselektronenmikroskop (TEM)





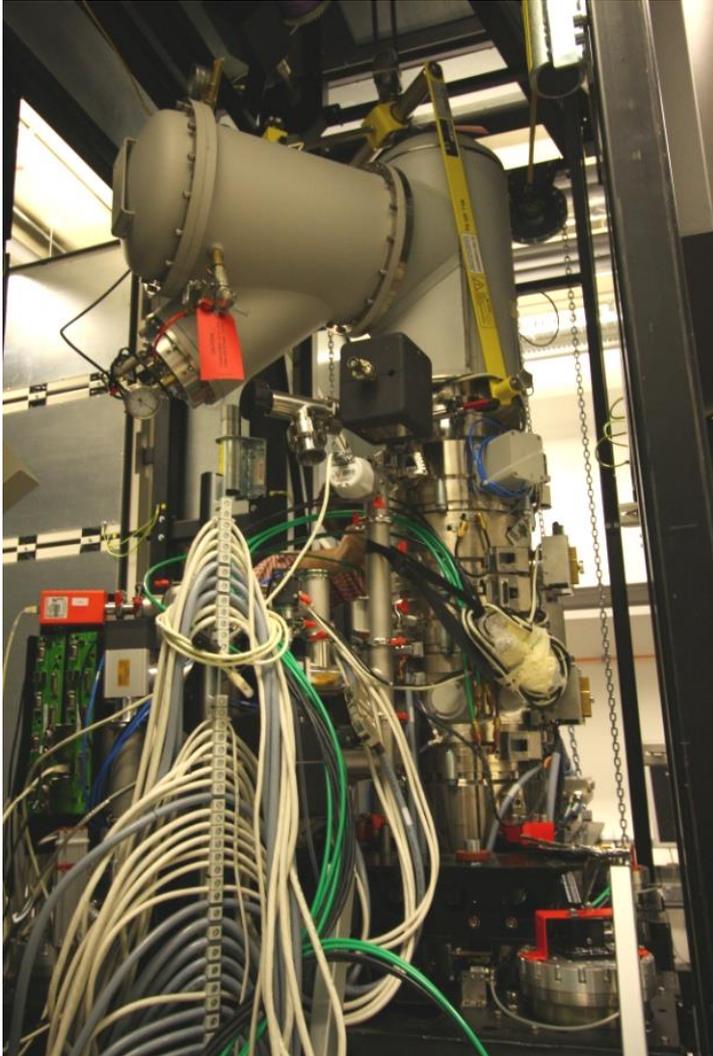
TEM-Probenpräparation durch

- Schneiden
- Polieren
- Ätzen
- Ionenstrahlen



Das Transmissionselektronenmikroskop (TEM)

FEI TITAN³ 80-300



Quelle: LEM-KIT

- räumliche Auflösung besser als 0.1 nm bei 300keV
- energiedispersive Röntgenanalyse (EDXS)
- Elektronenenergieverlustspektroskopie (EELS) auf sub-Nanometerskala
- Energieauflösung um 0.2 eV bei EELS
- Tomographie, Elektronenholographie

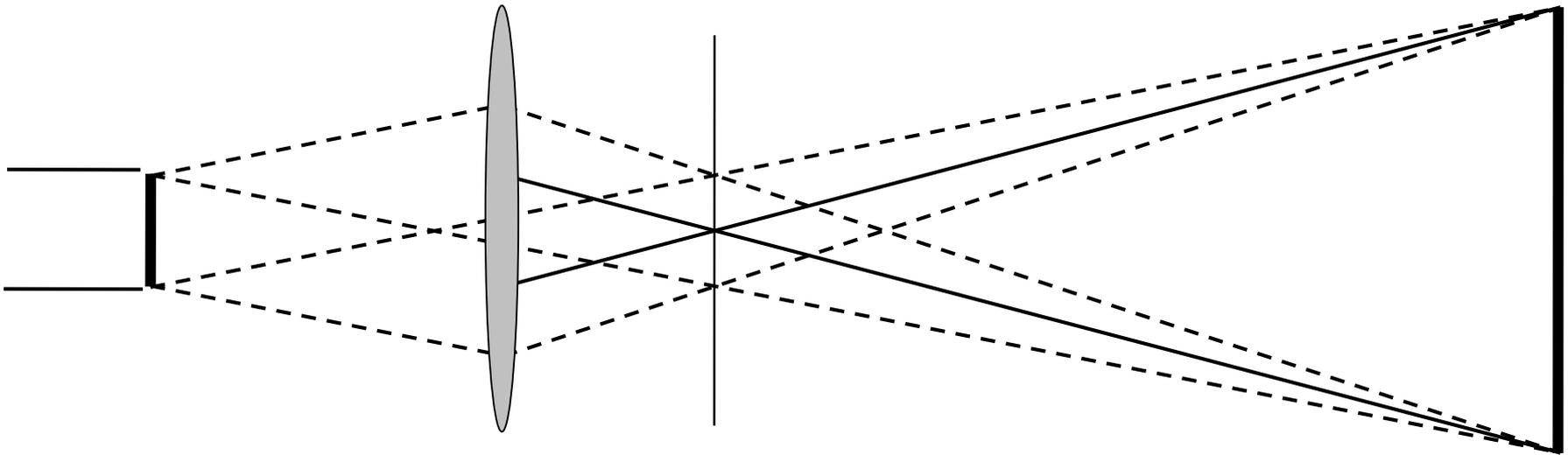


TEM Abbildungsmodus

Objekt

Linse

Bildebene



Objektwelle: $\Psi_o(\mathbf{r})$

$F[\Psi_o(\mathbf{r})] \cdot T(\mathbf{u})$

Bild: $\Psi_o(\mathbf{r}') * F^{-1}[T(\mathbf{u})]$

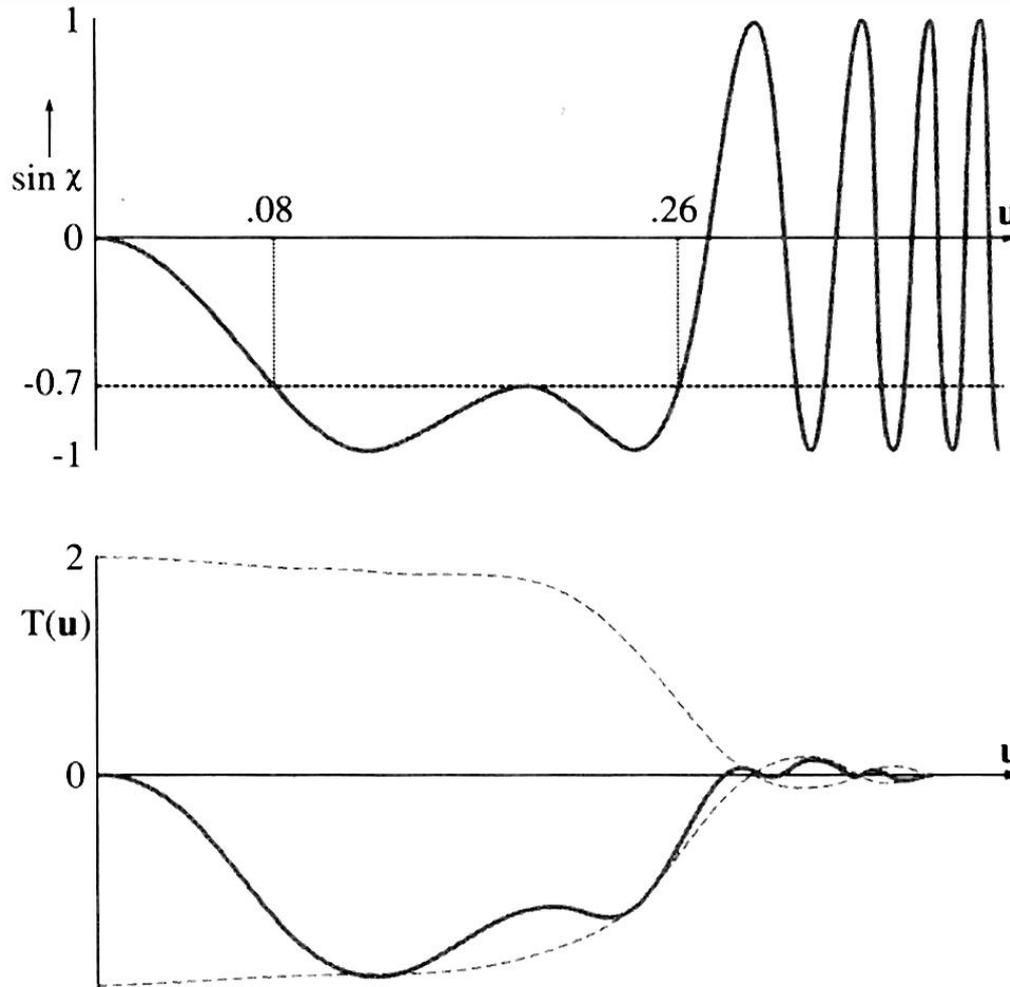
Fourier Transformation

inverse Fourier Transformation

Faltung!

Kontrasttransferfunktion $T(\mathbf{u}) = A(\mathbf{u}) \cdot E(\mathbf{u}) \cdot \exp(i\chi(\mathbf{u}))$; $\chi(\mathbf{u}) = (\pi/\lambda) (\Delta f \cdot \mathbf{u}^2 + C_s/2 \cdot \mathbf{u}^4)$

Kontrasttransferfunktion



Williams, Carter, Transmission Electron Microscopy, p. 467

Einfluss von Defokussierung auf Phasenfaktor am Beispiel Si in [011]-ZA

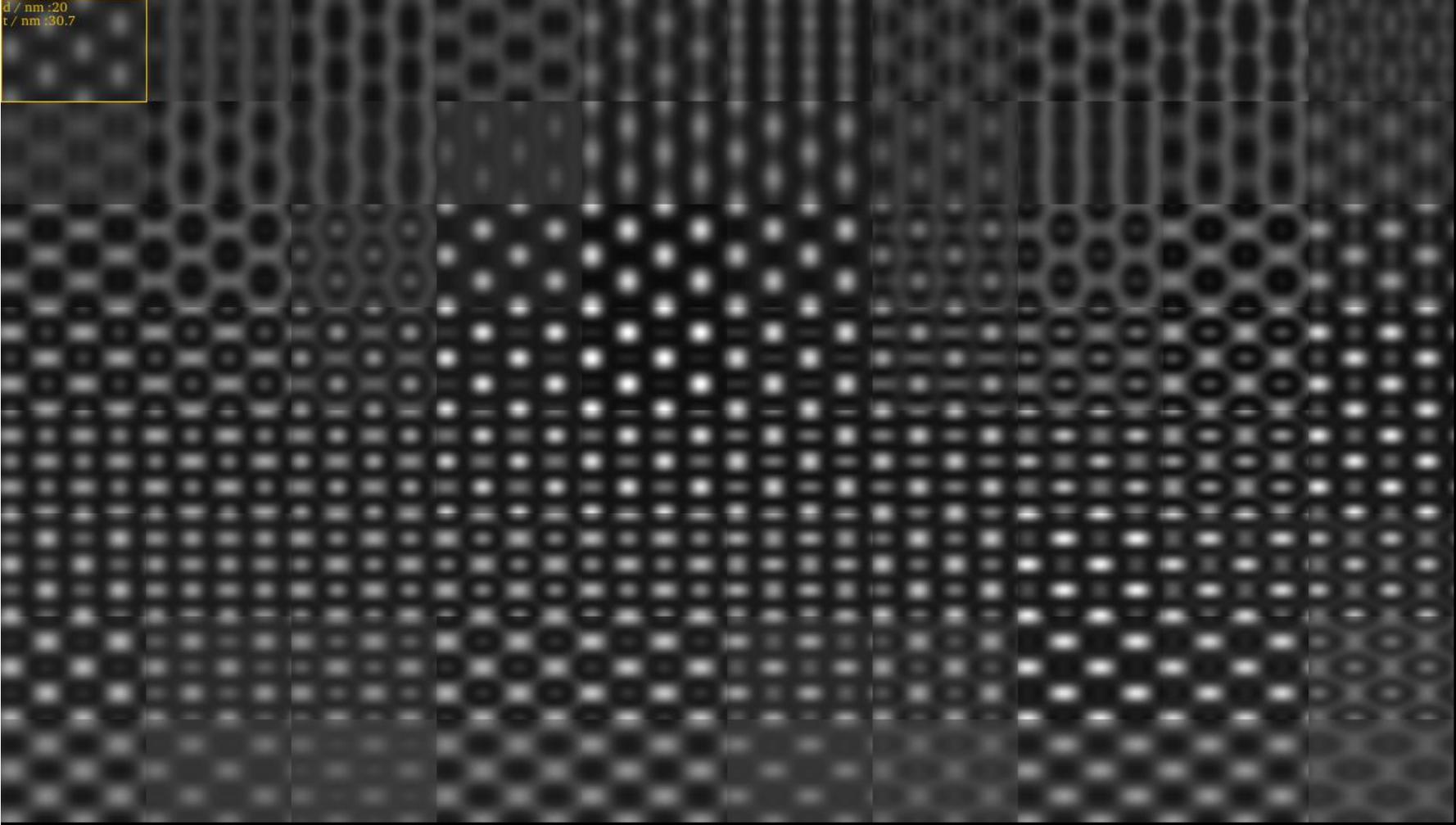
$\Delta f = -20 \text{ nm}$

$t = 30,7 \text{ nm}$

$\Delta f = -120 \text{ nm}$

d / nm : 20
t / nm : 30,7

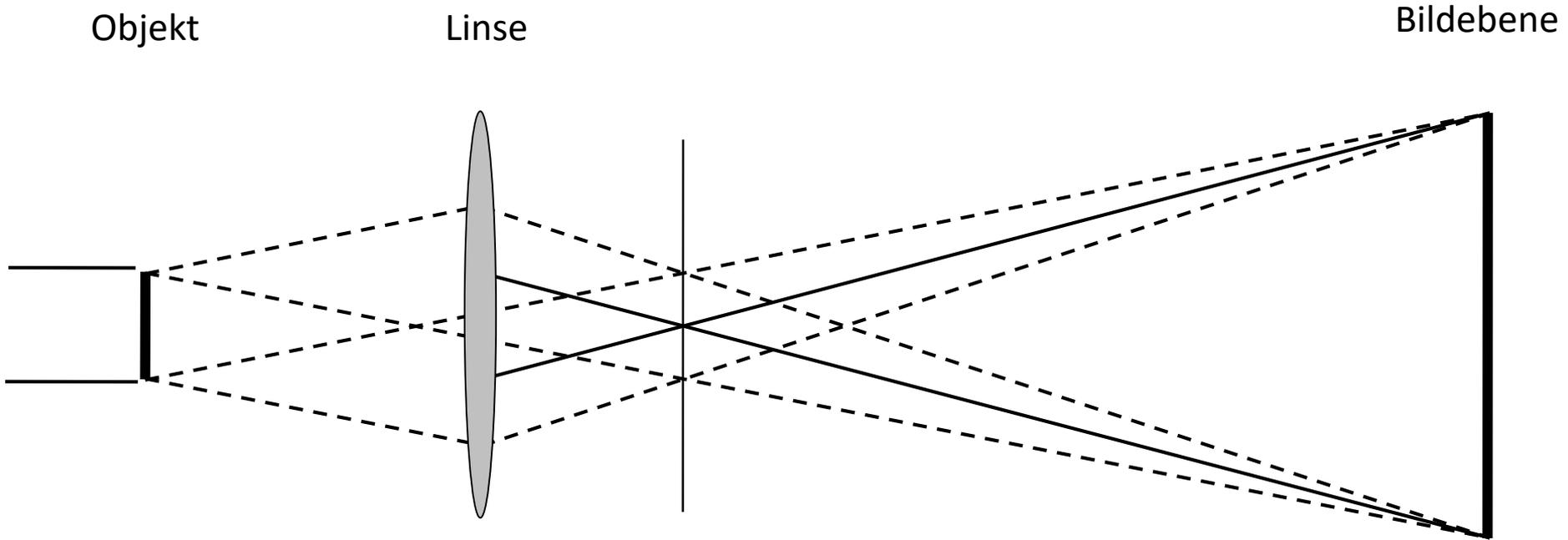
↑
Probendicke



$t = 3,8 \text{ nm}$

Defokussierung

TEM Abbildungsmodus



Objektwelle: $\Psi_o(\mathbf{r})$

$F[\Psi_o(\mathbf{r})] \cdot T(\mathbf{u})$

Bild: $\Psi_o(\mathbf{r}') * F^{-1}[T(\mathbf{u})]$



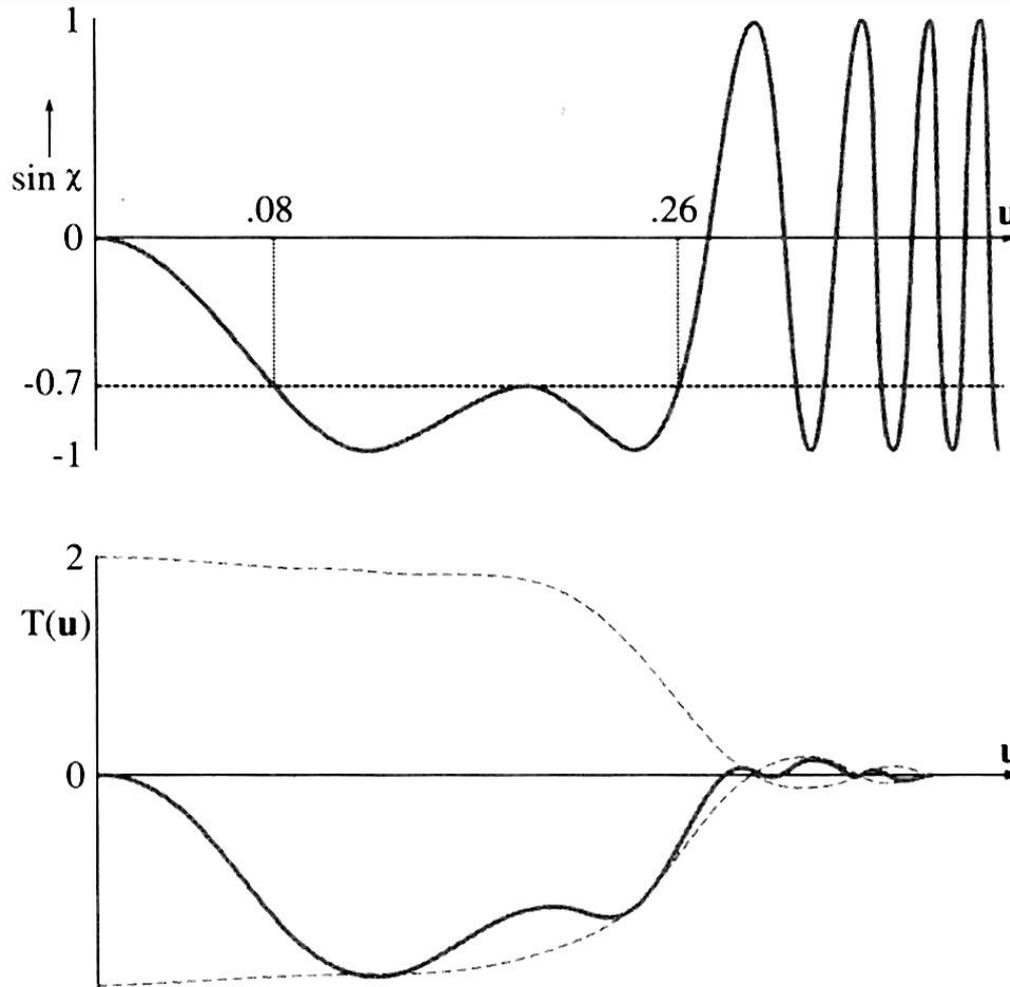
Fourier Transformation

inverse Fourier Transformation

Faltung!

Kontrasttransferfunktion $T(\mathbf{u}) = A(\mathbf{u}) \cdot E(\mathbf{u}) \cdot \exp(i\chi(\mathbf{u}))$; $\chi(\mathbf{u}) = (\pi/\lambda) (\Delta f \cdot \mathbf{u}^2 + C_s/2 \cdot \mathbf{u}^4)$

Kontrasttransferfunktion



Williams, Carter, Transmission Electron Microscopy, p. 467

Einfluss von Defokussierung auf Phasenfaktor am Beispiel Si in [011]-ZA

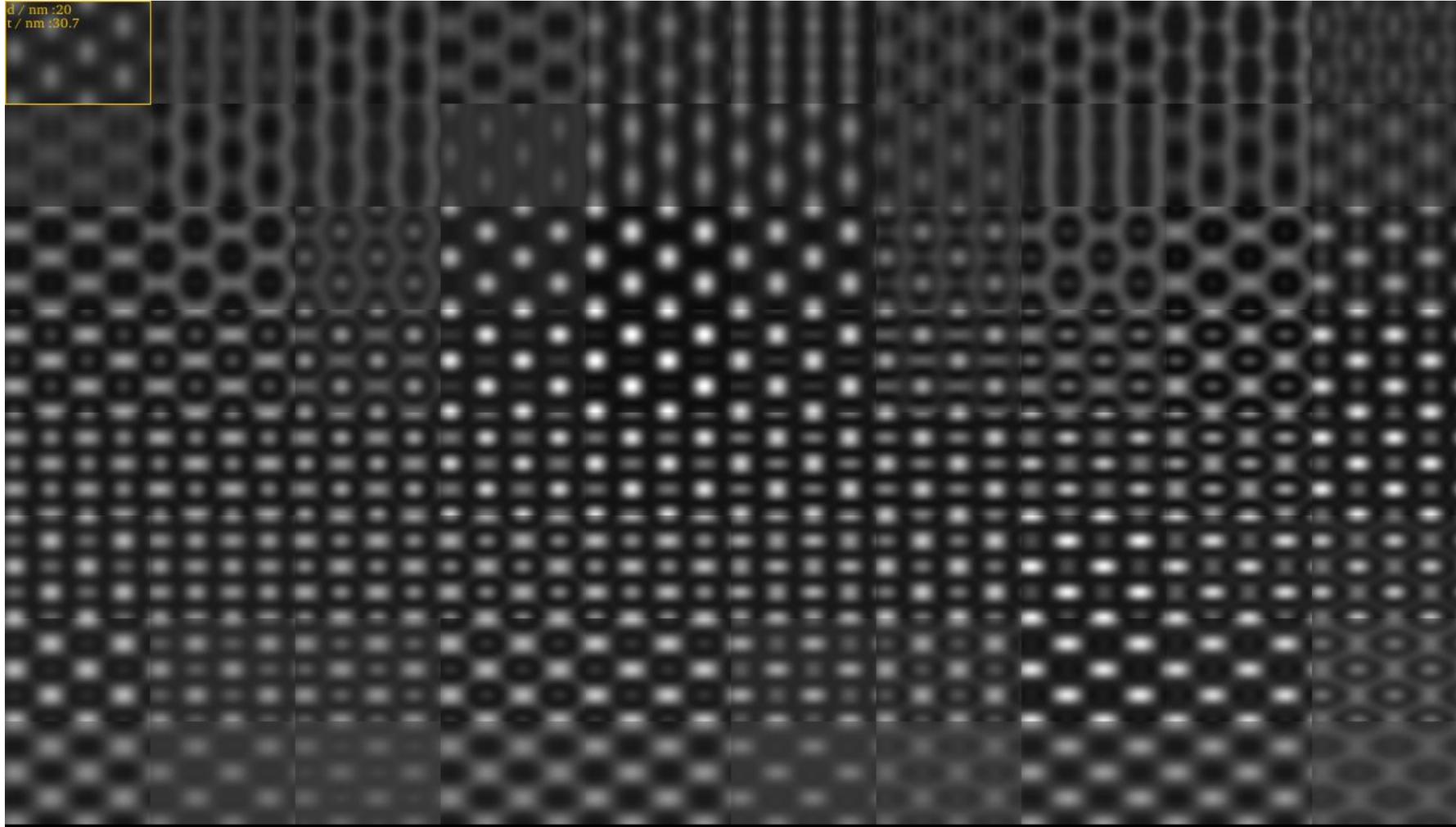
$\Delta f = -20$ nm

$t = 30,7$ nm

$\Delta f = -120$ nm

d / nm : 20
t / nm : 30,7

↑
Probendicke



$t = 3,8$ nm

Defokussierung

Quantifizierung von HRTEM Abbildungen

Präzise Messung von Atomsäulenpositionen

heller Atomkontrast, $C_s < 0$, $Z > 0$, Probendicke wenige nm (verifiziert durch Bildsimulationen)

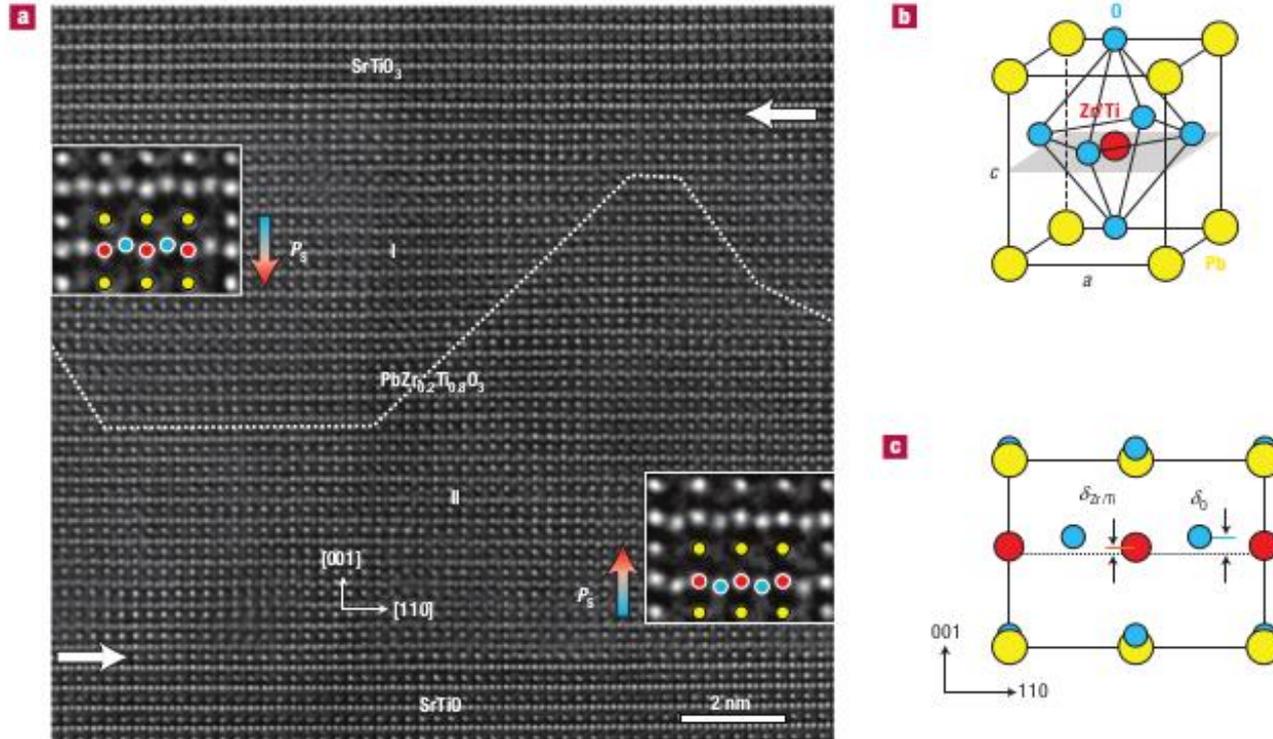
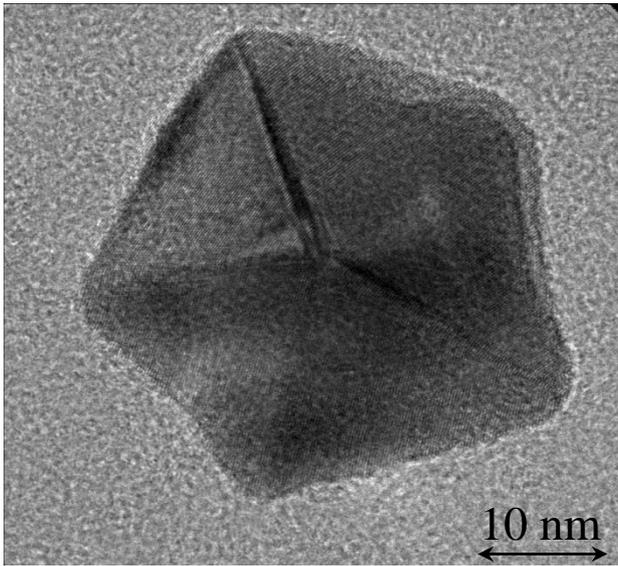


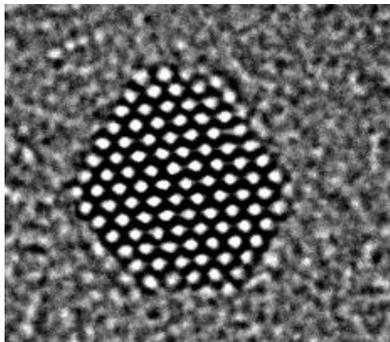
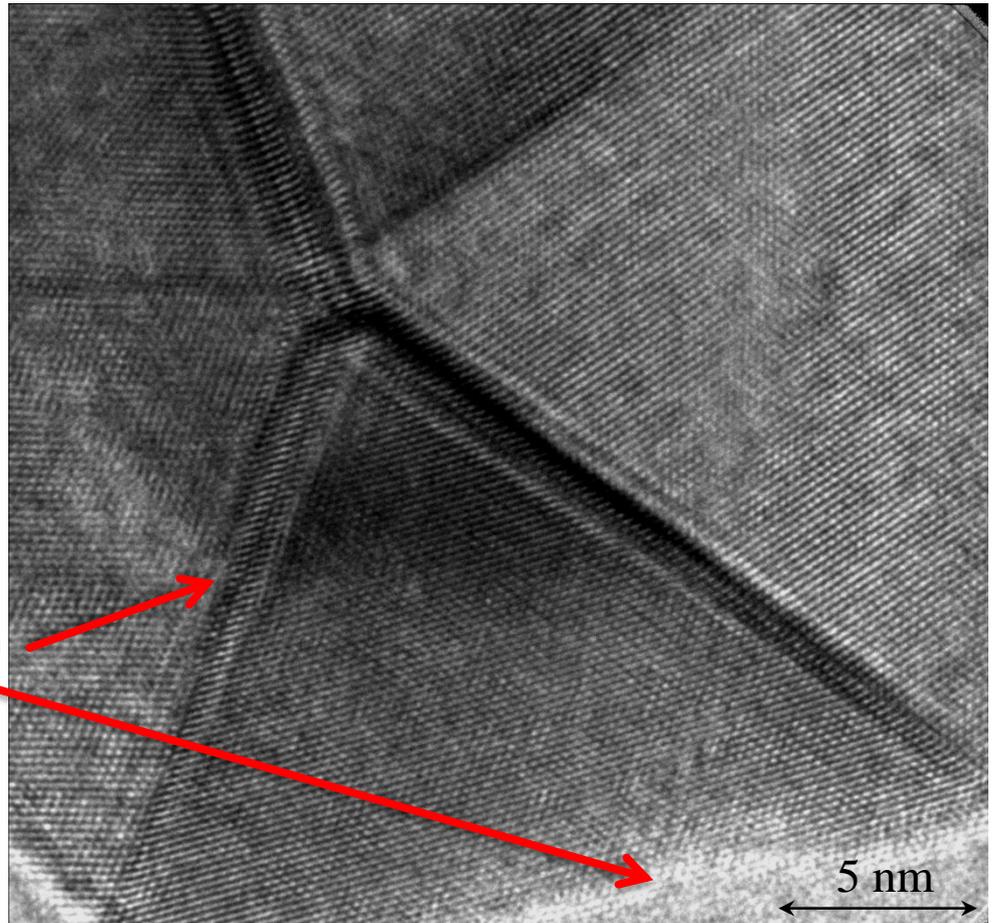
Figure 1 Atomic-scale imaging of the electric dipoles formed by the relative displacements of the Zr/Ti cation columns and the O anion columns. **a**, Image of a SrTiO₃/PbZr_{0.2}Ti_{0.8}O₃/SrTiO₃ thin-film heterostructure. The image is recorded under negative spherical-aberration imaging conditions with the incident electron beam parallel to the $[\bar{1}10]$ direction. The atom columns appear bright on a dark background. The horizontal arrows denote the horizontal interfaces between the PbZr_{0.2}Ti_{0.8}O₃ and the top and the bottom SrTiO₃ film layers. The dotted line traces the 180° domain wall. The arrows denoted by 'P_s' show the directions of the polarization in the 180° domains. The insets show magnifications of the dipoles formed by the displacements of ions in the unit cells (yellow: PbO, red: Zr/Ti, blue: O). **b**, Schematic perspective view of the unit cell of ferroelectric PbZr_{0.2}Ti_{0.8}O₃. **c**, Projection of the unit cell along the $[\bar{1}10]$ direction. $\delta_{Zr/Ti}$ and δ_O denote the shifts of the Zr/Ti atoms and the oxygen atoms, respectively, from the centrosymmetric positions.

Jia et al., Nat. Mat. (2008)

Delokalisierung am Beispiel von HRTEM an Pt-Nanoteilchen



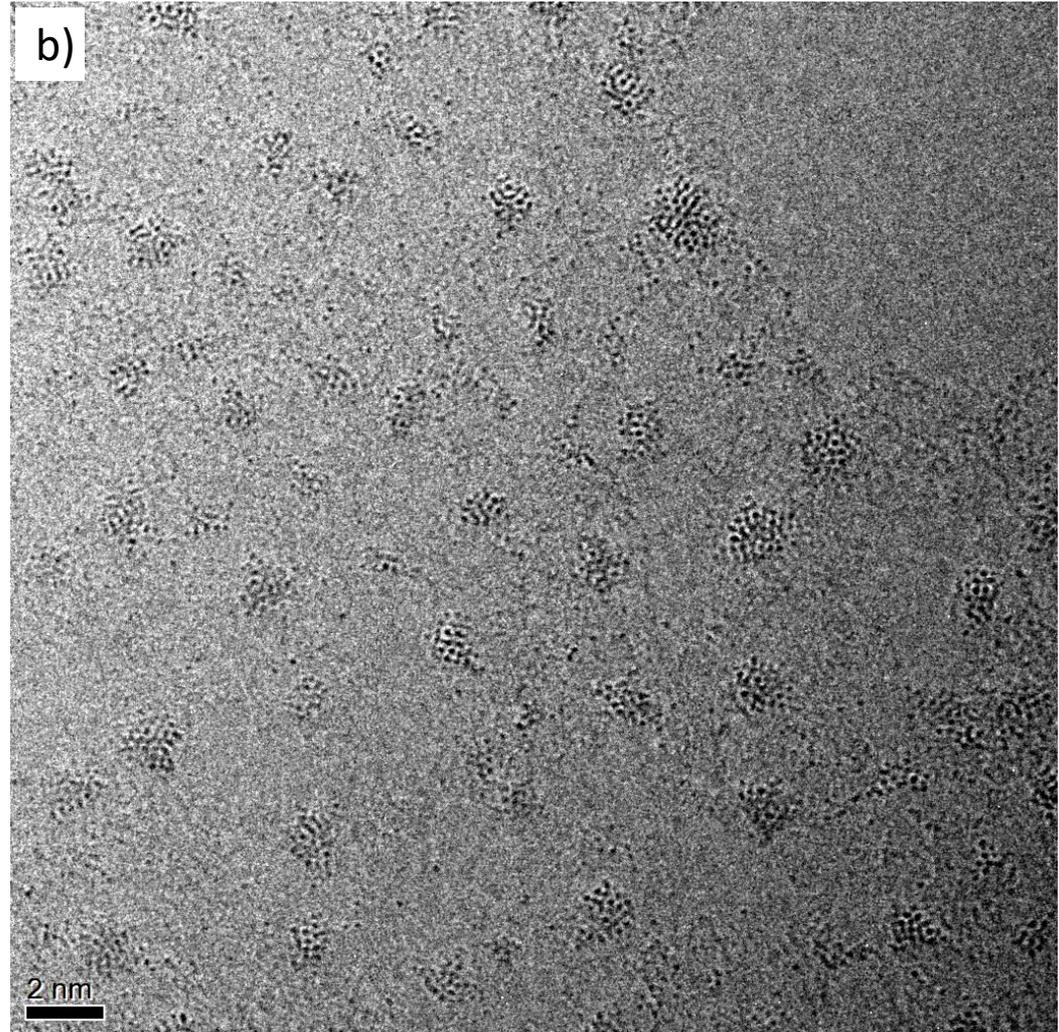
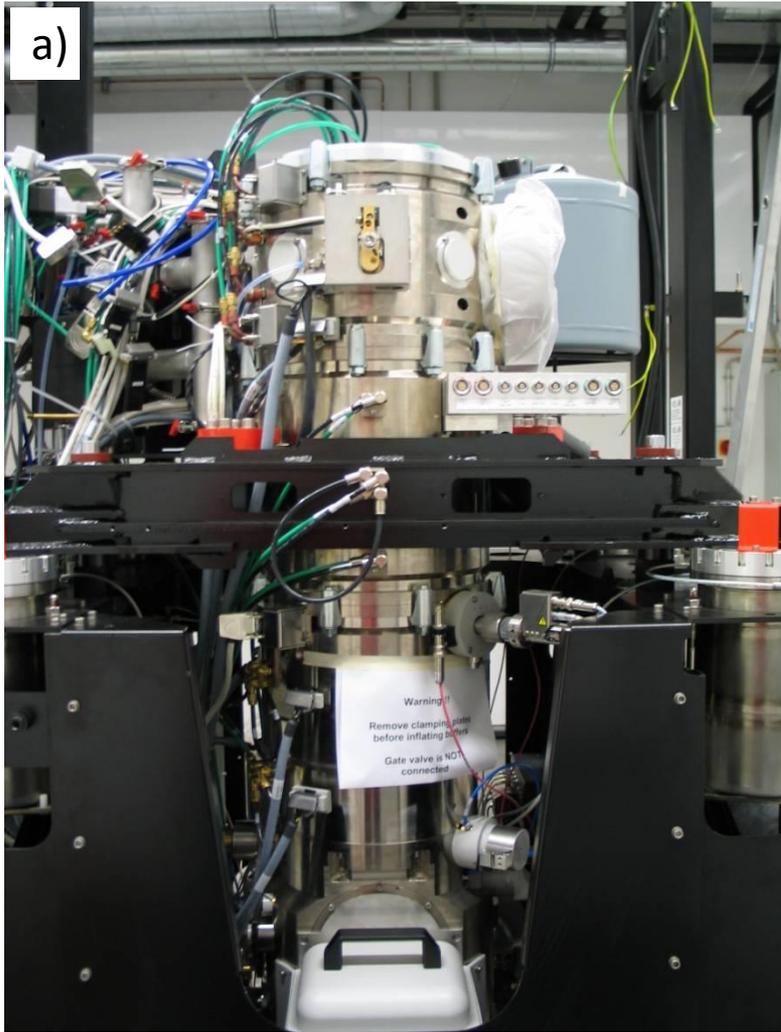
Kontrastverschmierung an Grenzflächen
(Delokalisierung) durch Öffnungsfehler



Bei $C_s < 1 \mu\text{m}$ keine Delokalisierung sichtbar

R. Schneider (LEM)

Hochauflösende Elektronenmikroskopie



HRTEM mit einem C_s -korrigierten FEI TITAN 80-300 (LEM, KIT Campus Süd); a) Foto des C_s -Korrektors, b) HRTEM-Abbildung von einzelnen Pt-Atomen und -Clustern (R. Schneider, LEM)

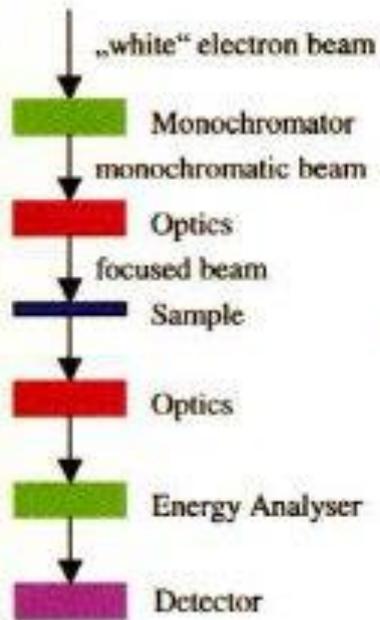
		Emitted and analyzed response		
		Electrons	Ions	Photons
Incident excitation probe	Electrons	TEM, SEM LEEM EELS AES		IPES EDX
	Ions		RBS SIMS	
	Photons	XPS PEEM		XRD EXAFS XRF Ellipso- metry

Table 1: Selected near surface sensitive investigation methods.

Abbreviations:

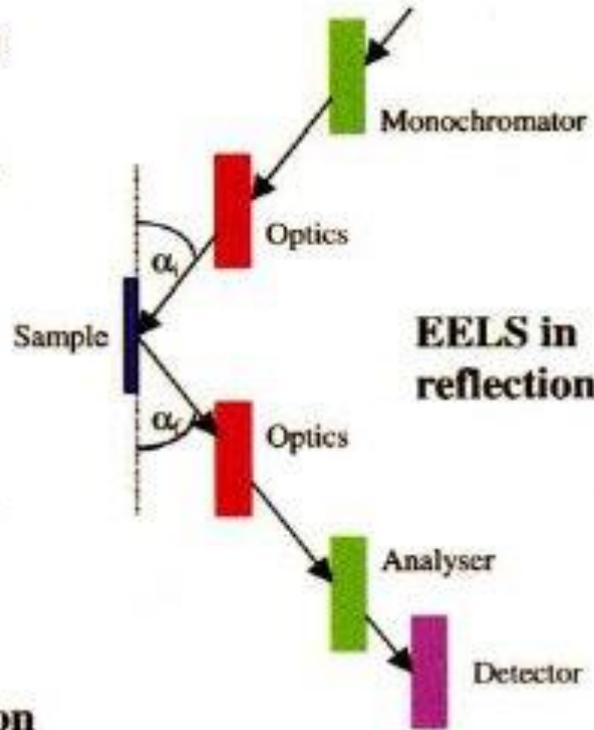
- TEM: Transmission Electron Microscopy
- SEM: Scanning Electron Microscopy
- LEEM: Low Energy Electron Microscopy
- EELS: Electron Energy Loss Spectroscopy
- AES: Auger Electron Spectroscopy
- IPES: Inverse Photo Electron Spectroscopy
- EDX : Energy Dispersive X-ray Analysis
- RBS: Rutherford Backscattering Spectrometry
- SIMS: Secondary Ion Mass Spectrometry
- XPS: X-ray Photoelectron Spectroscopy
- PEEM: Photo Emission Electron Microscopy
- XRD: X-Ray Diffraction
- XRF: X-Ray Fluorescence
- EXAFS: Extended X-ray Absorption Fine Structure

Elektronenenergieverlust-Spektroskopie

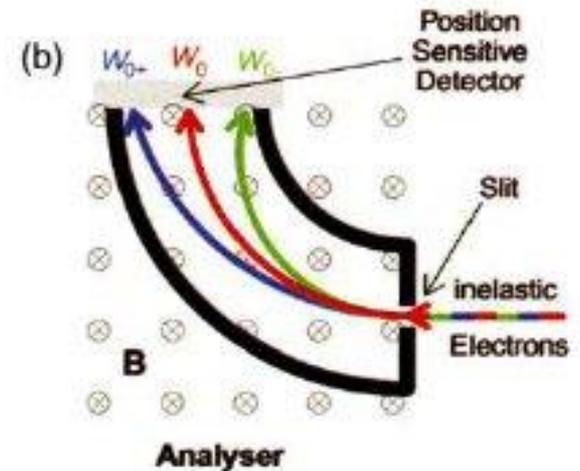
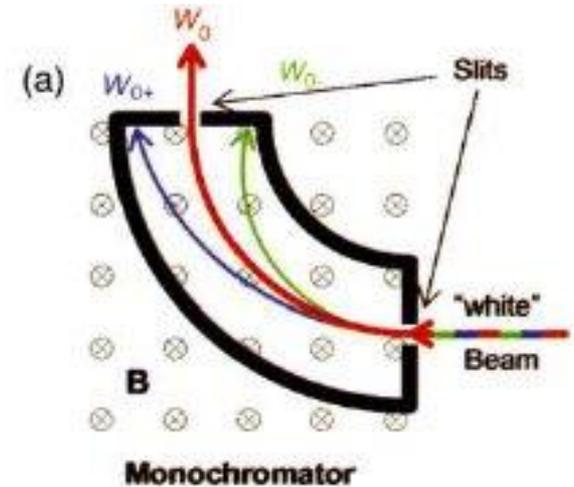


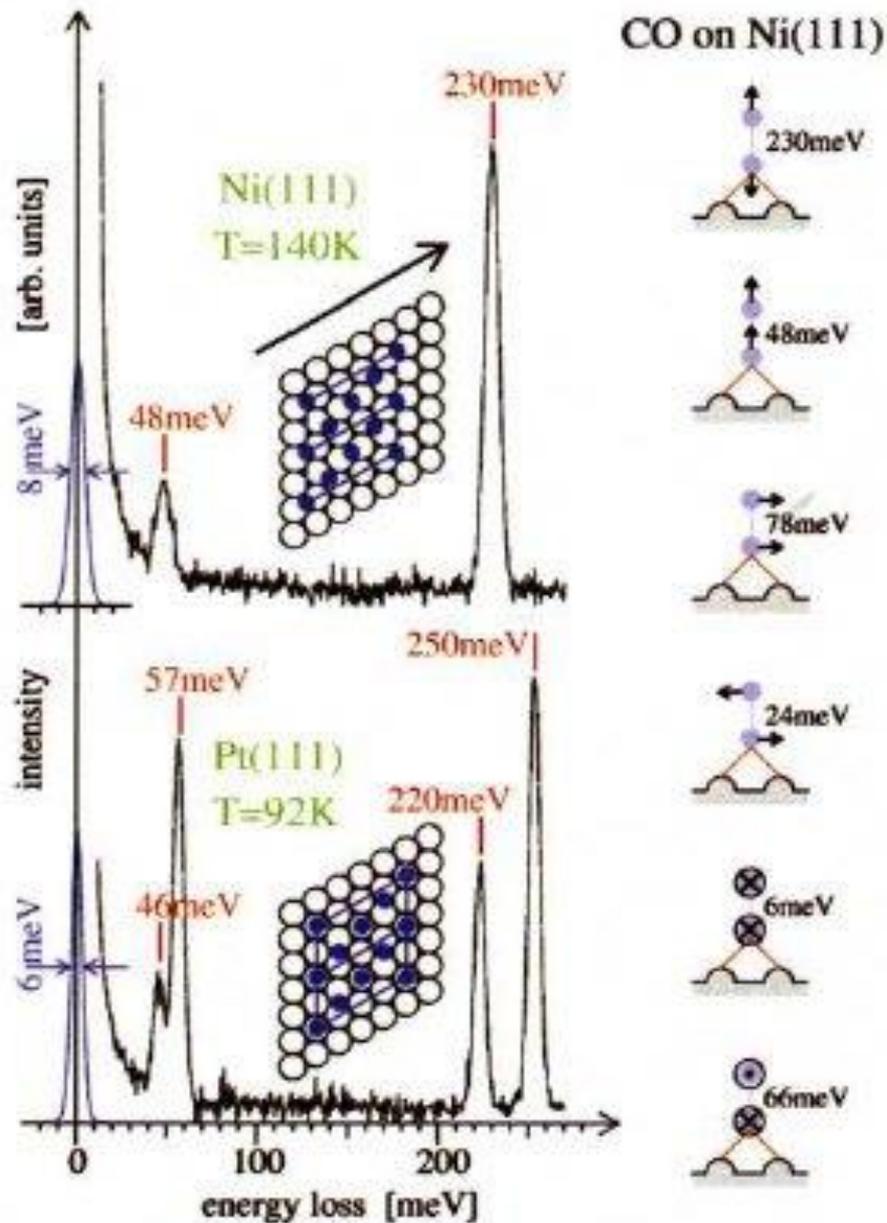
EELS in transmission

„bulk“-sensitiv, zur Untersuchung mittlerer und hoher Energieverluste



oberflächensensitiv, zur Untersuchung kleiner Energieverluste





HREELS-Spektrum von adsorbierten CO-Molekülen auf Ni (111) bzw. Pt (111) Oberflächen

Auf Grund von Dipolauswahlregeln werden nur senkrechte Moden angeregt

Unterschiedliche Lagesymmetrie der CO-Moleküle auf Pt und Ni

→ unterschiedliche Spektren

Röntgen-Photoelektronen-Spektroskopie (XPS)/ Auger-Elektronen-Spektroskopie (AES)

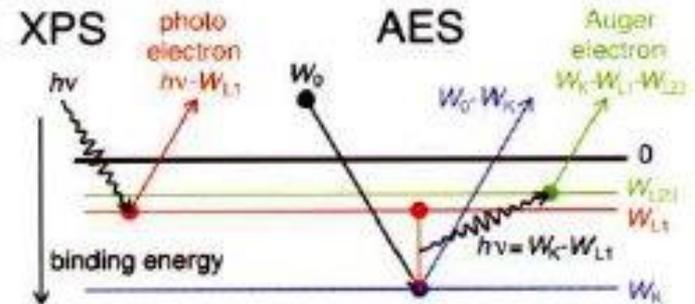
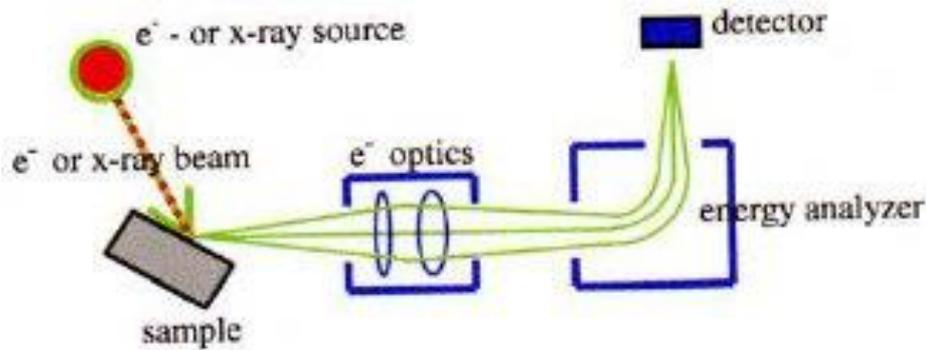
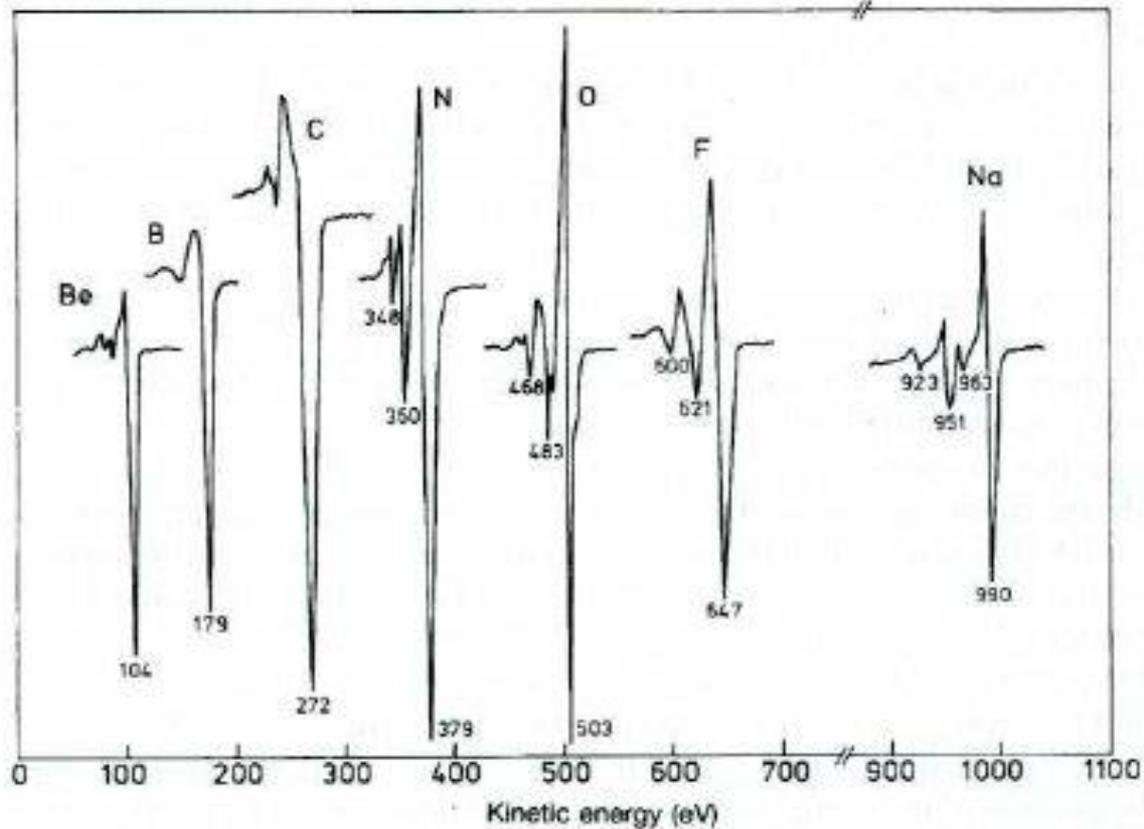


Figure 28: Schemes of the processes which occur for XPS (left hand side) and AES (right hand side) experiments. XPS requires a photon of known energy $h\nu$. The removed photoelectron carries the energy $W_{h\nu} - W_{br}$. For the Auger process in this example a K-electron is removed by the incident electron. The vacancy is filled by an L1-electron which transfers its energy via a photon to an L23-electron to kick it out of the atom. The energy of the Auger electron is $W_K - W_{L1} - W_{L23}$.

Auger-Elektronen-Spektroskopie (AES) leichter Elemente



der jeweils größte peak resultiert aus einem K-L1-L23-Übergang

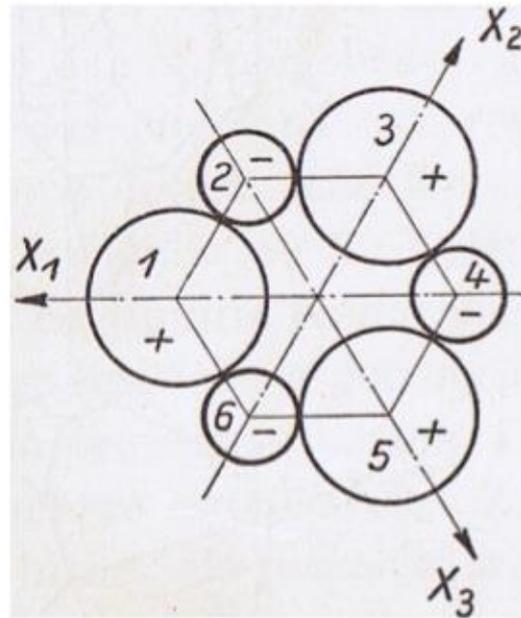
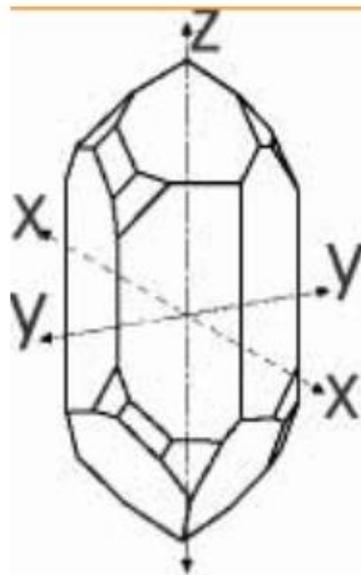
Grundlegendes zum Piezoelektrischen Effekt

- 1880 Brüder Curie entdecken Piezoelektrizität
(piezo griech.: Druck)
- 1881 Entdeckung des reziproken Piezoeffekt



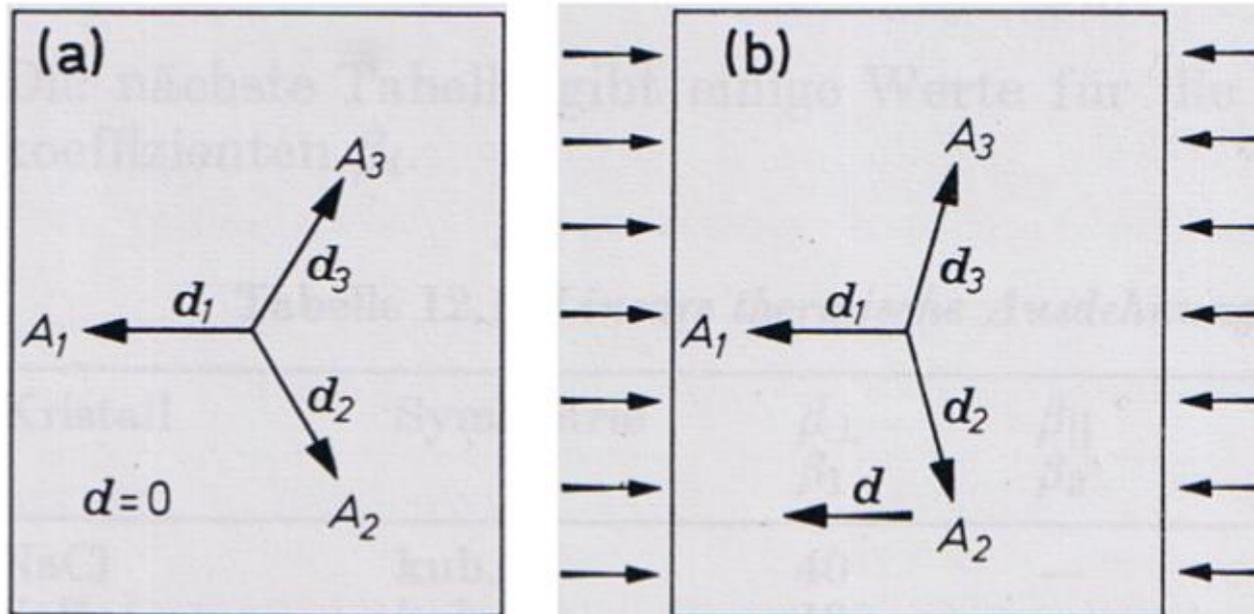
Polare Achse

- Ein Kristall gilt als polar, wenn sein Dipolmoment ungleich Null ist, bzw. wenn der Kristall nicht inversions-symmetrisch ist.
- Zu jeder polaren Achse gibt es auch eine neutrale Achse.



Polare Achse

Deformation (rechts) erzeugt ein Netto-Dipolmoment

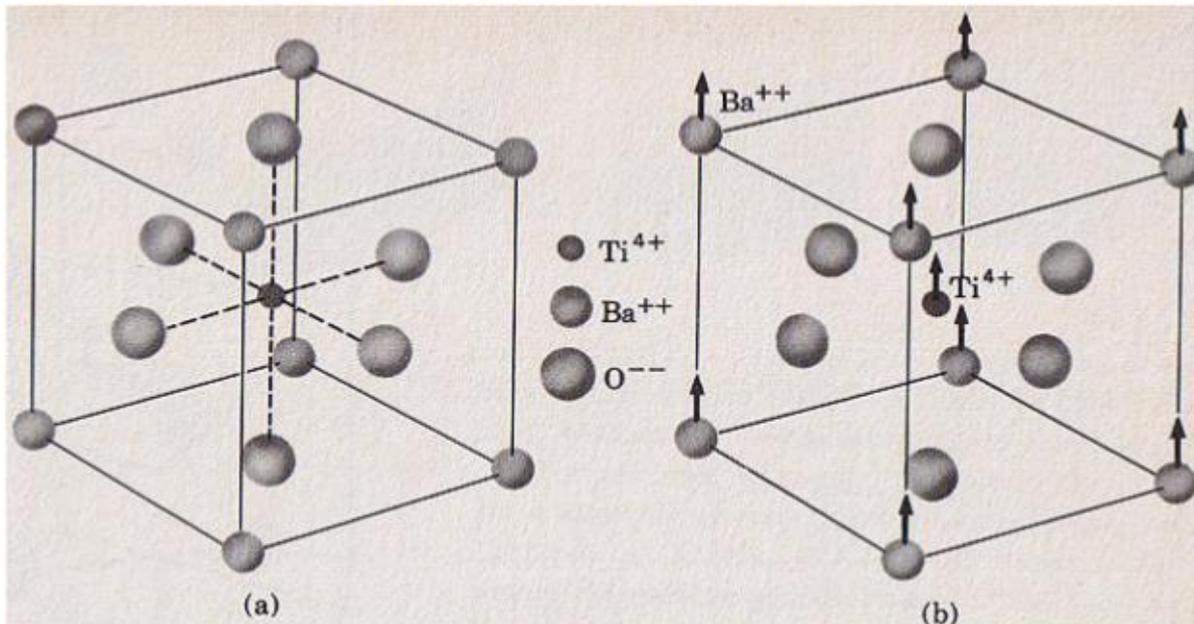


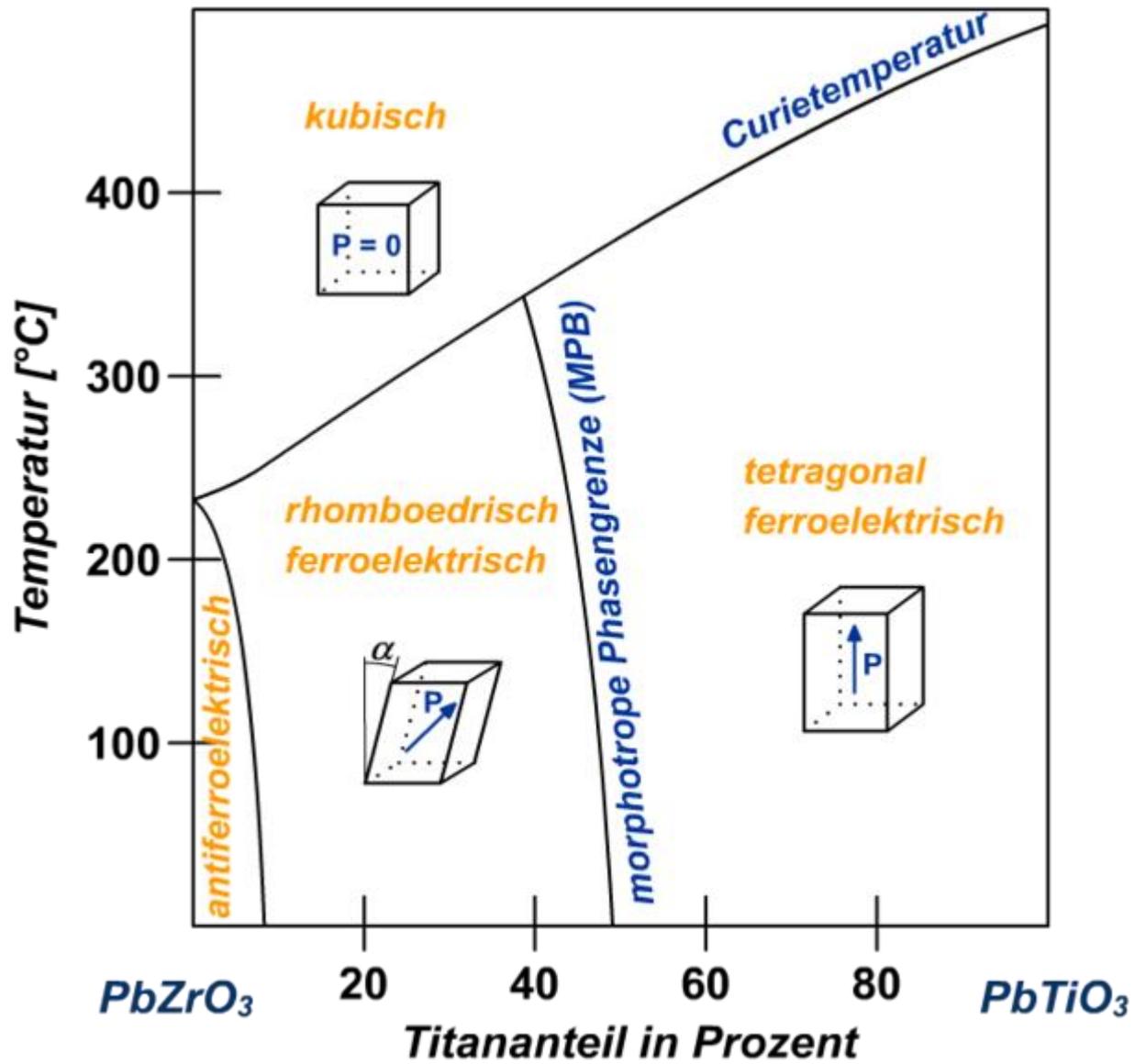
Ferroelektrika

...sind Materialien, die aufgrund einer strukturellen Verschiebung unterhalb einer kritischen Temperatur eine polare Achse besitzen.

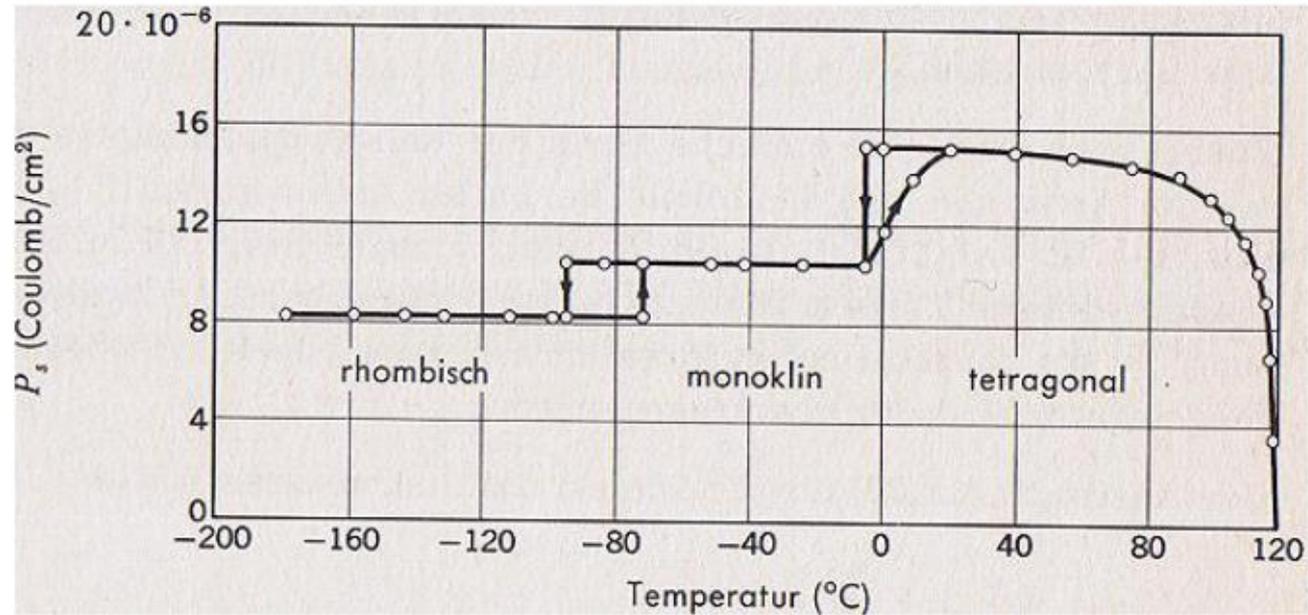
Wichtigstes Beispiel: Perowskit-Struktur z.B. Bariumtitanat

hohe Temperaturen (kubisch) tiefe Temperaturen (tetragonal)

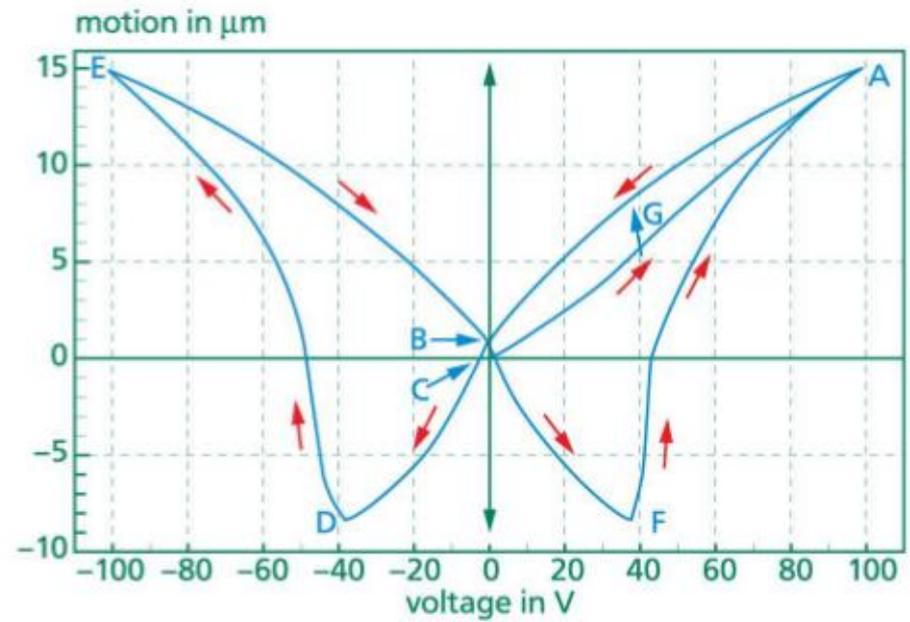
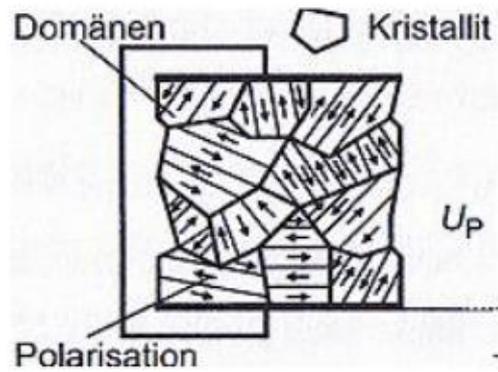




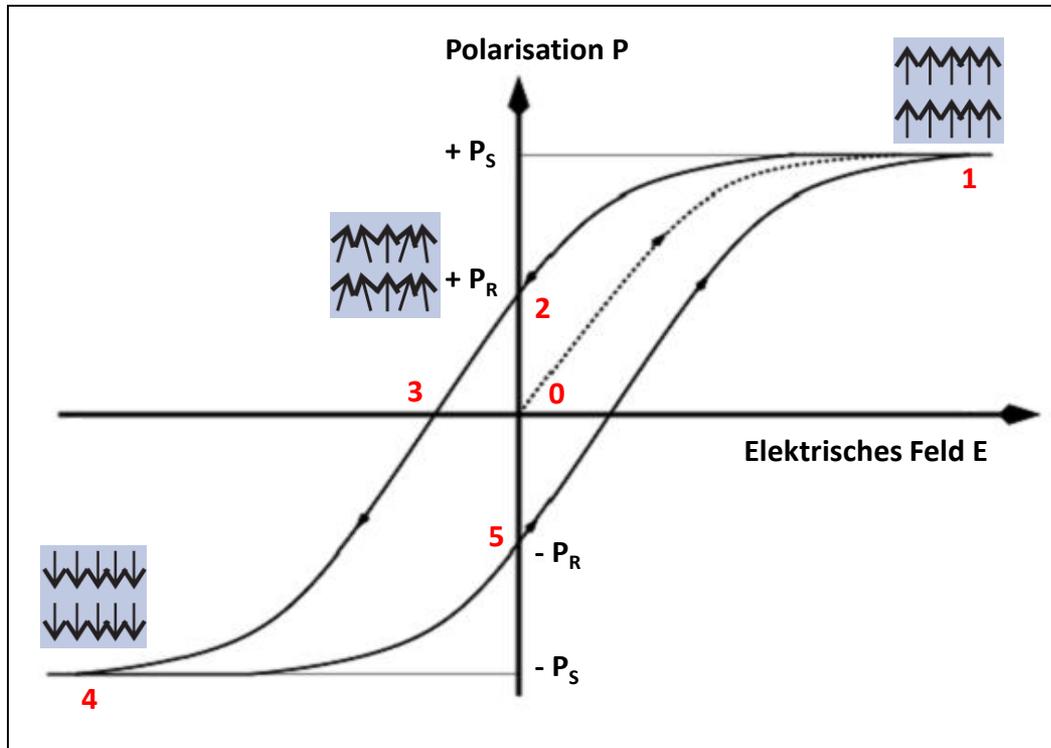
Temperaturabhängigkeit der Polarisierung bei Bariumtitanat



Domänenstruktur und Hysterese



Ferroelektrische Hysterese von Piezokeramiken



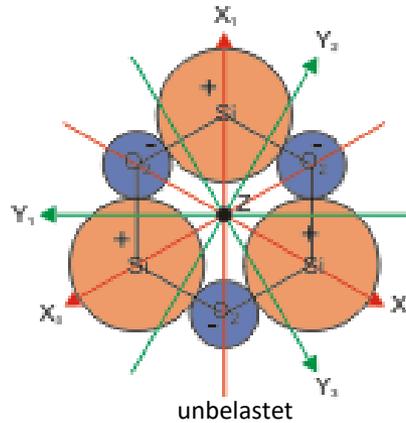
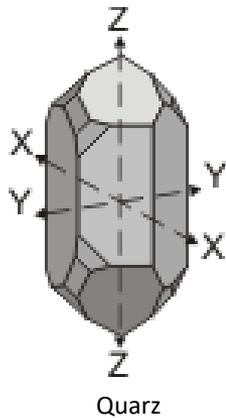
0: $E = 0 \Rightarrow P = 0$

1: P_S Sättigungspolarisation

2: P_R remanente Polarisation

3: Koerzitivfeldstärke $\Rightarrow P = 0$

Longitudinal-/Transversaleffekt

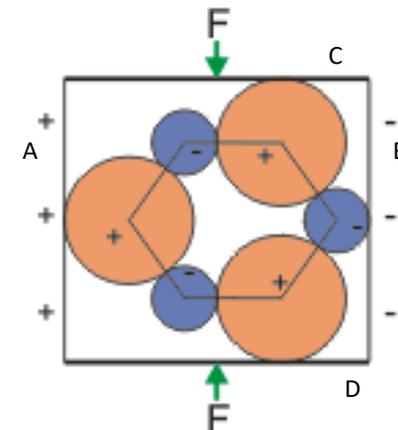
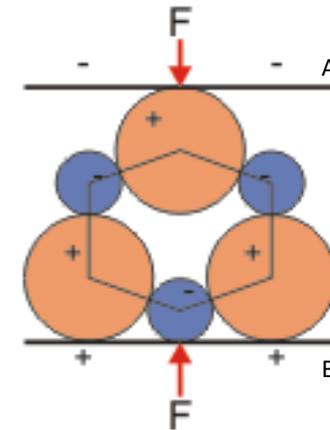


- Longitudinaler piezoelektrischer Effekt:

Anregung (Dilatation oder Kompression) \parallel polare Achse

- Transversaler piezoelektrischer Effekt:

Anregung \perp polare Achse
= Anregung entlang neutraler Achse

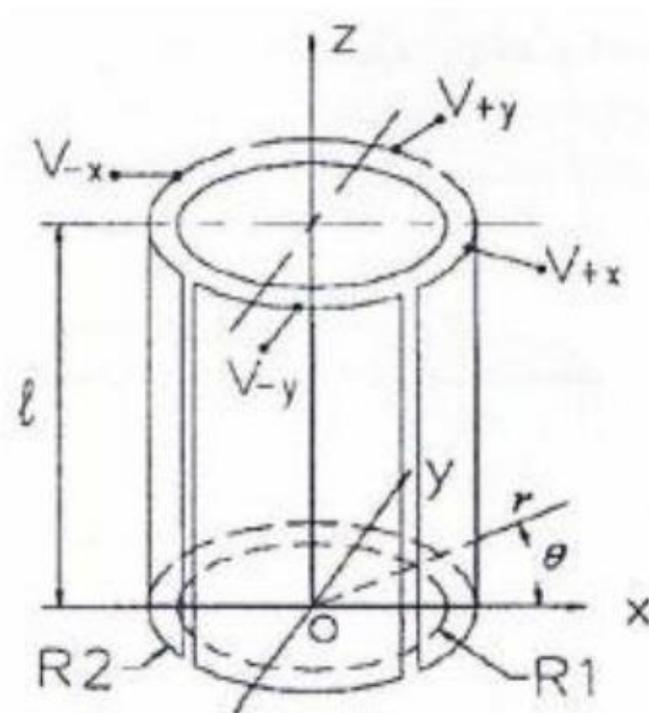


Piezo-Röhrchen (tube scanner)

Polarisation der Keramik in radialer Richtung

Elektrisches Feld (vier Quadranten) bewirkt Änderung der Wandstärke

Quereffekt ändert die Länge oder bewirkt eine Krümmung des Röhrchens



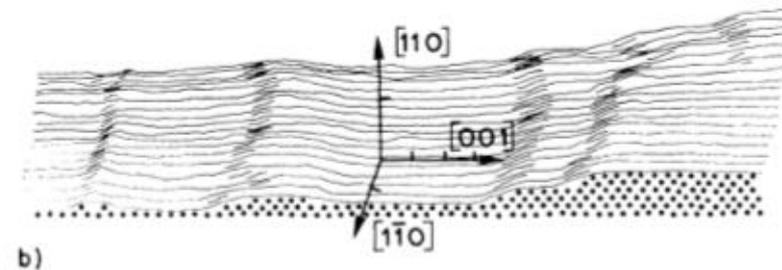
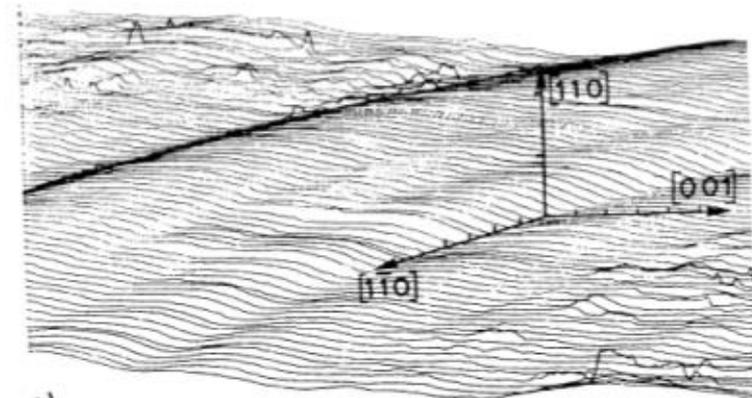
Erfindung der Rastertunnelmikroskopie Nobel Preis für Physik 1986

atomare Stufen auf Au(110)



Heinrich Rohrer und Gerd Binnig

- atomare Auflösung in z-Richtung
- laterale atomare Auflösung

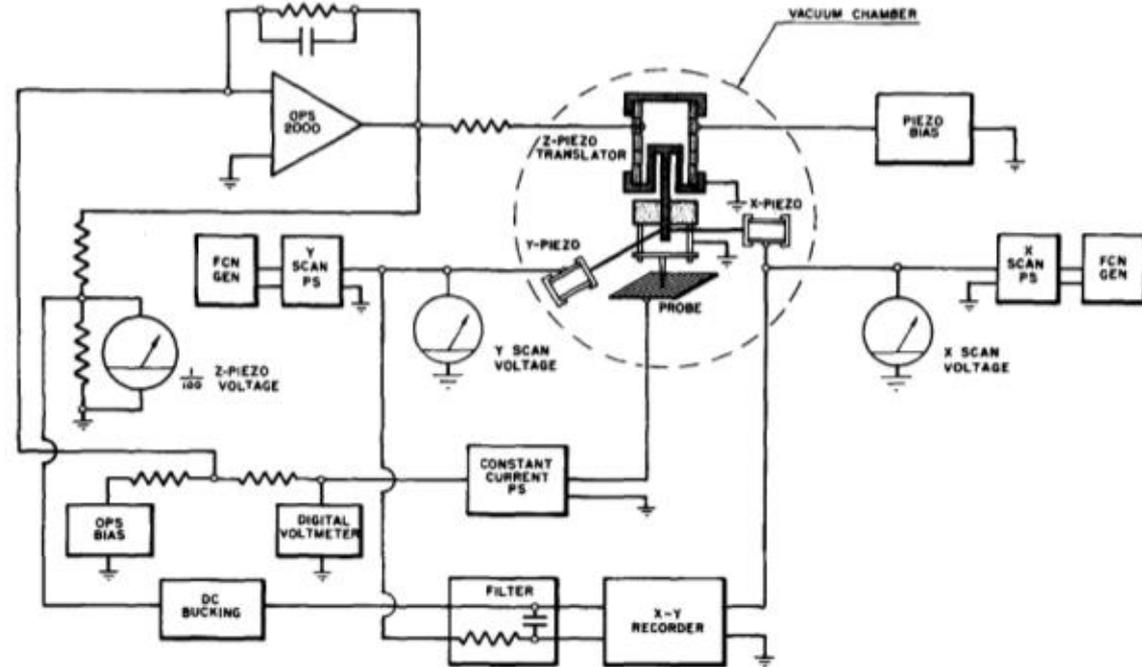


Binnig, Rohrer, Gerber, Weibel, APL 40, 178 (1982), ibid. PRL 49, 57 (1982)

Der "Topografiner": Ein Instrument zur Messung der Mikrotopographie einer Oberfläche

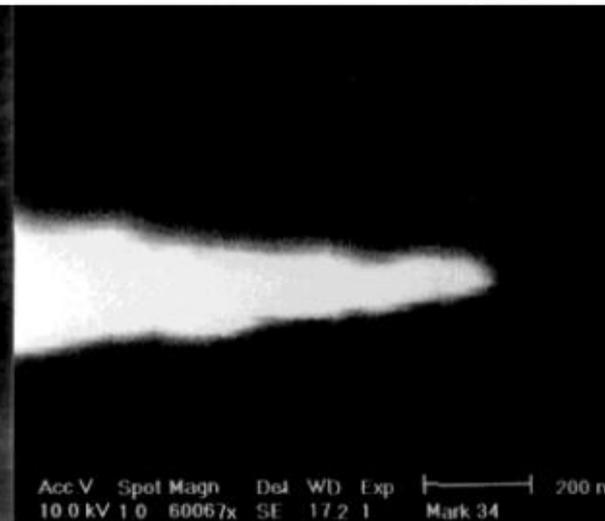
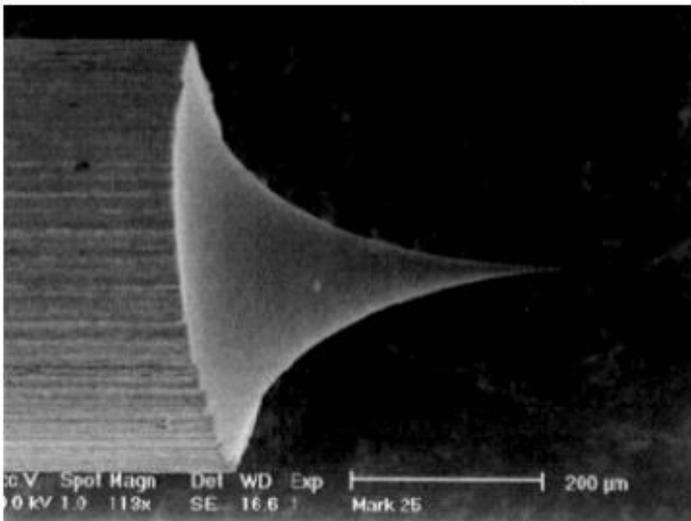
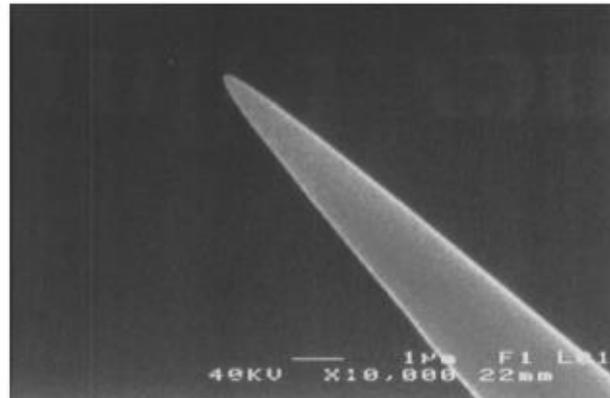
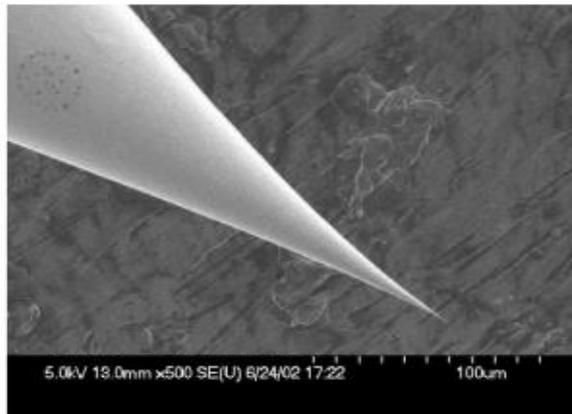


Russell Young, John Ward, und Fredric Scire



Review of Scientific Instruments 43, 999 (1972)

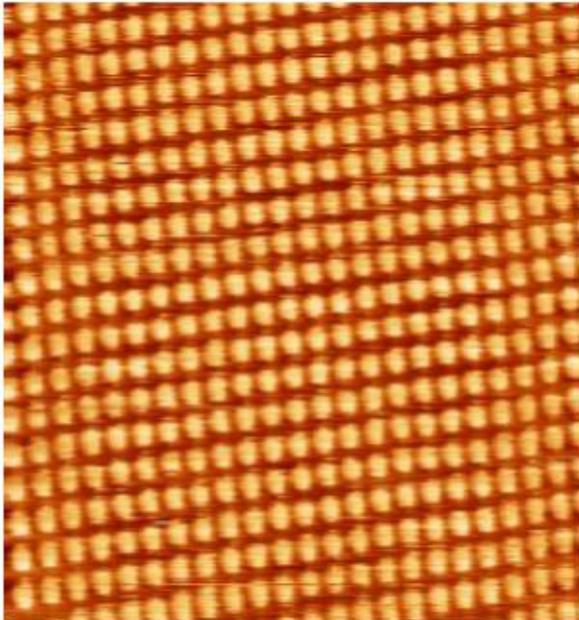
Wolfram-Spitzen



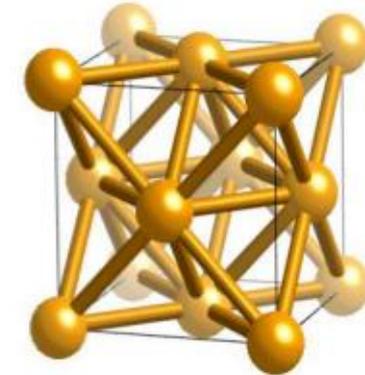
Scharfe und regelmäßige Spitzen durch Ätzen eines W Drahts

Atomare Auflösung auf Metallen

Cu(100) bei 300K

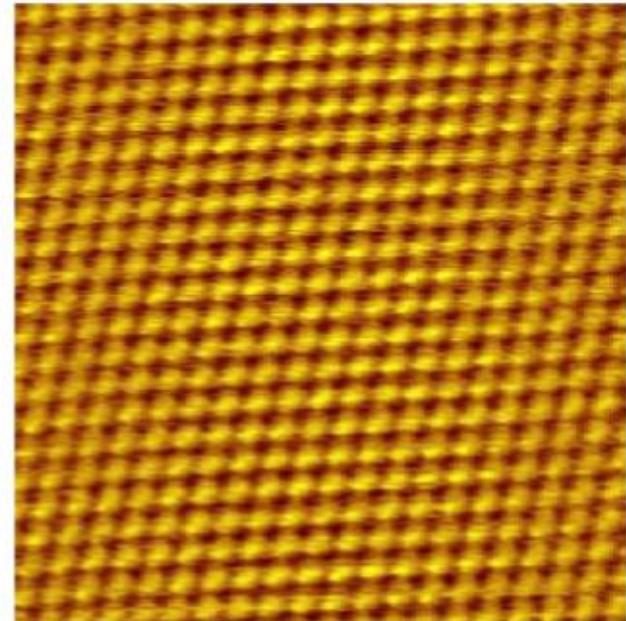


5x5nm

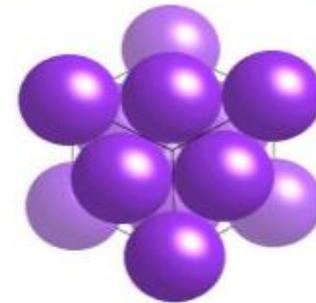


kubisch-
flächenzentriert

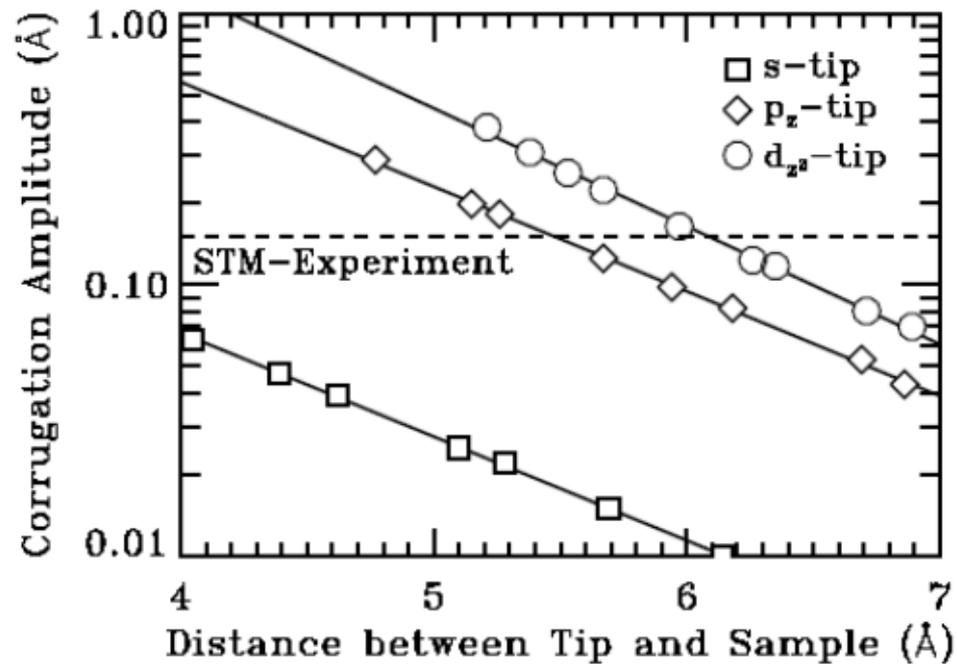
Cu(111) bei 4K



5x5nm



Vergleich Experiment – Theorie (Tersoff-Haman) an W(110)



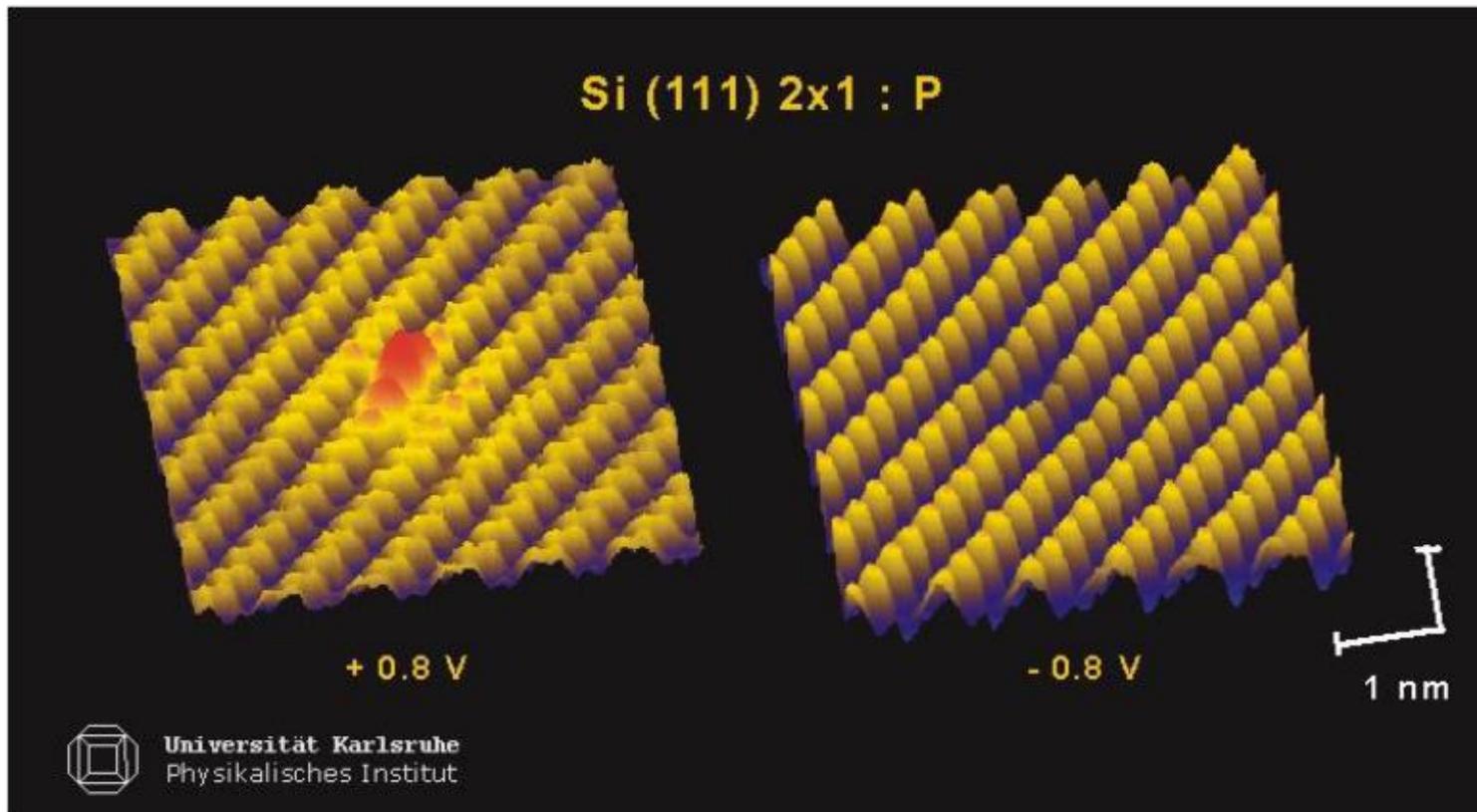
Bei W-Spitzen auf W(110) sind die beobachteten Korrugationen (STM-Experiment) nicht vereinbar mit s-Spitzenorbitalen sondern mit p- oder d-Orbitalen.

Tunnel-Raster-Mikroskopie

Constant current mode

+0.8V: Elektronen tunneln aus der Spitze in unbesetzte Zustände der Probe

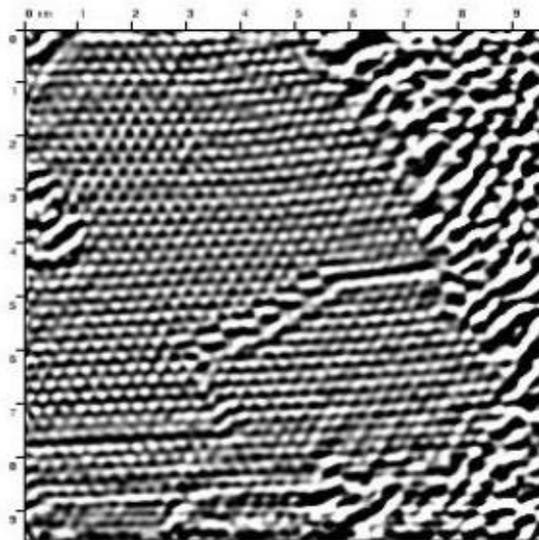
- 0.8V: Elektronen tunneln aus besetzten Zuständen der Probe in die Spitze



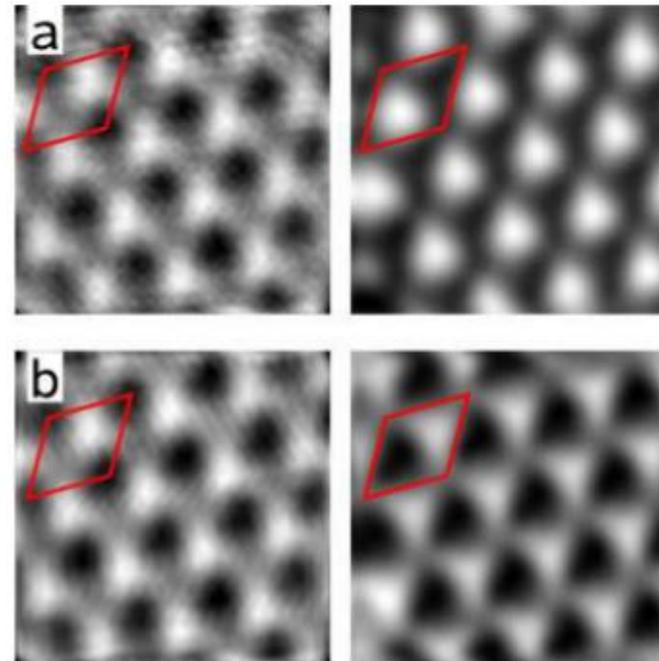
T. Trappmann et al. Appl. Phys. A 68, 167– 172 (1999)

Tunnel-Raster-Spektroskopie

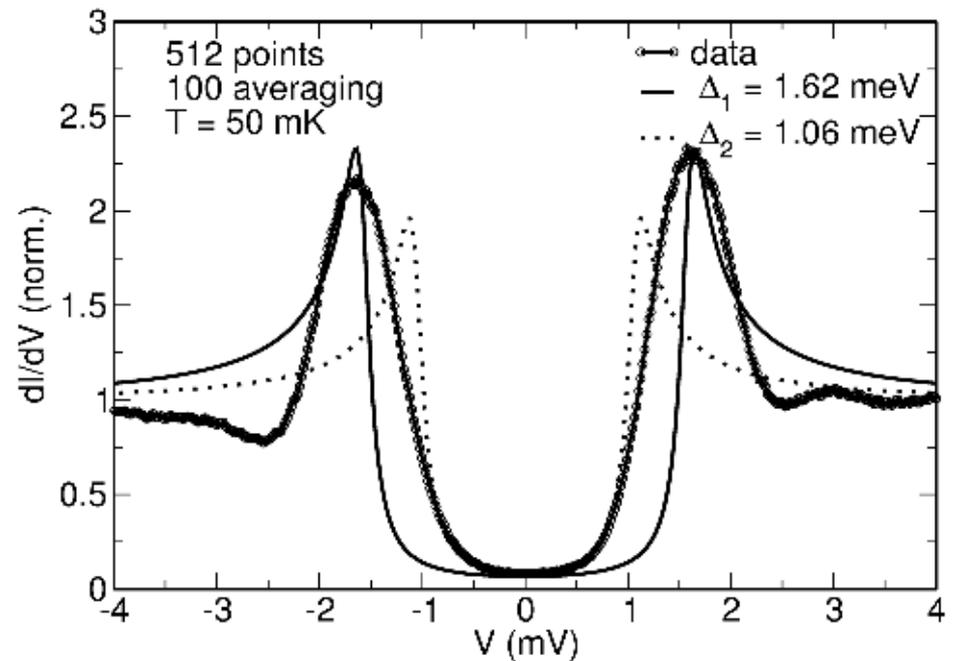
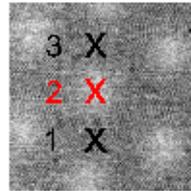
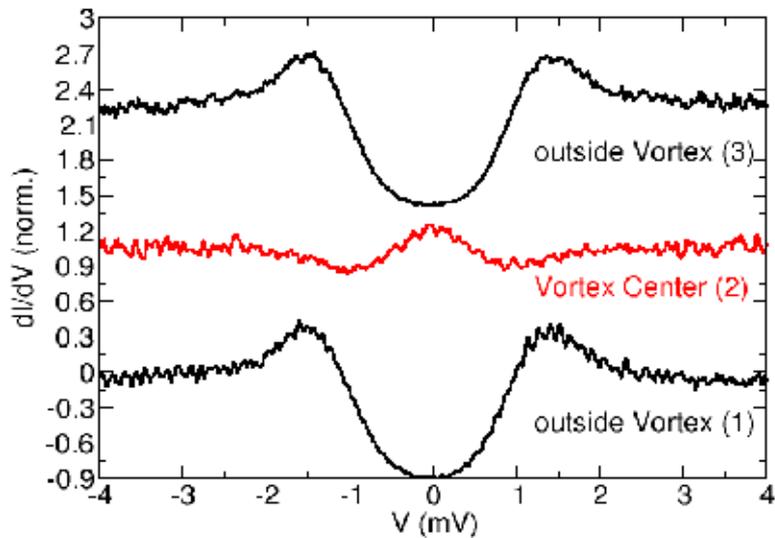
Fe auf Cu (111)
Bild der lokalen Austrittsarbeit d/dz



MnSi
links: Topografie
rechts: lokale differentielle Leitfähigkeit dI/dV

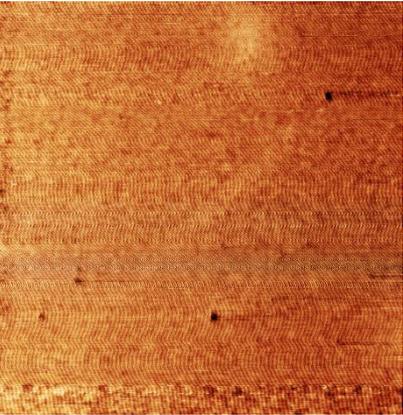


Tunnelling spectroscopy

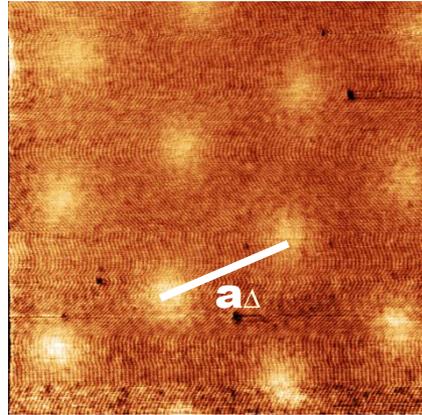


Vortex lattice of NbSe₂

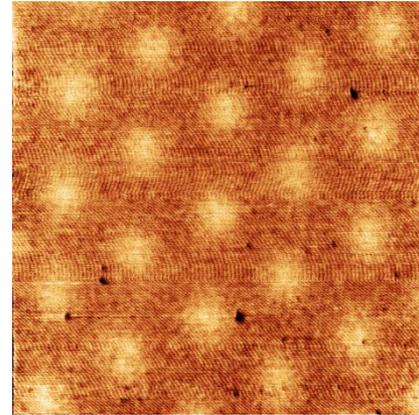
$B = 0$



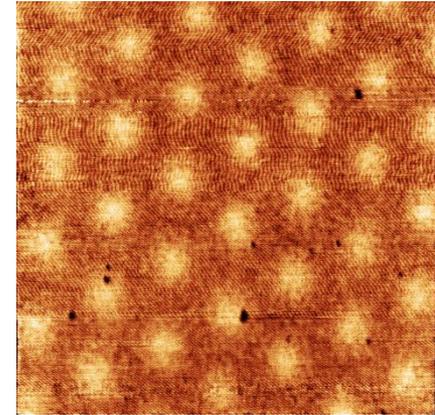
$B = 100 \text{ mT}$



$B = 200 \text{ mT}$

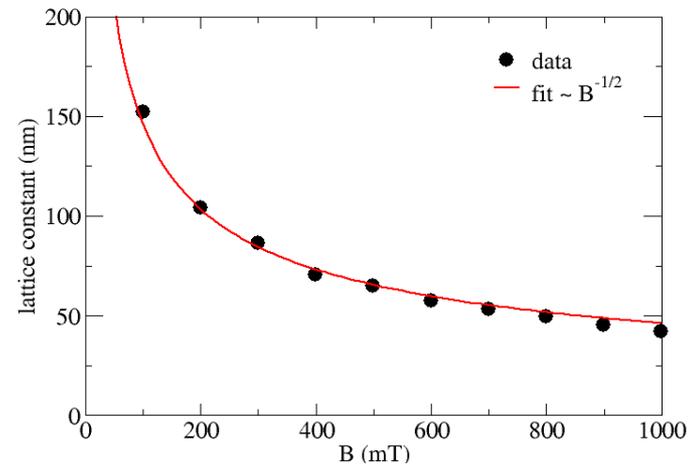


$B = 300 \text{ mT}$



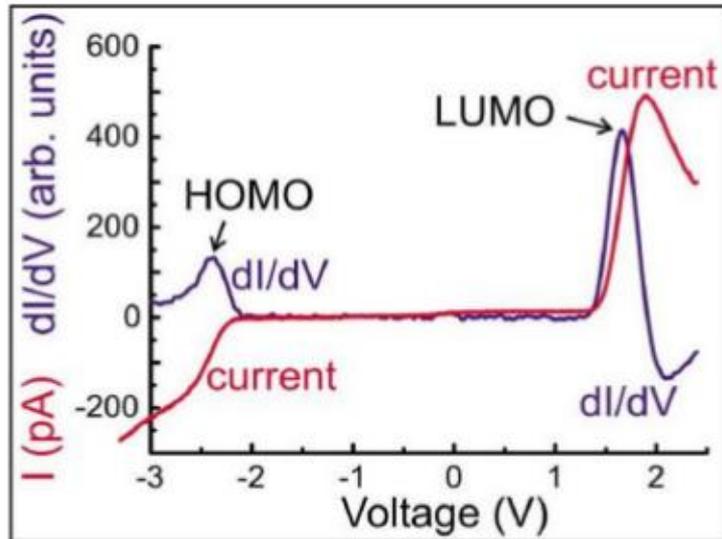
$$a_{\Delta} = 1.075 (\Phi_0/B)^{1/2}$$

$$B = 100 \text{ mT} \rightarrow a_{\Delta} = 152 \text{ nm}$$

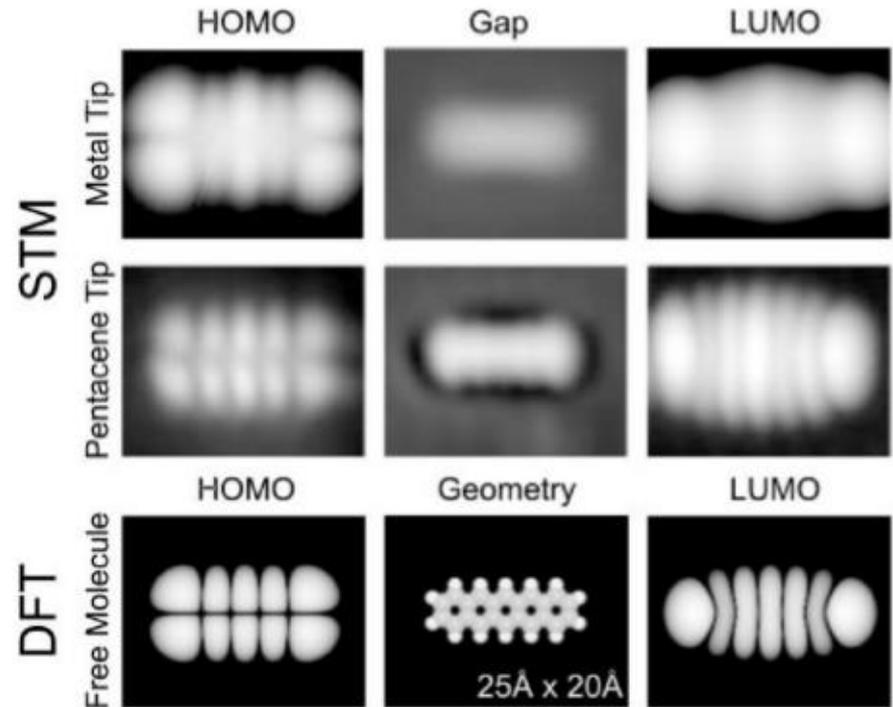


Tunnel-Raster-Spektroskopie

Organisches Molekül auf dünner, isolierender Oberfläche



I - V -Kennlinie und differentieller Widerstand dI/dV



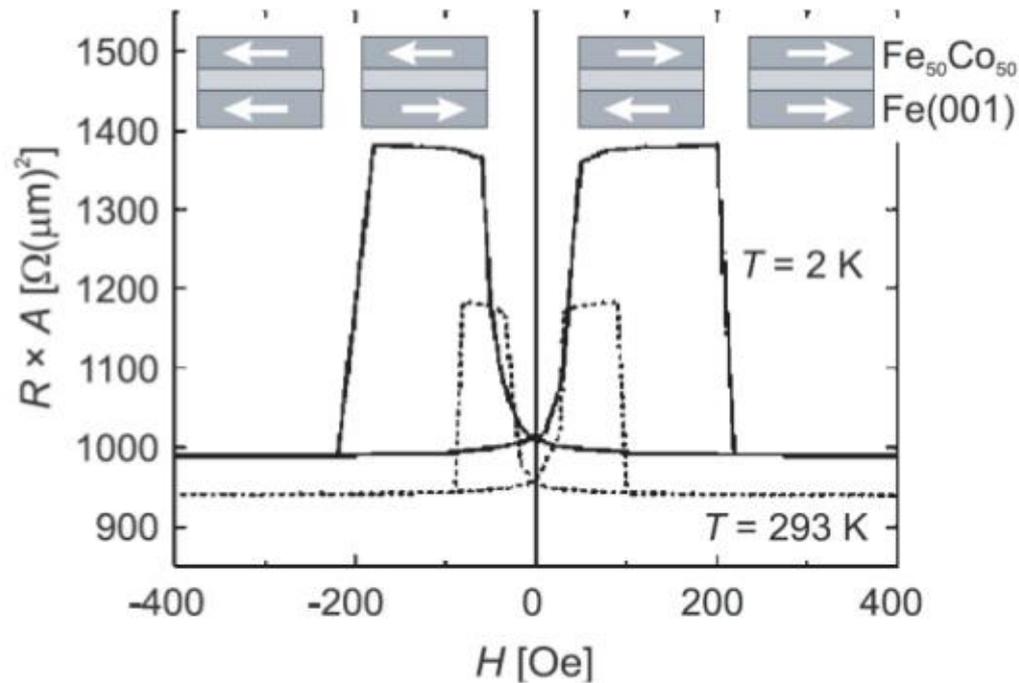
Repp, Meyer, Phys. Rev. Lett 94, 026803 (2005)

Spinpolarisierte Tunnel-Raster-Mikroskopie und -Spektroskopie

zum Verständnis des Tunnelmagnetowiderstands:

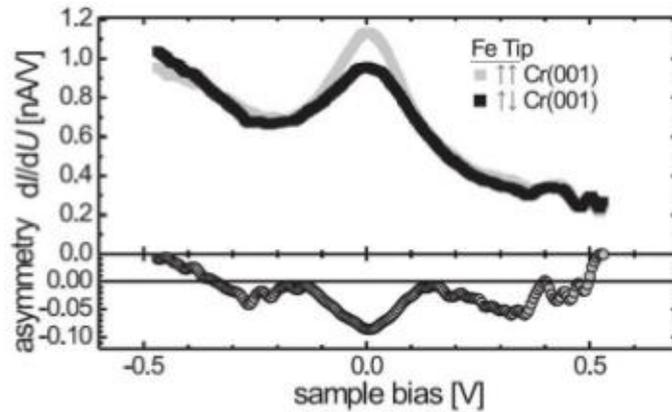
FeCo-Schicht/Isolator/Fe-Schicht

Hysteretisches Schaltverhalten in Abhängigkeit eines äußeren Magnetfelds



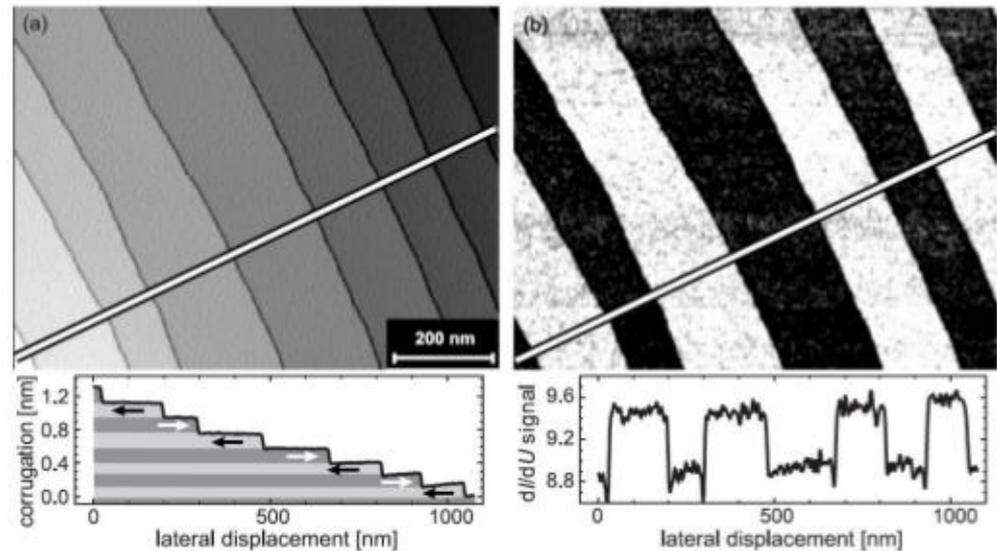
S. Yuasa et al, Europhys. Lett. 52, 344 (2000)

Spinpolarisierte Tunnel-Raster-Mikroskopie und -Spektroskopie



Spektroskopie
fester Ort

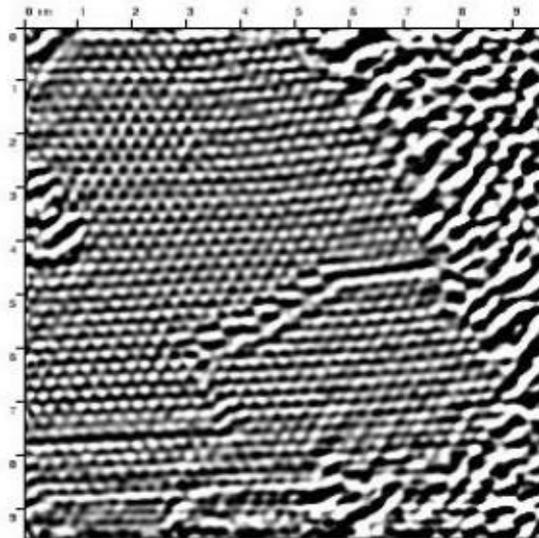
Topografie (links) und
magnetische LDOS im
Spektroskopie-Modus
(rechts)



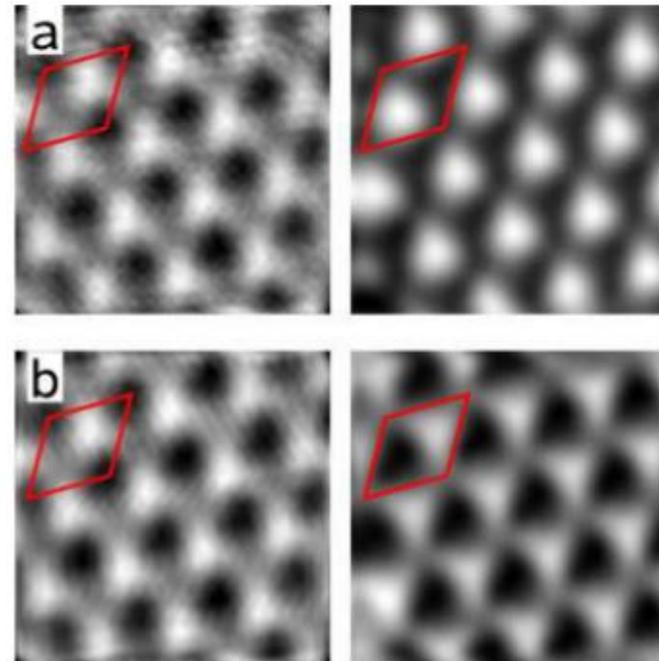
M.Bode Rep. Prog. Phys. 66, 523 (2003)

Tunnel-Raster-Spektroskopie

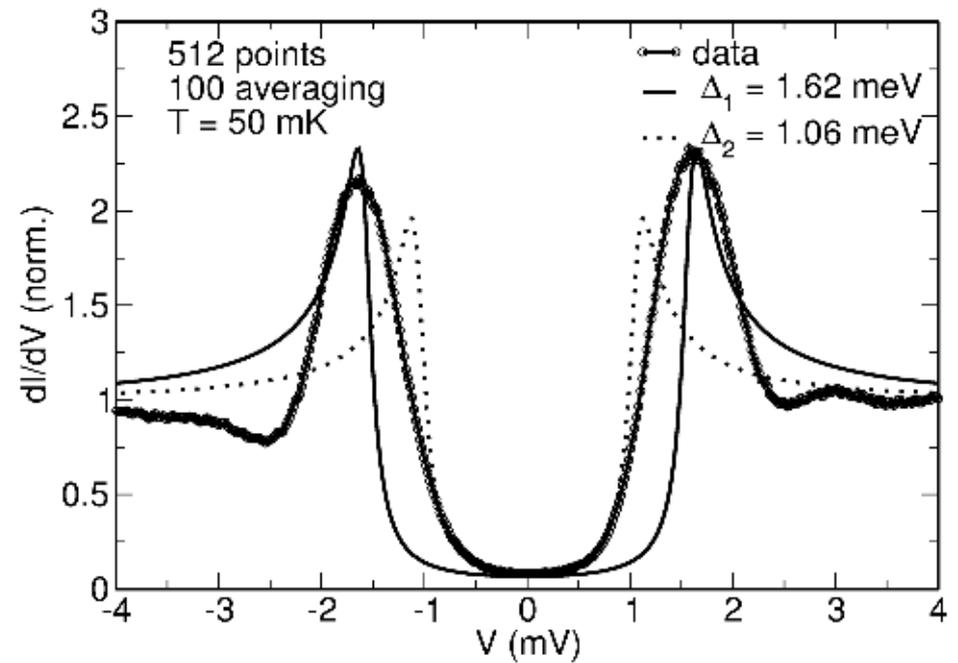
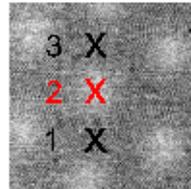
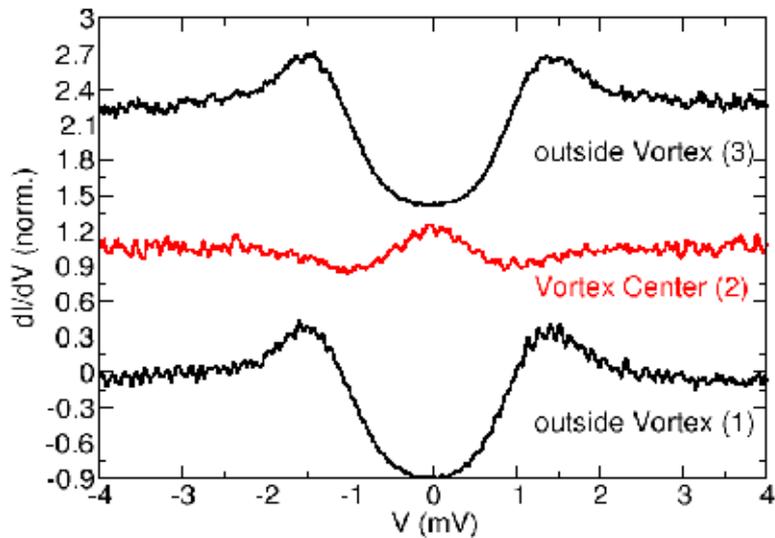
Fe auf Cu (111)
Bild der lokalen Austrittsarbeit d/dz



MnSi
links: Topografie
rechts: lokale differentielle Leitfähigkeit dI/dV



Tunnelling spectroscopy

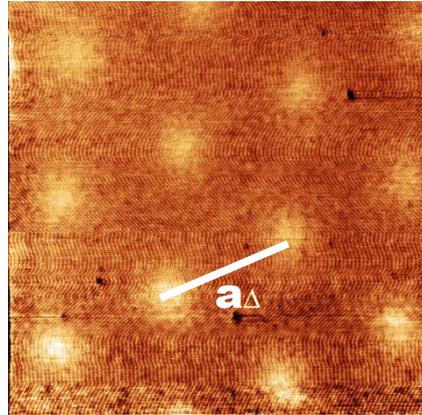


Vortex lattice of NbSe₂

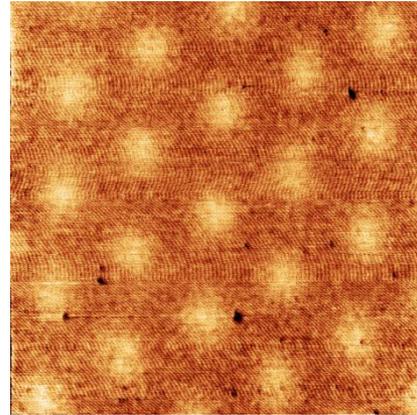
$B = 0$



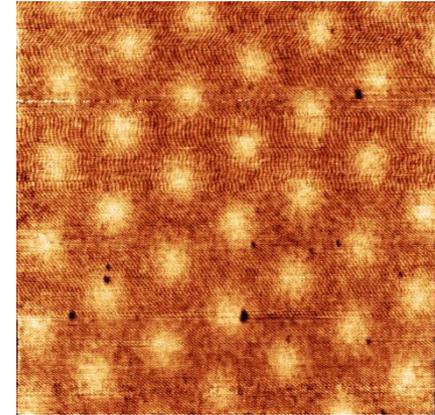
$B = 100 \text{ mT}$



$B = 200 \text{ mT}$

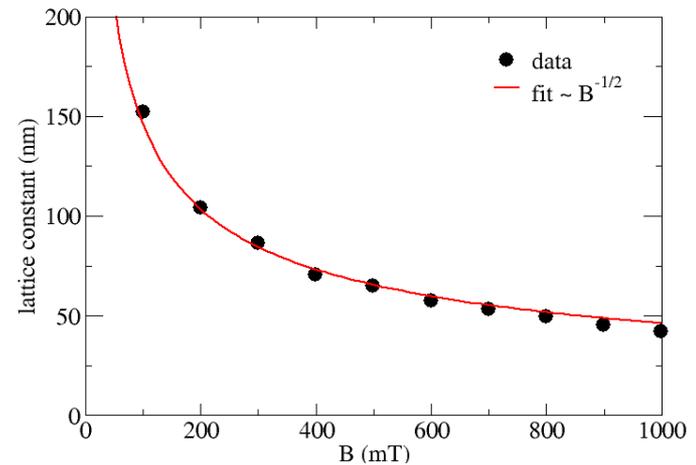


$B = 300 \text{ mT}$



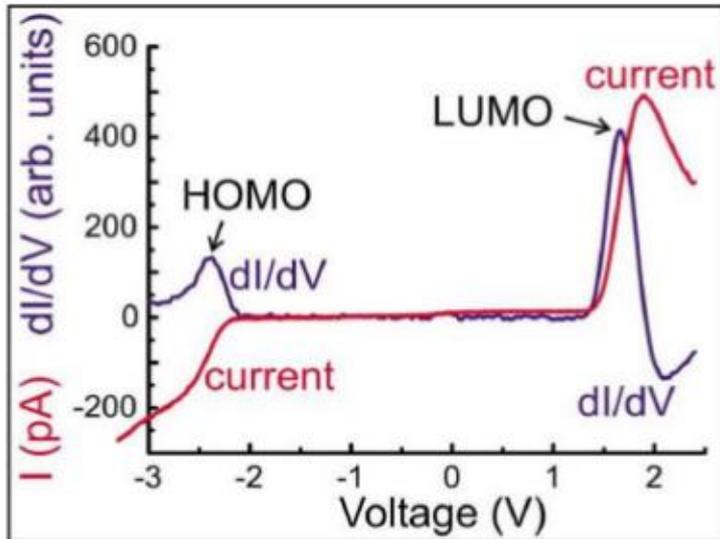
$$a_{\Delta} = 1.075 (\Phi_0/B)^{1/2}$$

$$B = 100 \text{ mT} \rightarrow a_{\Delta} = 152 \text{ nm}$$

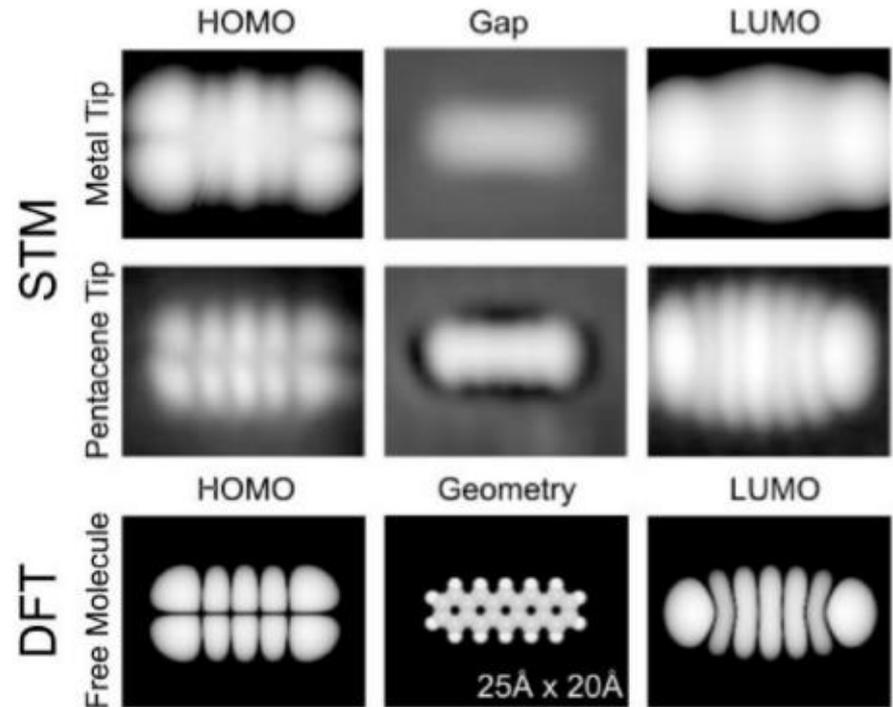


Tunnel-Raster-Spektroskopie

Organisches Molekül auf dünner, isolierender Oberfläche



I - V -Kennlinie und differenzieller Widerstand dI/dV



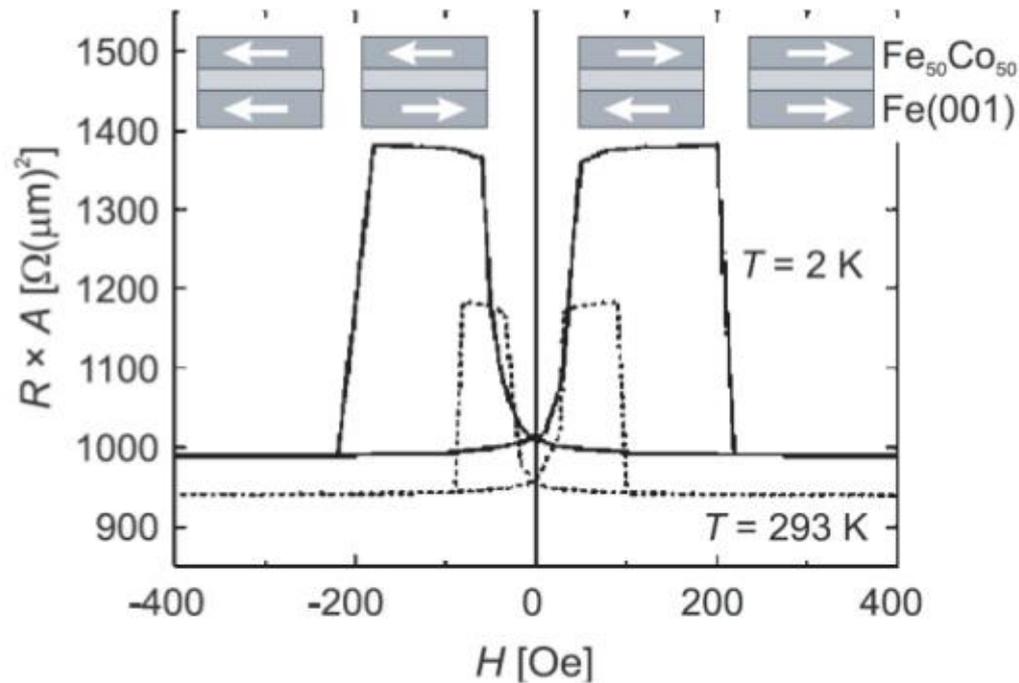
Repp, Meyer, Phys. Rev. Lett 94, 026803 (2005)

Spinpolarisierte Tunnel-Raster-Mikroskopie und -Spektroskopie

zum Verständnis des Tunnelmagnetowiderstands:

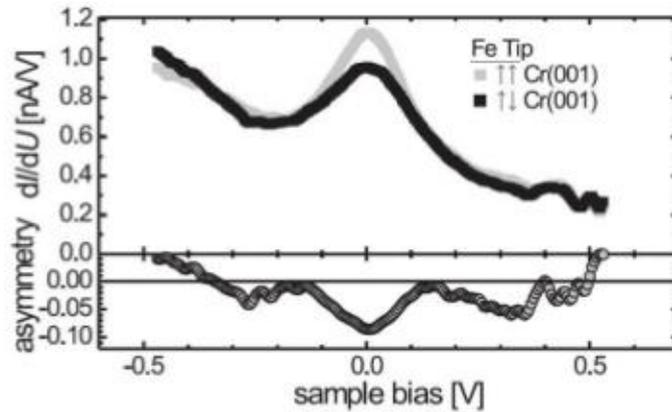
FeCo-Schicht/Isolator/Fe-Schicht

Hysteretisches Schaltverhalten in Abhängigkeit eines äußeren Magnetfelds



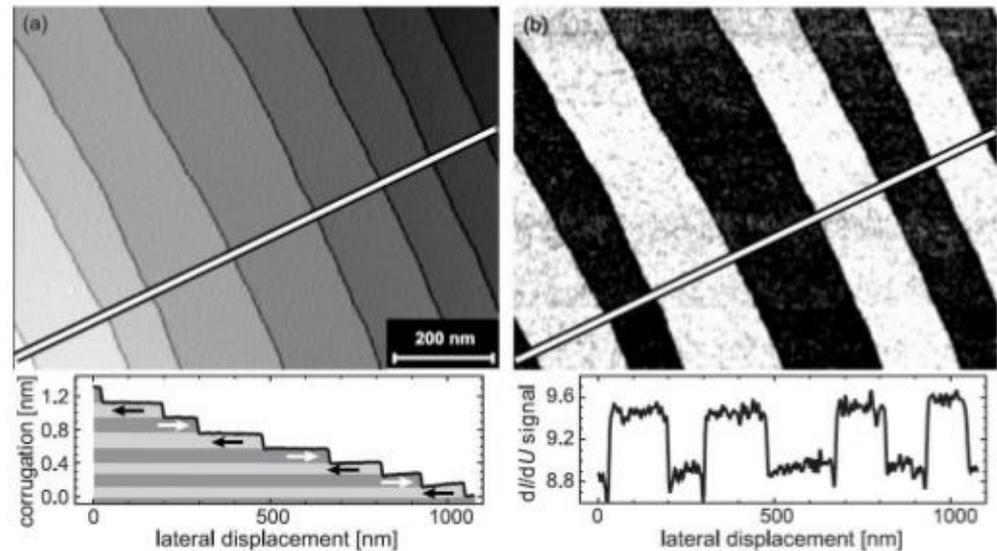
S. Yuasa et al, Europhys. Lett. 52, 344 (2000)

Spinpolarisierte Tunnel-Raster-Mikroskopie und -Spektroskopie



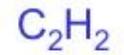
Spektroskopie
fester Ort

Topografie (links) und
magnetische LDOS im
Spektroskopie-Modus
(rechts)

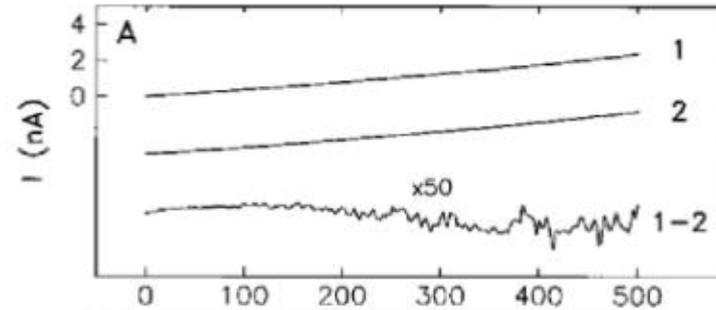
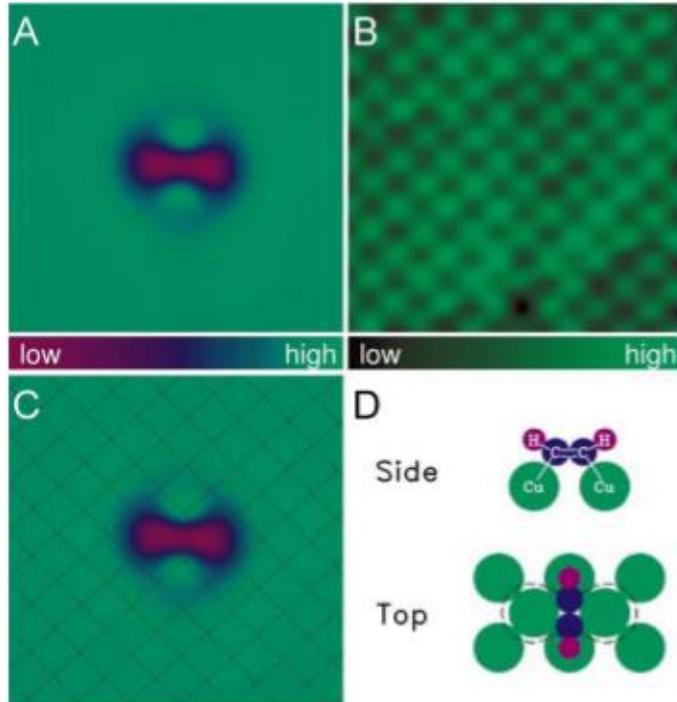


M.Bode Rep. Prog. Phys. 66, 523 (2003)

Inelastische Tunnel-Spektroskopie

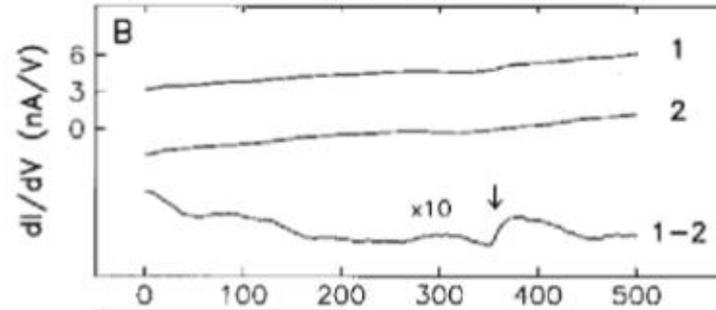


Acetylen auf Cu (100)

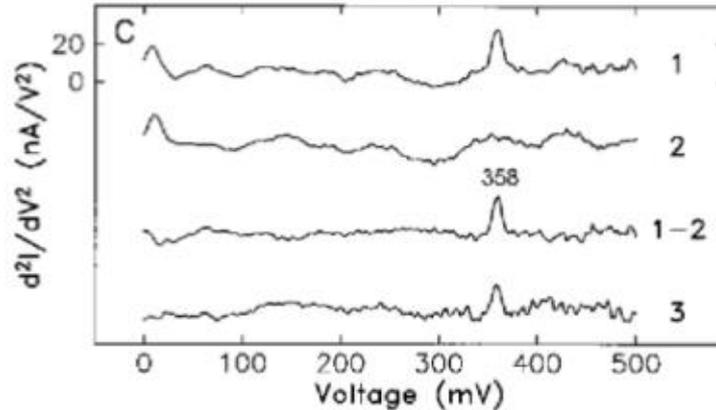


I - V
Kennlinie

1: Molekül
2: Substrat



dI/dV

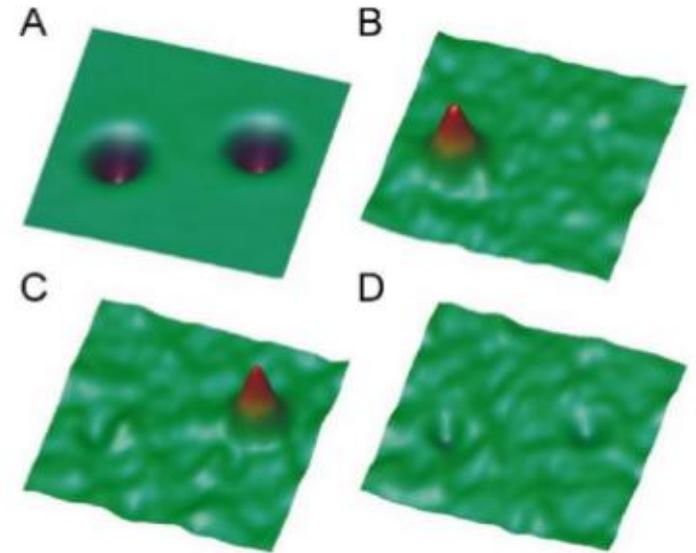
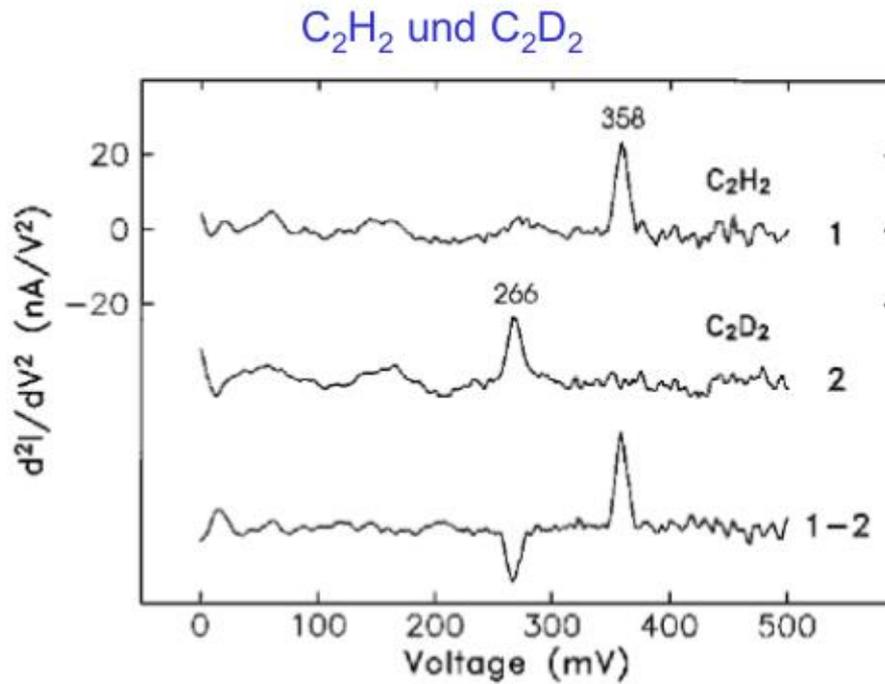


d^2I/dV^2

B.C. Stipe, M.A. Rezaei, W. Ho, Science **280** (1998)

Inelastische Tunnel-Spektroskopie

Acetylen auf Cu (100)



HC_2D

A: Topografie

B: d^2I/dV^2 -Karte bei 358 mV

C: d^2I/dV^2 -Karte bei 266 mV

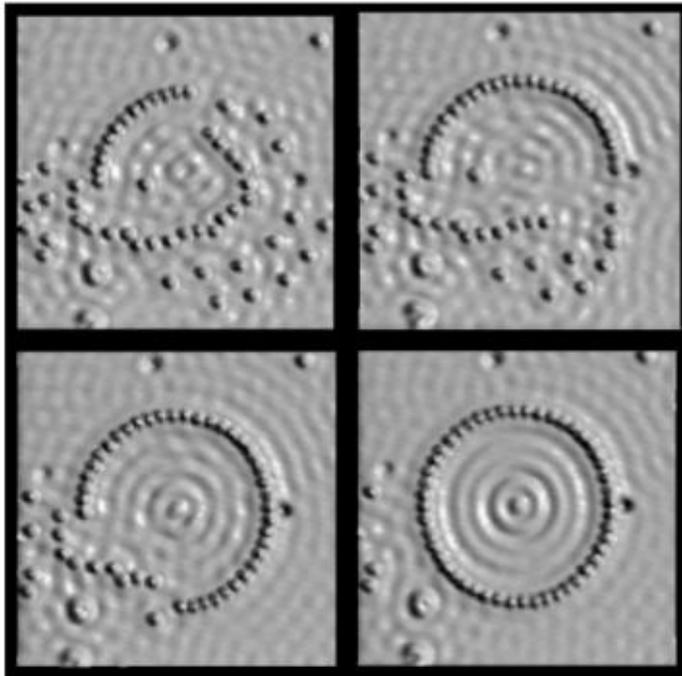
D: d^2I/dV^2 -Karte bei 311 mV

B.C. Stipe, M.A. Rezaei, W. Ho, Science **280** (1998)

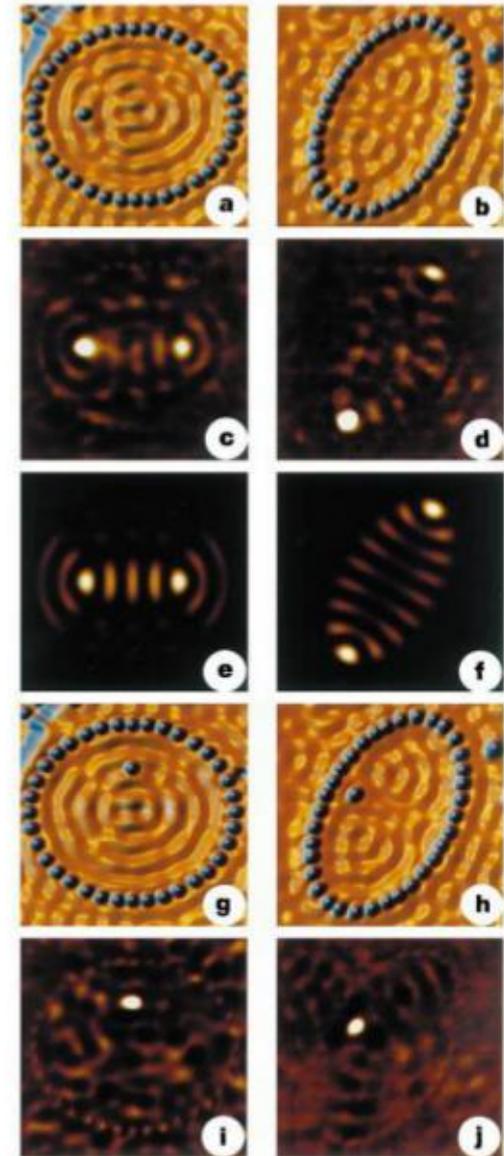
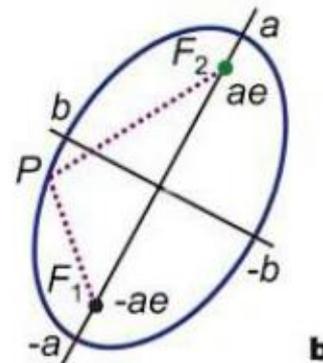
Atomare Manipulation

Herstellung von Quanten-Gehegen
D.Eigler-Gruppe IBM

Fe-Atome auf Cu (111)
mit Elektronen-Dichtewellen

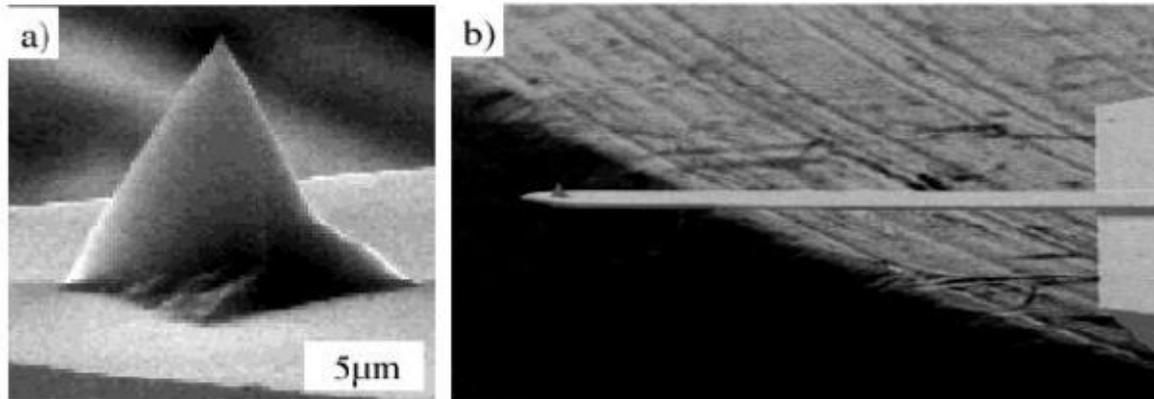


Quantum-Mirage-
Effekt bei
Positionierung
eines Co-Atoms
im Brennpunkt
eines elliptischen
Geheges



D. Eigler et al., E.K. Schweizer, Nature 344, 524 (1990)
Science 262, 218 (1993)
Physics Today 46, 17 (1993)

Raster-Kraft-Mikroskopie



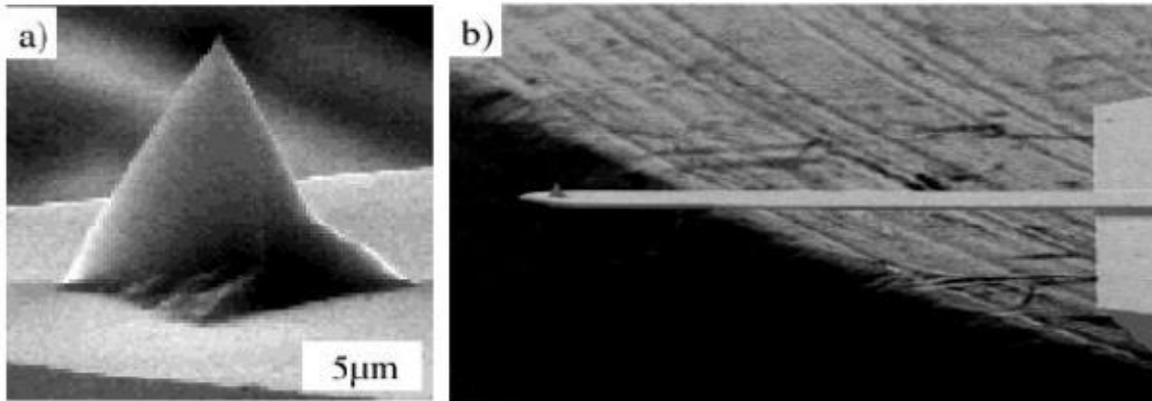
Biegebalken (cantilever)

typische Größen: 200 μm lang, 30 μm breit, 5 -10 μm dick

Resonanzfrequenz: 100 – 200 kHz

Federkonstante: 1 - 100 N/m

Raster-Kraft-Mikroskopie



Biegebalken (cantilever)

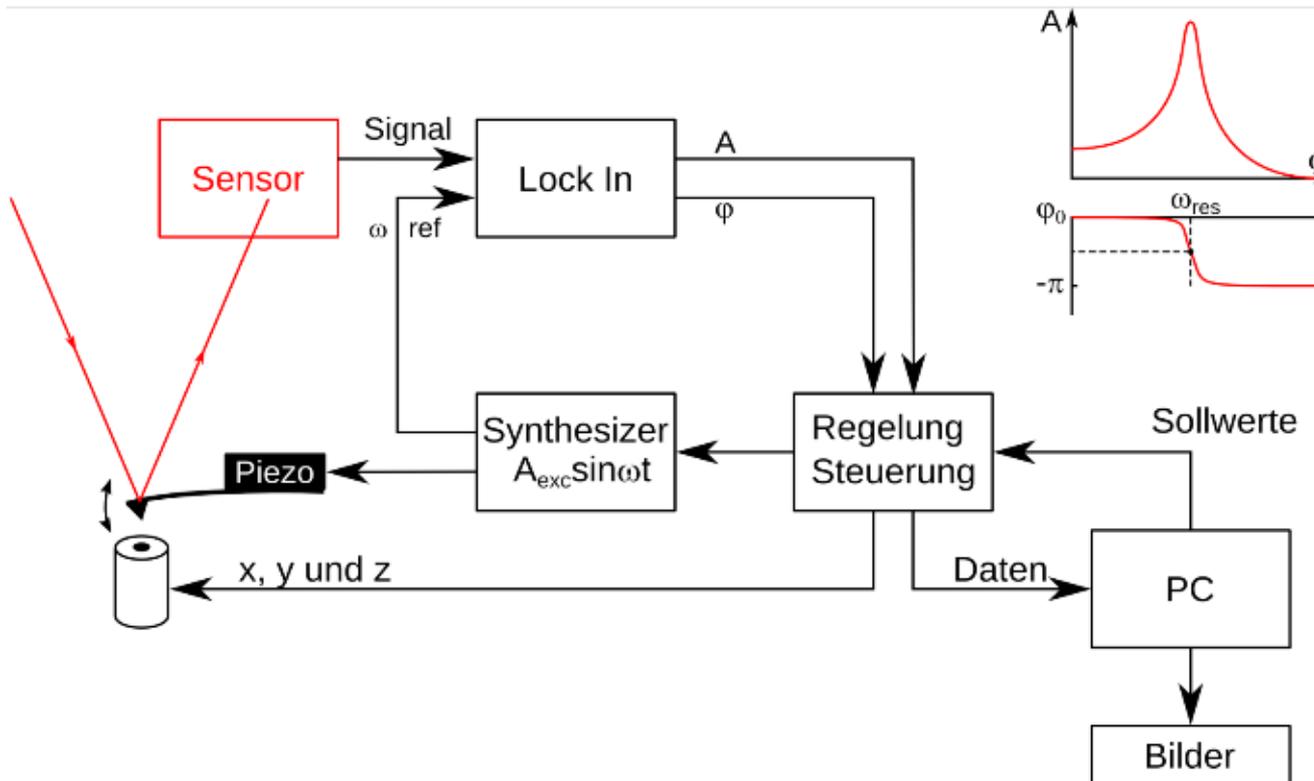
typische Größen: 200 μm lang, 30 μm breit, 5 -10 μm dick

Resonanzfrequenz: 100 – 200 kHz

Federkonstante: 1 - 100 N/m

Dynamische Rasterkraftmikroskopie

Generelles Blockschaltbild



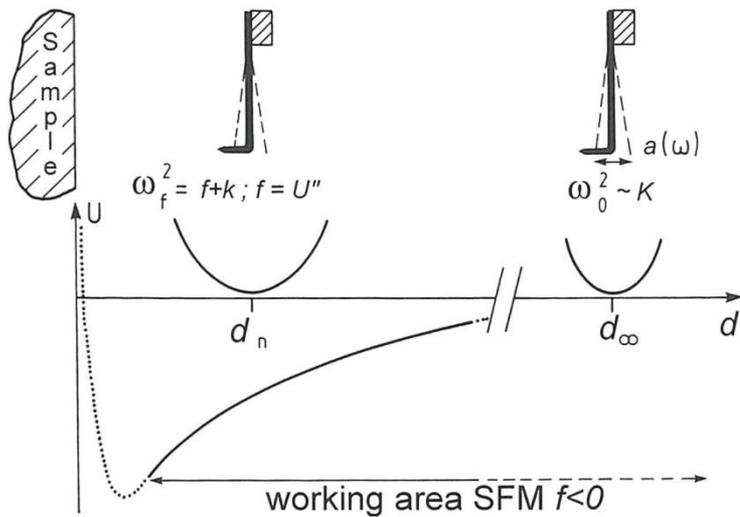


Figure 16: Schematic representation of the effect of the van der Waals interaction potential on the vibration frequency of the spring with tip. As the tip approaches the surface, the resonance frequency of the leaf spring is shifted. (from [23]).

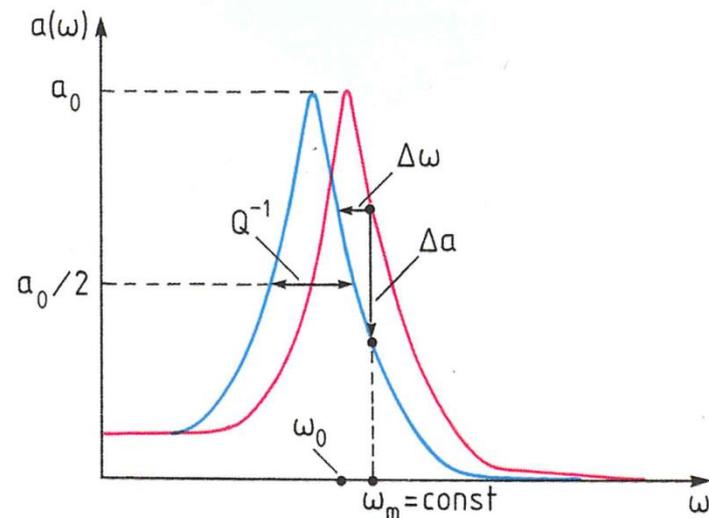
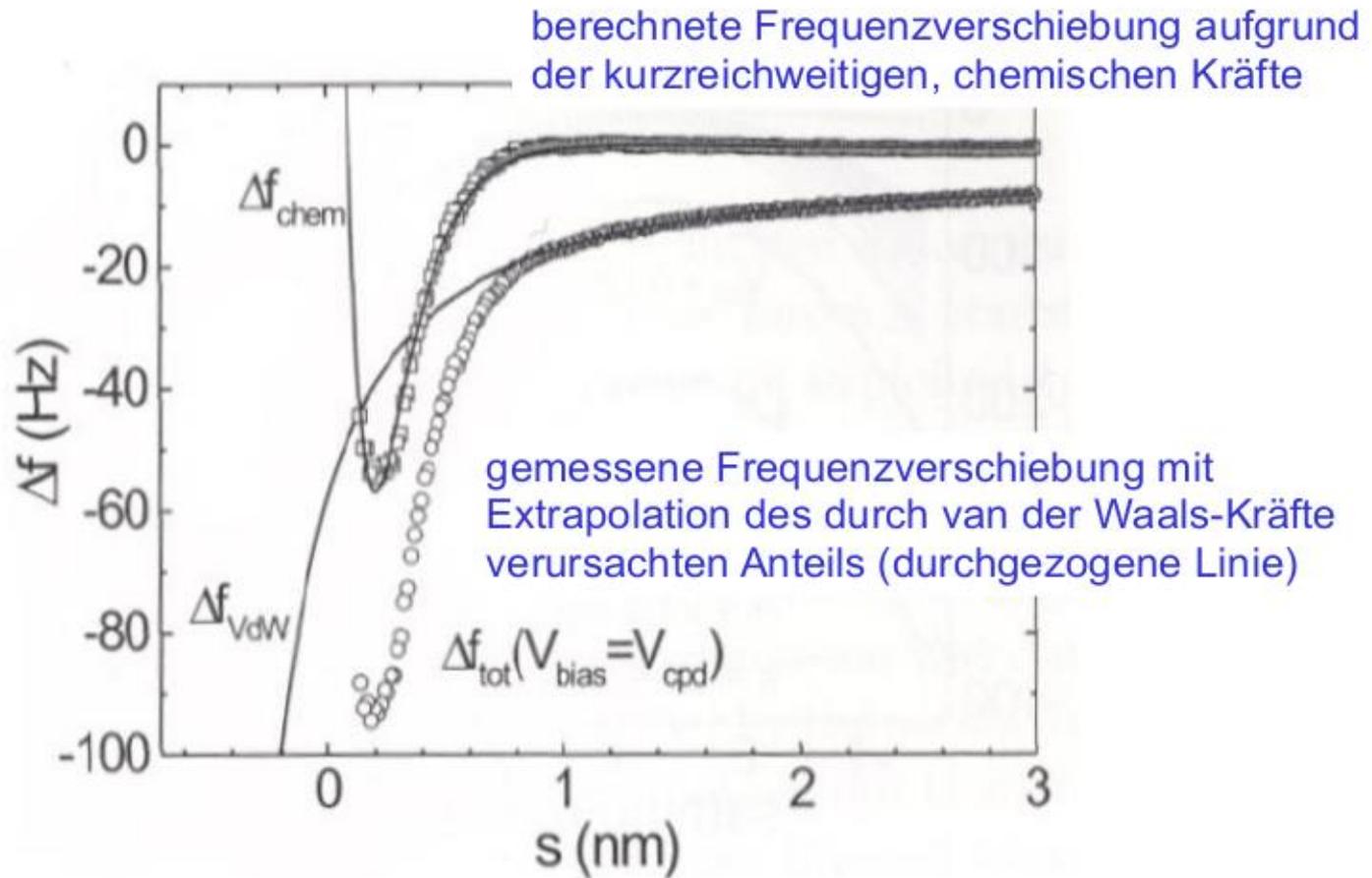
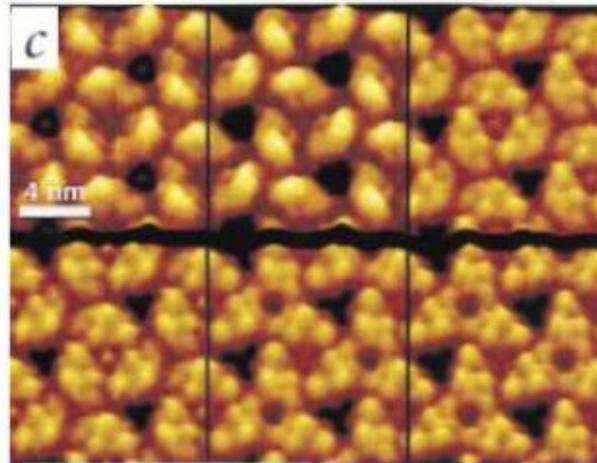


Figure 17: Resonance curves of the tip without and with interaction with a van der Waals potential. The interaction leads to a shift $\Delta\omega$ of the resonance frequency with the consequence that the tip excited with the frequency ω_m has a vibration amplitude $a(\omega)$ attenuated by Δa [23].

Dynamische Kraft-Mikroskopie - Spektroskopie



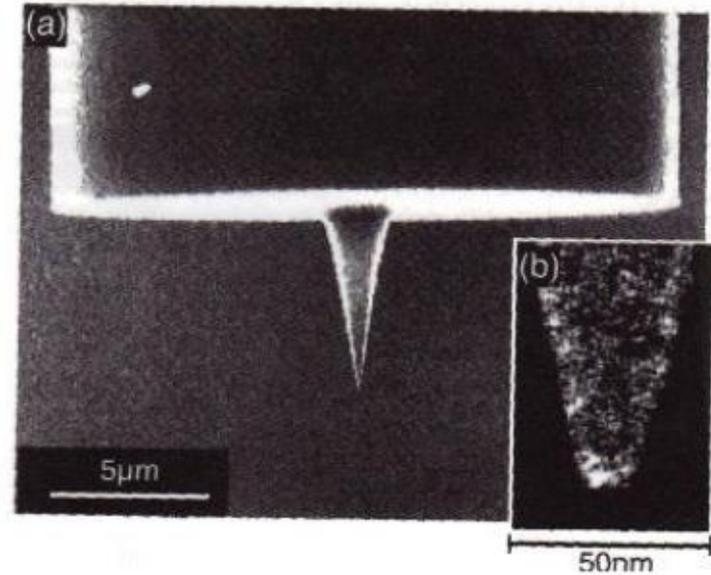
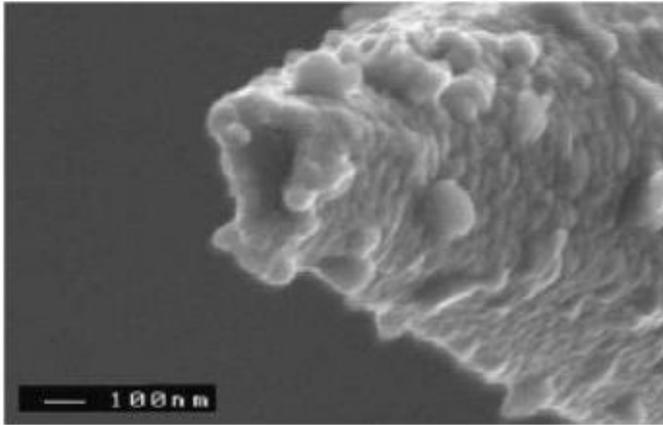
Observing single biomolecules at work with the atomic force microscope



Andreas Engel¹ and Daniel J. Müller^{1,2}

nature structural biology • volume 7 number 9 • september 2000

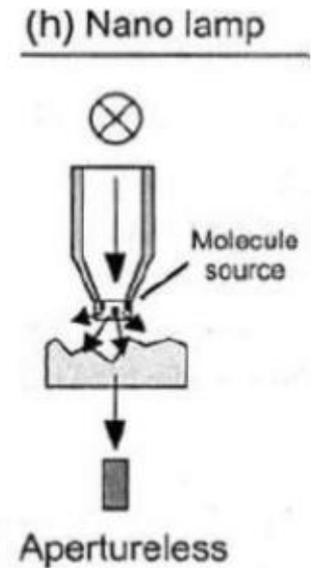
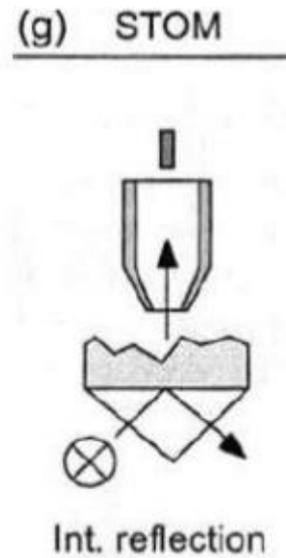
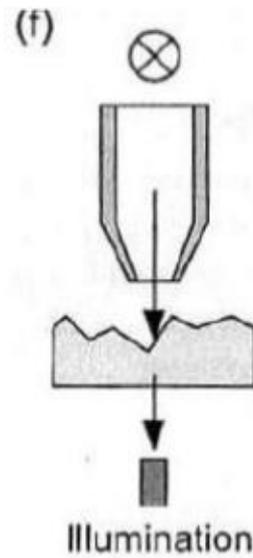
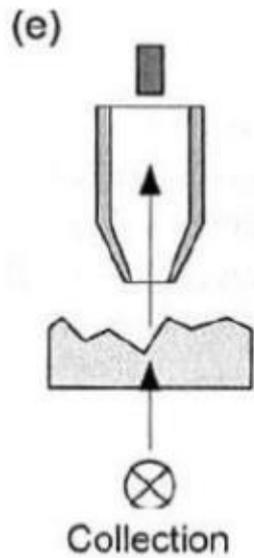
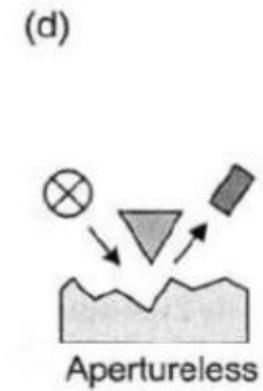
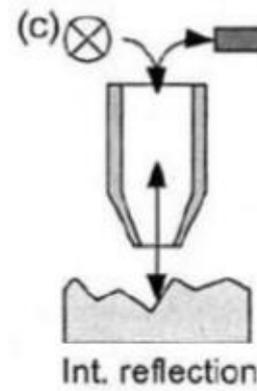
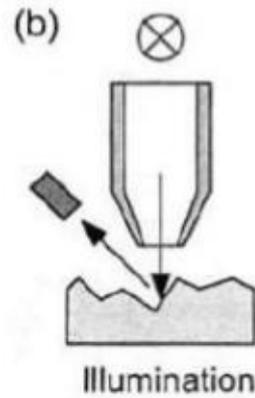
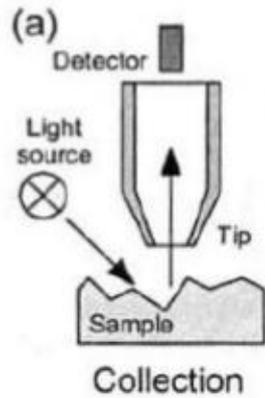
SNOM-Sonden



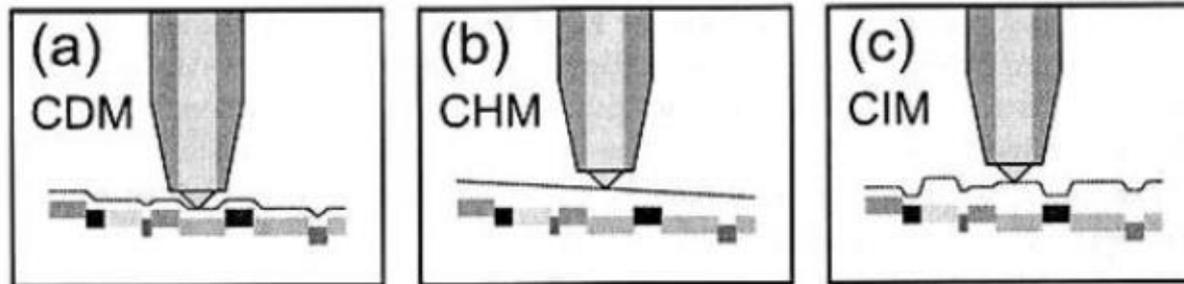
optische Fasern, dünn ausgezogen
bedampft mit metallischen Filmen

mit ‚focussed ion beam‘ nachbearbeitet (links)

SNOM-Familie



SNOM-Betriebsmodi

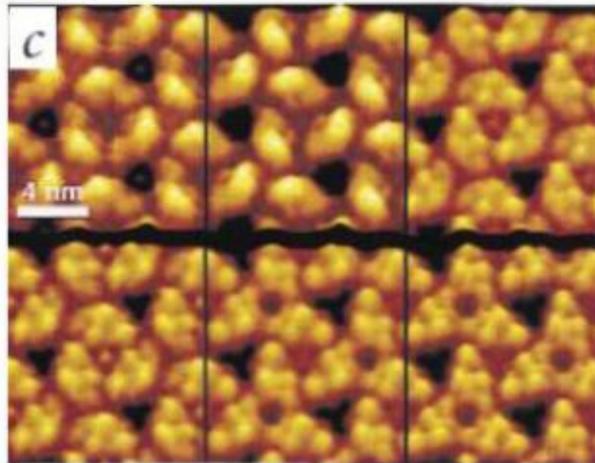


CDM – constant distance

CHM – constant height

CIM – constant intensitiy

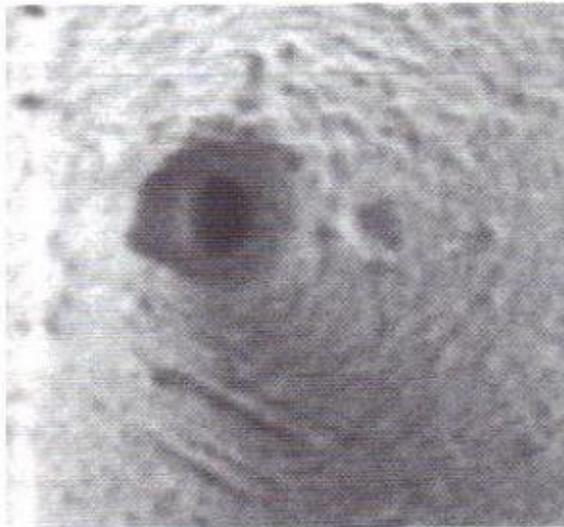
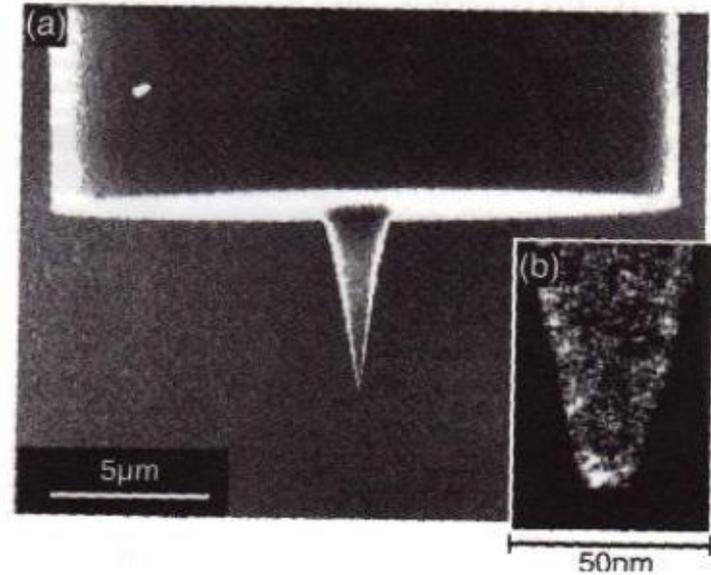
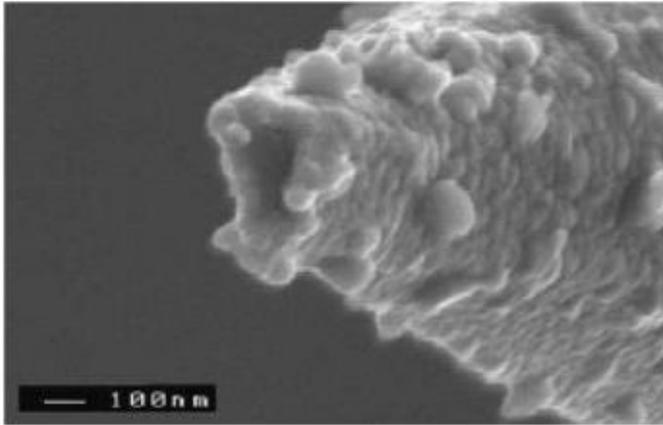
Observing single biomolecules at work with the atomic force microscope



Andreas Engel¹ and Daniel J. Müller^{1,2}

nature structural biology • volume 7 number 9 • september 2000

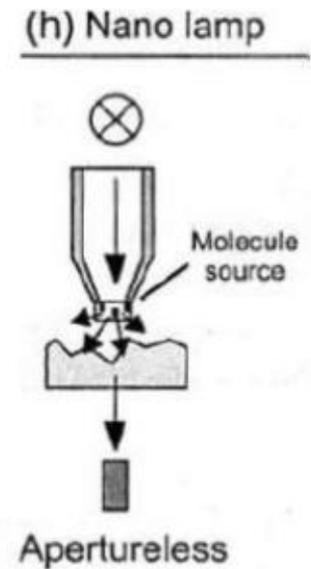
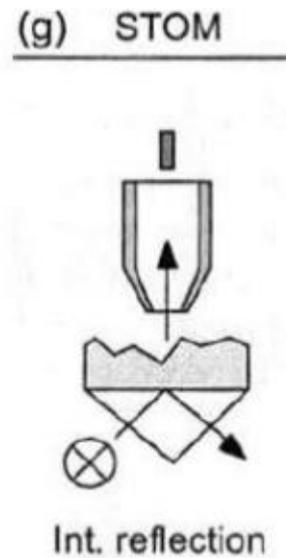
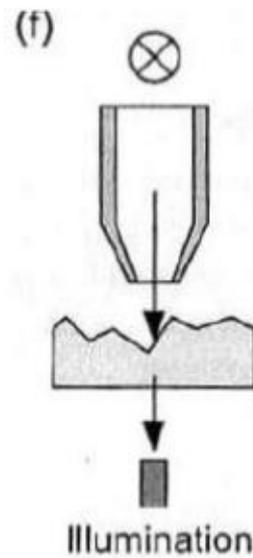
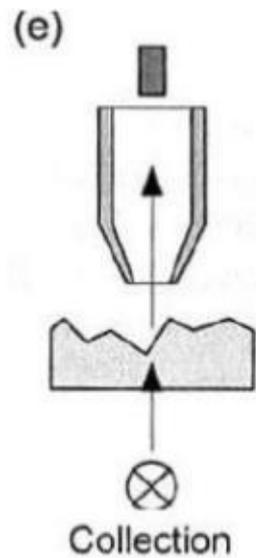
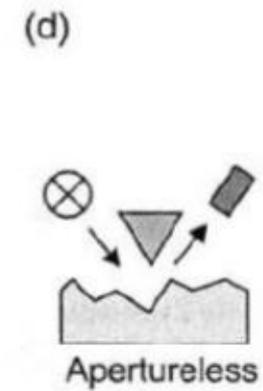
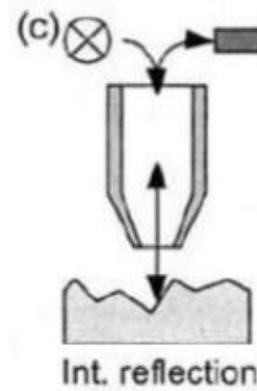
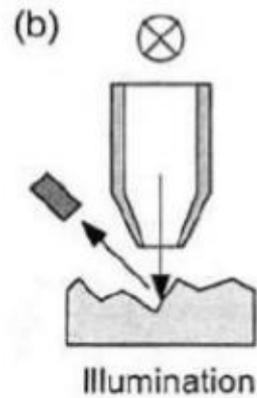
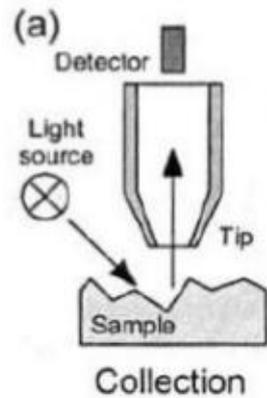
SNOM-Sonden



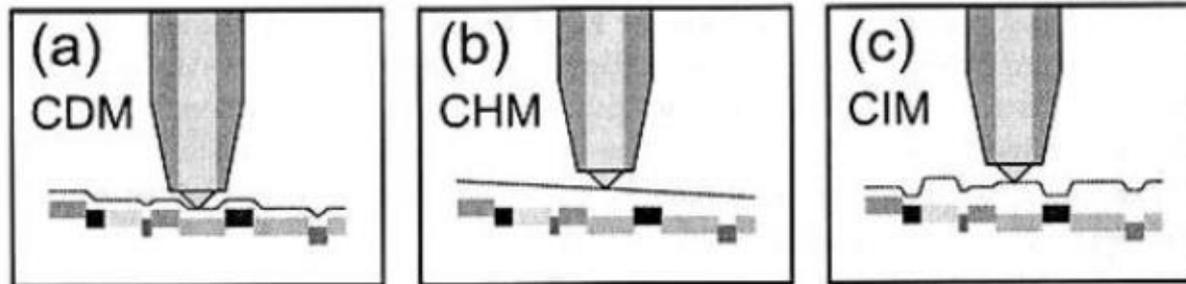
optische Fasern, dünn ausgezogen
bedampft mit metallischen Filmen

mit ‚focussed ion beam‘ nachbearbeitet (links)

SNOM-Familie



SNOM-Betriebsmodi



CDM – constant distance

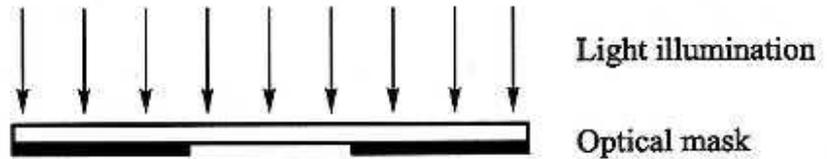
CHM – constant height

CIM – constant intensitiy

Einfacher planarer Mikrofabrikationsprozess



(a) Coat photoresist



(b) Expose through a photomask

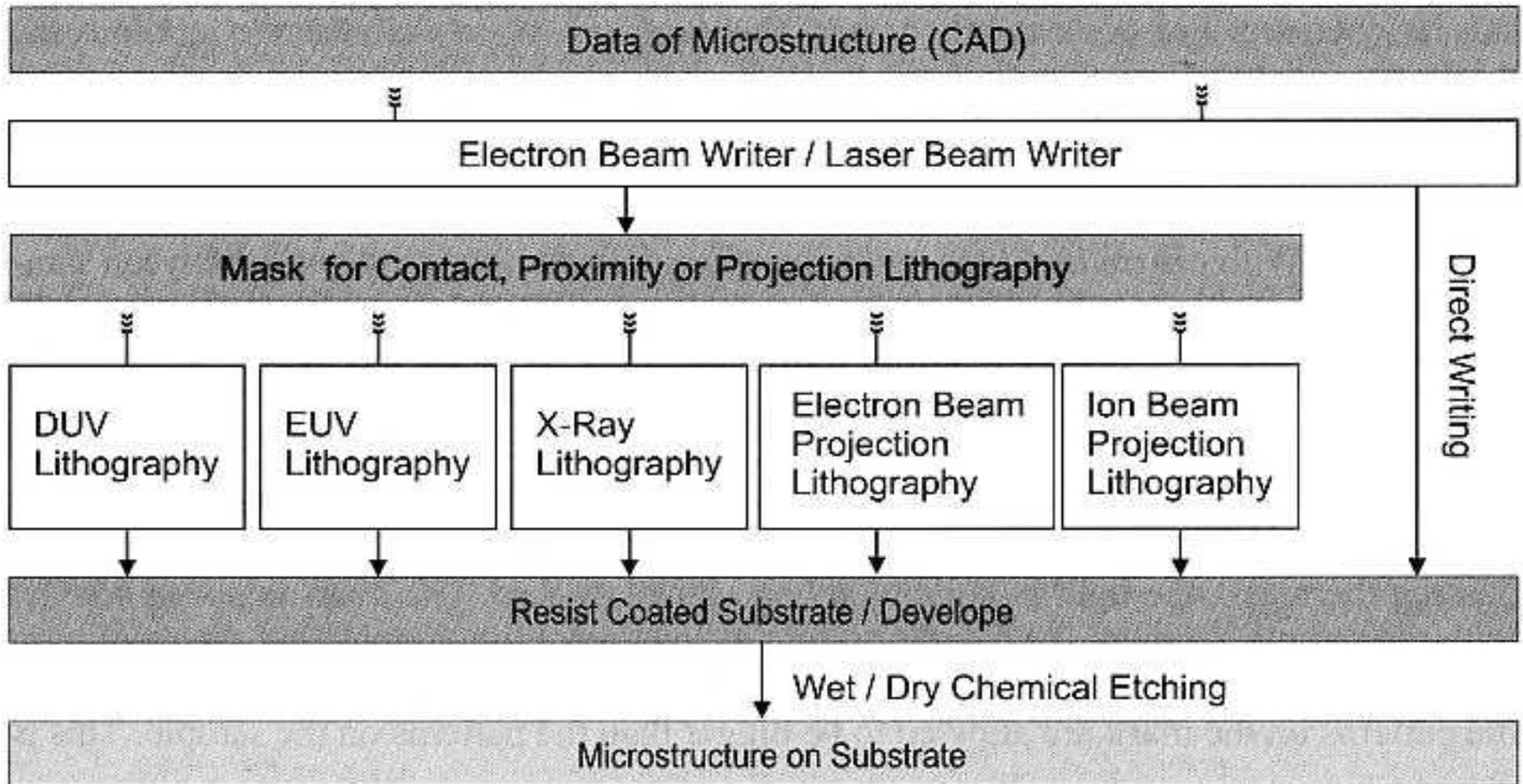


(c) Develop photoresist pattern

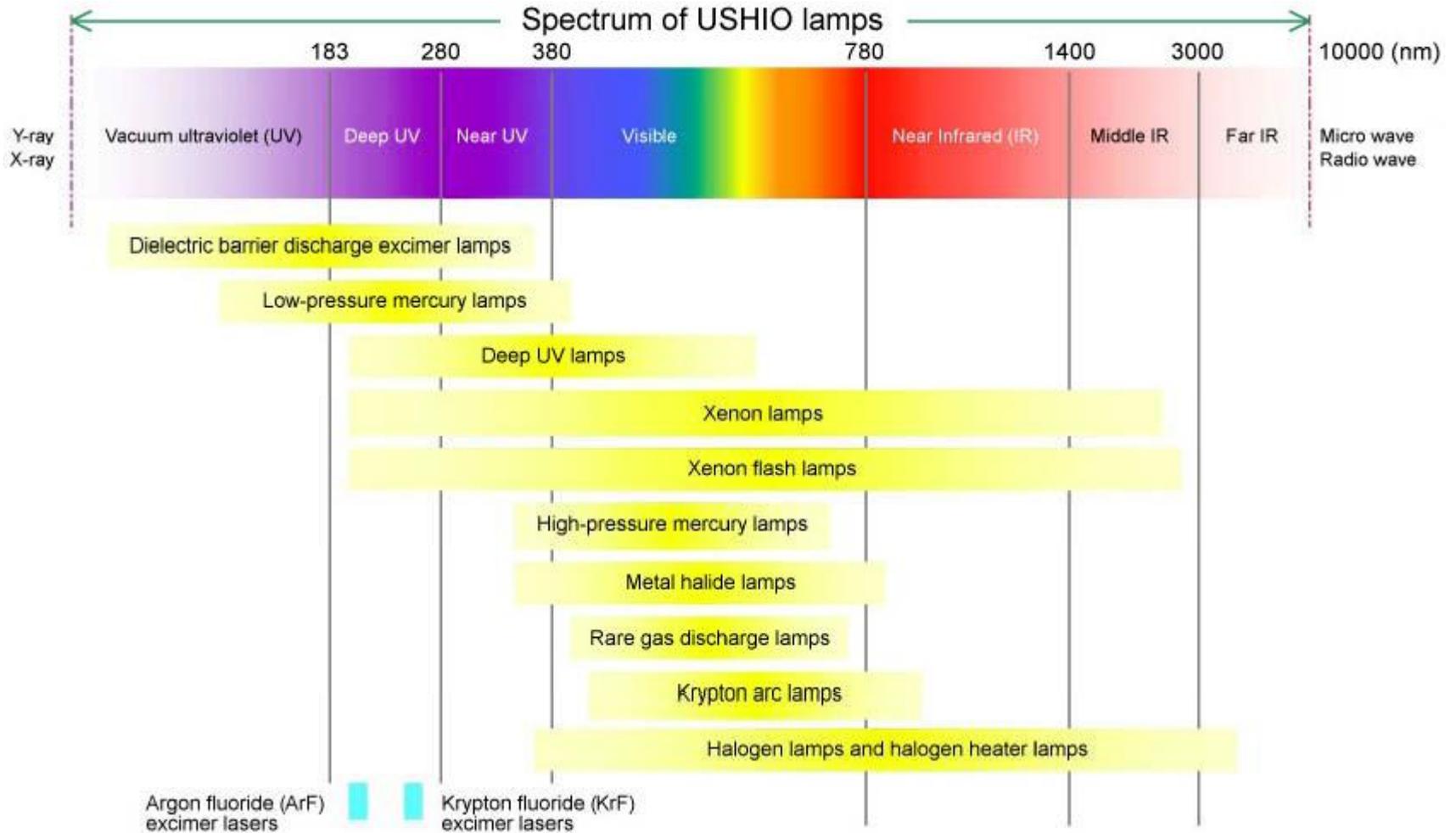


(d) Transfer photoresist pattern into substrate

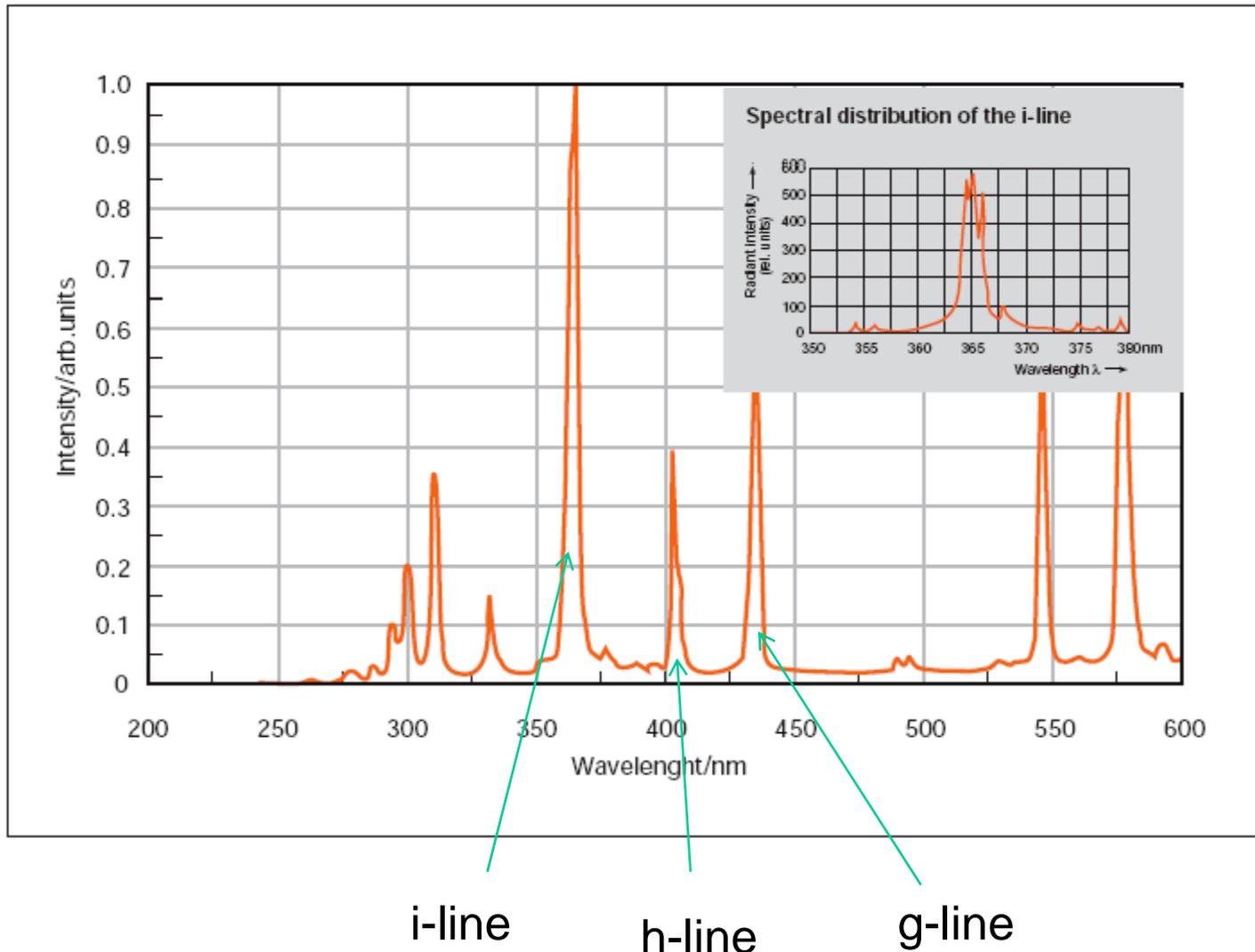
Einfacher planarer Mikrofabrikationsprozess



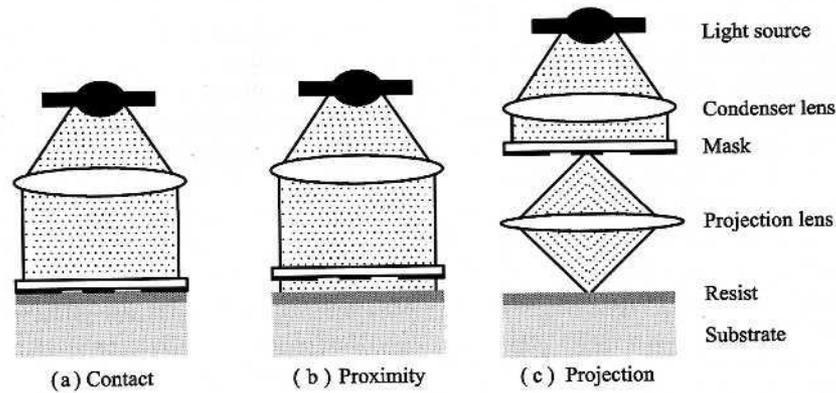
Wellenlängenspektrum verschiedener Lichtquellen für Lithografie



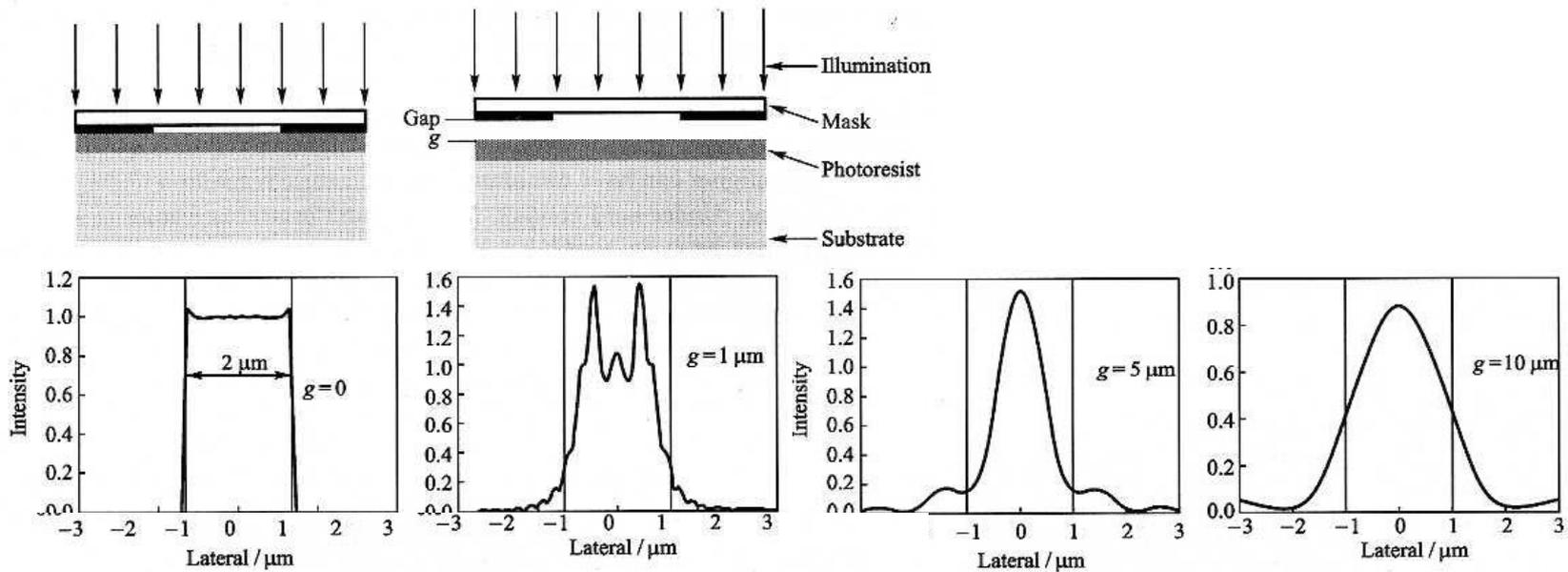
Wellenlängenspektrum einer Hg-Dampflampe



Grundprinzipien optischer Lithografieverfahren



Unschärfe des Abbildes nimmt mit wachsendem Abstand g zu



Lampenhaus

TSA Mikroskop

Maskenhalter

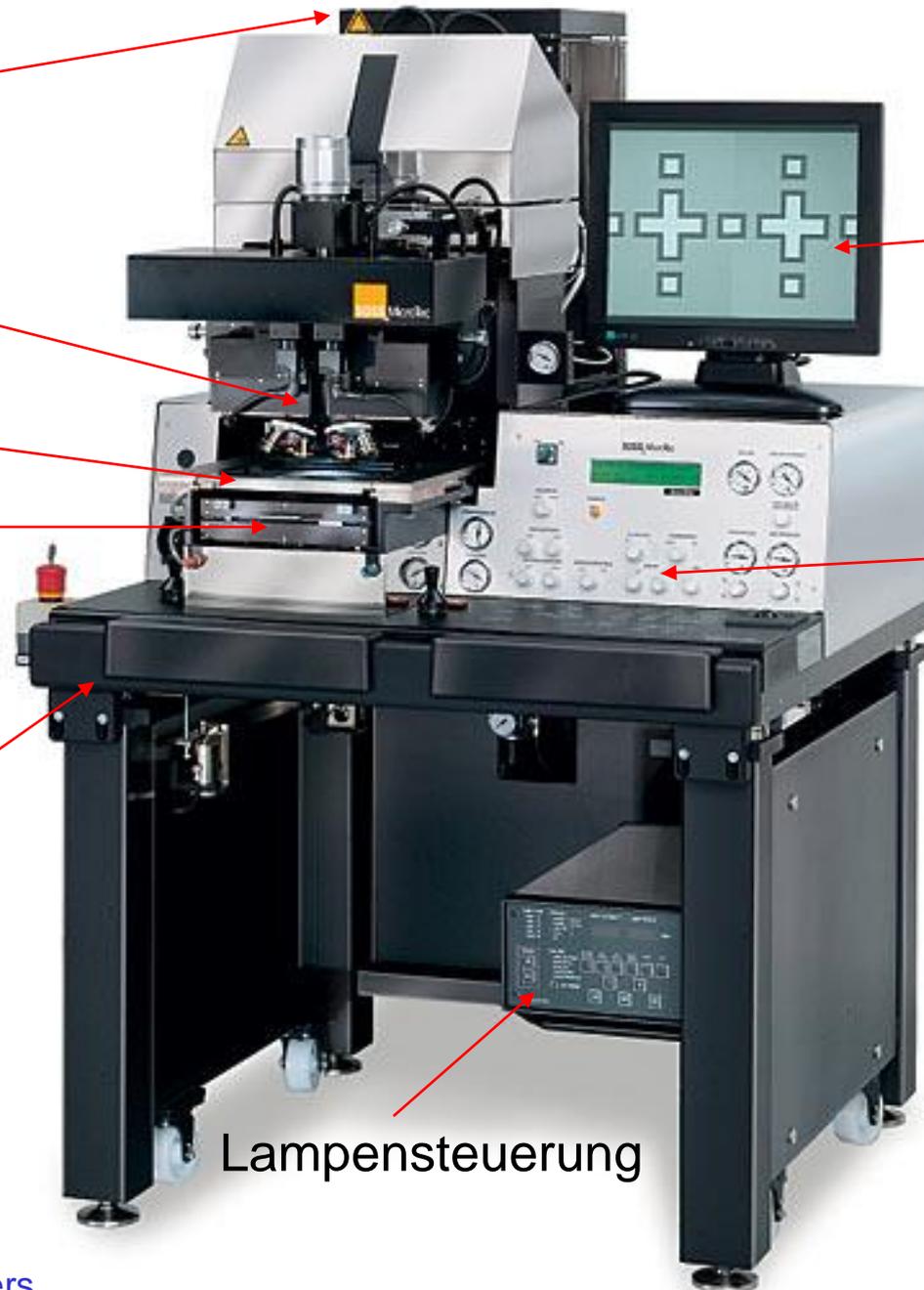
Wafer-Ladeschlitten

schwingungs-
gedämpfter
Tisch

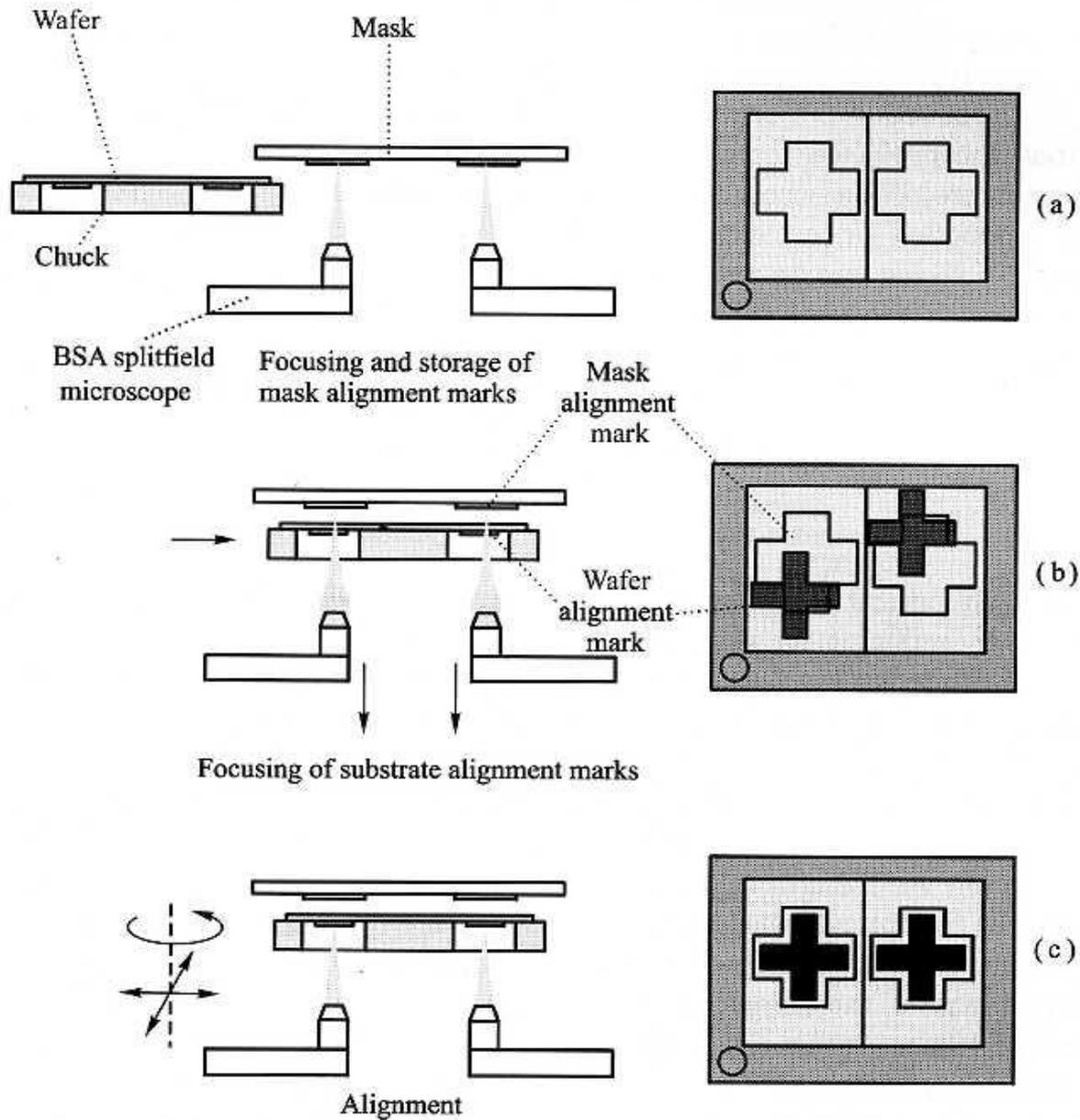
Lampensteuerung

Monitor

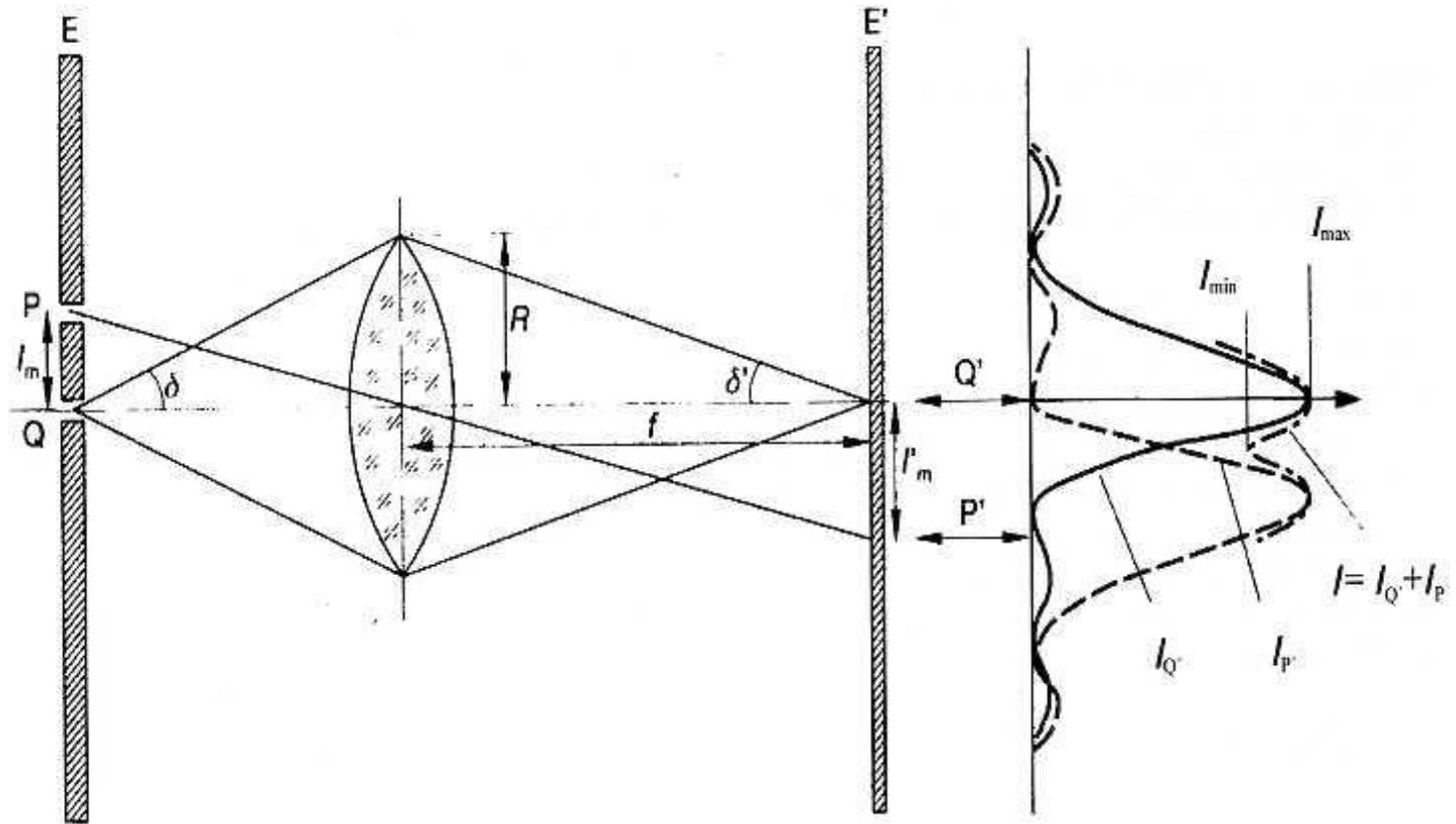
Bedienkonsole



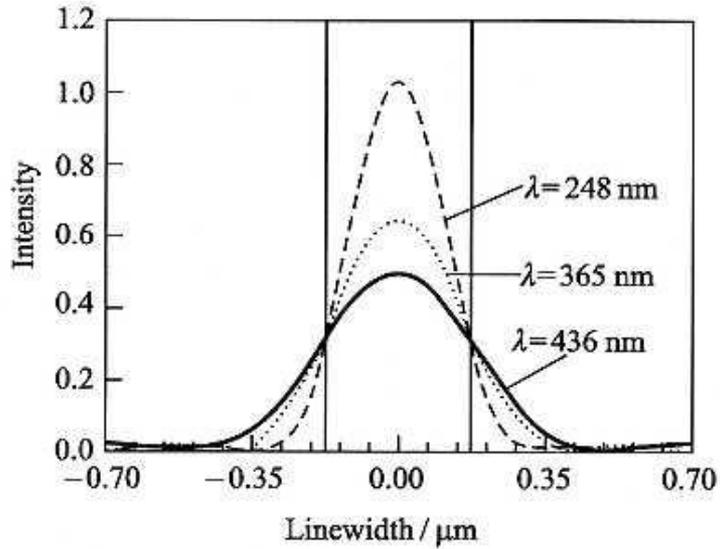
Beispiel für das Ausrichten einer Maske im Maskaligner



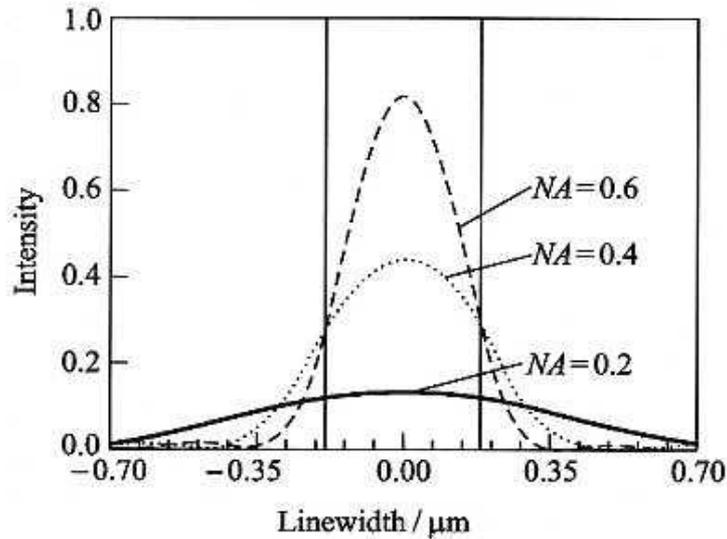
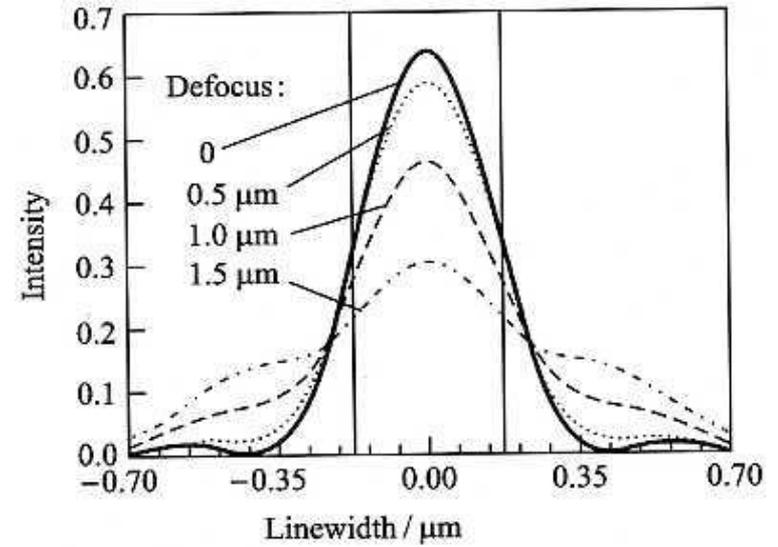
Rayleigh-Kriterium der Auflösung



Abhängigkeit der Auflösung von Wellenlänge, numerischer Apertur und Tiefenschärfe



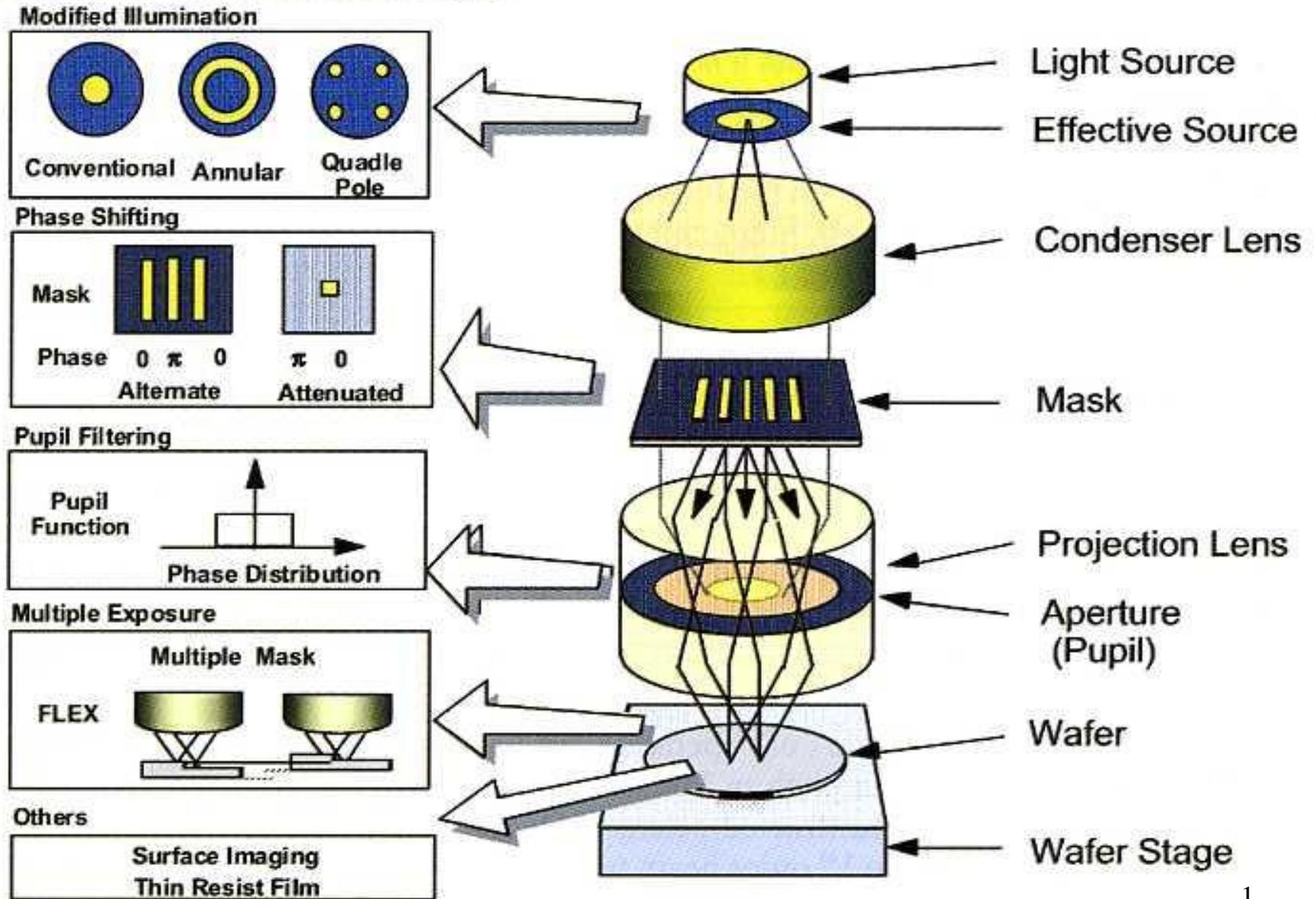
(a) Effect of wavelength

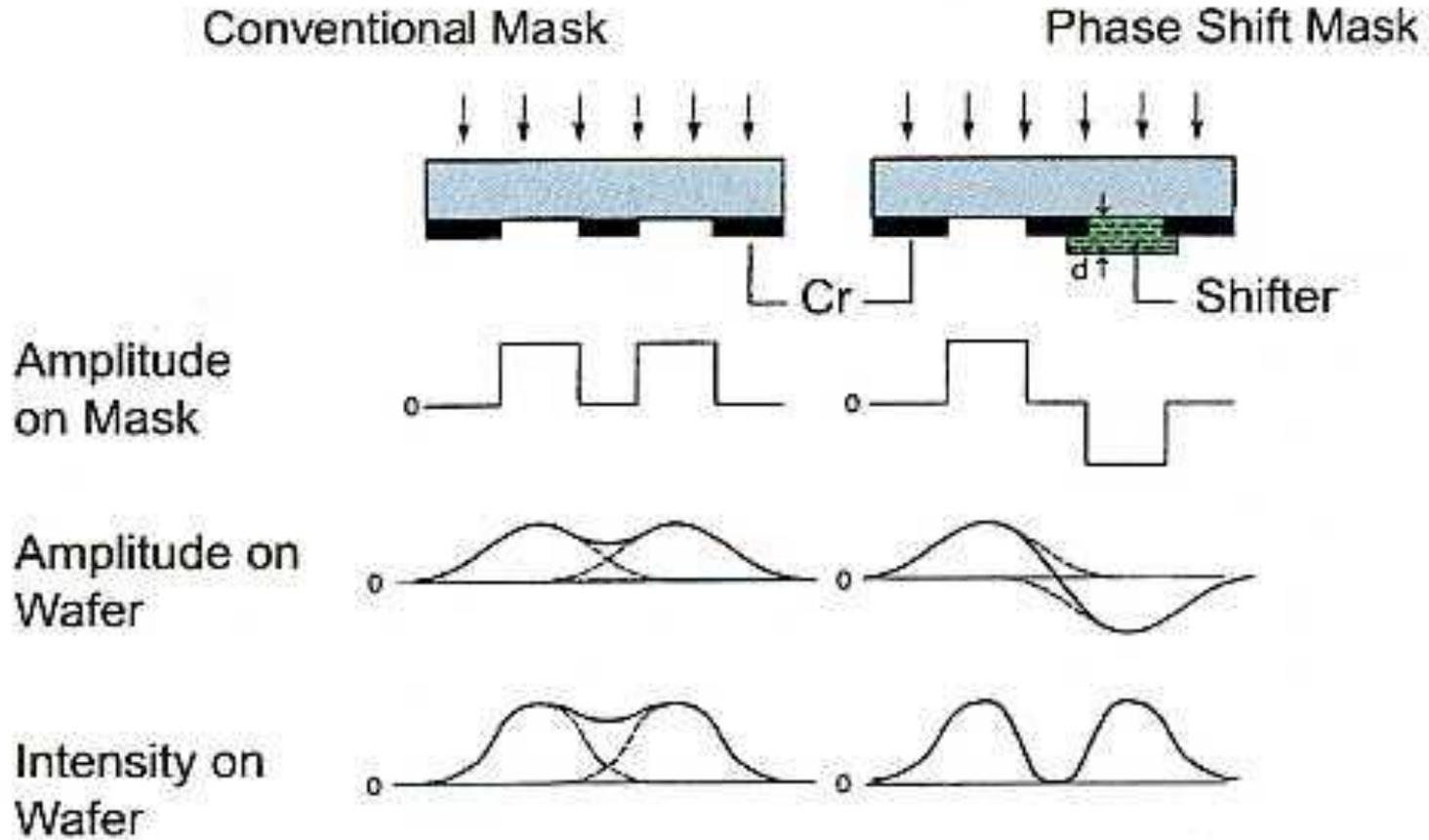


(b) Effect of numerical aperture

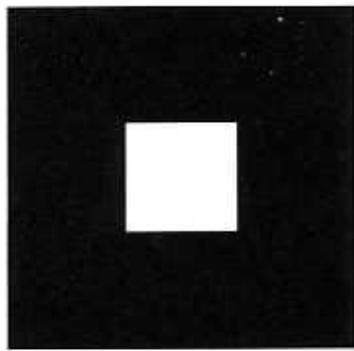
Verfahren zur Verbesserung der Auflösung

Resolution Enhancement Technologies

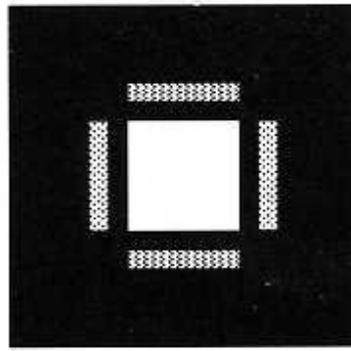




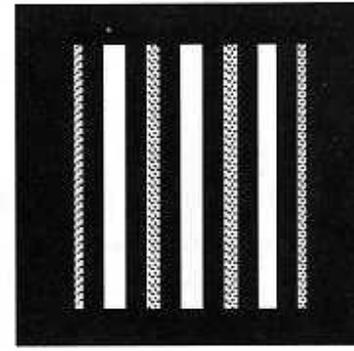
Phasenschieber-
techniken



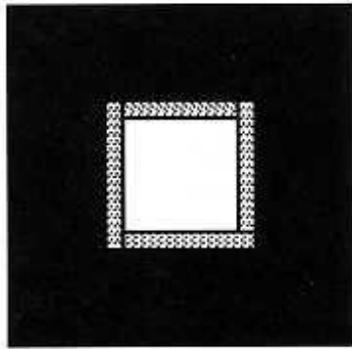
(a) Conventional



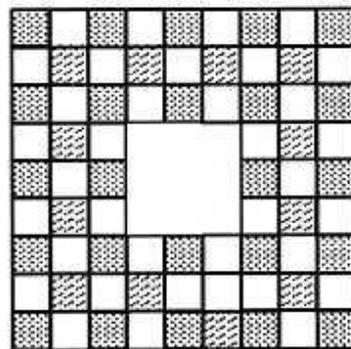
(b) Auxillary



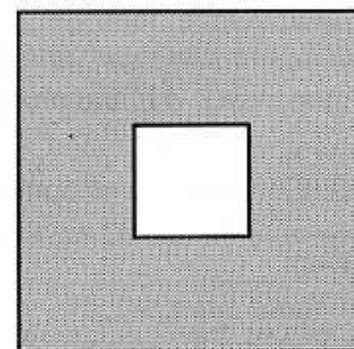
(c) Alternating



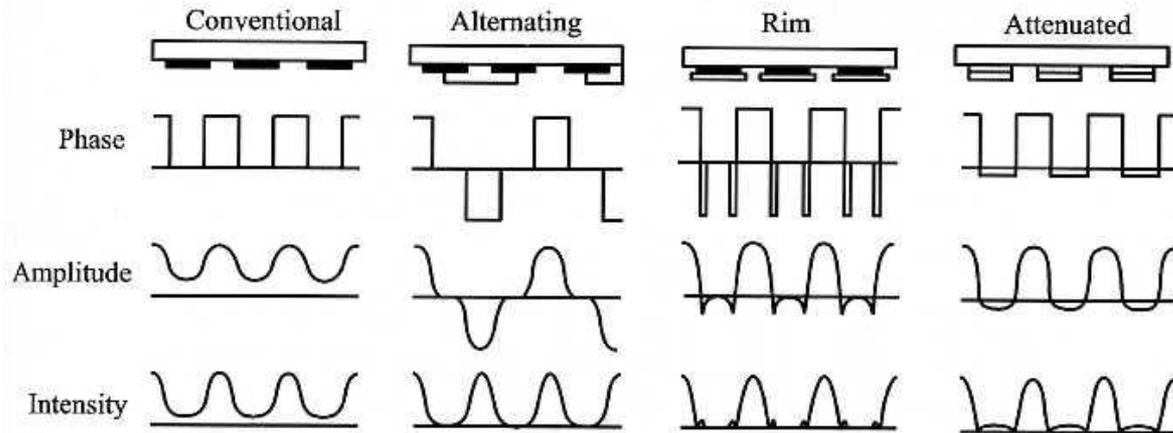
(d) Rim



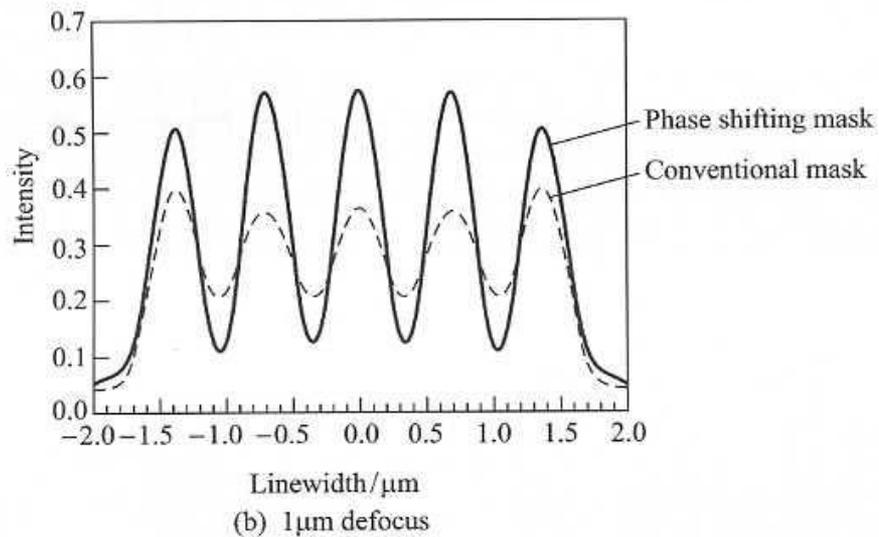
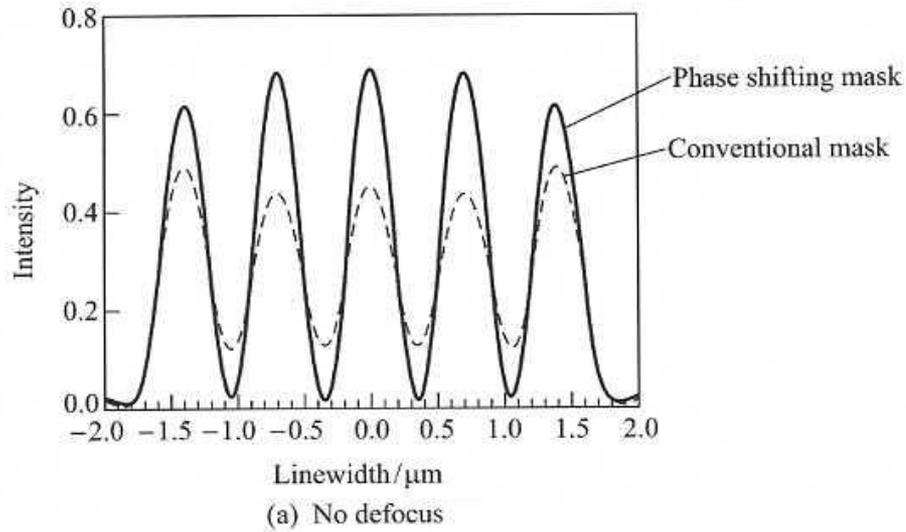
(e) Chromeless



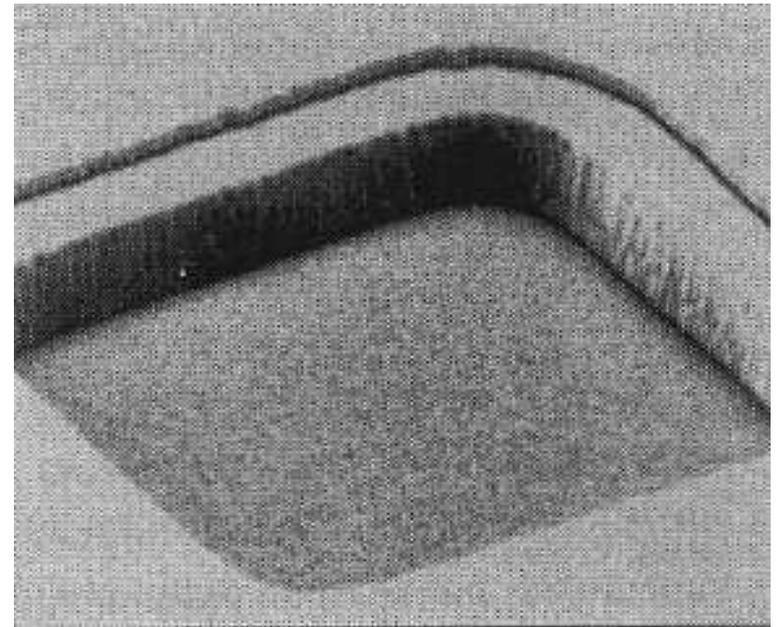
(f) Attenuated



Verbesserung der Auflösung durch Phasenschiebertechniken



Beispiel einer RIM-Phasenschiebermaske



Vor- und Nachteile verschiedener Phasenschiebertechniken

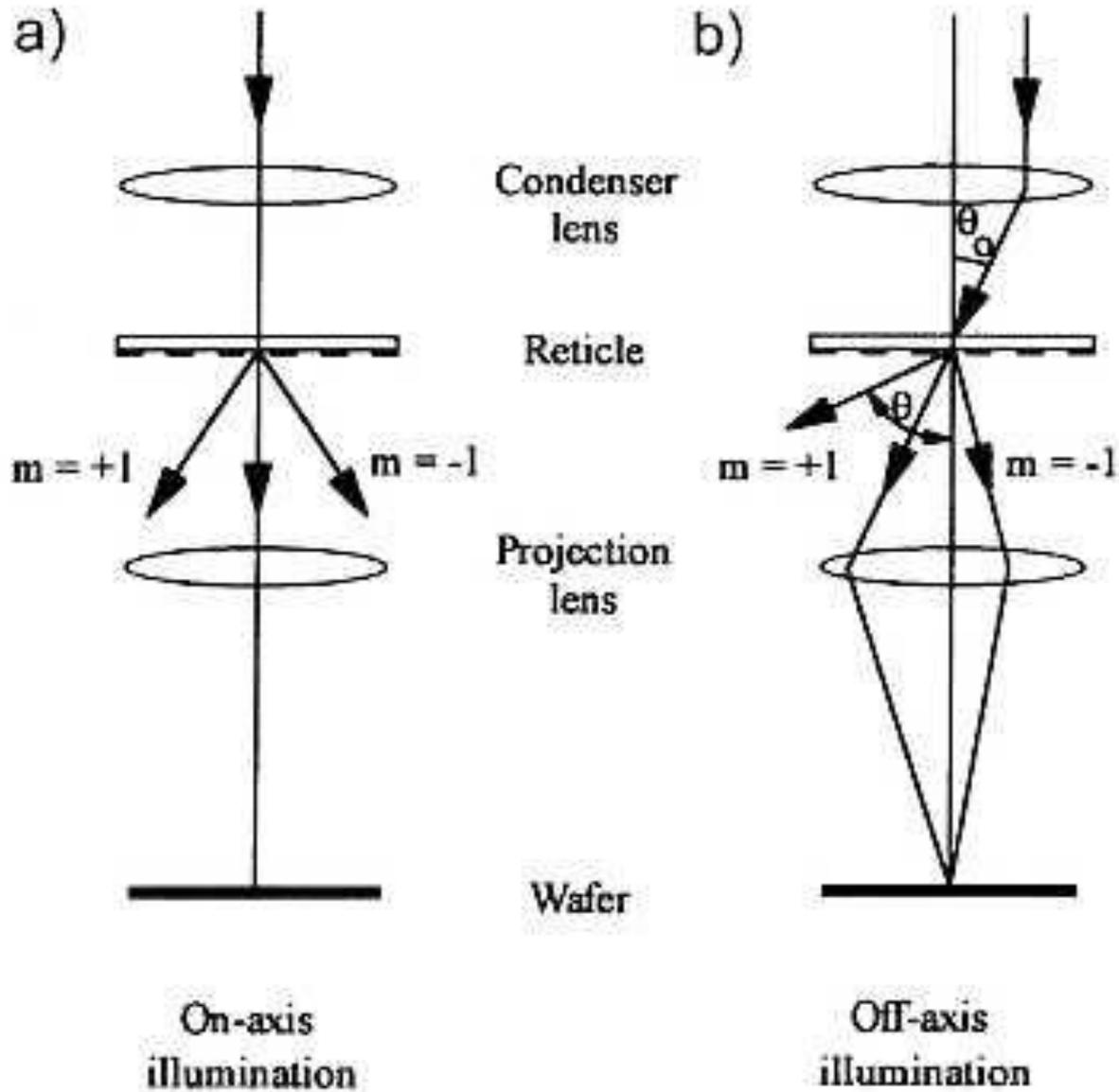
PSM Typ ->

Alternating Chromeless Auxiliary Rim Attenuating

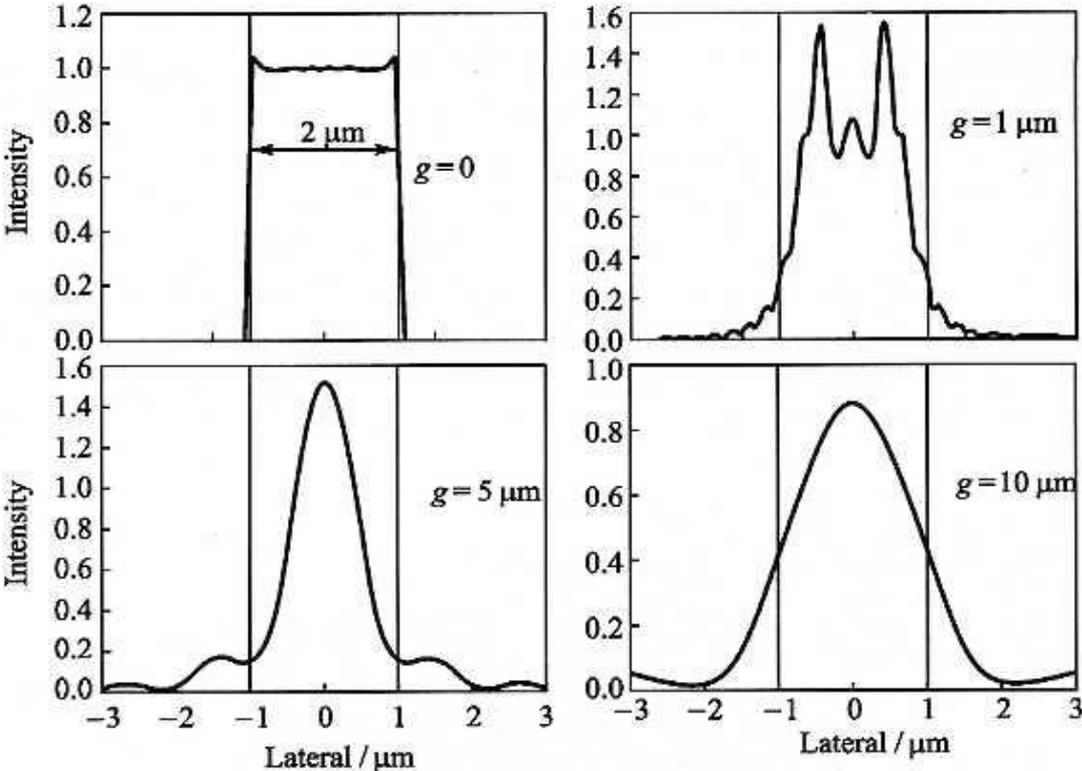
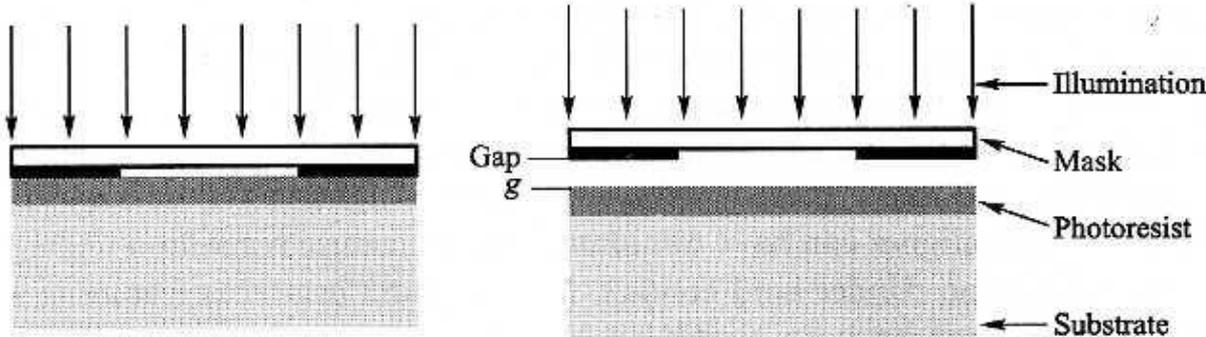
Eigenschaften

Starke Phasenverschiebung	Starke Phasenverschiebung	Schwache Phasenverschiebung	Schwache Phasenverschiebung	Schwache Phasenverschiebung (besser als rim PSM)
Signifikante Verbesserung von Kontrast und Tiefenschärfe bis zu 50%	Signifikante Verbesserung von Kontrast und Tiefenschärfe bis zu 50%	Nur für isolierte oder weit auseinanderliegende Strukturen geeignet	Verbesserung von Kontrast und Tiefenschärfe um 10-20%	Verbesserung von Kontrast und Tiefenschärfe um 10-20%
Schwierige Herstellung	Schwierige Herstellung	Relativ schwierige Herstellung	Einfache Herstellung	Einfache Herstellung
Benötigt 2 Belichtungsschritte	Benötigt große Zahl von Phasenmuster unterhalb der Auflösungsgrenze	Benötigt Hilfsstruktur zur 180° Phasendrehung	Seiteneffekte	Benötigt spezielles Maskenmaterial, Seiteneffekte abhängig von der Dämpfung
Kompliziertes Design, schwierige automatische Implementierung	Kompliziertes Design, schwierige automatische Implementierung	Kompliziertes Design, schwierige automatische Implementierung	Einfaches Design	Design wie konventionelle Maske

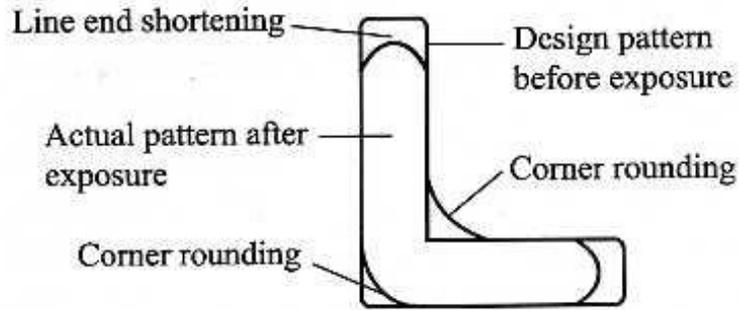
Kontrasterhöhung durch Off-Axis-Beleuchtung



Optischer Proximity-Effekt



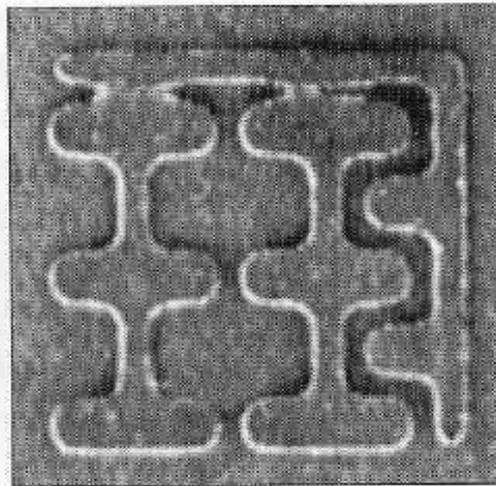
Optischer Proximity-Effekt



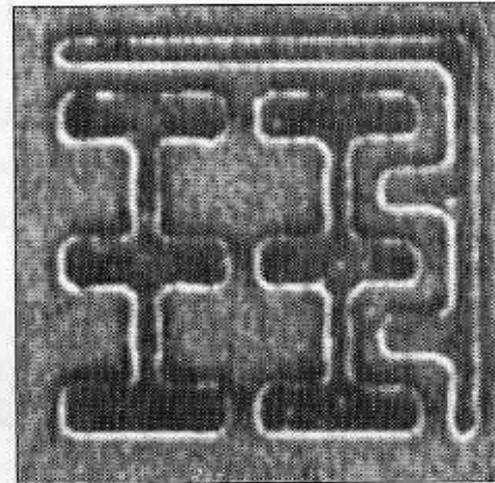
(a) Illustration of optical proximity effect



(b) Optical proximity correction design

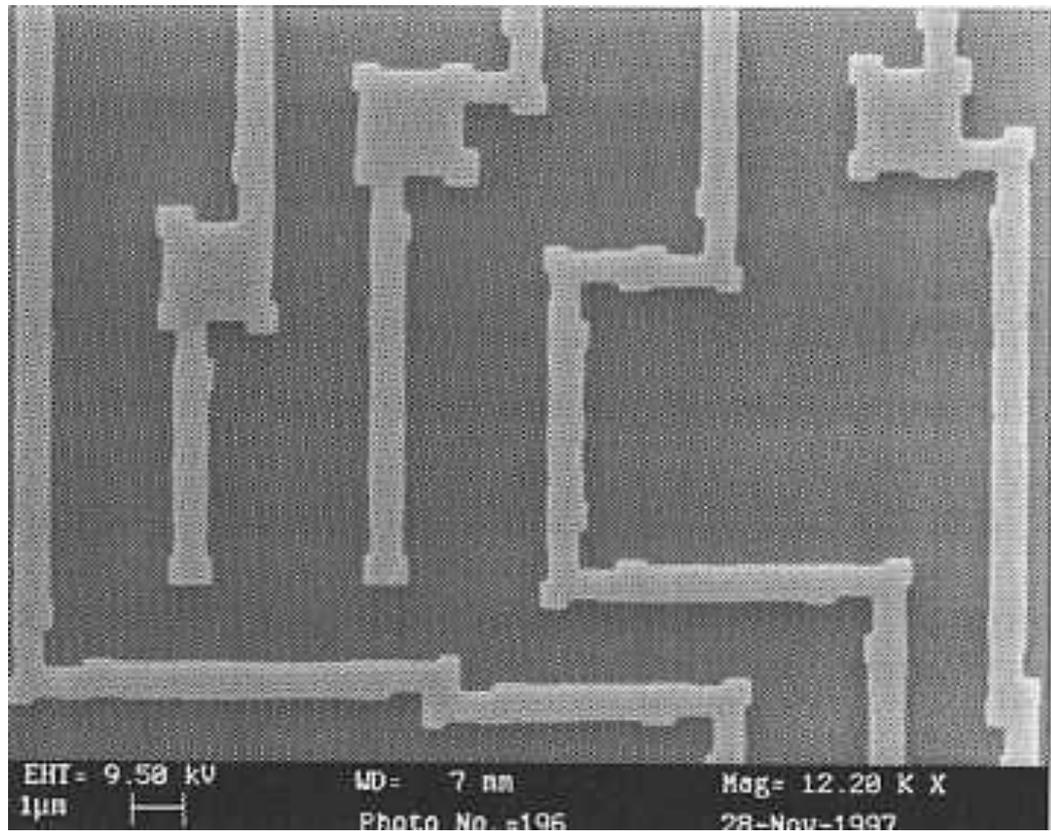


(a) Photoresist image without OPC



(b) Photoresist image with OPC

Korrektur des optischer Proximity-Effekts durch regelbasierte und modellbasierte Verfahren

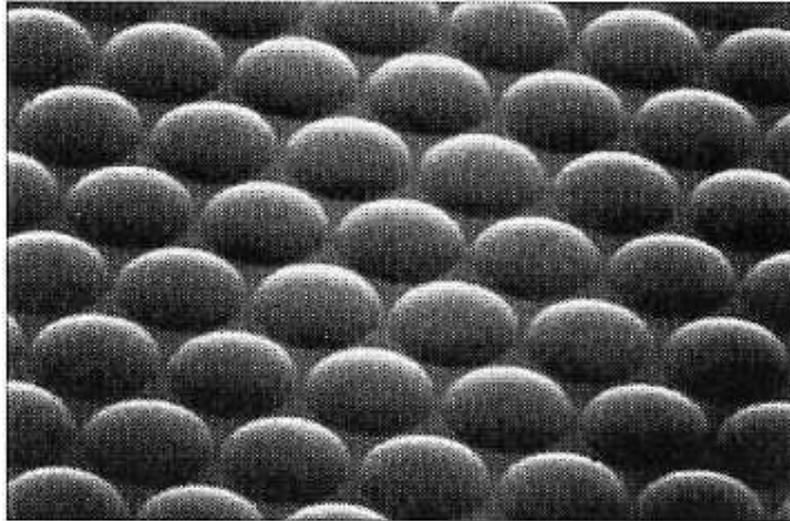


Grenzen der optischen Lithografie am Beispiel des DRAM chips

Table-2.5. Mask levels and their resolution requirements for different generations of DRAM chip

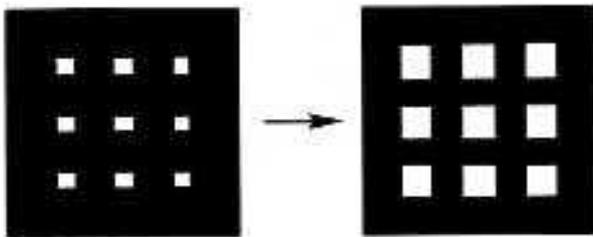
density of DRAM	16MB	64MB	256MB	1GB
total mask levels	21	23	24	26
0.18 ~ 0.25 μm				5
0.25 ~ 0.35 μm			5	4
0.35 ~ 0.50 μm		4	4	4
0.50 ~ 0.65 μm	4	4	4	3
0.65 ~ 0.75 μm	4	5	4	3
$\geq 0.75 \mu\text{m}$	13	10	7	7

Graustufen- Fotolithografie

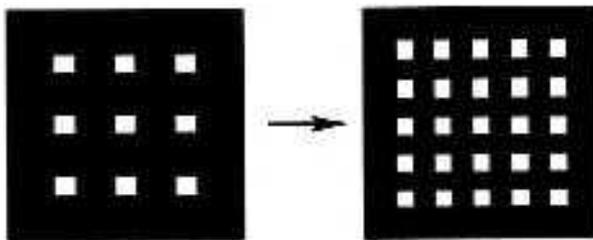


Microlens array made by photolithography through a grey-scale mask

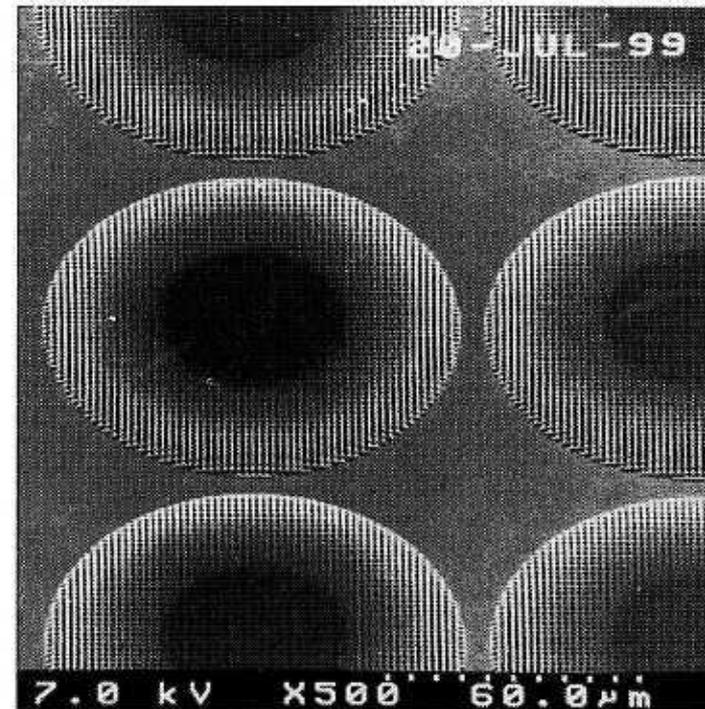
Graustufen- Fotolithografie



(a) Pulse Width Modulation (PWM) method

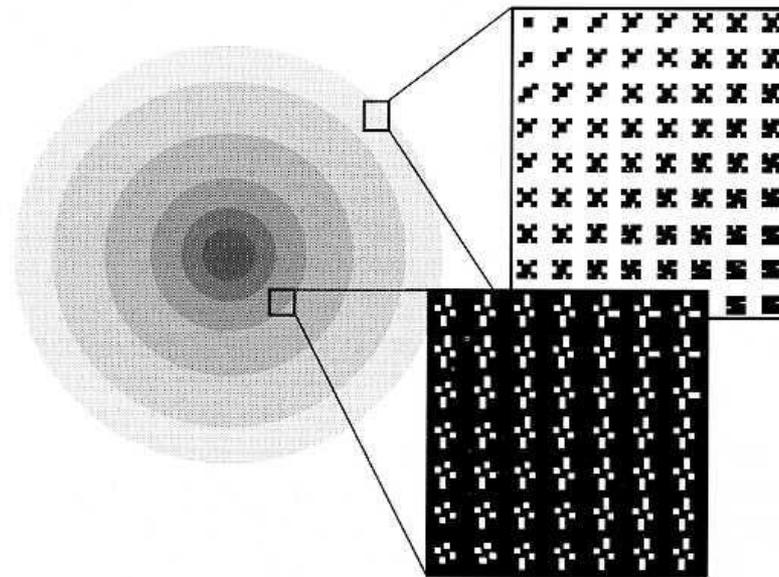


(b) Pulse Density Modulation (PDM) method



Pixel image in photoresist due to large pitch

Graustufen- Fotolithografie

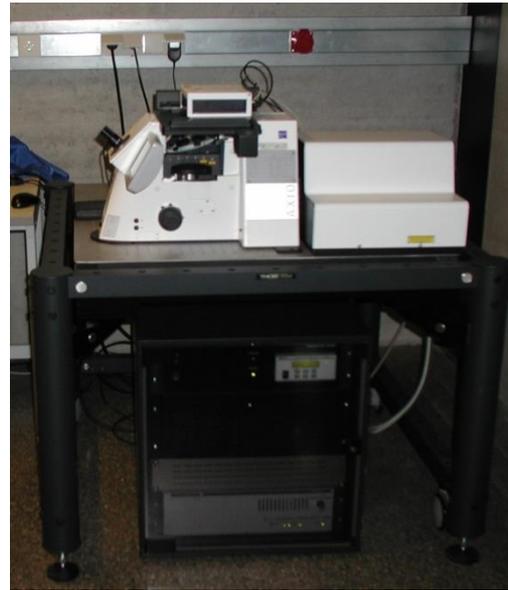


A grey-scale mask design for a microlens pattern

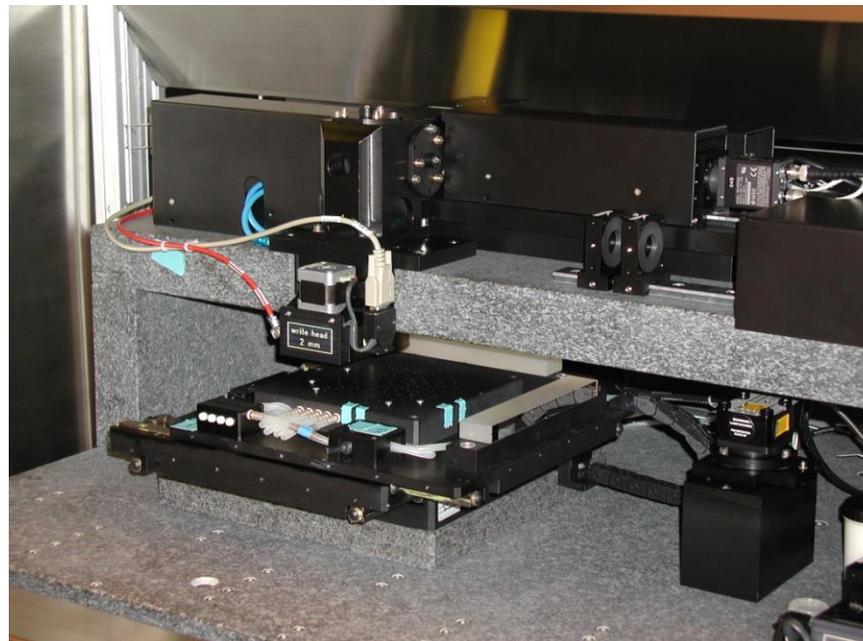
2D- und 3D- Direct Laser Writing

Fa. Heidelberg Instruments, DWL

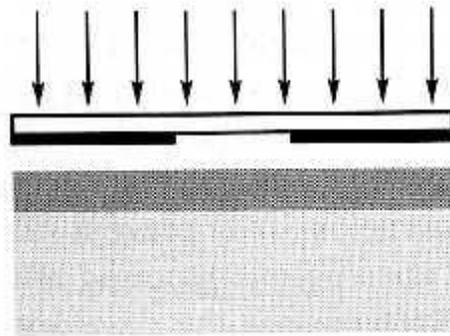
- Laser diode $\lambda = 442 \text{ nm}$
- interferometer stage
- substrates up to 9"
- minimum feature size $0.7 \mu\text{m}$
- alignment accuracy $0.5 \mu\text{m}$



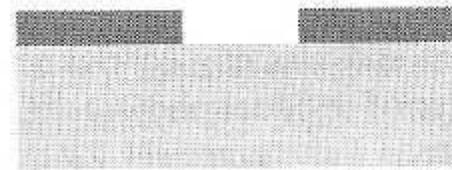
Fa. Nanoscribe, DLW



Eigenschaften von Fotolacken



(a) Before exposure



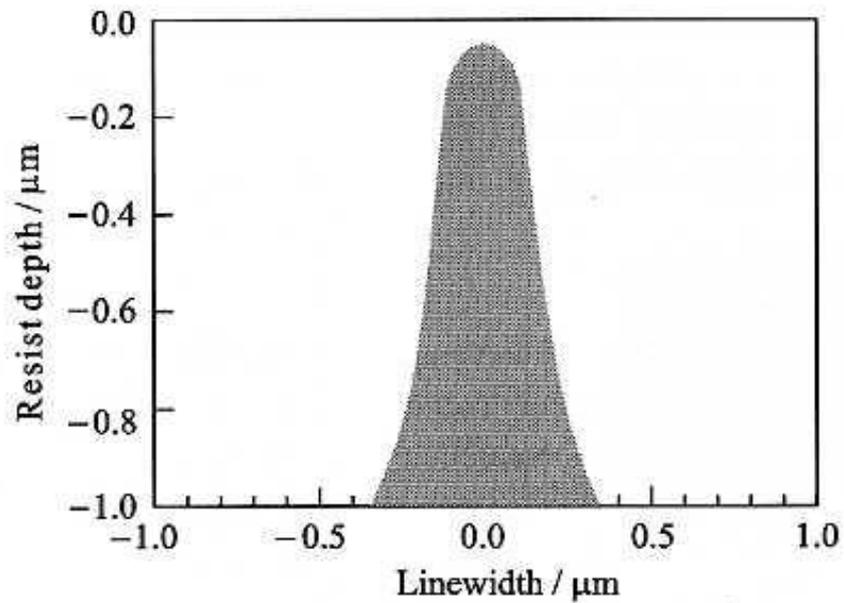
Positive resist



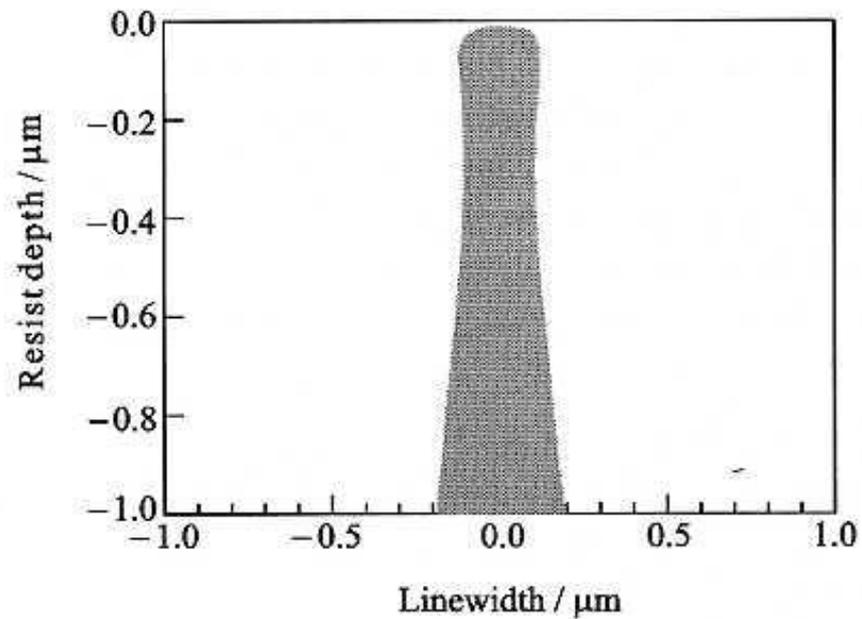
Negative resist

(b) After development

2. Kontrast



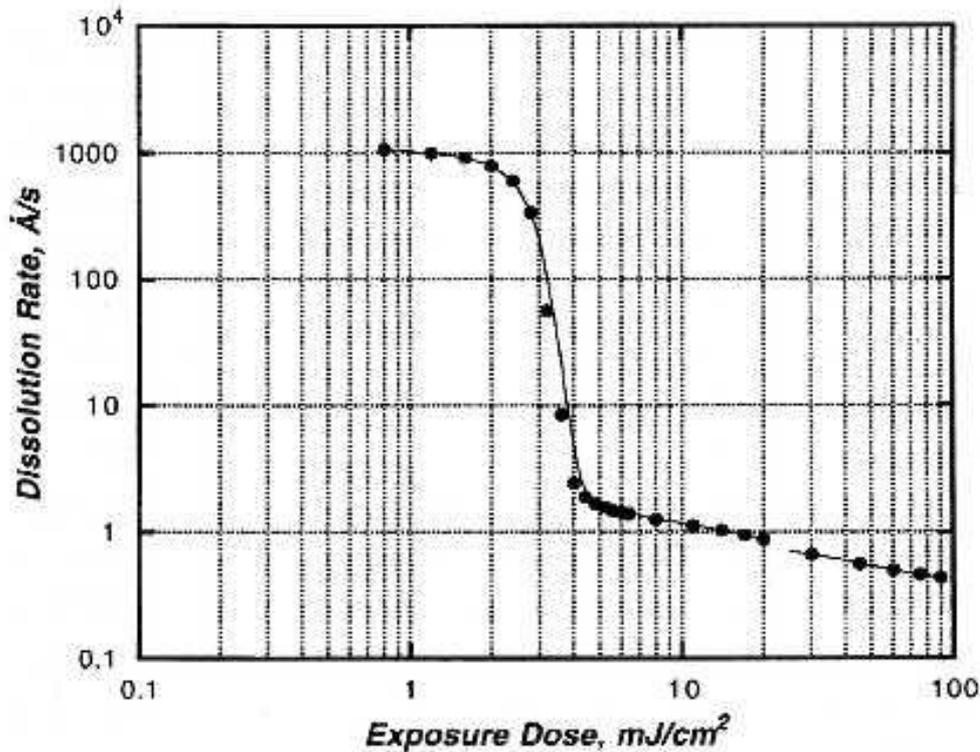
(a) Low contrast profile



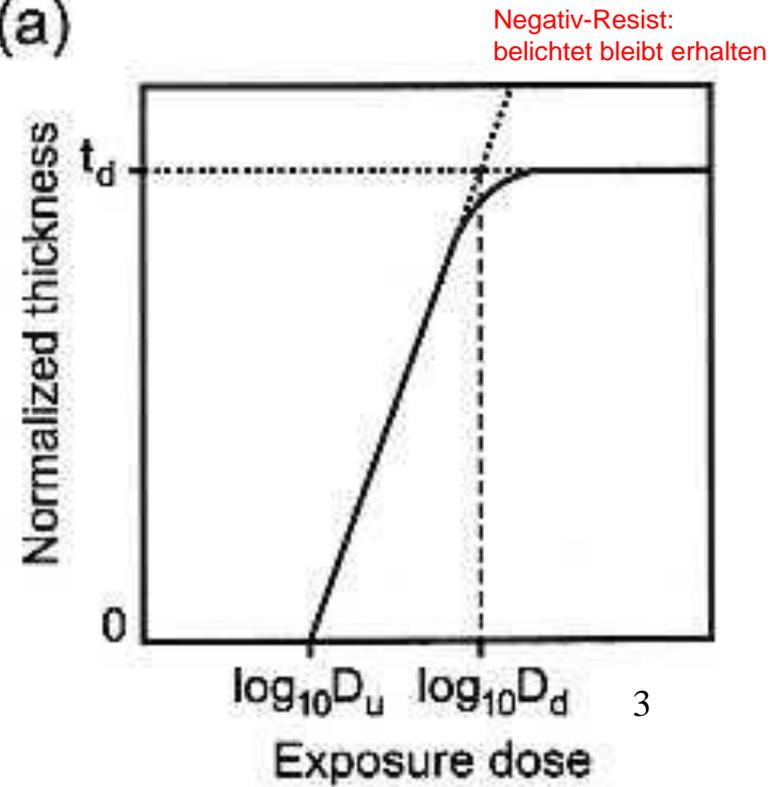
(b) High contrast profile

2. Kontrast

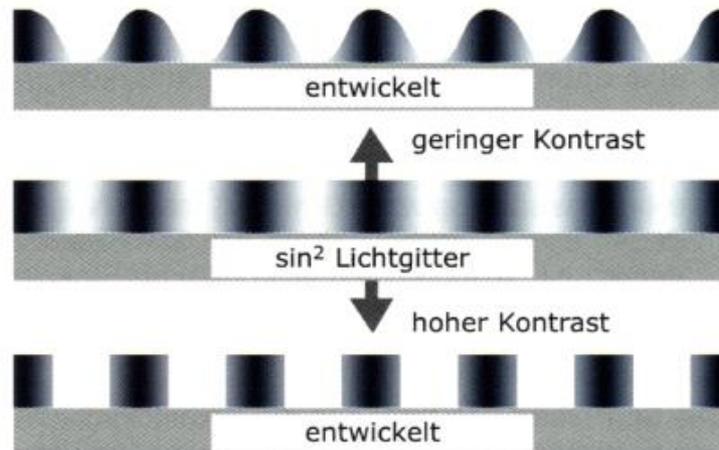
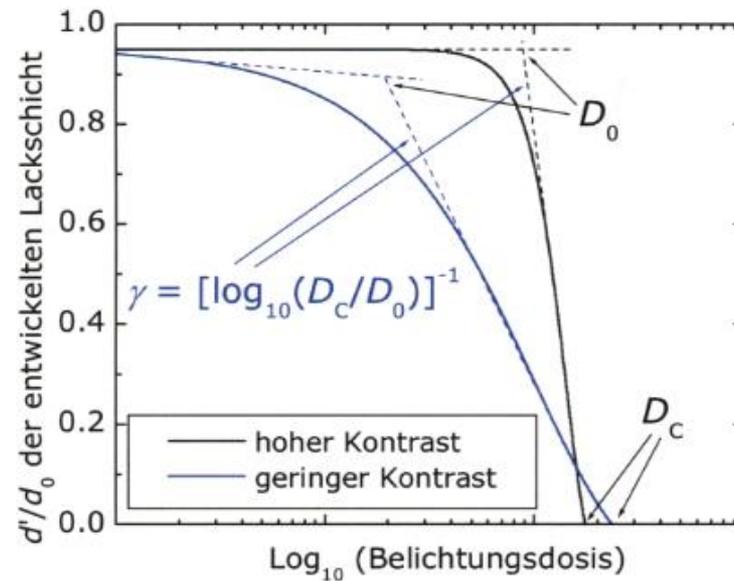
Kontrastkurve eines Negativ-PR



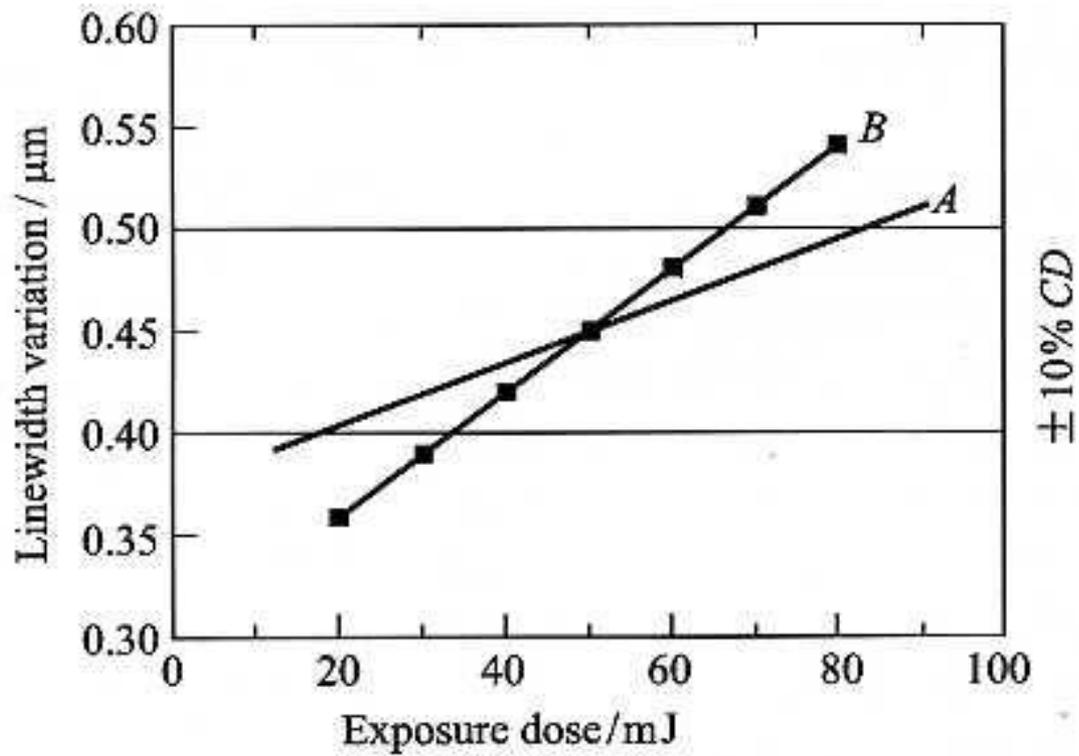
(a)



2. Kontrast

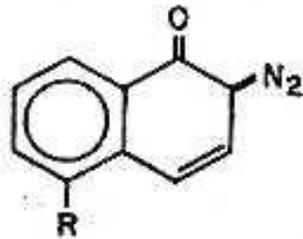


5. Belichtungsspielraum

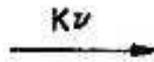


Fotolacke für optische Lithografie – Belichtungsprozess von DNQ

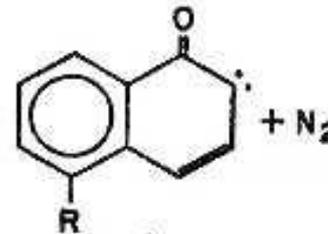
Naphthoquinone diazide
sulfonylchloride



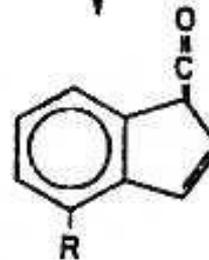
**BASE INSOLUBLE
SENSITIZER**



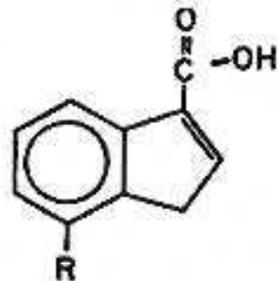
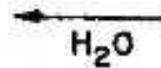
Keto-carbene (instabil)



**WOLFF
REARRANGEMENT**



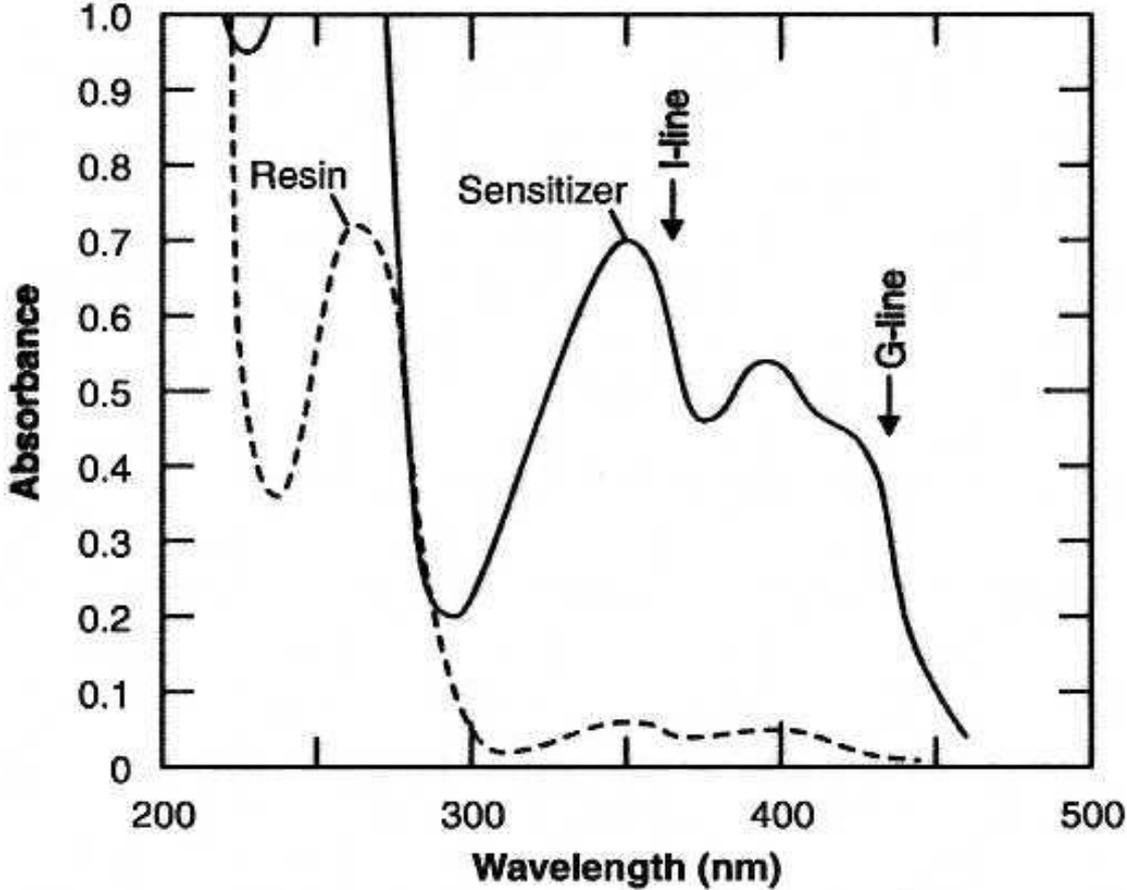
KETENE (hygroskopisch)



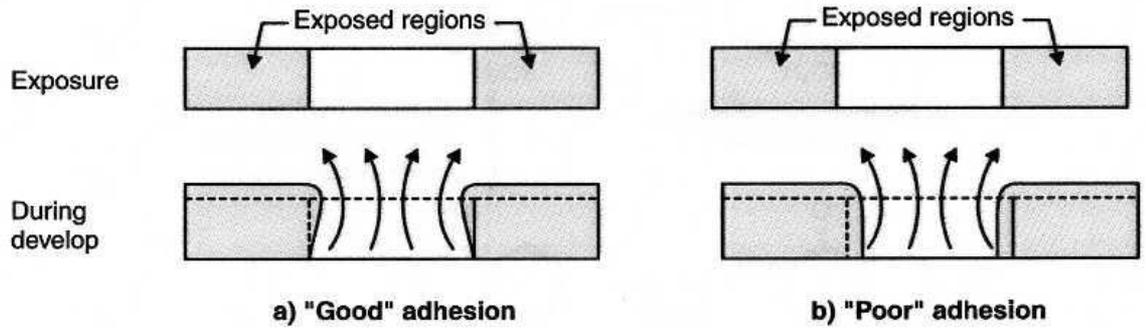
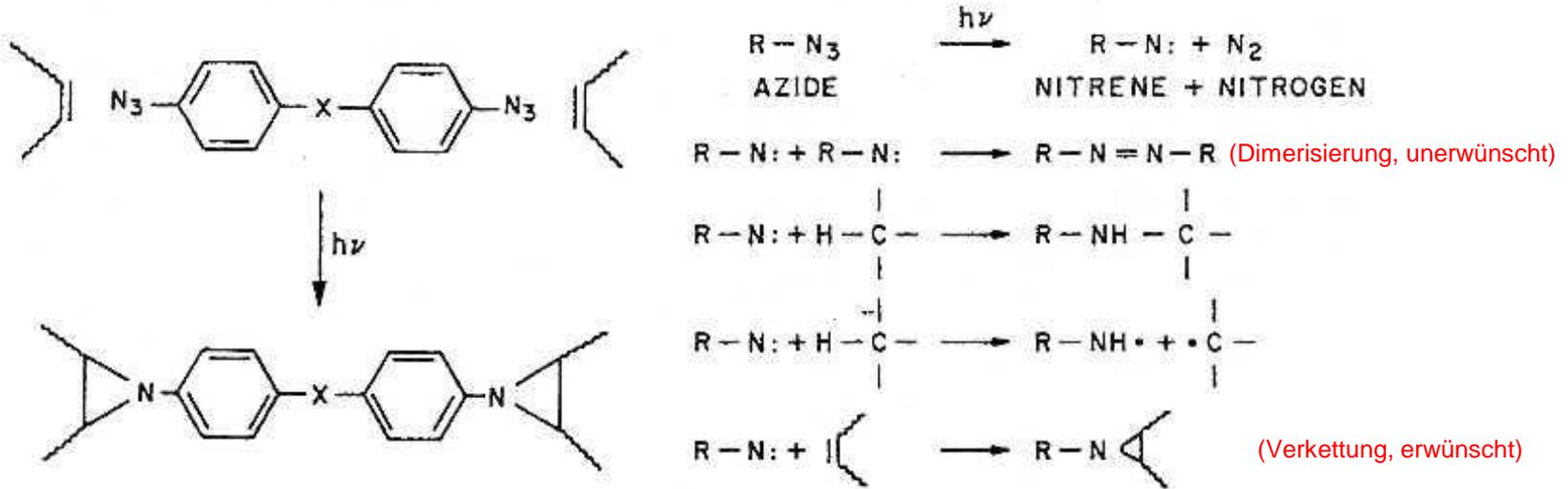
**BASE SOLUBLE
PHOTOPRODUCT**

(löslich in basischen Entwicklern, z.B. NaOH)

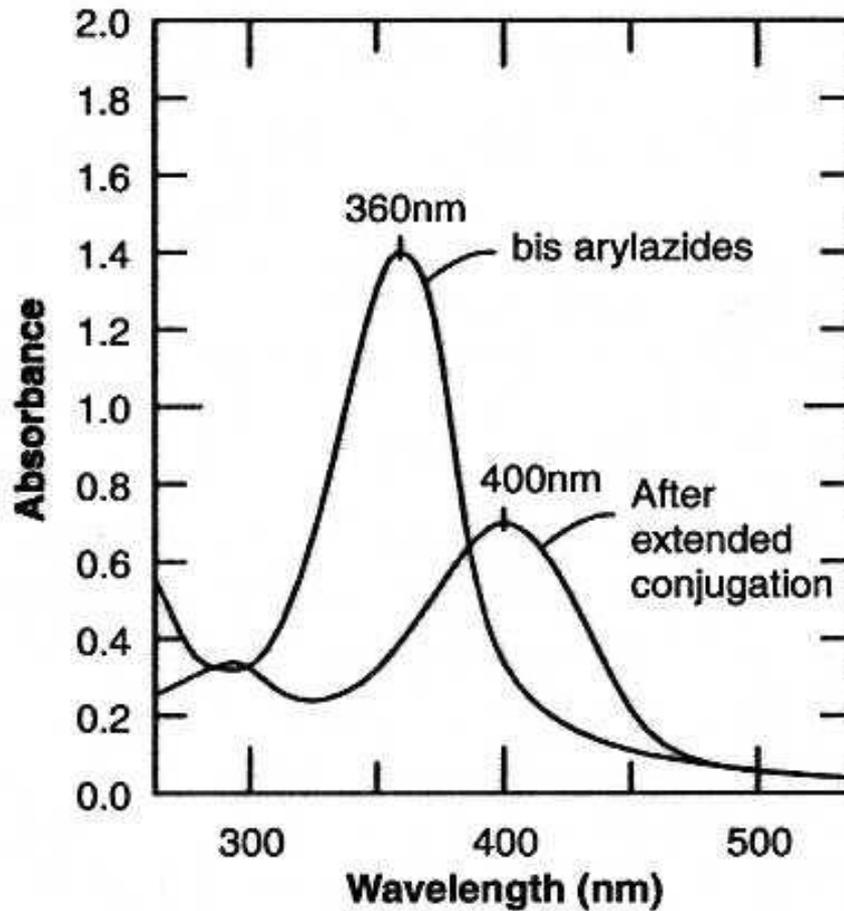
Absorbance des Positivlacks Novolak-DNQ



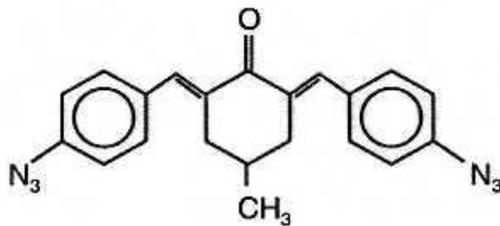
Belichtungsprozess der Azide



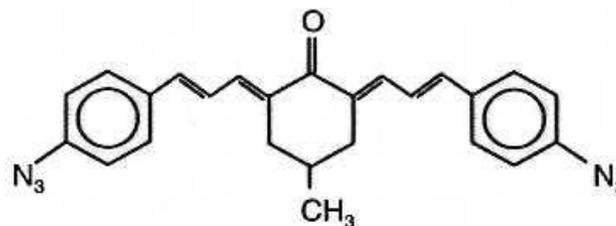
Absorbanz des Negativlacks bis-arylazide



Absorbance versus wavelength for bis-arylazide sensitizer

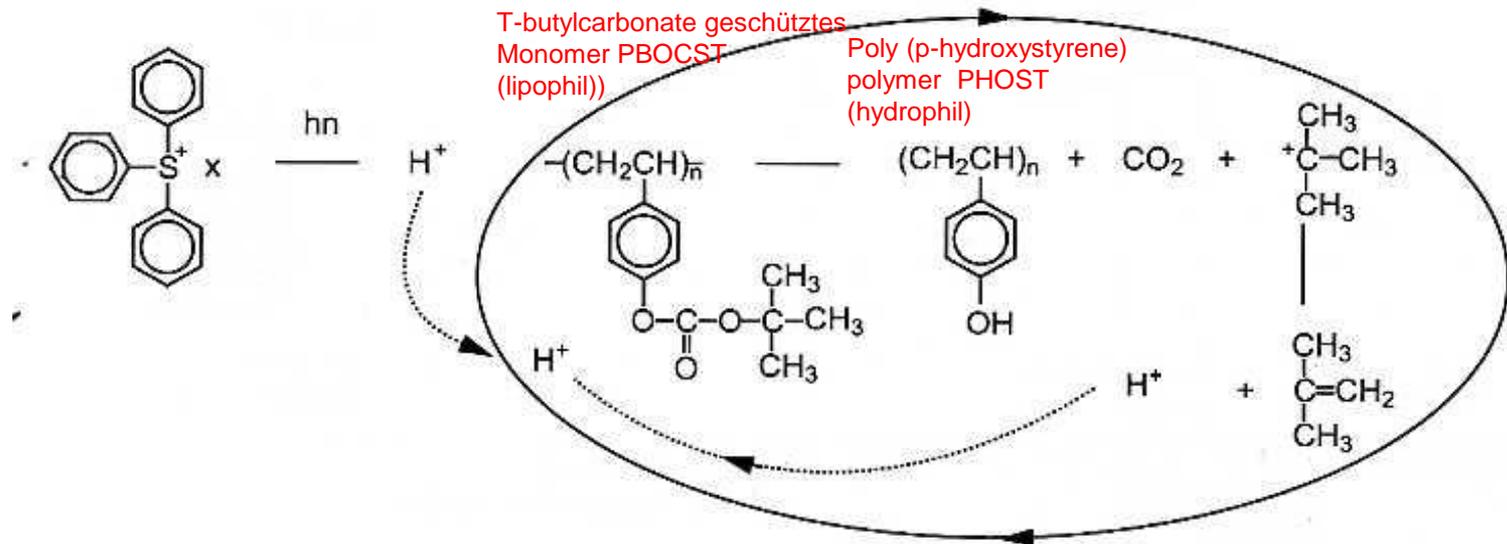


a) bis-arylazide



b) bis-arylazide after extended conjugation

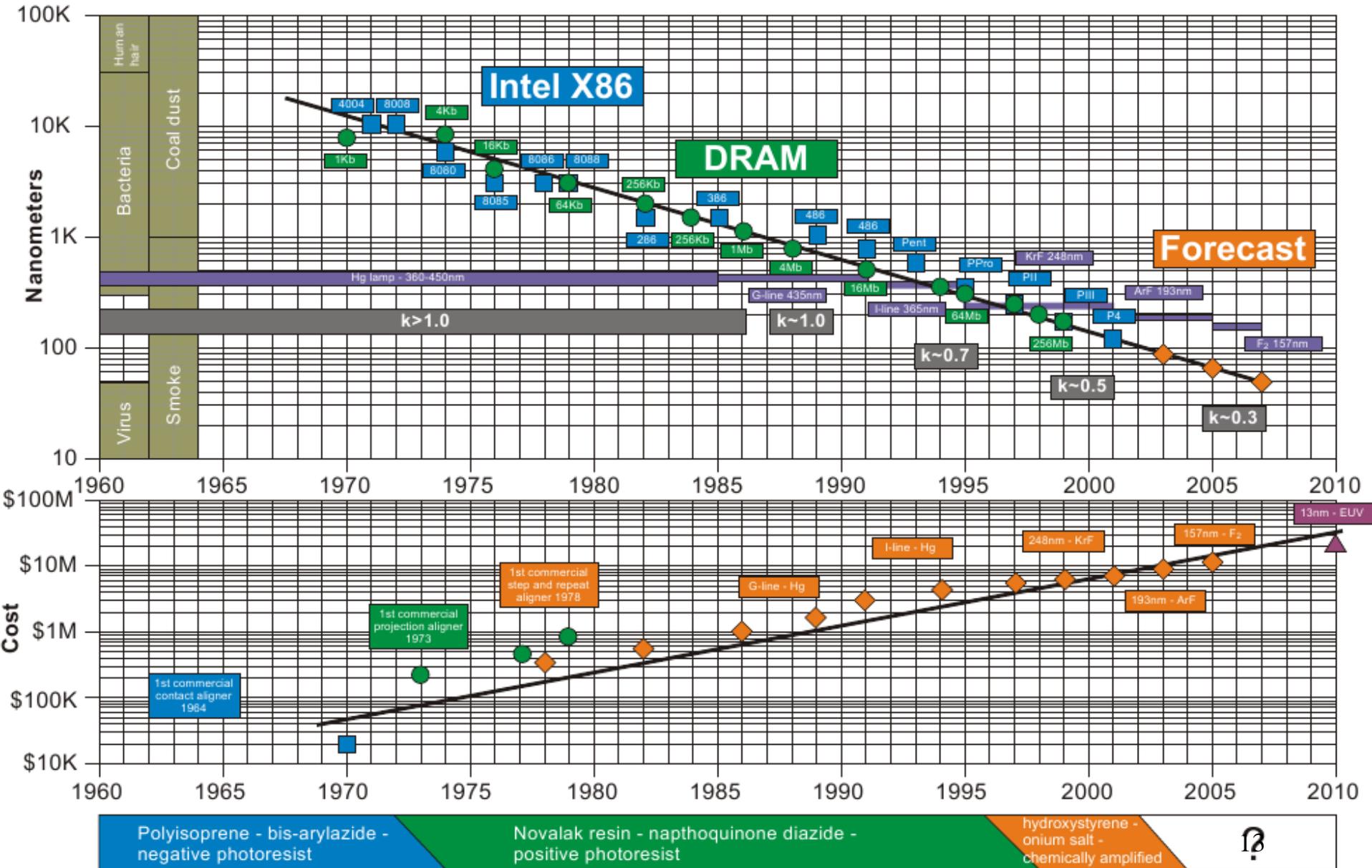
Belichtungsprozess der chemisch verstärkten Fotolacke



Characteristic	bis-arylazide - polyisoprene	DQN	tBoc
Type	Negative	Positive	Negative or Positive
Exposure wavelength (nm)	350-450	365, 436	248
Usable resolution (nm)	~2,000	~250	50?
Cost (\$/gal)	~\$100	\$300-\$800	~\$2,000
Special sensitivities	Oxygen during exposure	None	Amines between exposure and PEB
Humidity comments	High humidity causes loss of adhesion - 30 - 40% RH ideal	Humidity required during develop - 35 - 45% RH ideal	
Adhesion	Excellent	Good	Good
Plasma etch and implant compatibility	Excellent	Good	Good to fair
Developing reaction	Solvent develop swells polymer	Aqueous develop dissolves resist without swelling	Aqueous or solvent develop dissolves resist without swelling.
Wet strip	Sulfonic acid strippers that form acid with water and are hard to dispose of	NMP or aqueous based stripper with reduced moisture sensitivity and easier disposal.	

Microlithography Trends

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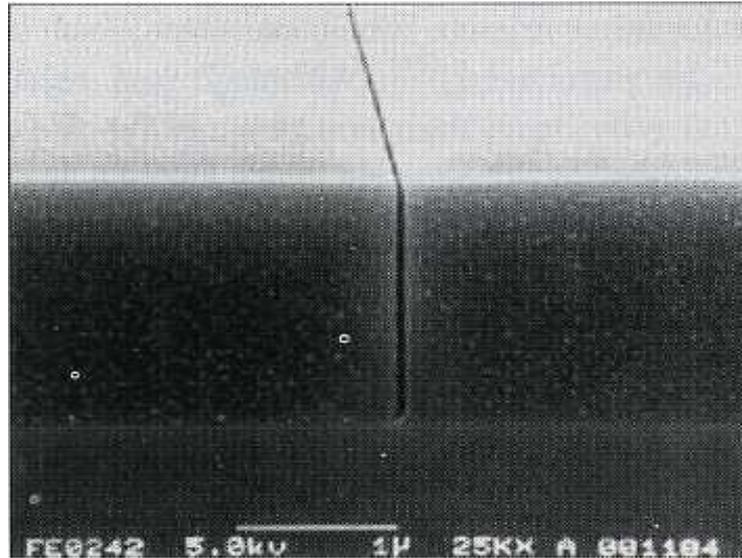
Hochauflösende Fotolacke für Elektronenstrahlithografie

	resist tone	resolution / nm	sensitivity*	developer
PMMA	+	10	100	MIBK:IPA
ZEP-520	+	10	30	xylene : p-dioxane
ma-N 2400	-	80	60	MIF726
EBR-9	+	200	10	MIBK:IPA
PBS	+	250	1	MIAC: 2-pentanone 3:1
COP	-	1,000	0.3	MEK : ethanol 7:3

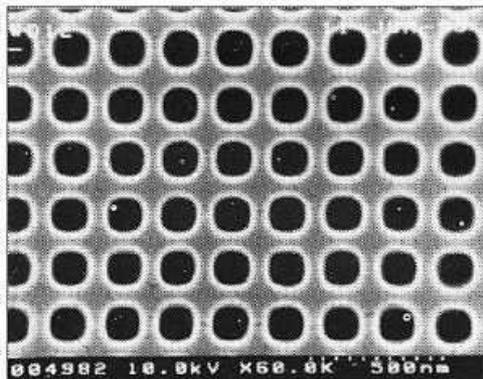
* sensitivity measured at 20 keV beam energy, unit: $\mu\text{C}/\text{cm}^2$.

Some widely used high resolution e-beam resists are introduced as following.

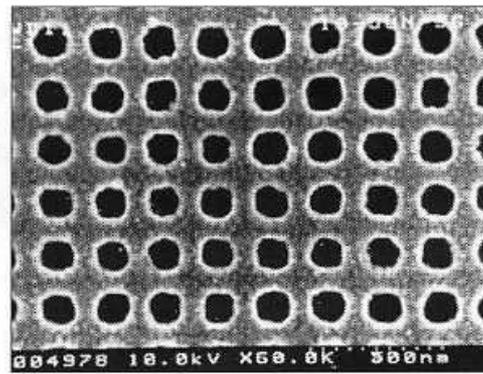
developer concentration (MIBK : IPA)	sensitivity	resolution
1:3	low	extremely high
1:2	medium	very high
1:1	high	high
pure MIBK	very high	low



50nm Linie in 1,5µm ZEP-520



(a) 100 nm holes in PMMA ($1,450 \mu\text{C} \cdot \text{cm}^{-2}$)



(b) 100 nm holes in AZPF 514 ($25 \mu\text{C} \cdot \text{cm}^{-2}$)

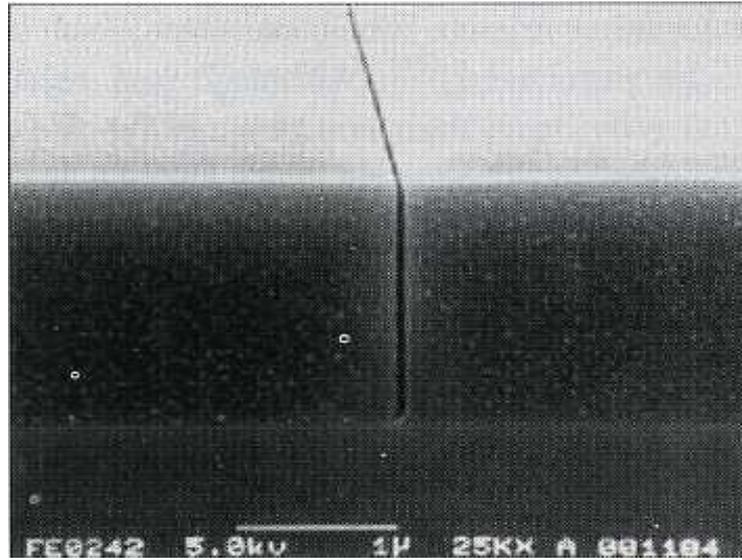
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	resist tone	resolution / nm	sensitivity*	developer
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PBS	+	250	1	MIK: 2-pentanone 3:1
COP	-	1,000	0.3	MEK : ethanol 7:3

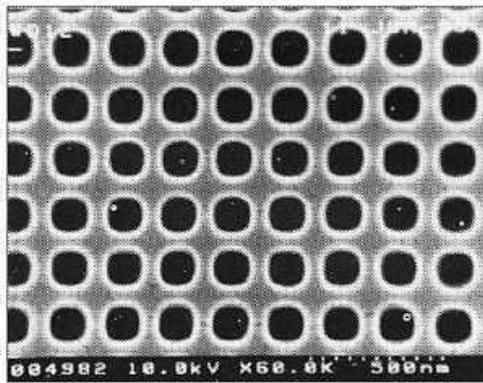
* sensitivity measured at 20 keV beam energy, unit: $\mu\text{C}/\text{cm}^2$.

Some widely used high resolution e-beam resists are introduced as following.

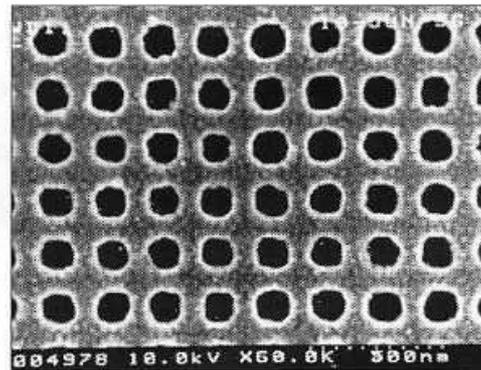
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50nm Linie in 1,5µm ZEP-520



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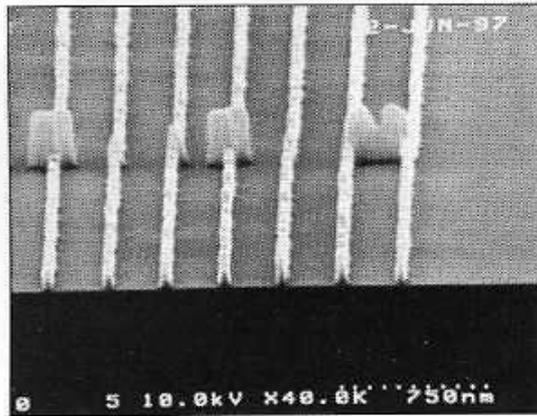


(b) 100 nm holes in AZPF 514 ($25 \mu\text{C} \cdot \text{cm}^{-2}$)

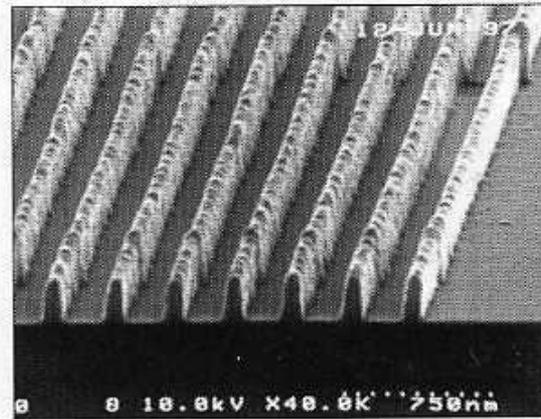
Prozessparameter chemisch verstärkter Fotolacke für Elektronenstrahlithografie

resist	tone	prebake	exposure dose	postbake	development	minimum feature
APEX-E	+	90° C 1 minute	3 ~ 6 $\mu\text{C}/\text{cm}^2$	85° C 1 minute	MF319 1 minute	150 nm
AZPF514	+	120° C 2 minutes	5 ~ 15 $\mu\text{C}/\text{cm}^2$	60° C 1 minute	AZ518MIF 1 minute	100 nm
UV3	+	150° C 1 minute	20 ~ 30 $\mu\text{C}/\text{cm}^2$	140° C 1 minute	CD26	<50 nm
SAL601	—	90° C 10 minutes	5 ~ 15 $\mu\text{C}/\text{cm}^2$	115° C 1 minute	MF322 2 ~ 5 minutes	<100 nm
SNR-200		120° C 2 minutes	>6.5 $\mu\text{C}/\text{cm}^2$	110° C 2 minutes	MF CD-14 20 seconds	<100 nm
UVN30		140° C 90 seconds	5 ~ 15 $\mu\text{C}/\text{cm}^2$	130° C 40 seconds	MF702 30 seconds	<50 nm
AZPN114		120° C 2 minutes	5 ~ 15 $\mu\text{C}/\text{cm}^2$	105° C 5 minutes	AZ518MIF 10 ~ 30 seconds	<50 nm
NEB-22	—	110° C 2 minutes	7 ~ 12 $\mu\text{C}/\text{cm}^2$	95° C 2 minutes	MF321 2 ~ 5 minutes	<50 nm

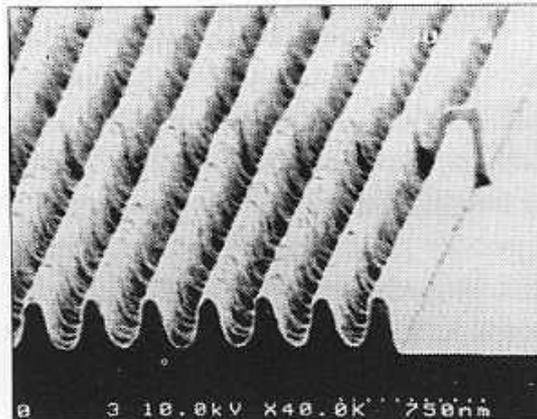
Post-exposure bake-Abhängigkeit chemisch verstärkter Fotolacke



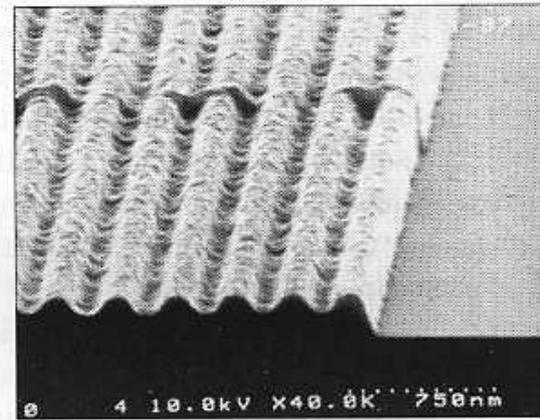
(a) PEB=103°C



(b) PEB=105°C

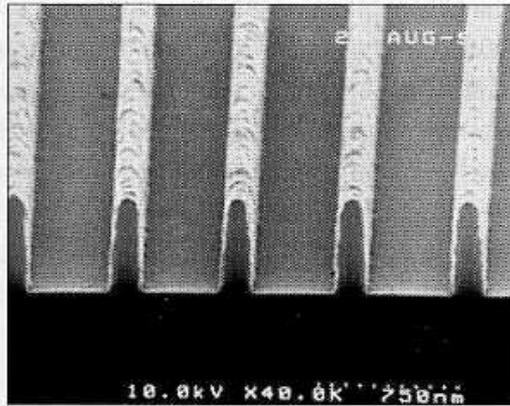


(c) PEB=107°C

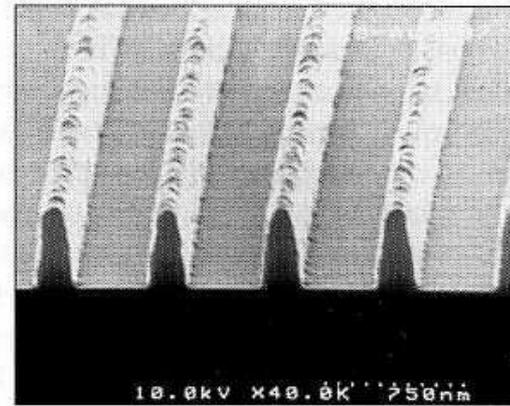


(d) PEB=109°C

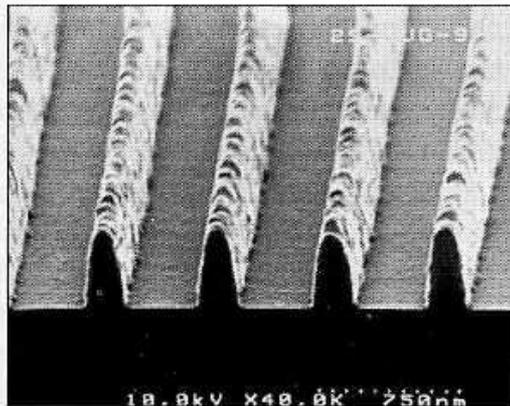
Post-exposure delay-Abhängigkeit chemisch verstärkter Fotolacke



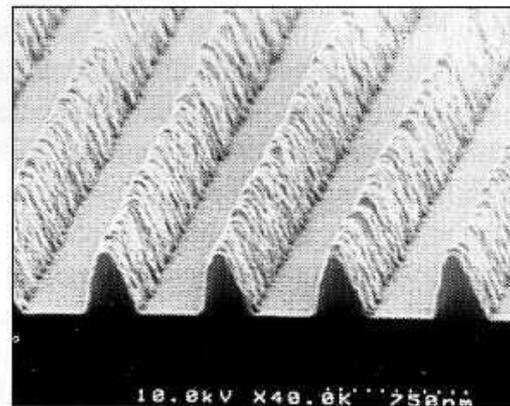
(a) PED=0



(b) PED=1 h

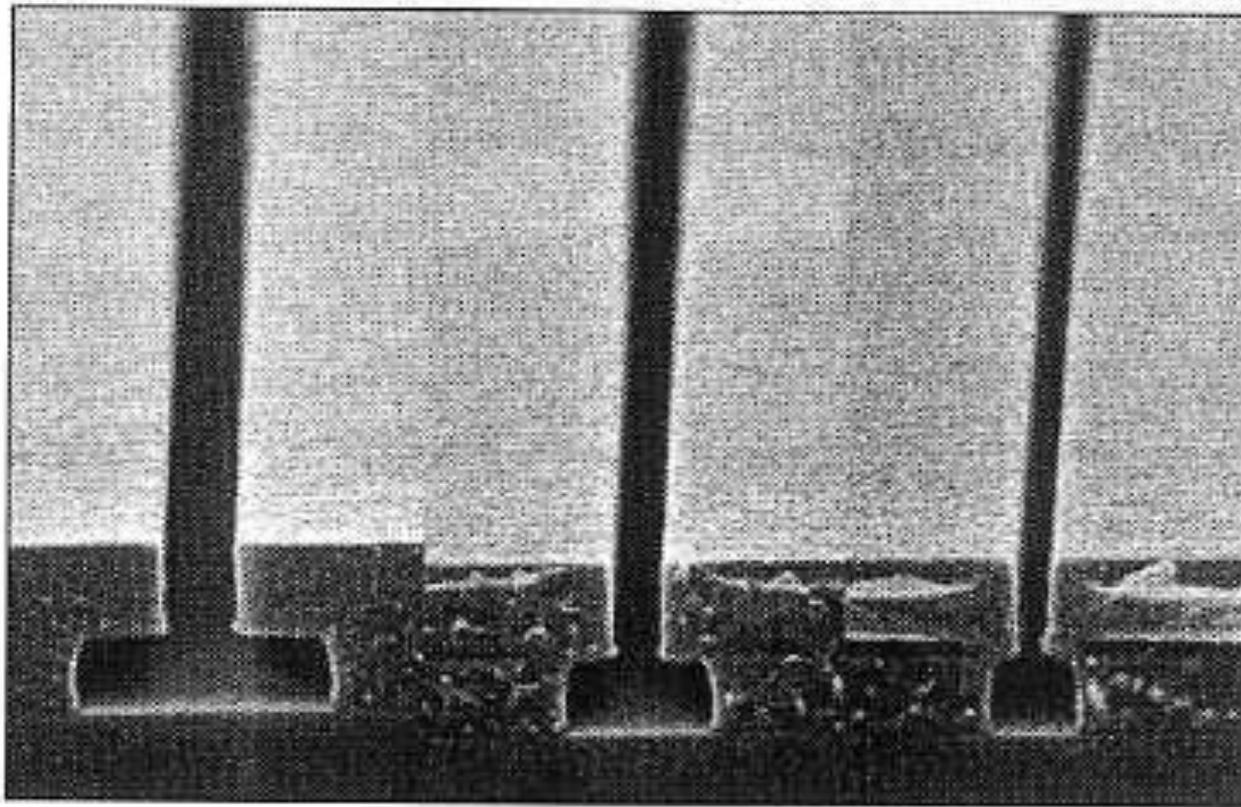


(c) PED=17 h



(d) PED=24 h

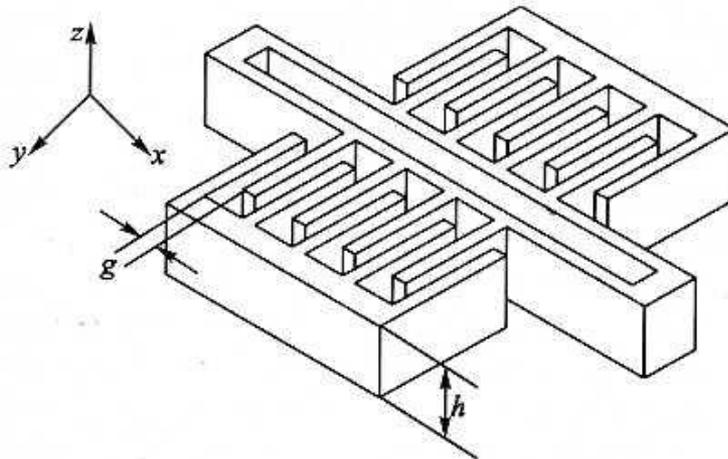
Multilagen-Resist-Prozesse



500 nm

Doppellage aus PMMA/LOR, PMMA dient als Maske für nachfolgenden Ätzprozess

Dickschicht-Lithografie



Electrostatic force generated by comb structure:

$$F_y = \epsilon_0 V^2 \frac{nh}{g}$$

V : voltage, n : finger number, h : height of fingers, g : gap between fingers

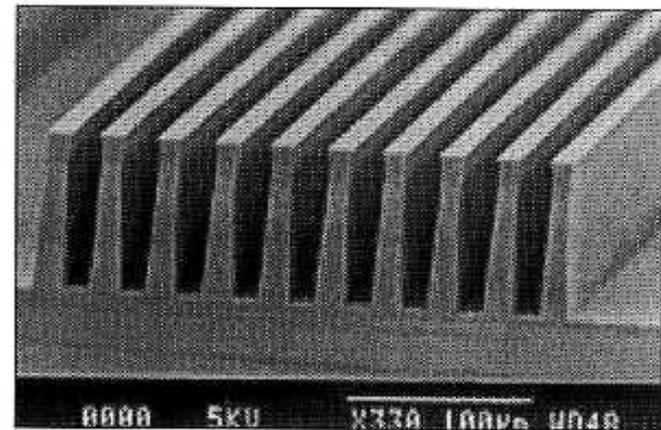
Dickschicht-Lithografie

	Hochauflösender I-Linien Fotoresist	Dickschicht- Fotoresist
PAC Konzentration:	18% - 26%	10% - 20%
Lichtabsorption	stark	schwach
Typische Transmissionsdicke des Resists	~ 1 μ m	> 1 μ m
PAC-Index:	3 - 4	1 - 2
Polymergehalt:	20% - 25%	> 40%
	geringe Viskosität	hohe Viskosität

Dickschicht-Lithografie



(a) Without process optimisation

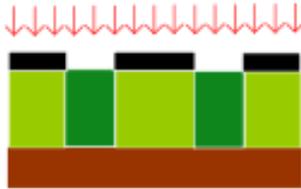


(b) With process optimisation

Dickschicht-Lithografie: LIGA-Verfahren



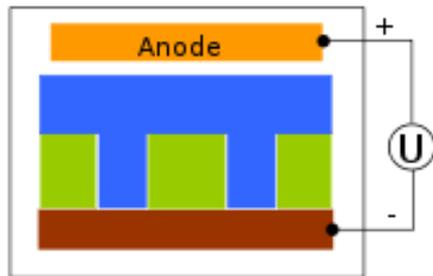
a) Aufbringen einer bis zu 1mm starken röntgenempfindlichen Kunststoffschicht (PMMA) auf eine Grundplatte mit elektrisch leitender Deckschicht



b) Lithographische Tiefenstrukturierung mittels paralleler Synchrotronstrahlung



c) Herauslösen der belichteten Bereiche mit einem geeigneten Entwickler



d) Galvanisches Abscheiden von Metall in den Strukturzwischenräumen bis 5mm über die Resisthöhe



e) Metallstruktur nach Herauslösen des Resist



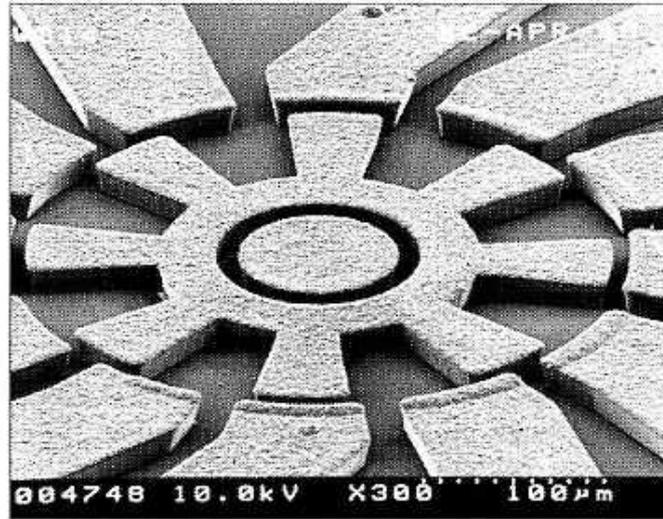
f) Vervielfältigung durch Kunststoffabformung der Metallstruktur

Lithografie

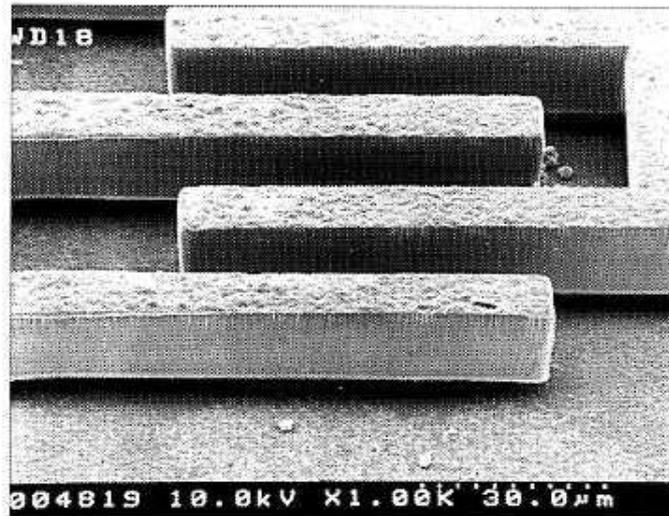
Galvanik

Abformung

Dickschicht-Lithografie: LIGA-Verfahren



SEM photo of micromotor made by UV LIGA technique



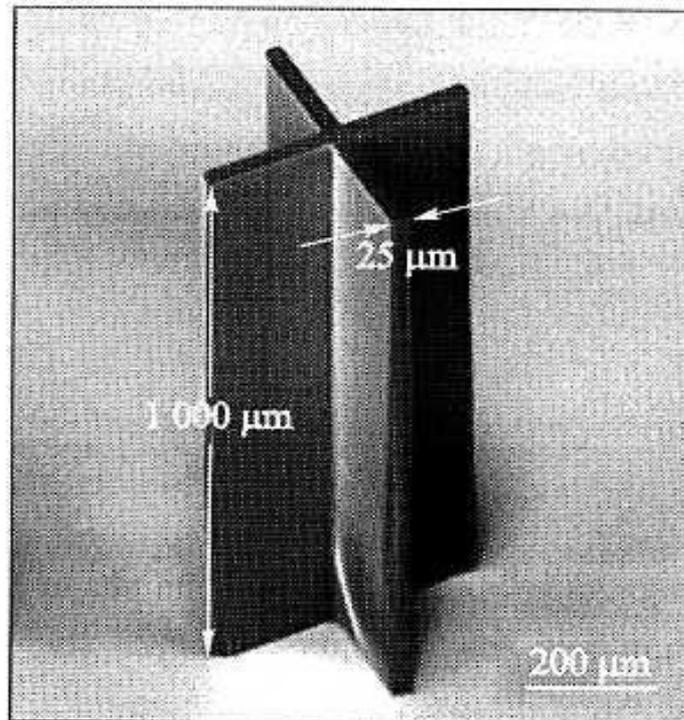
Nickel comb structure after removal photoresist sacrificial layer

Dickschicht-Lithografie

SU-8*	solid content / %	kinetic viscosity / (cm ² · s ⁻¹)	coating thickness / μm**
5	51.8	265	12
10	59.1	989	30
25	63.3	2,646	58
50	69.1	14,953	150
100	72.9	52,407	320

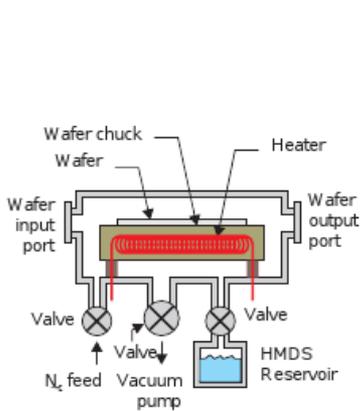
* Product code of commercial SU-8 from MicroChem Corp.

** Data from the technical manual of EV150 spinner (Electronic Visions Group) at 900 rpm.

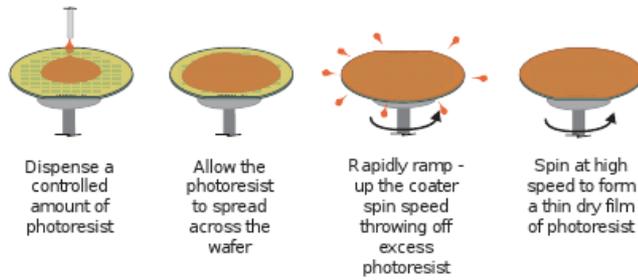


High aspect ratio (40:1) SU-8 structure made by maskaligner exposure

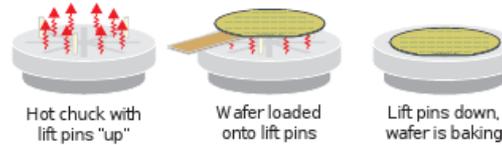
DUV Photolithography Process



1) Surface Prime



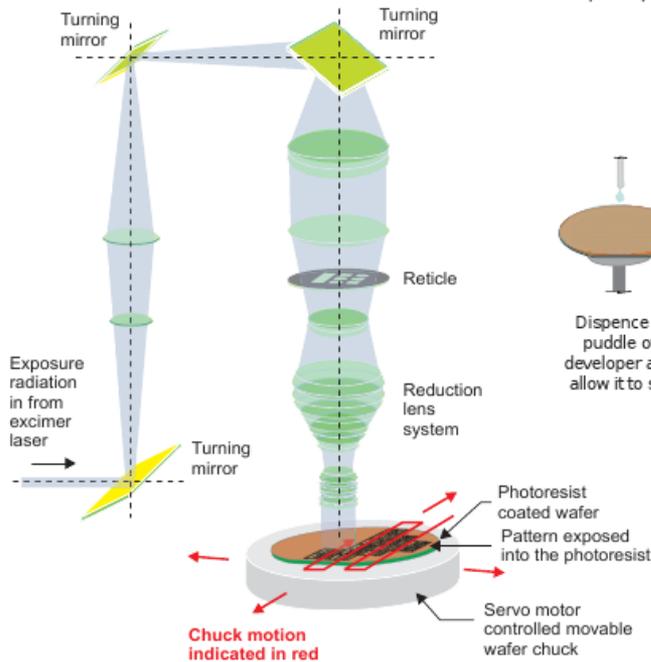
2) Coat



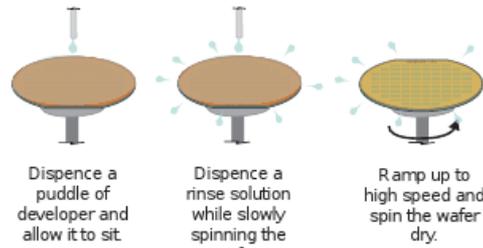
3) Pre-bake

5) Post Exposure Bake

7) Hard Bake



4) Expose

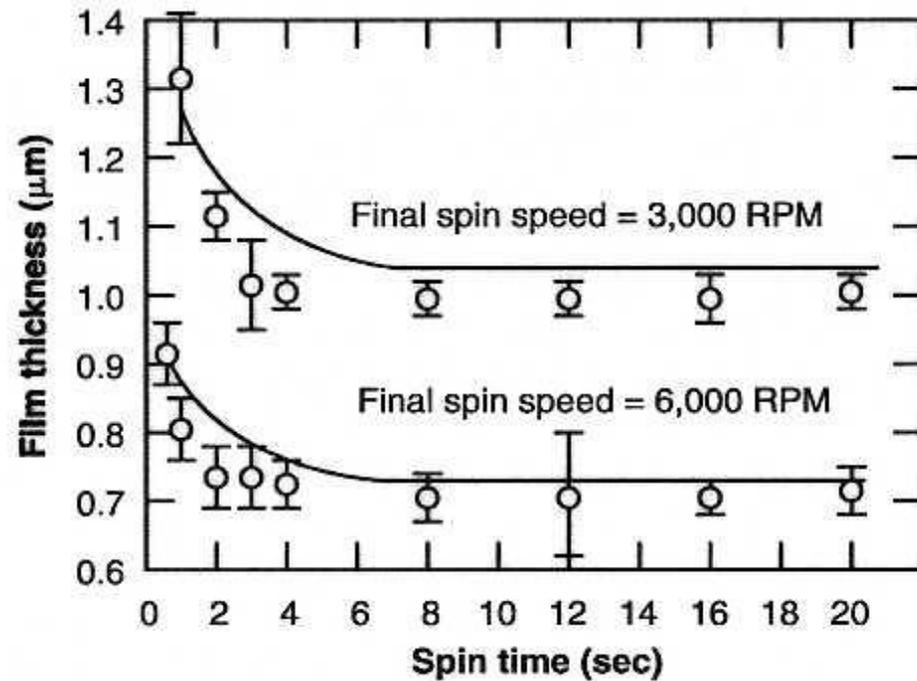
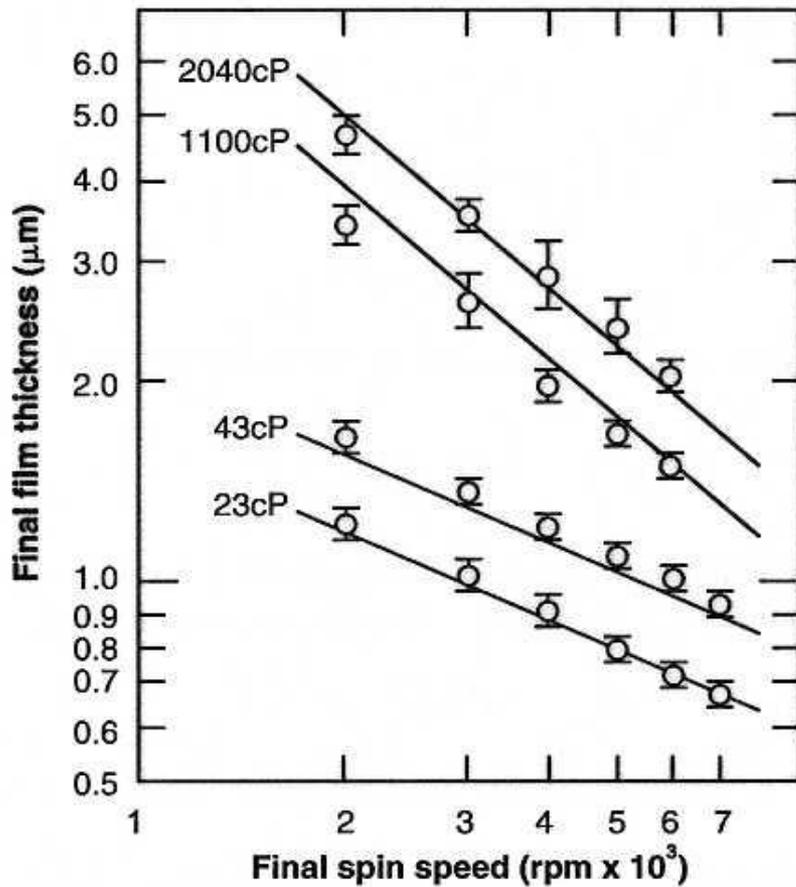


6) Develop

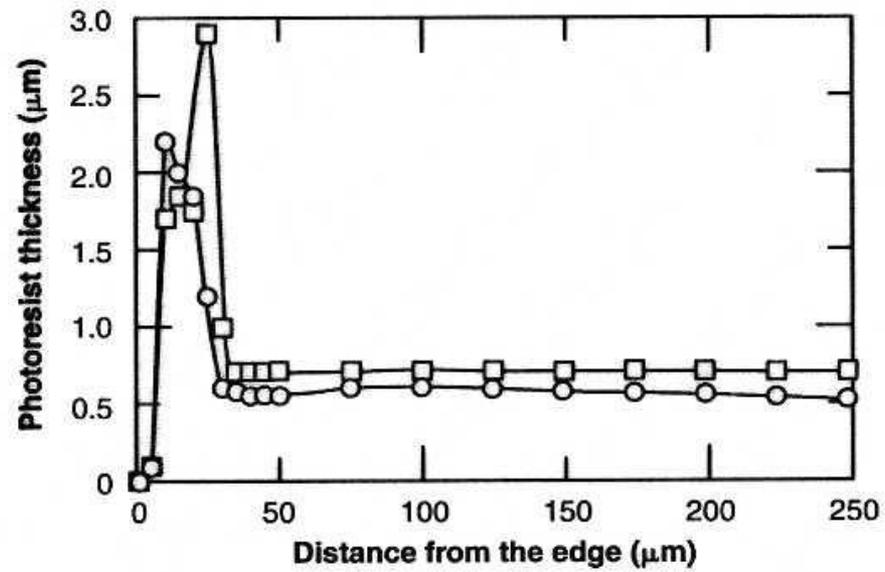
Belackung im Spincoater



Abhängigkeit der Filmdicke von Rotationsgeschwindigkeit und -dauer

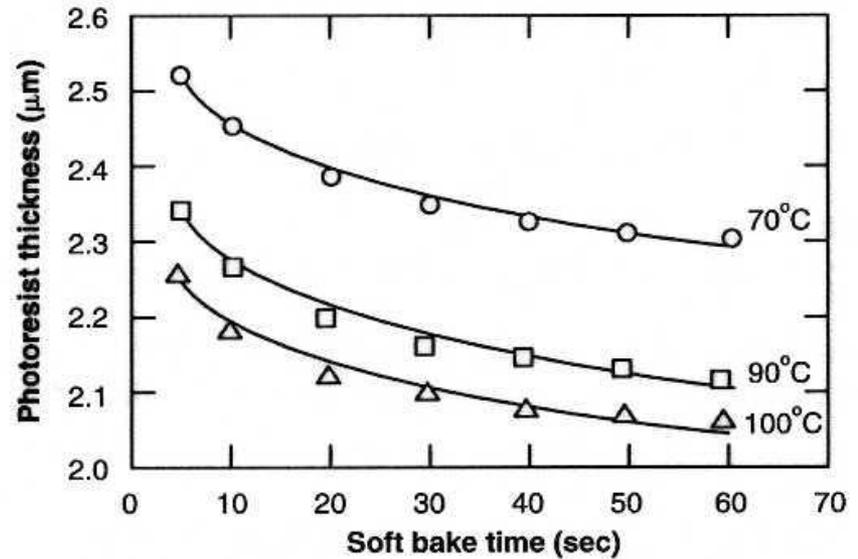
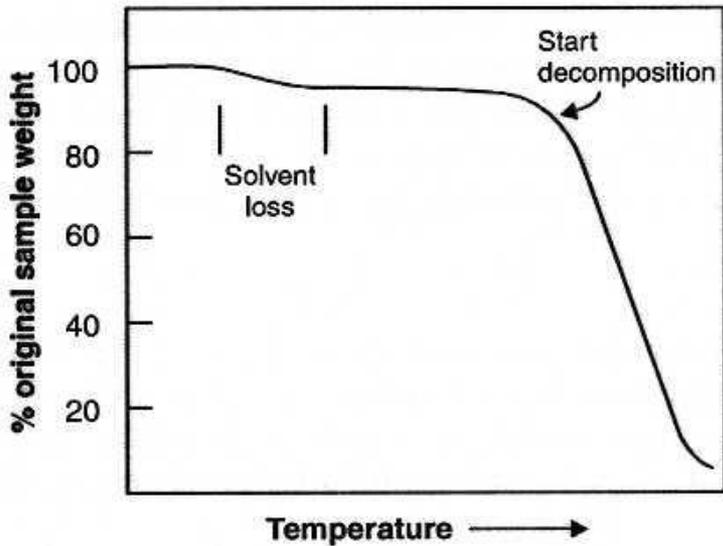
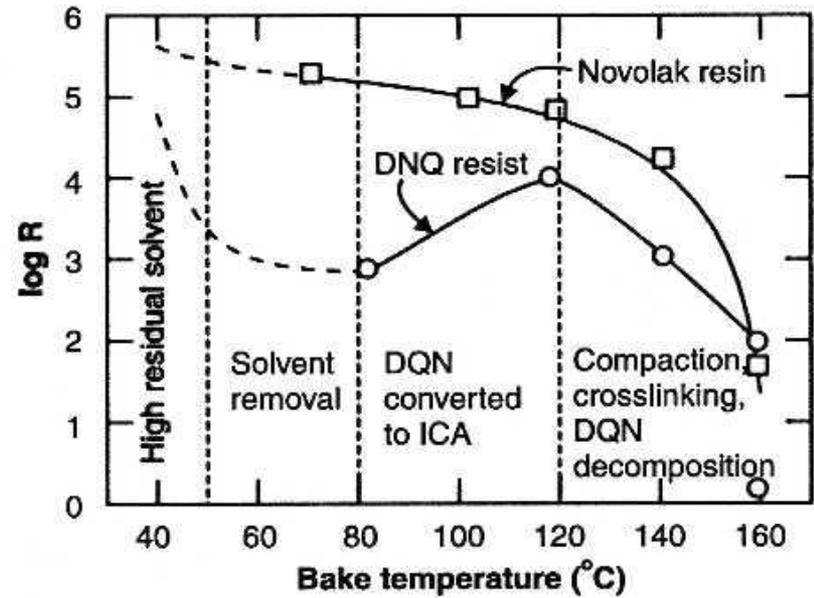


Entfernen der Kanten



Soft bake Parameter:

Entwicklungsrate vs. Temperatur
 Lösungsmittelgehalt vs. Temperatur
 Ausheizdauer



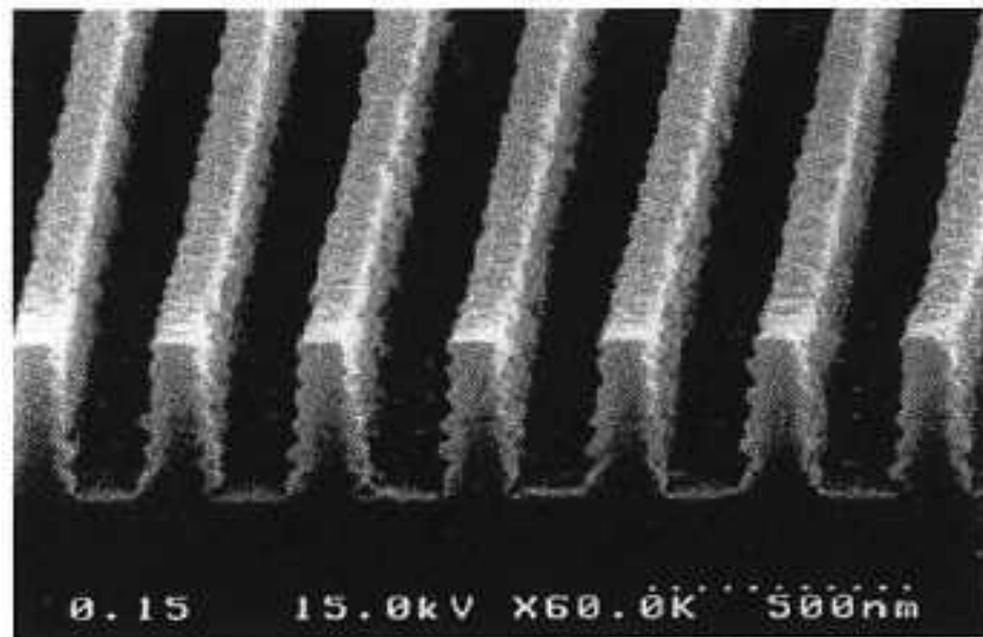
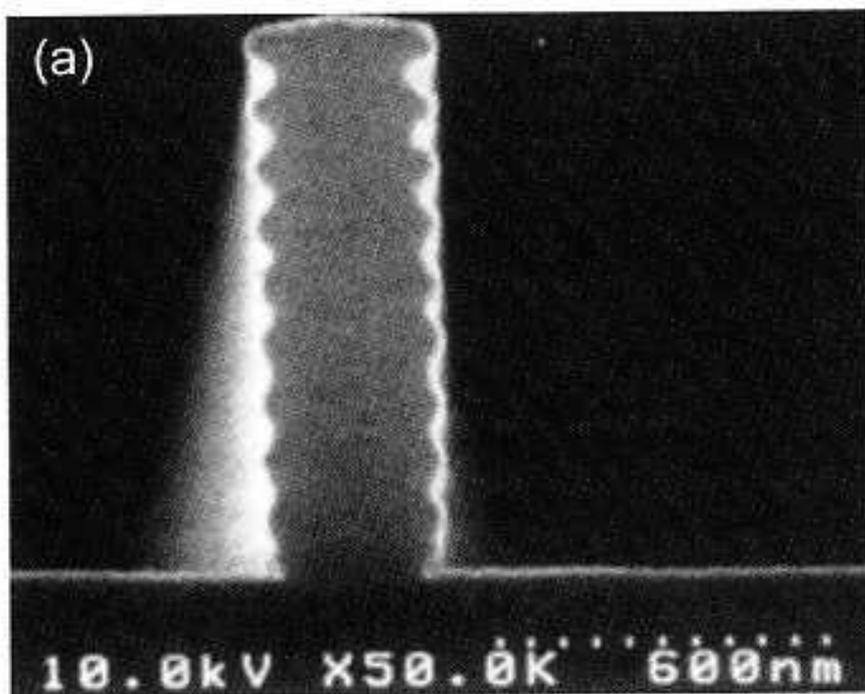
Film thickness loss during softbake - m-p cresol novolak photoresist

Wahl der soft bake Temperatur

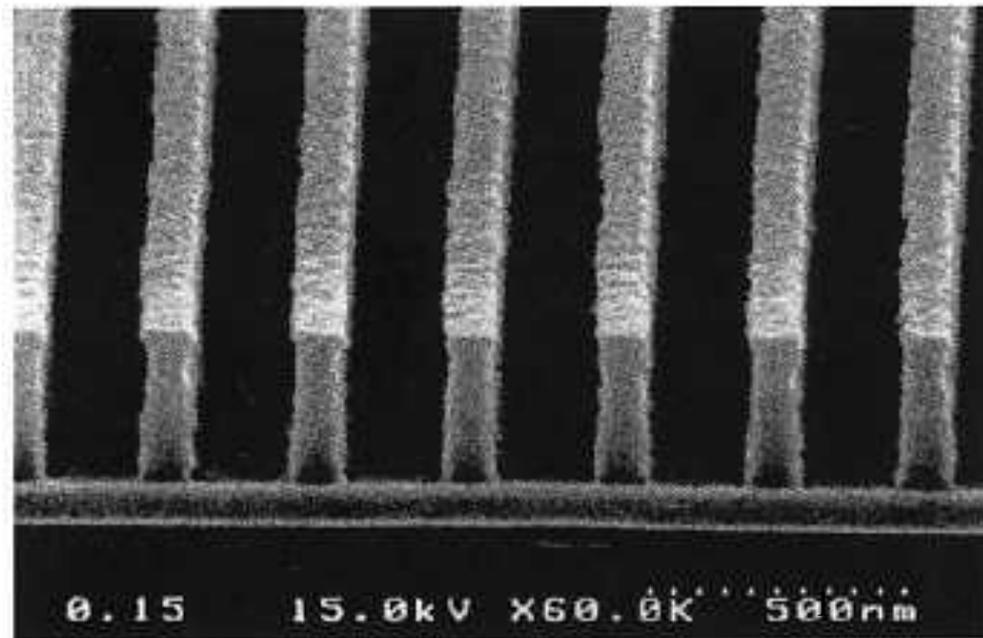
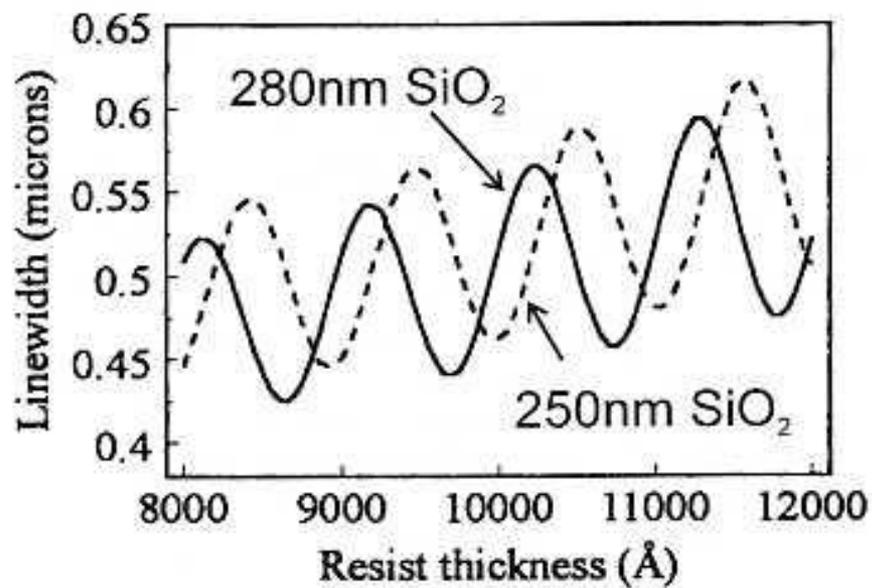
Photoresist	Solvent	Evaporation rate ^a	Boiling point (°C)
Polybutene SO ₂	Methyl 2-ethoxyethyl acetate	31	145
DQN	Cellosolve acetate	20	156
	Butyl acetate	100	126
	Diglyme	18	162
PMMA	Chlorobenzene	102	126
Rubber azide	Xylene	62	140

^a evaporation rates are relative to butyl acetate.

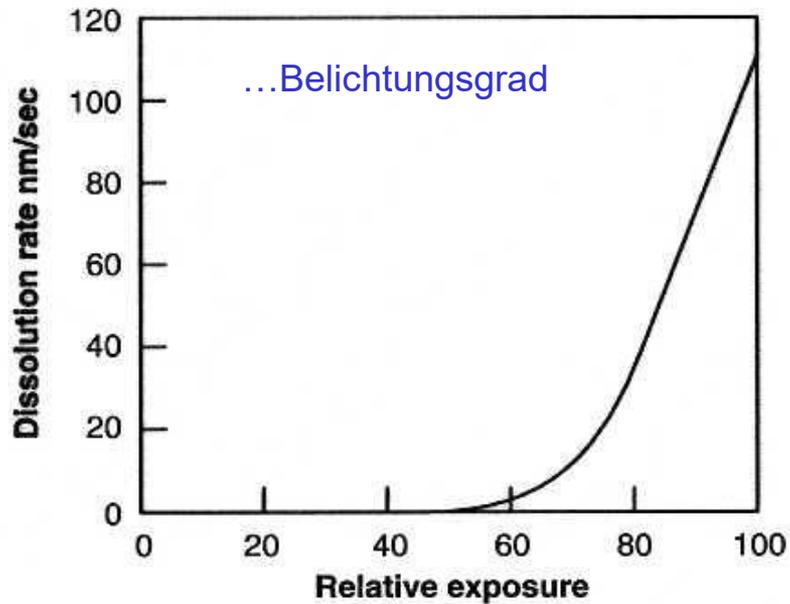
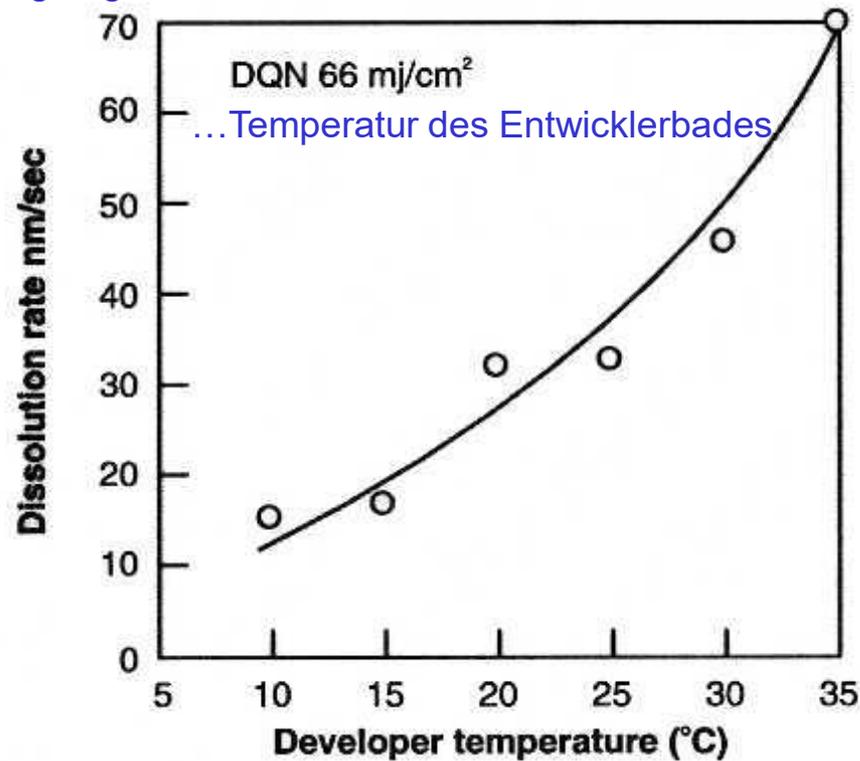
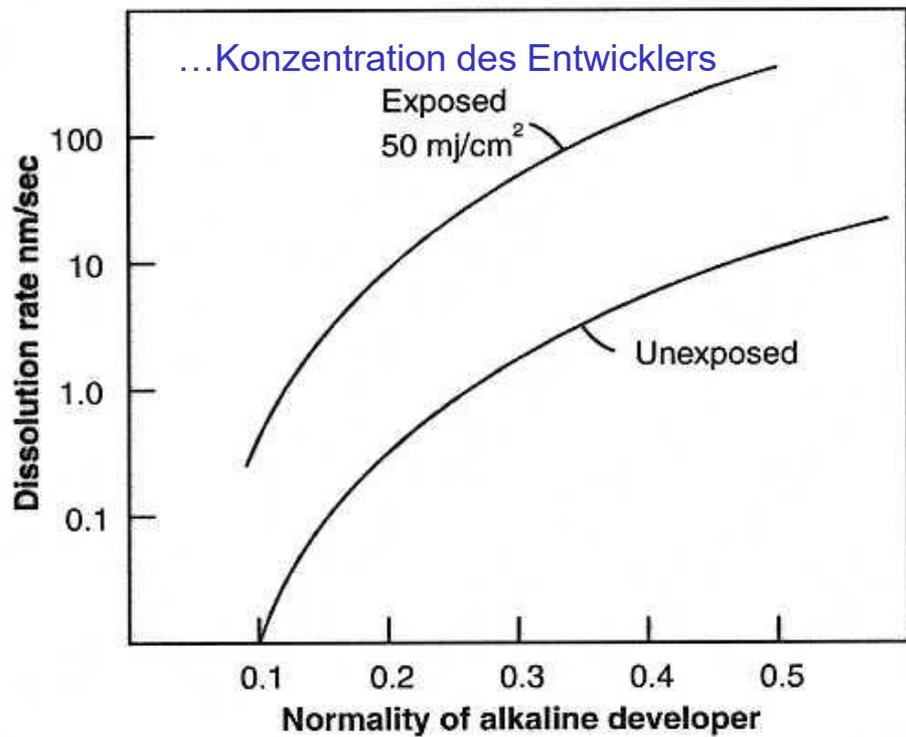
Component	T _g (°C)	T _d (°C)
Rubber	54	200
Azide		100
Novolak	70-120	150-300
Diazoquinone		100
PMMA	105	200
Polybutene SO ₂	65	125



(b) Bsp. für post-exposure bake



Abhängigkeit des Entwicklungsergebnis von...

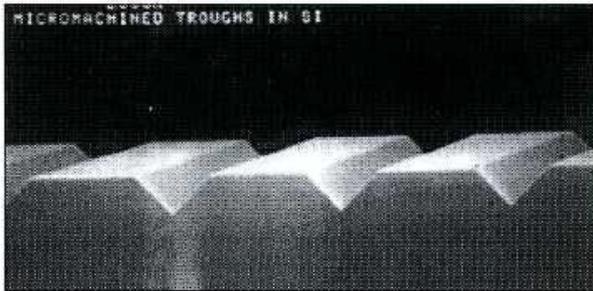
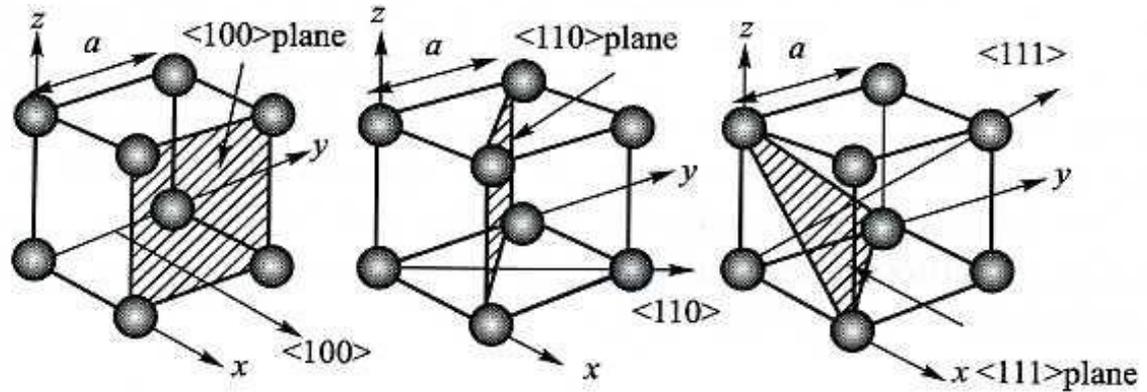


Typischer Prozessflow für PMMA-Liftoff-Prozess

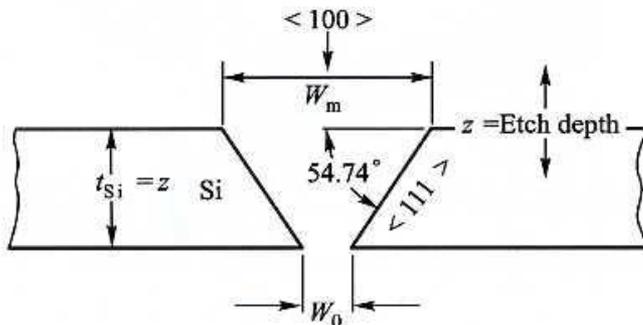
EXAMPLE PROCESS: PMMA POSITIVE EXPOSURE AND LIFTOFF

1. Start with 496K PMMA, 4% solids in chlorobenzene. Pour resist onto a Si wafer and spin at 2500 rpm for 40 to 60 seconds.
2. Bake in an oven or on a hotplate at 180 °C for 1 h.
Thickness after baking: 300 nm.
3. Expose in e-beam system at 50 kV, with doses between 300 and 500 $\mu\text{C}/\text{cm}^2$. (Other accelerating voltages may be used. The dose scales roughly with the voltage.)
4. Develop for 1 min in 1:3 MIBK:IPA. Rinse in IPA. Blow dry with nitrogen.
5. Optional descum in a barrel etcher: 150W, 0.6 Torr O_2 .
6. Mount in evaporator and pump down to 2×10^{-6} Torr.
7. Evaporate 10 nm Cr, then 100 nm Au.
8. Remove from evaporator, soak sample in methylene chloride for ~10 min.
9. Agitate substrate and methylene chloride with an ultrasonic cleaner for ~1 min to complete the liftoff. Rinse in IPA. Blow dry.¹⁴¹

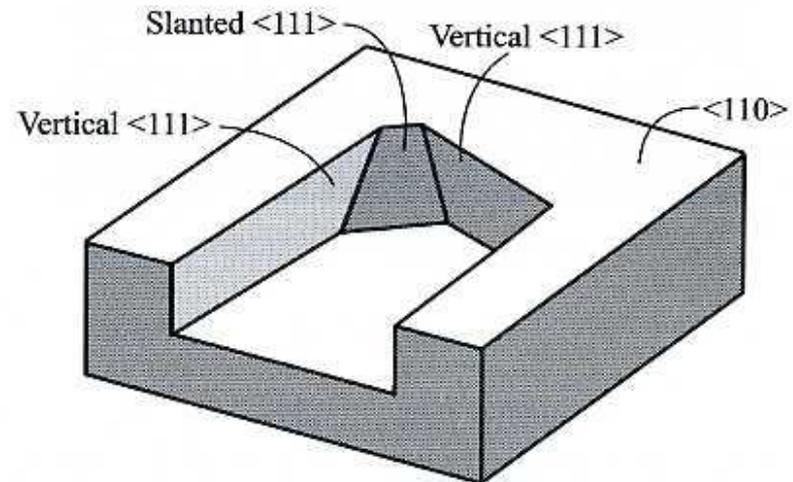
Anisotropes Ätzen von Silizium



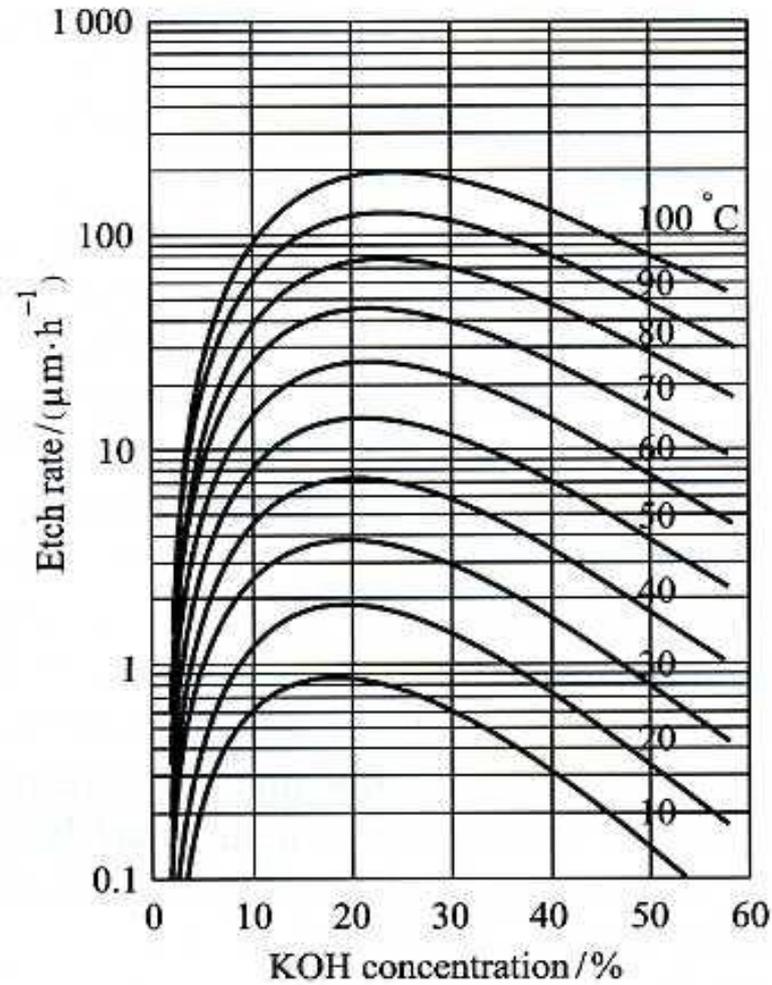
(a) "V" grooves formed by anisotropic etching



(b) Schematic of etched opening W_0



Konzentrationsabhängigkeit der Ätzrate



Markierung der Kristallorientierung kommerzieller Si-Wafer

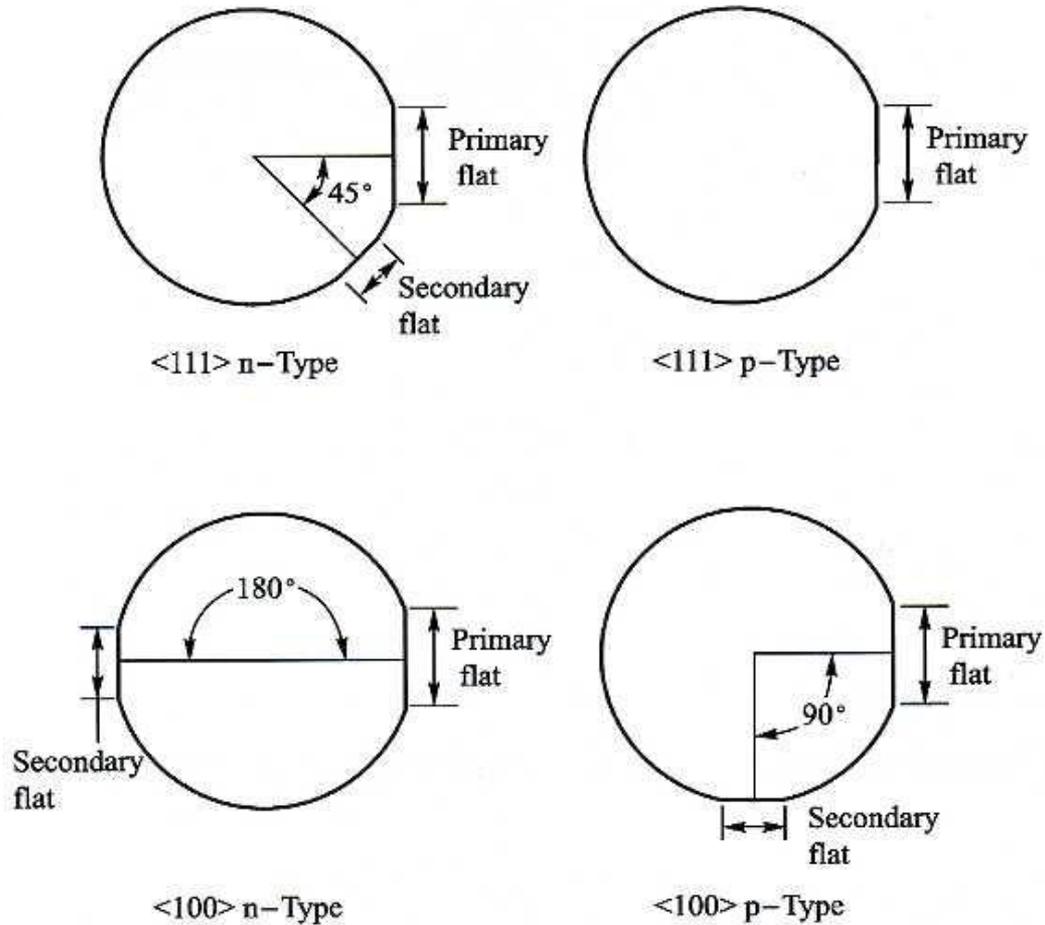
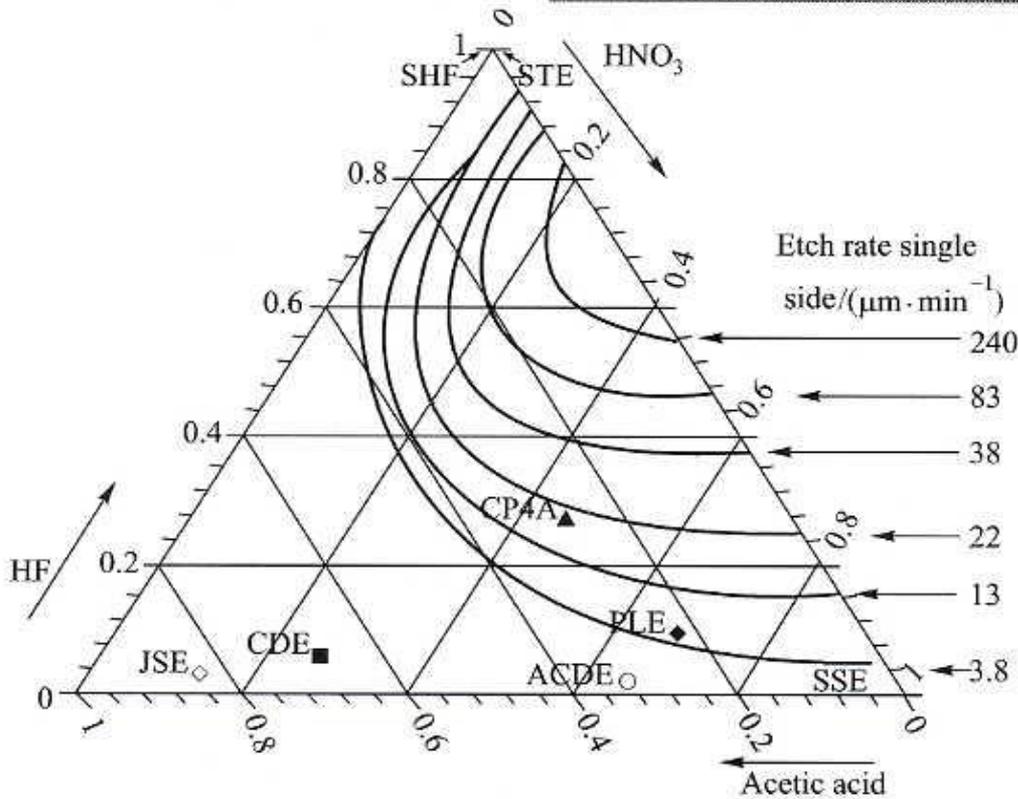


Table-6.1. Common Si etchant formulas and etch rate

HNA formulas	volume / % HF:HNO ₃ :acetic	etch rate	main applications
CP4A ^[10]	27:46:27	16 μm/min	surface chemical polishing
CDE ^[11]	8:25:67	2 μm/min for $R < 0.001 \Omega \cdot \text{cm}$ 0.001 μm/min for $R > 0.1 \Omega \cdot \text{cm}$	doping dependent etching
SSE ^[12]	1:99:0	2 μm/min ~ 0.5 μm/min	slow etch (initial faster then slower)
SHF ^[13]	100:0:0	0.3 Å/min	pure HF has very low etching of silicon

Isotropes Ätzen von Silizium:



Ätzlösung: HNA

Wirkmechanismus:

HNO₃ oxidiert Si

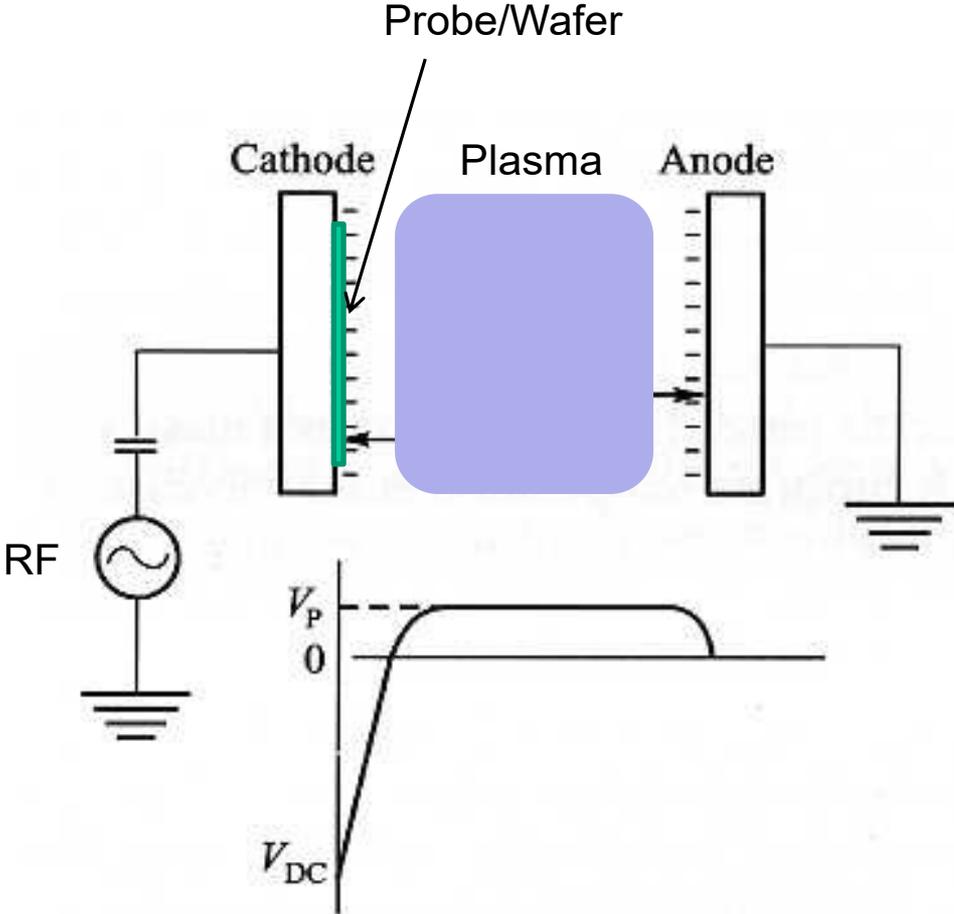
HF löst SiO_x

CH₃COOH wirkt als Puffer

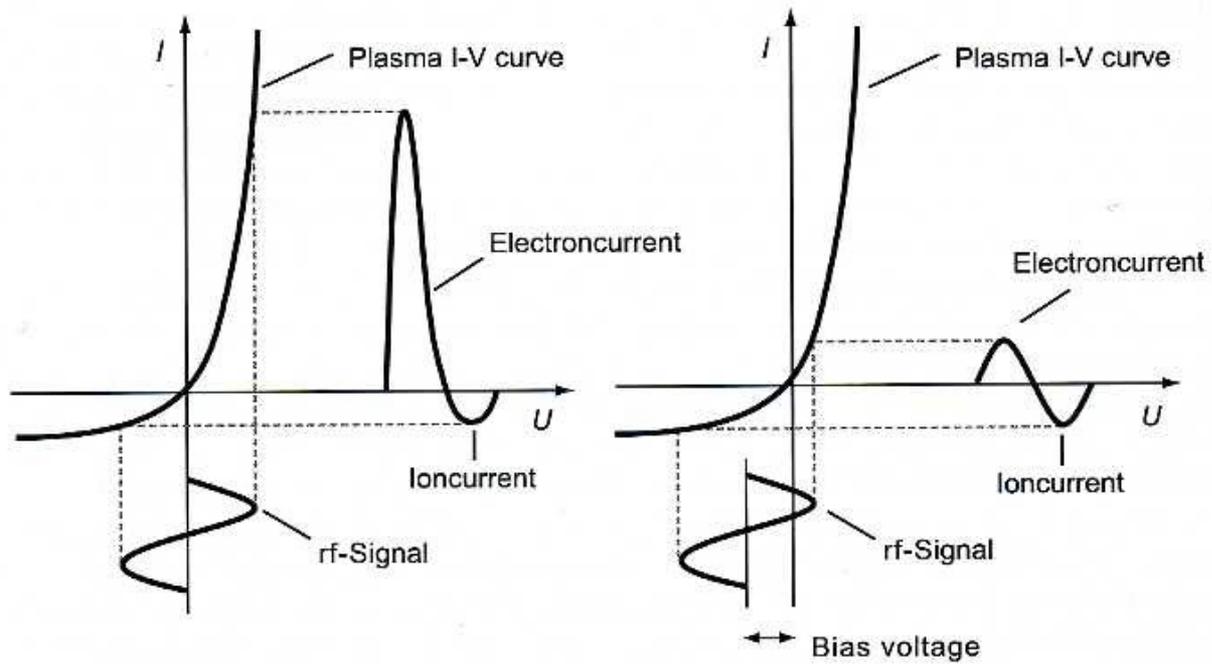
Ätzmasken: SiO₂, Si₃N₄, Cr films, Au films

Three phase diagram of HNA concentration ratio and etch rate

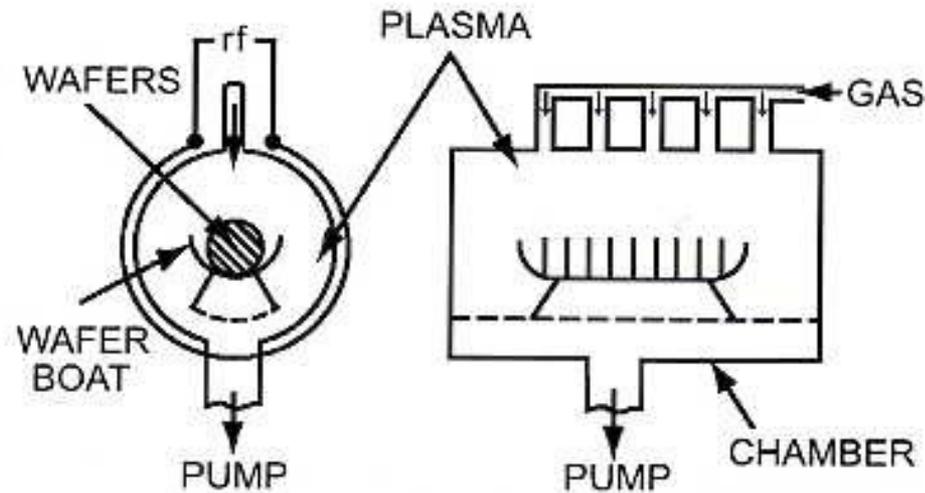
Plasmaerzeugung



Entstehung der Vorspannung durch Anlegen eines RF-Signals

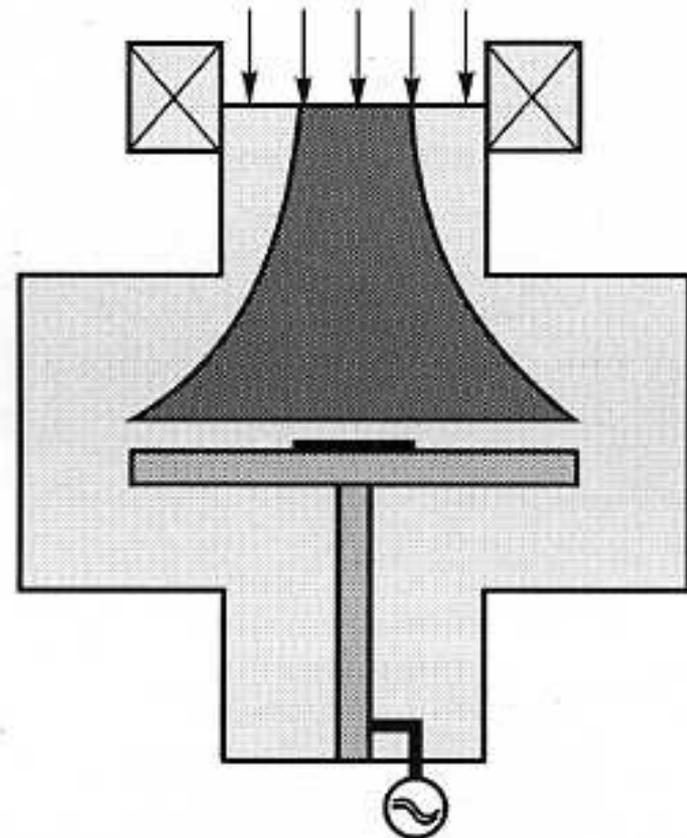
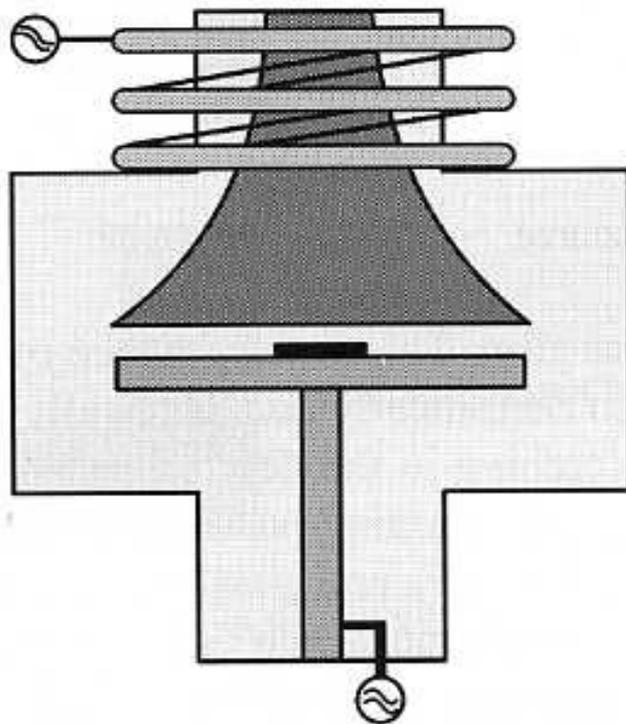


Beispiel eines Barrel-Reaktors: zur Entfernung von PR-Resten und Oberflächenreinigung
hauptsächlich chem. Ätzen
geringe Plasmadichte $\sim 10^{10}$ Ionen/cm³
Ätzgase: O₂, manchmal SF₆ oder CF₄

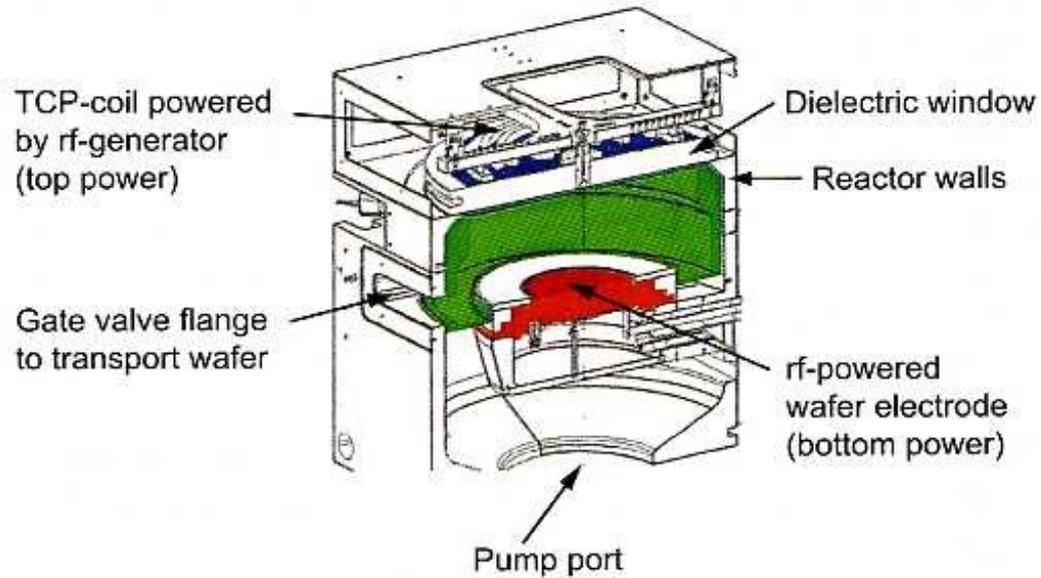
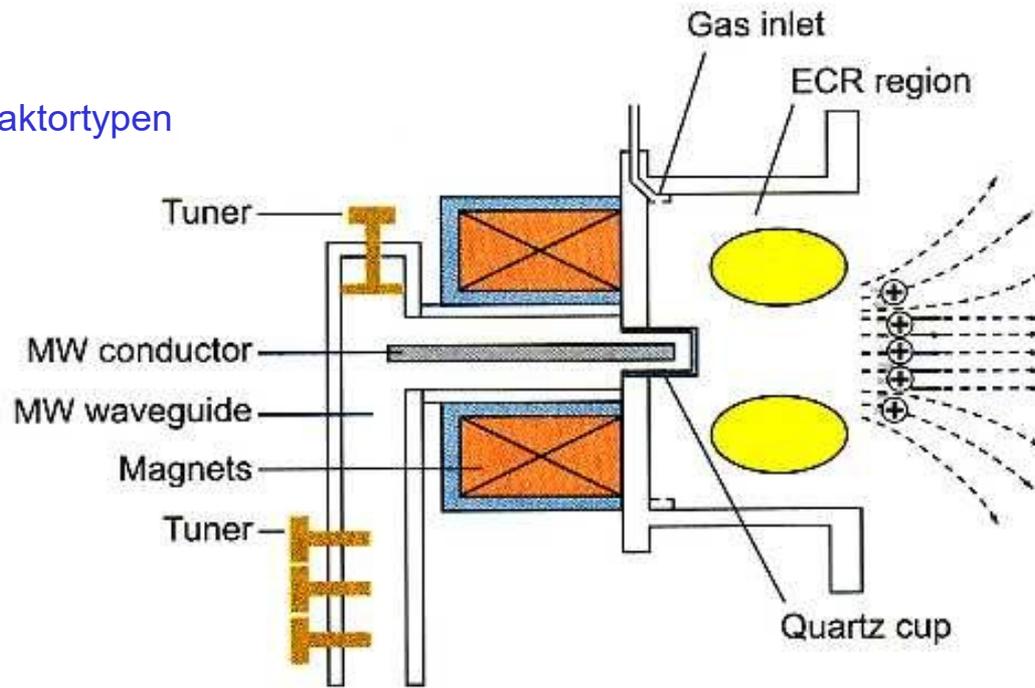


Plasma-Reaktoren: Plasmadichte und Ionenenergie können unabhängig voneinander kontrolliert werden
→ zwei Quellen zur Steuerung des Plasmas

Beispiel einer ICP-Quelle



Verschiedene Reaktortypen



Liste häufiger Ätzgase

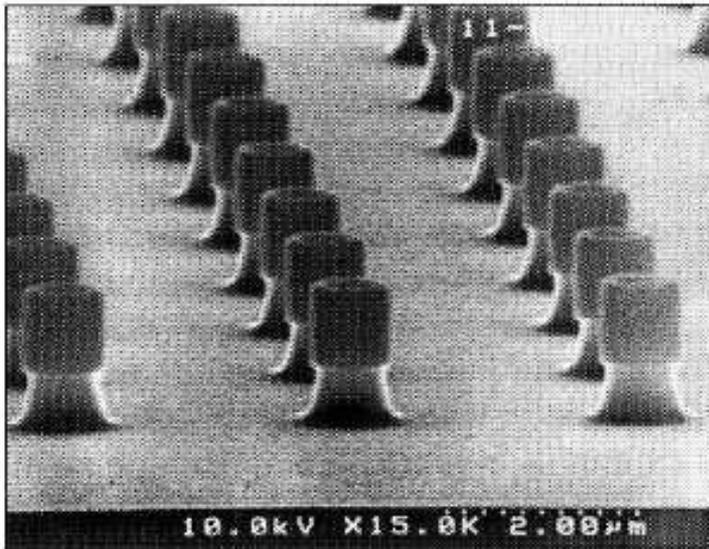
Table-6.2. Chemical gases for RIE and etched materials

materials to be etched	chemical gases (multi choices)
single crystal silicon	CF ₃ Br, HBr/NF ₃ , SF ₆ /O ₂
polysilicon	SiCl ₄ /Cl ₂ , BCl ₃ /Cl ₂ , HBr/Cl ₂ /O ₂ , HBr/O ₂ , Br ₂ /SF ₆
Al	SiCl ₄ /Cl ₂ , BCl ₃ /Cl ₂ , HBr/Cl ₂
Al-Si-Cu, Al-Cu	BCl ₃ /Cl ₂ +N ₂
W	SF ₆ , NF ₃ /Cl ₂
TiW	SF ₆
WSi ₂ , TiSi ₂ , CoSi ₂	CCl ₂ F ₂ /NF ₃ , CF ₄ /Cl ₂
SiO ₂	CCl ₂ F ₂ , CHF ₃ /CF ₄ , CHF ₃ /O ₂ , CH ₃ CHF ₂
Si ₃ N ₄	CF ₄ /O ₂ , CF ₄ /H ₂ , CHF ₃ , CH ₃ CHF ₂
GaAs	SiCl ₄ /SF ₆ , SiCl ₄ /NF ₃ , SiCl ₄ /CF ₄
InP	CH ₄ /H ₂
photoresists	O ₂

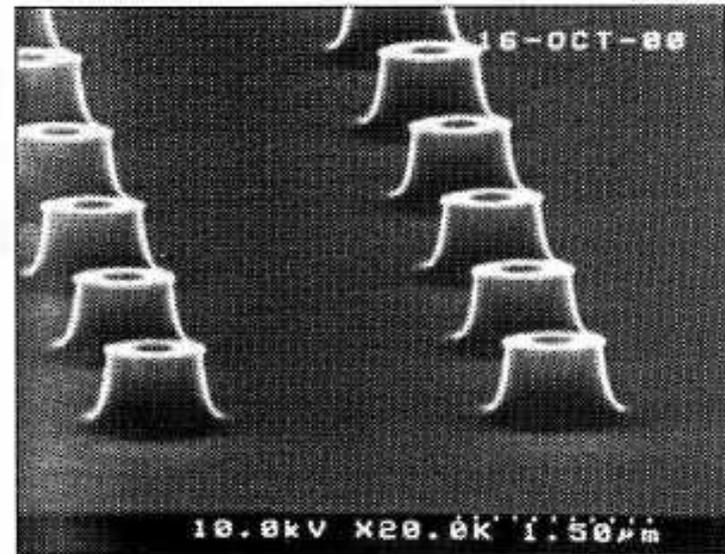


Beispiel einer ICP

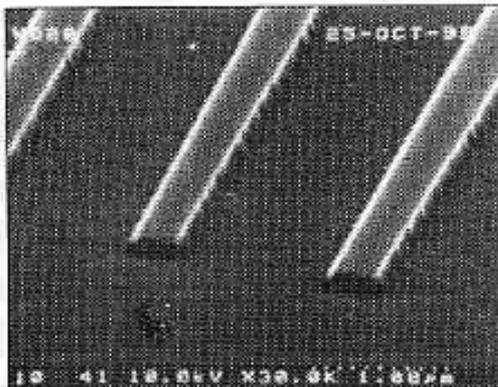
Anwendungen des „deep reactive ion etching“



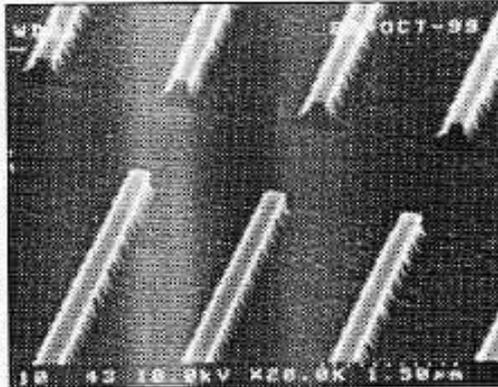
(a) Before removing resist mask



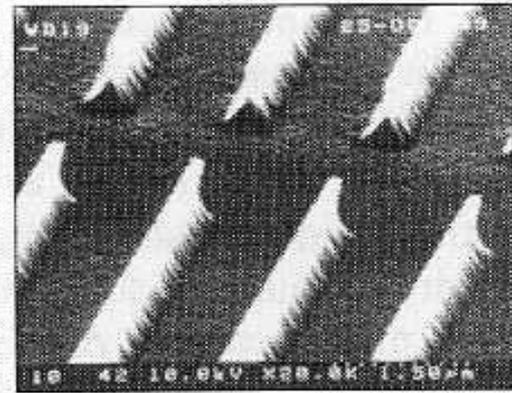
(b) After the resist mask on top has been removed



(a) Etching 1 minute

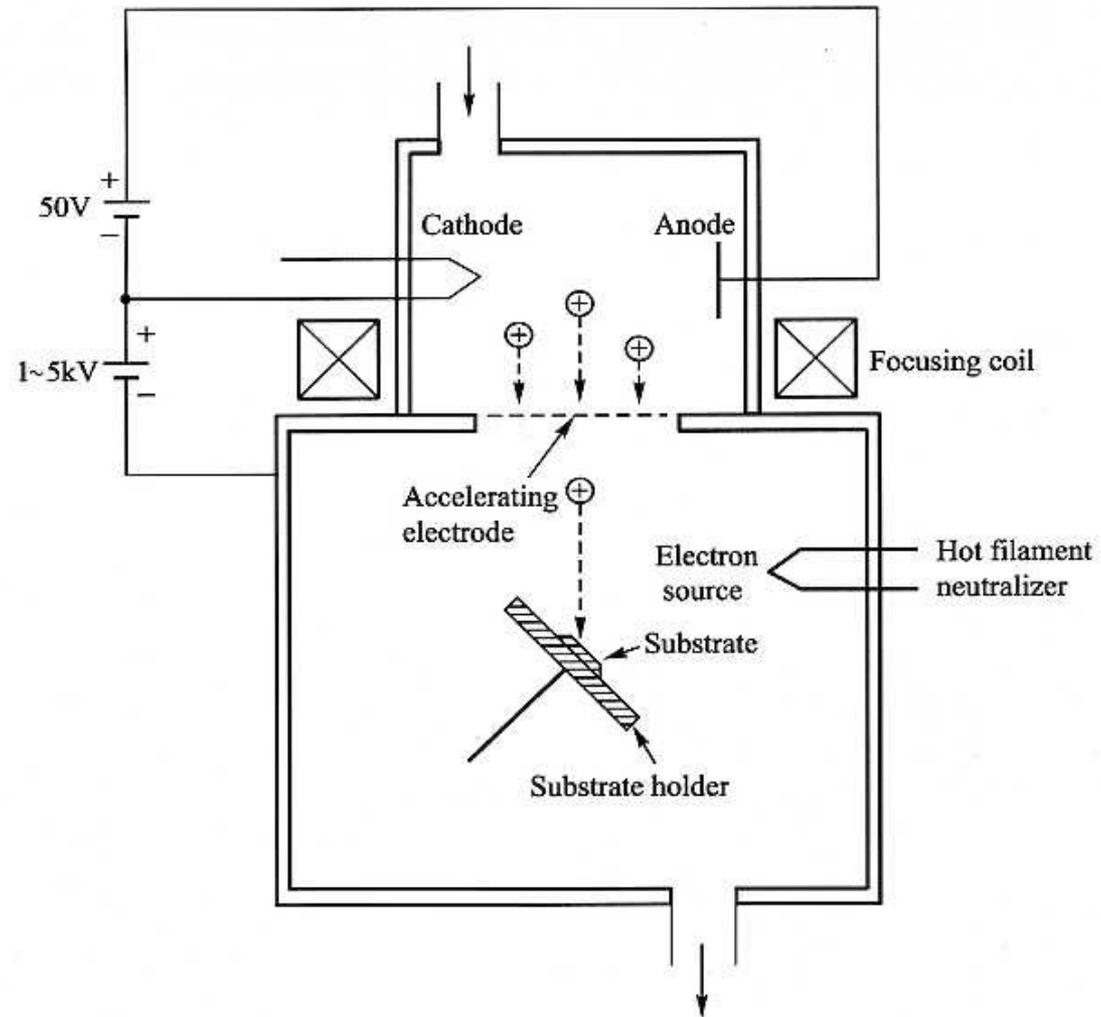


(b) Etching 2 minutes



(c) Etching 3 minutes

Ionenstrahlspattern



Schematic of ion beam milling system

Etching rates of some materials by ion beam sputtering

materials	etch rate / ($\text{\AA}/\text{min}$)
gold	1,000
copper	700
photoresist (AZ-1350)	200
nichrome (NiCr)	170
alumina (Al_2O_3)	90

Reaktivgasätzen

Selectivity of some masking materials for XeF_2 etch of silicon

masking material	selectivity
LPCVD SiO_2	3,000:1
silicon nitride	400 ~ 800:1
hard baked photoresists (AZ4400, AZ1518)	1,000:1
metal film (Al, Au, Cu, Ni)	1,000:1



Undercut created by XeF_2 etching of silicon

Beispiele für Reaktivgasätzen: 1. Ätzen von Si:

- Si-Gate-Leiterbahnen, Ätzselektivität 1:1, Verwendung von HBr/Cl₂/HCl Ätzgasen
- Ätzen tiefer Gräben z.B. in DRAM Strukturen hohe Aspektverhältnisse 1:30, Flankensteilheit, Ätzen der SiO₂ Hartmaske mit HBr/NF₃/Cl₂ Ätzprozess, Zugabe von O₂ zur Kontrolle der Flankensteilheit
- Si-Tiefenätzen/Bosch-Prozess sehr hohe Aspektverhältnisse bei vertikalen Seitenwänden Ätzprozess aus abwechselnden SF₆-Ätz- und C₄F₈-Passivierungsschritten
Advanced Silicon Etch: Weiterentwicklung des Bosch-Prozesses

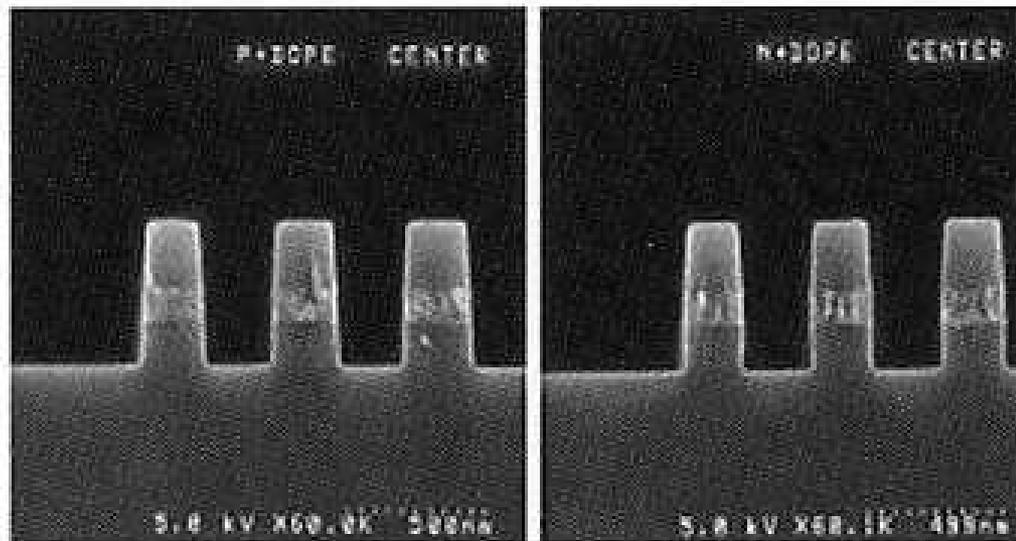
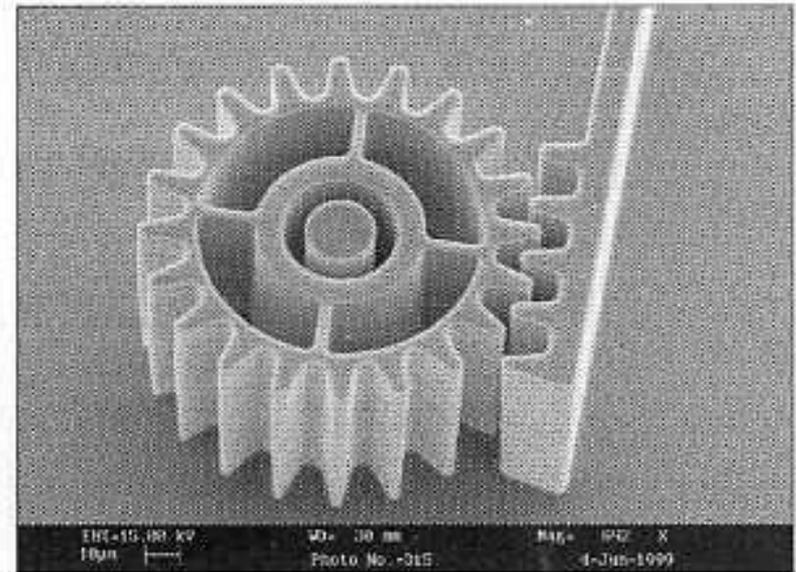
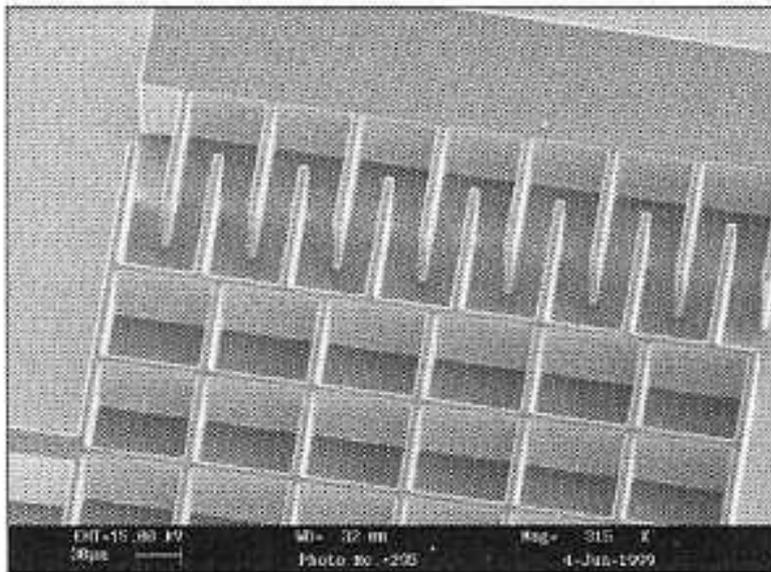
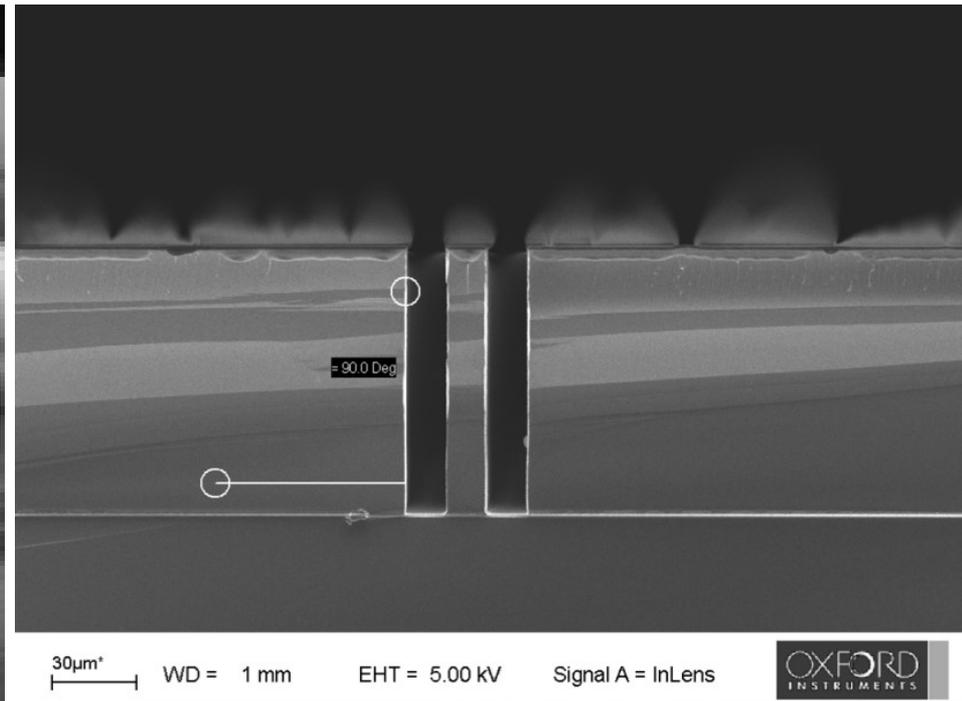
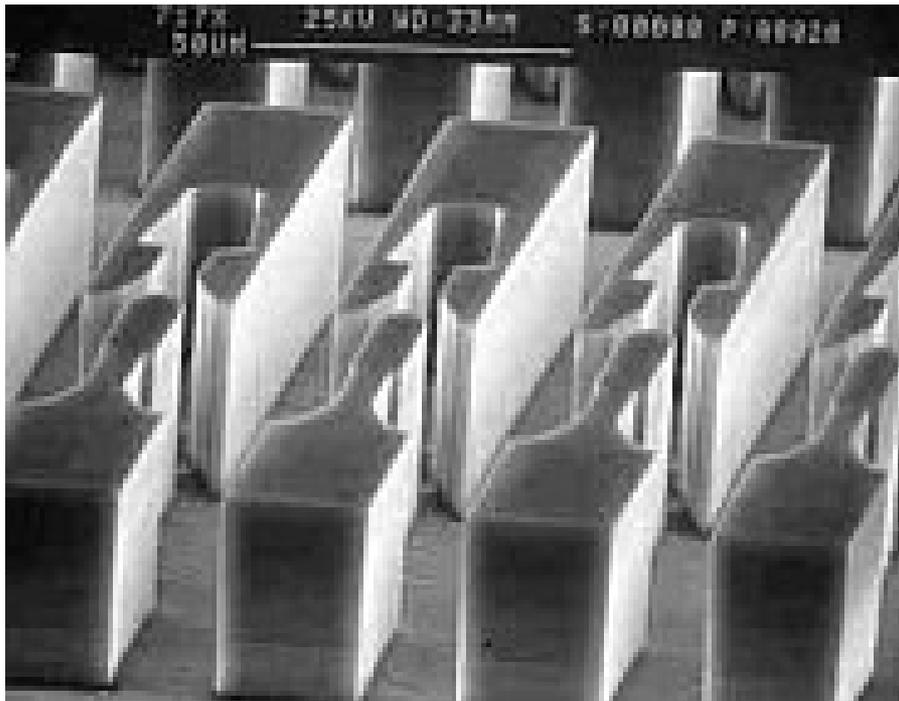


Figure 11: SEM micrograph of a gate etch for dual doped wafer – courtesy of Lam Research.

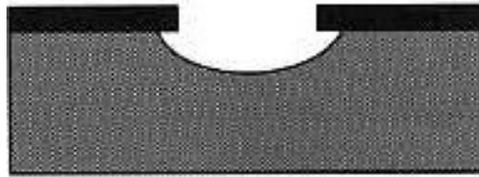
Beispiele für Reaktivgasätzen: MEMS-Strukturen



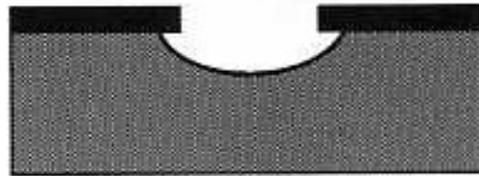
Beispiele für Reaktivgasätzen: MEMS-Strukturen



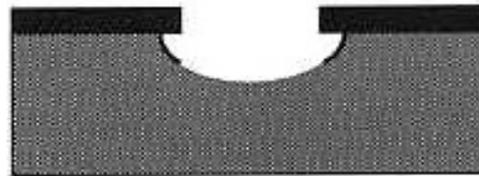
Beispiele für Reaktivgasätzen: Bosch-Prozess



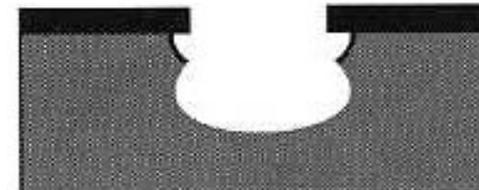
(a) Isotropic etching



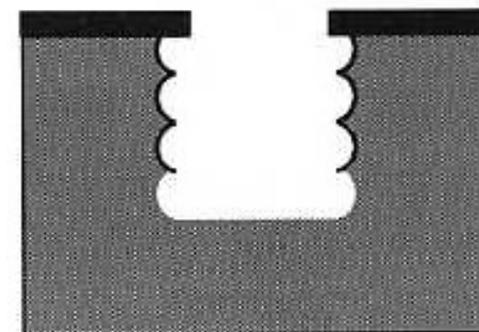
(b) Deposition (sidewall passivation)



(c) Removal of bottom passivation layer by ion bombardment



(d) Isotropic etching



(e) Resulting profile

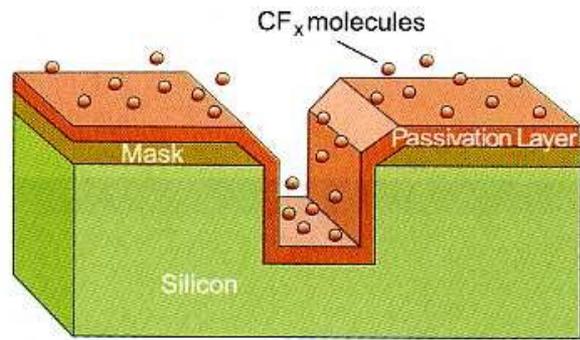
Table-6.4. Typical “Bosch” process conditions

process parameters	passivation	etching
C ₄ F ₈	85 sccm*	0 sccm
SF ₆	0 sccm	130 sccm
RF power at stage	0 W	12 W
RF power from coil	600 W	600 W
cycle time	7.0 s	9.0 s
delay time	0.5 s	0.5 s
etch rate		1.5 ~ 3 μm/min

* sccm: standard cubic centimetre per minute.

Table-6.5. Performances of ASE system from STS [26]

etch rate	1.5 ~ 3 μm/min
selectivity of oxide to silicon	120 ~ 200 : 1
selectivity of photoresist to silicon	50 ~ 100 : 1
sidewall verticality	90° ± 2°
maximum aspect ratio	30
etch uniformity over 4 ~ 6 inch wafer	±2.5% ~ 5%
etch depth	10 ~ 800 m



Beispiele für Reaktivgasätzen:
Advanced Silicon Etch

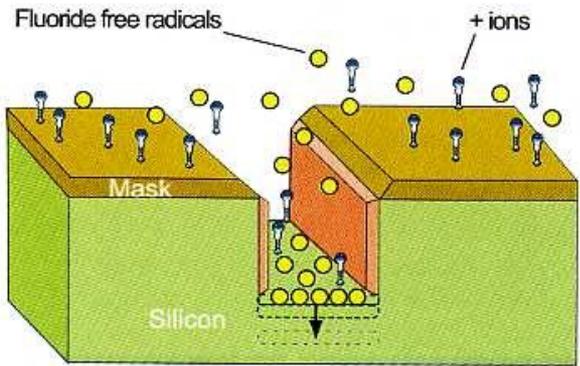
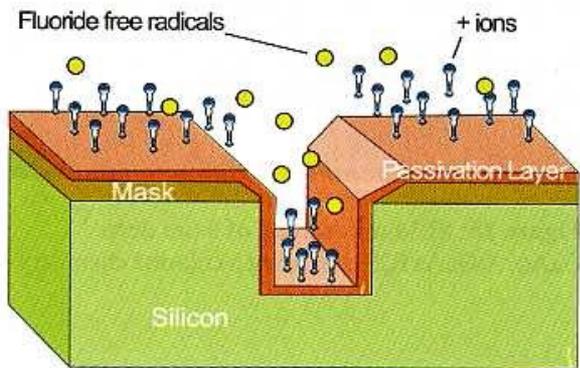


Figure 14: ASE mechanism – courtesy of STS.

Beispiele für Reaktivgasätzen: 2. Ätzen von Dielektrika (SiO_2 , Si_3N_4): vertikale Profile durch Seitenwandpassivierung, Ätzbarrieren
Ätzgase CF_4 , CHF_3 , C_4F_8

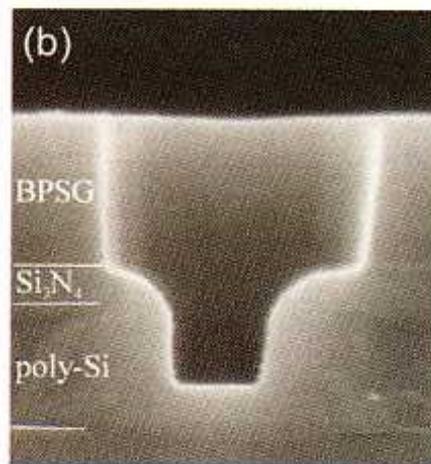
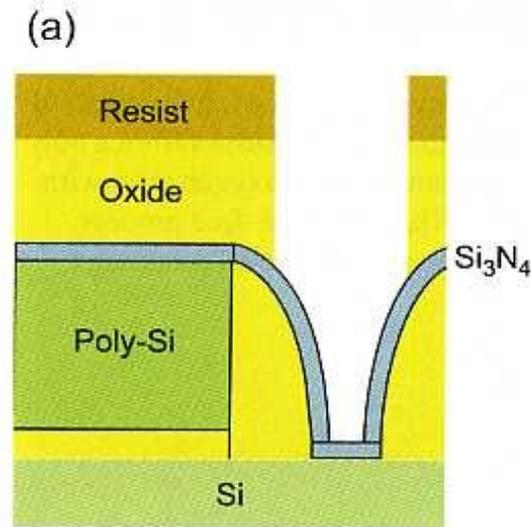


Figure 15:
(a) Schematic and
(b) cross-section
SEM micrograph
of a SAC structure.

Beispiele für Reaktivgasätzen: 3. Ätzen von Metallen:

- Aluminium: F-Chemie nicht möglich wegen AlF_3 -Bildung,
meist Cl-Chemie verwendet: BCl_3 oder Cl_2
- Edelmetalle (Pt, Ir): schwierig, Ätzen bei hohen Temperaturen (200°C)
Ätzgase: Cl_2/O_2 , Cl_2/CO , Cl_2/CO_2

Beispiele für Reaktivgasätzen: 4. Ätzen von Verbindungshalbleiter für optoelektronische Anwendungen, z.B. GaAs/AlGaAs Heterostrukturen
Ätzgase Cl_2 , CH_4/H_2

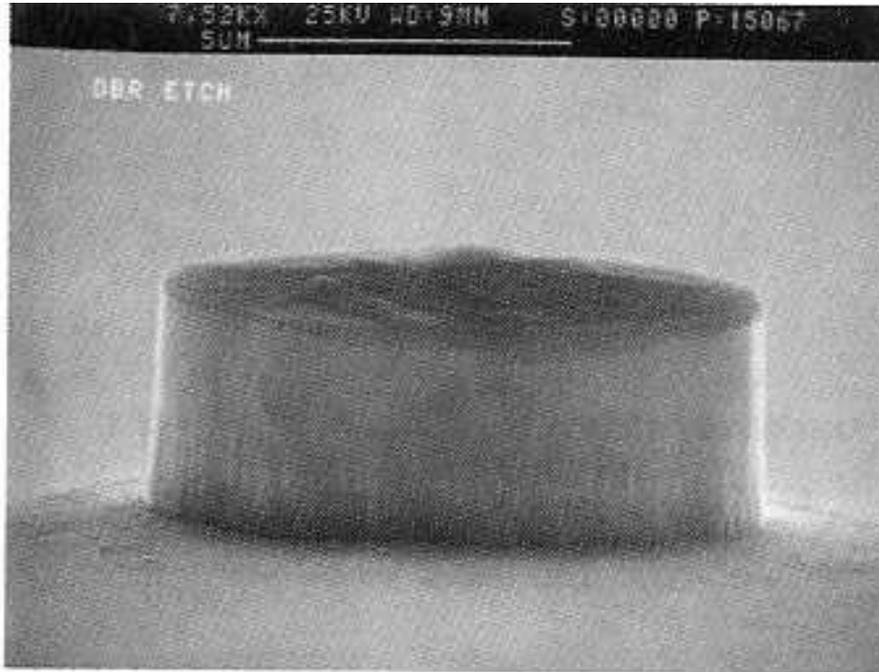


Figure 16: SEM micrograph of 5 μm deep GaAs/ AlGaAs ICP etch using a chlorine chemistry.

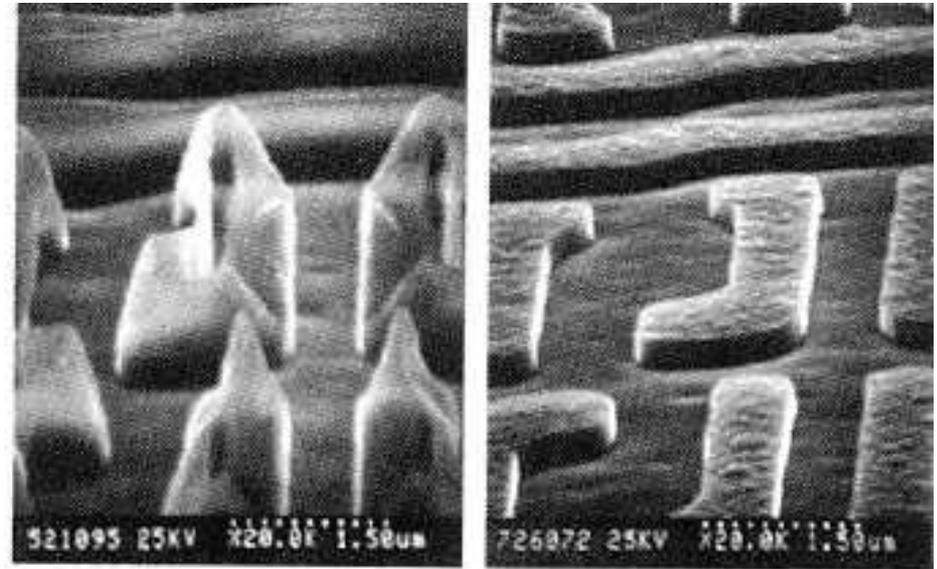


Figure 17: SEM micrograph showing the effect of a dry clean process to remove residues from a poly silicon etch step. Conventional oxygen strip with polymer remaining (left), residue-free process result (right). Courtesy of Mattson Technology.

Beispiele für Reaktivgasätzen:

5. PR-Veraschung, Polymer-Entfernung
O₂-Veraschung, CF₄ Plasma-Ätzen

6. Ätzen metallischer Multilag
Ätzgase: NF₃/Cl₂, HBr-basierte Gase

7. Ätzen komplexer Oxid-Verbindungen, z.B. Dielektrika, Ferroelektrika
Ätzgase: Cl₂/HBr

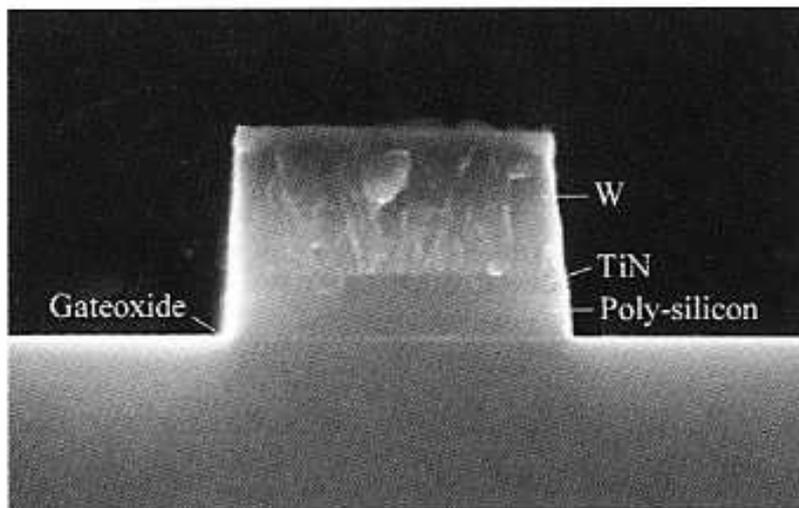


Figure 21: SEM micrograph cross-section of a dual metal gate structure etch.

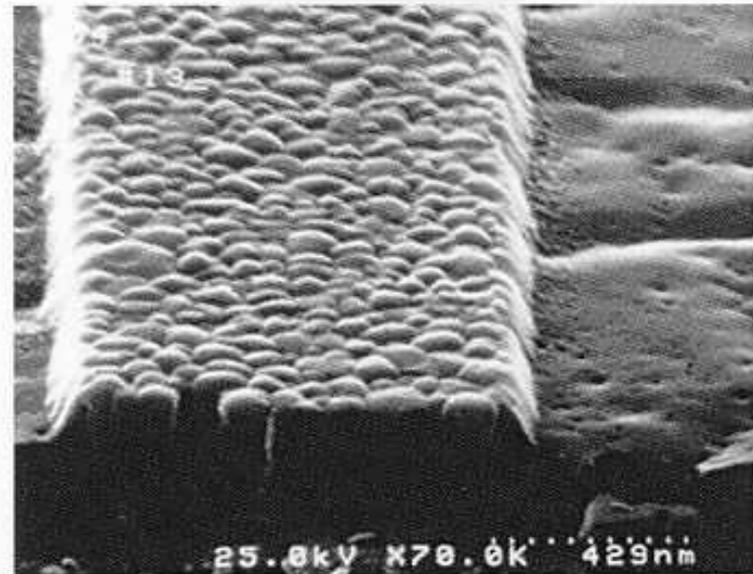


Figure 22: SEM micrograph cross-section of an etched BST line structure.

	Physical Vapor Deposition			Chemical Vapor Deposition
	Evaporation / MBE	Sputtering	PLD	CVD / MOCVD
Mechanism of production of depositing species	Thermal energy	Momentum transfer	Thermal energy	Chemical reaction
Deposition rate	High, up to 750,000 Å/min	Low, except for pure metals	Moderate	Moderate Up to 2,500 Å/min
Deposition species	Atoms and ions	Atoms and ions	Atoms, ions and clusters	precursor molecules dissociate into atoms
Energy of deposited species	Low 0.1 to 0.5 eV	Can be high 1-100 eV	Low to high	Low; Can be high with plasma-aid
Throwing power				
a) Complex shaped object	Poor, line of sight	Nonuniform thickness	Poor	Good
b) Into blind hole	Poor	Poor	Poor	Limited
Scalable to wafer size	up to large	up to large	limited	up to large

Einfluss der Restgase auf Filmwachstum

p , mbar	Mean free path, cm (between collisions)	Collisions / s (between molecules)	Molecules/(cm ² s) (sticking surface)	Monolayer / s*
10^0	$6.8 \cdot 10^{-3}$	$6.7 \cdot 10^6$	$2.8 \cdot 10^{20}$	$3.3 \cdot 10^5$
10^{-3}	$6.8 \cdot 10^0$	$6.7 \cdot 10^3$	$2.8 \cdot 10^{17}$	$3.3 \cdot 10^2$
10^{-6}	$6.8 \cdot 10^3$	$6.7 \cdot 10^0$	$2.8 \cdot 10^{14}$	$3.3 \cdot 10^{-1}$
10^{-9}	$6.8 \cdot 10^6$	$6.7 \cdot 10^{-3}$	$2.8 \cdot 10^{11}$	$3.3 \cdot 10^{-4}$

* Assuming the condensation coefficient is unity

Table 2: Some facts about residual air at 25 °C in a typical vacuum used for film deposition (after Chopra [2]).

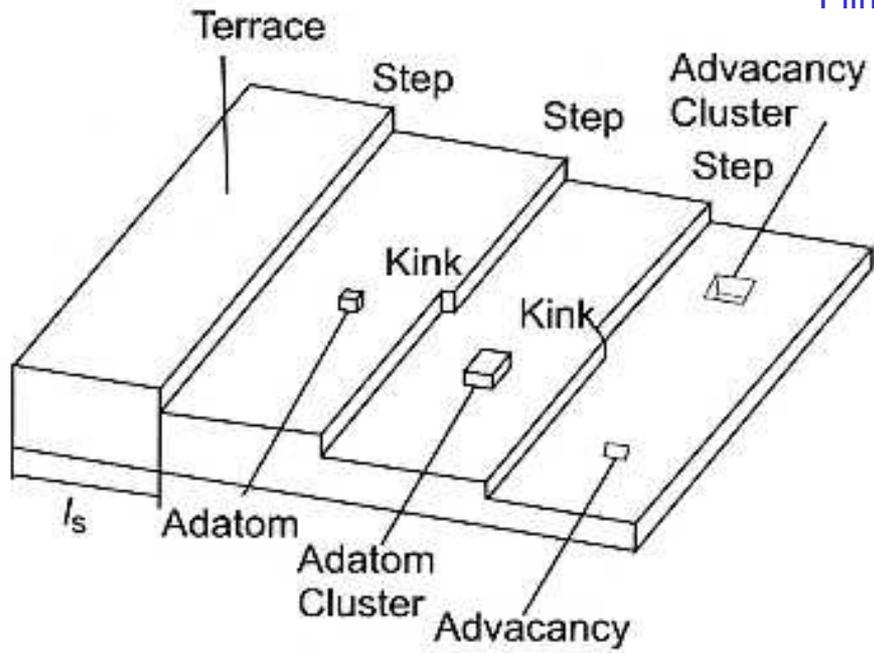


Figure 5: Schematic view of the elements of the surface morphology [3].

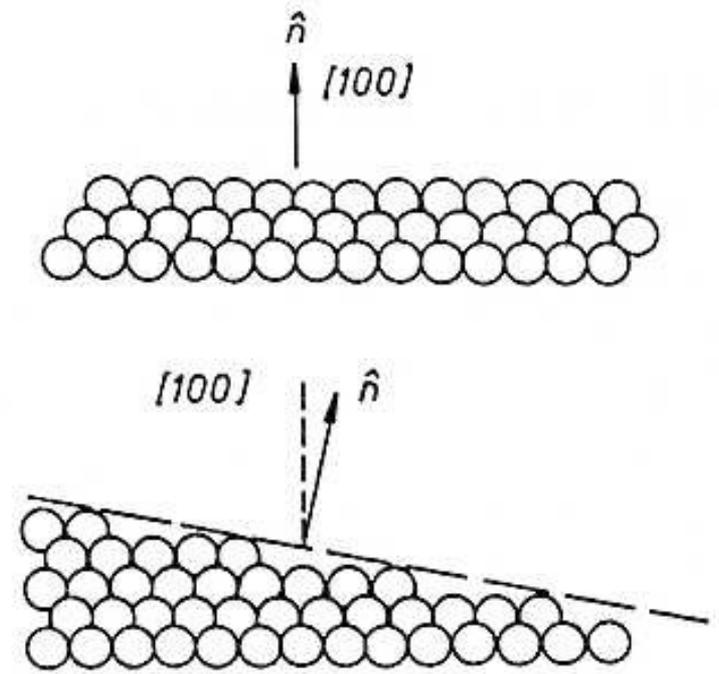


Figure 6: Change of the step distance, l_s , by cutting a surface at a small angle to a major crystallographic direction, i.e., forming a vicinal surface.

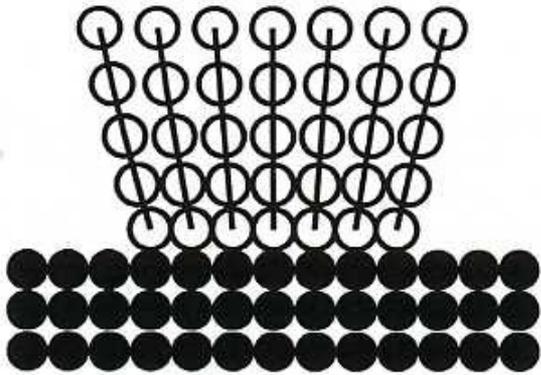


Figure 10: Strain relaxation in pseudomorphic (dislocation - free) islands.

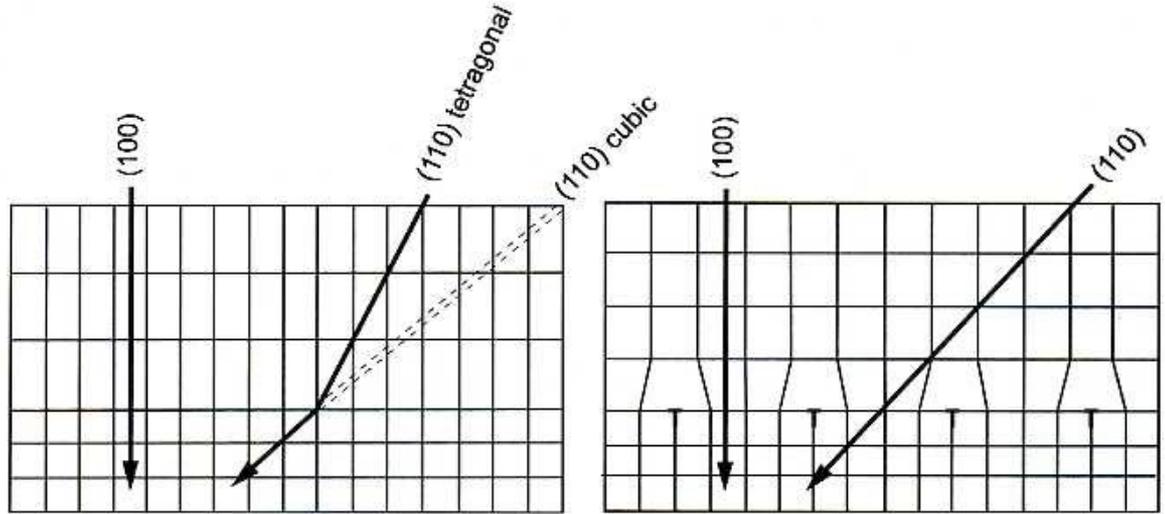


Figure 11: Strain relaxation by misfit dislocations for the example of two initially cubic crystals. As the film has a larger lattice constant than the substrate the forced matching at the interface yields a

tetragonal distortion of the film. By misfit dislocations this strain can be relaxed and the film can re-approach its cubic structure.

Filmwachstum bei Mischmaterialien

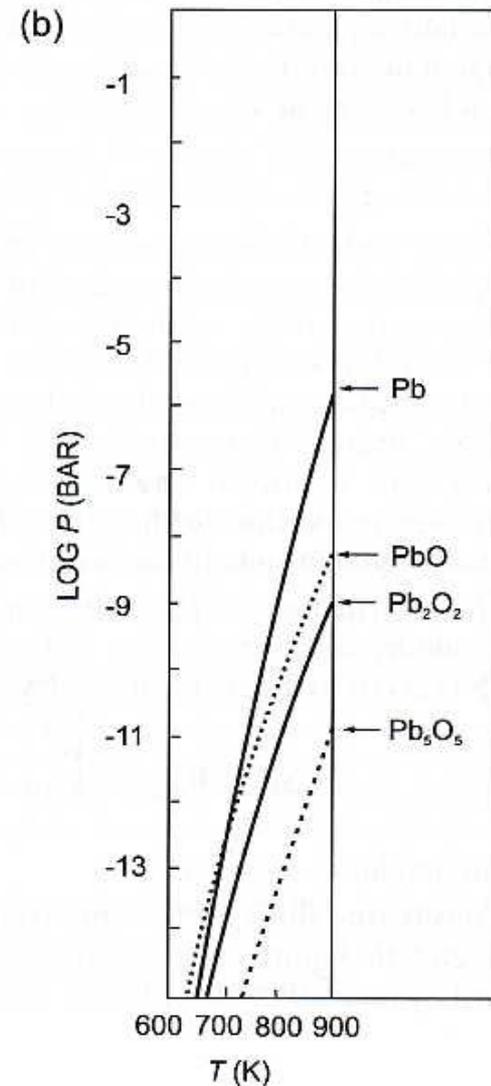
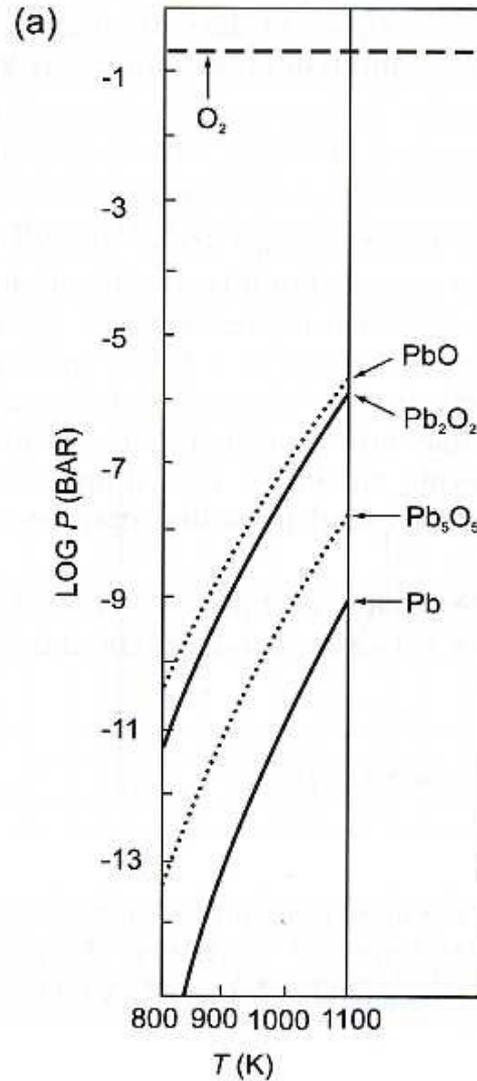
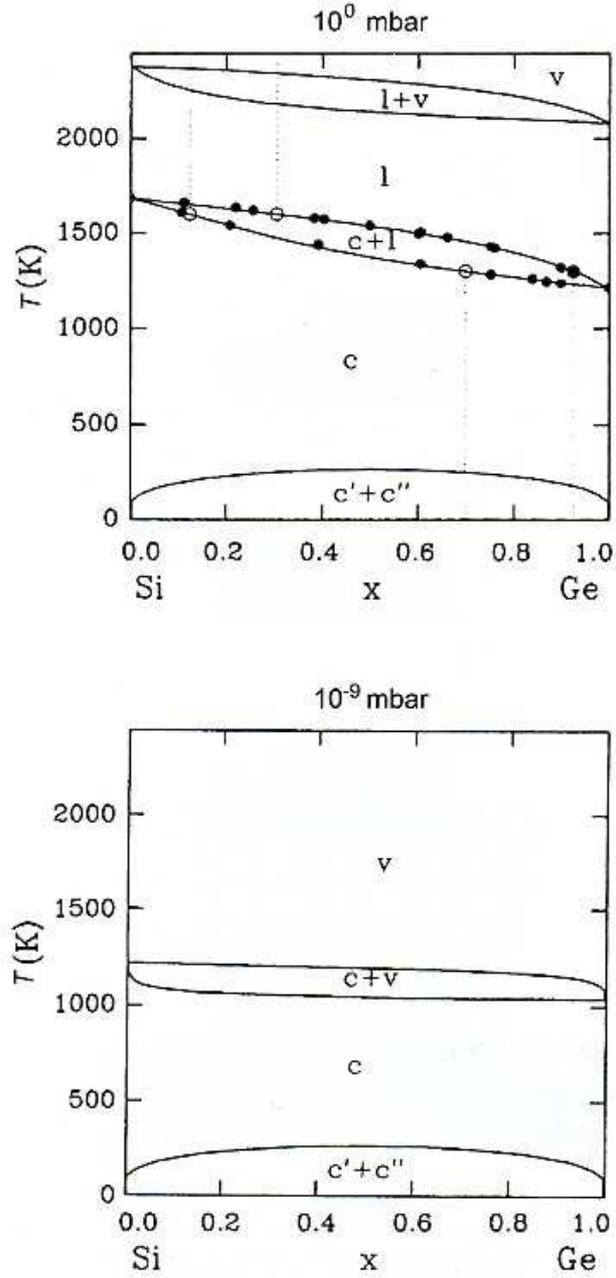
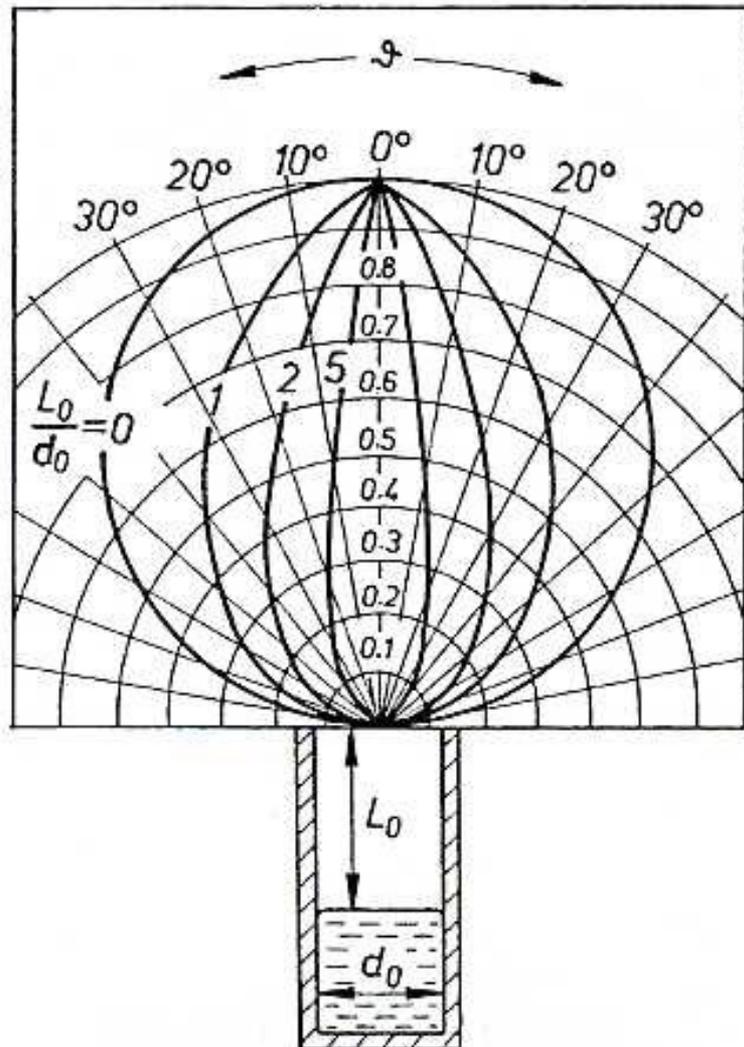


Figure 3: x - T phase diagram of the $\text{Si}_{1-x}\text{Ge}_x$ systems at 10^0 and 10^{-9} mbar [3].

Facilities	Components	Functions
Beam generators	Knudsen cells e^- - beam evaporators Gas or vapour cells	To provide stable, high-purity, atomic or molecular beams impinging onto substrate surface ⇒ MOMBE
Beam interruptors	Fast-action shutters	To completely close or open line of sight between source and substrate. Action should be rapid (< 0.1 s) and should cause minimal thermal disruption of source
Process environment	Multichamber UHV system	To provide ultraclean growth environment, with residual gas species (e.g. O_2, CO, H_2O, CO_2) < 10^{-11} mbar
Beam and growth monitors	RHEED Beam monitoring ionization gauge mass spectrometer	To provide dynamic information on the surface structure on beam intensities and on compositional information

Table 3: Principle operative systems in MBE and their function (after Parker [6]).

Knudsenzelle



Elektronenstrahlverdampfer

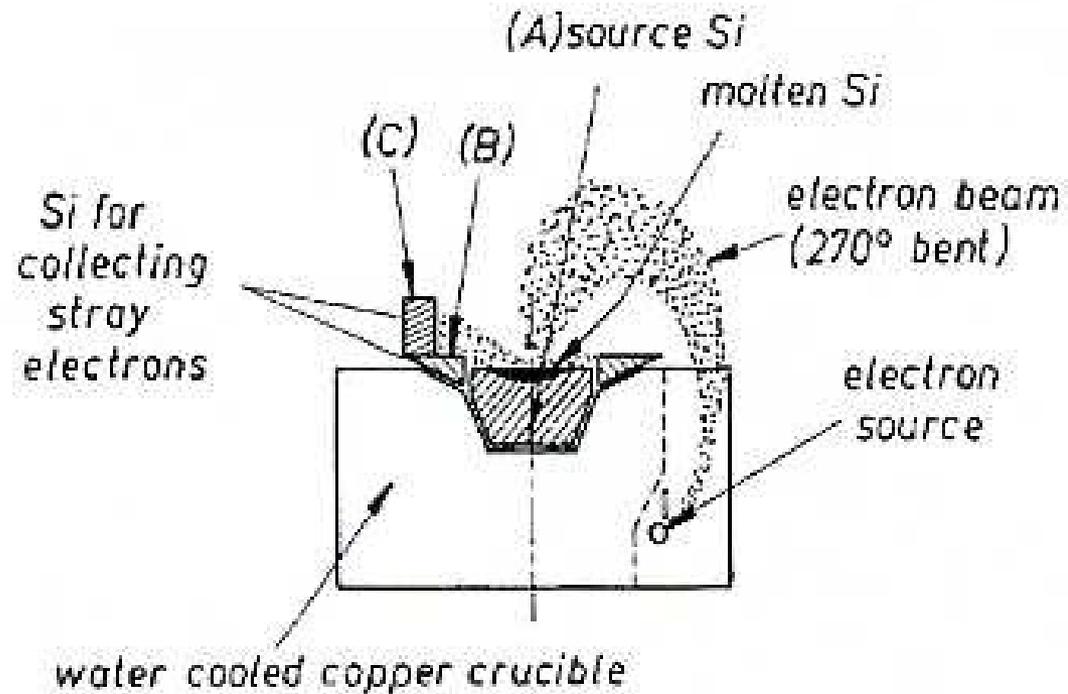
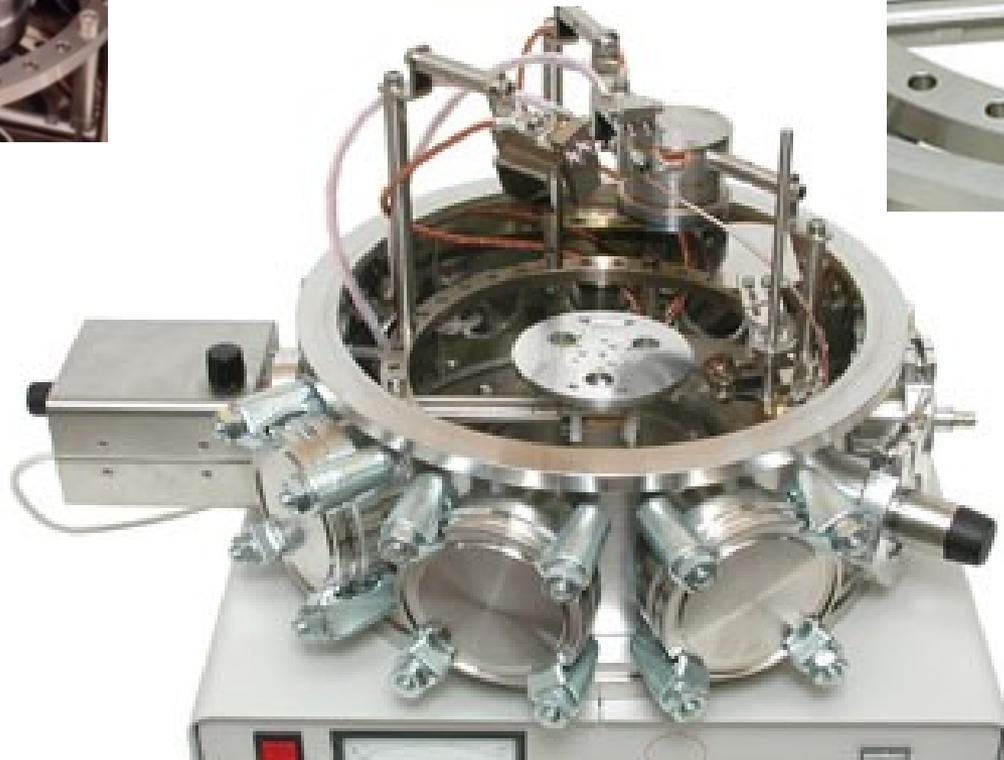
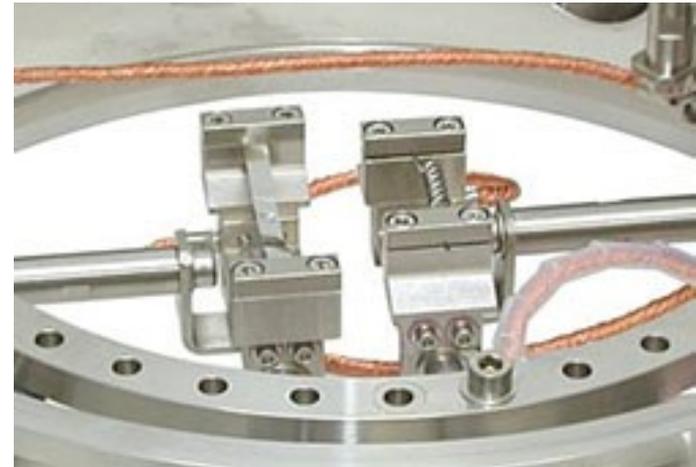
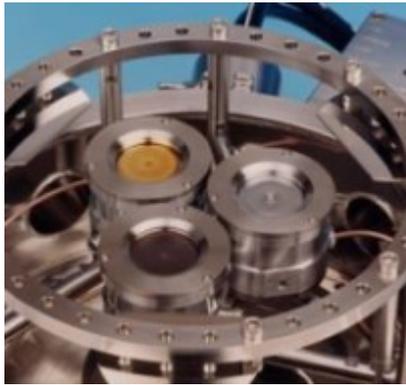


Figure 14: Schematics of a electron beam evaporator for Si evaporation [7]; B: Si guard ring, C: catcher for backscattered electrons.

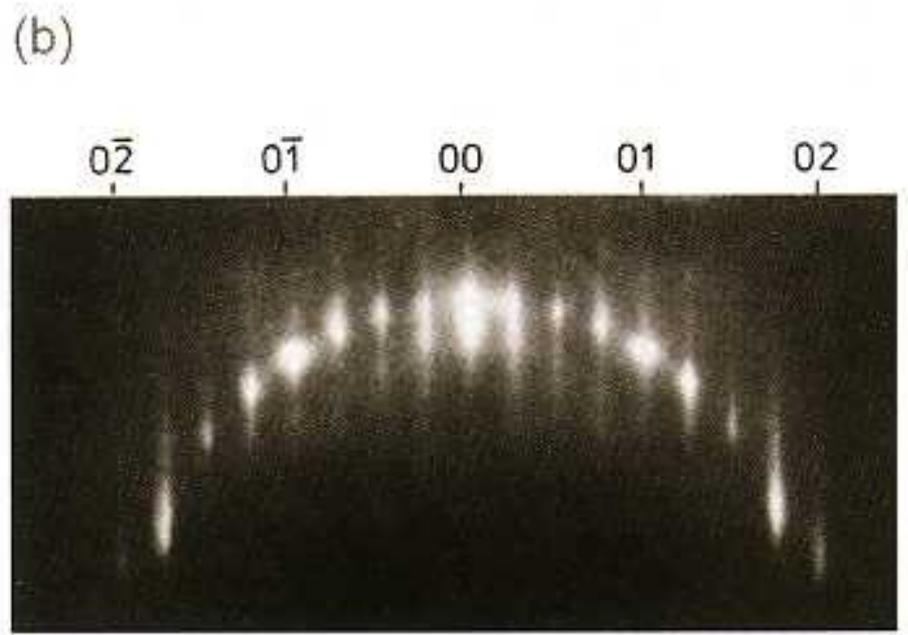
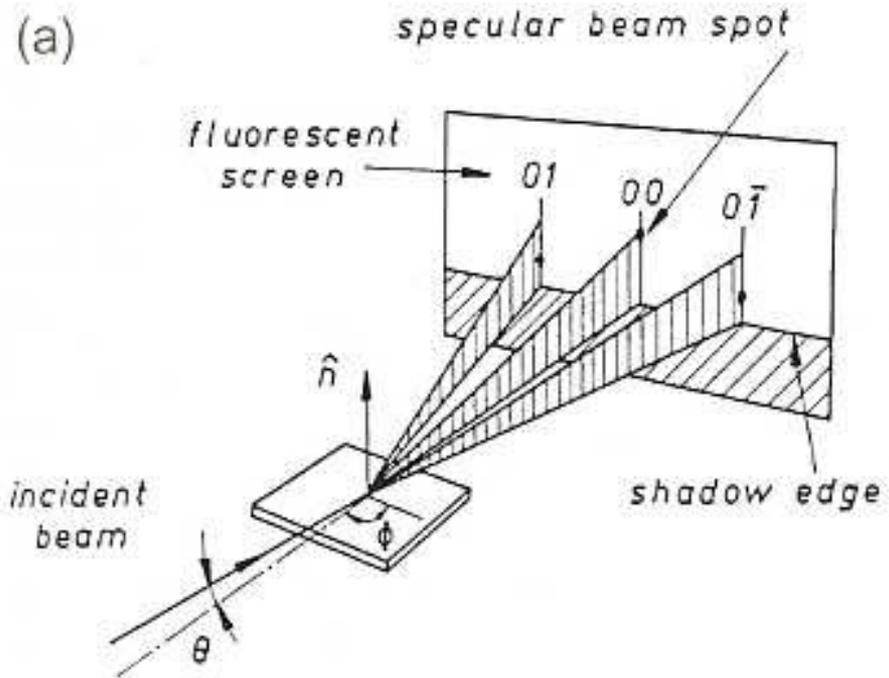
Beispiel einer Kleinbedampfungsanlage



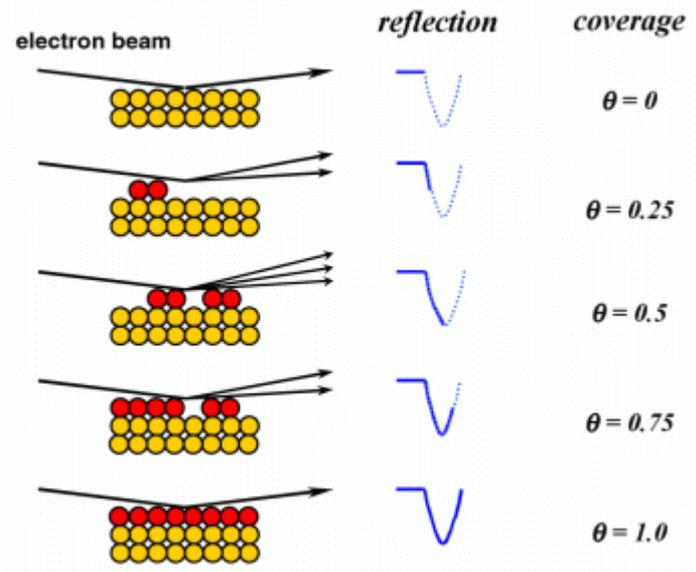
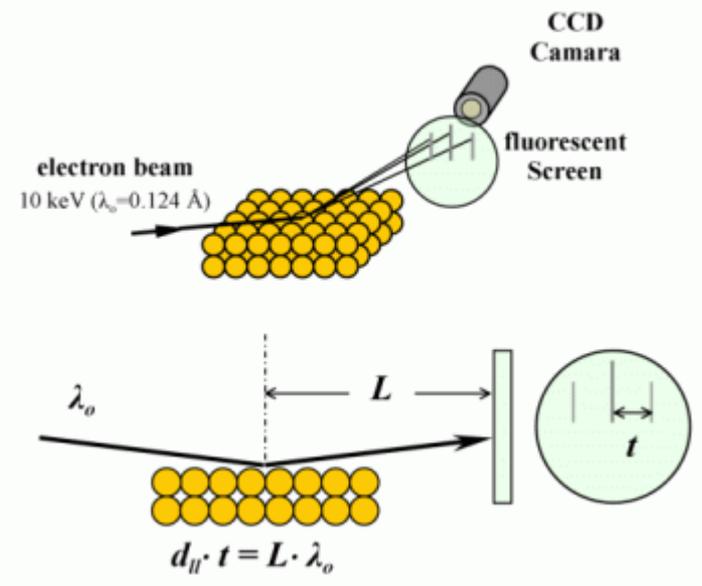
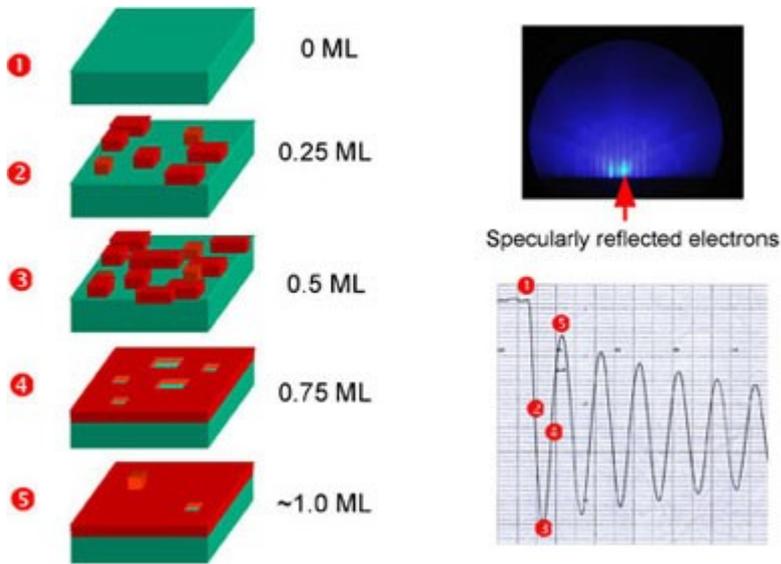
Beispiel einer MBE-Anlage



In-situ Analysetechniken: RHEED



In-situ Analysetechniken: RHEED



STM

0,0 Intensity

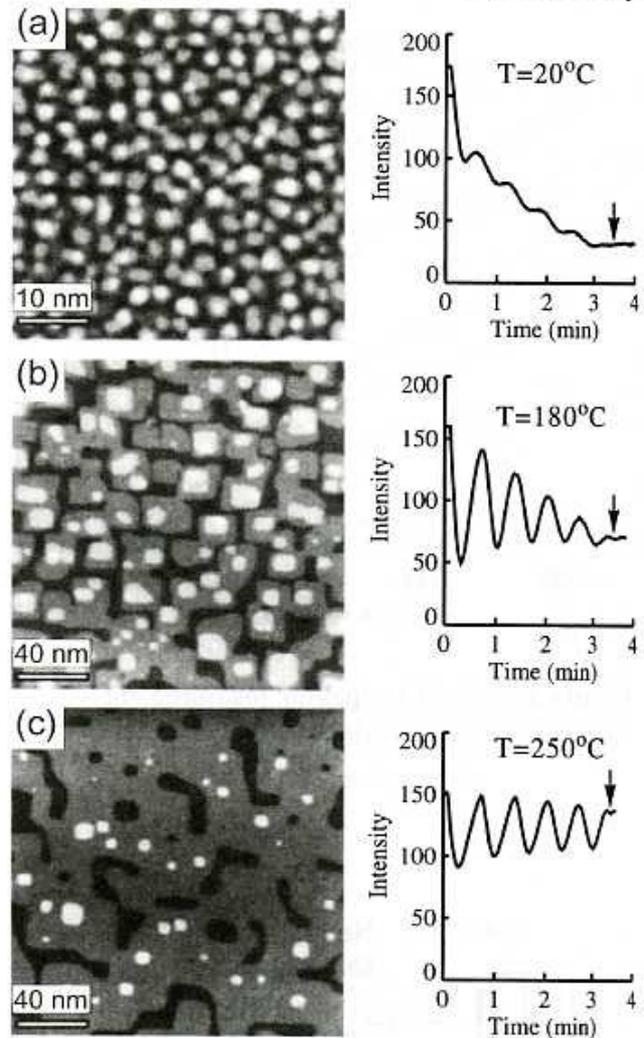


Figure 19: STM and RHEED results for the homo-epitaxial growth of Fe films on Fe(100) substrates. The growth was interrupted after 5 oscillations, as indicated by the arrow. The scale of the STM was changed between part a and b! The roughness of the films decreases strongly with temperature: rms (root mean square) amplitude 0.116 nm, 0.095 nm and finally at 250°C 0.06 nm [9].

In-situ Analysetechniken: RHEED

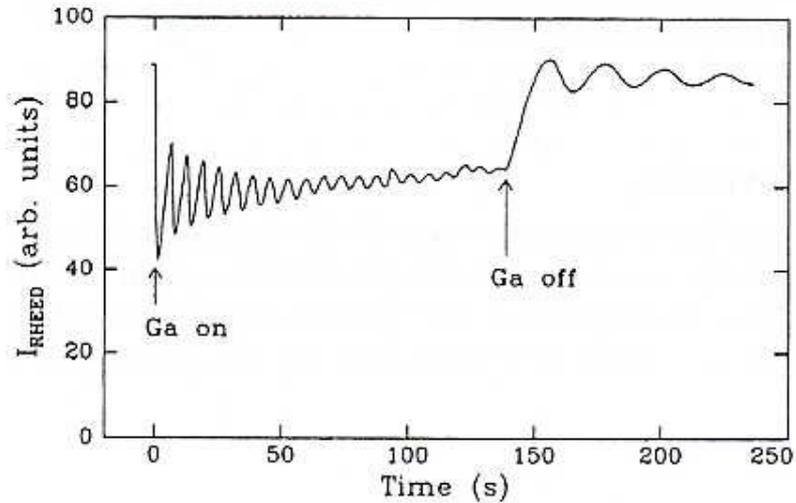
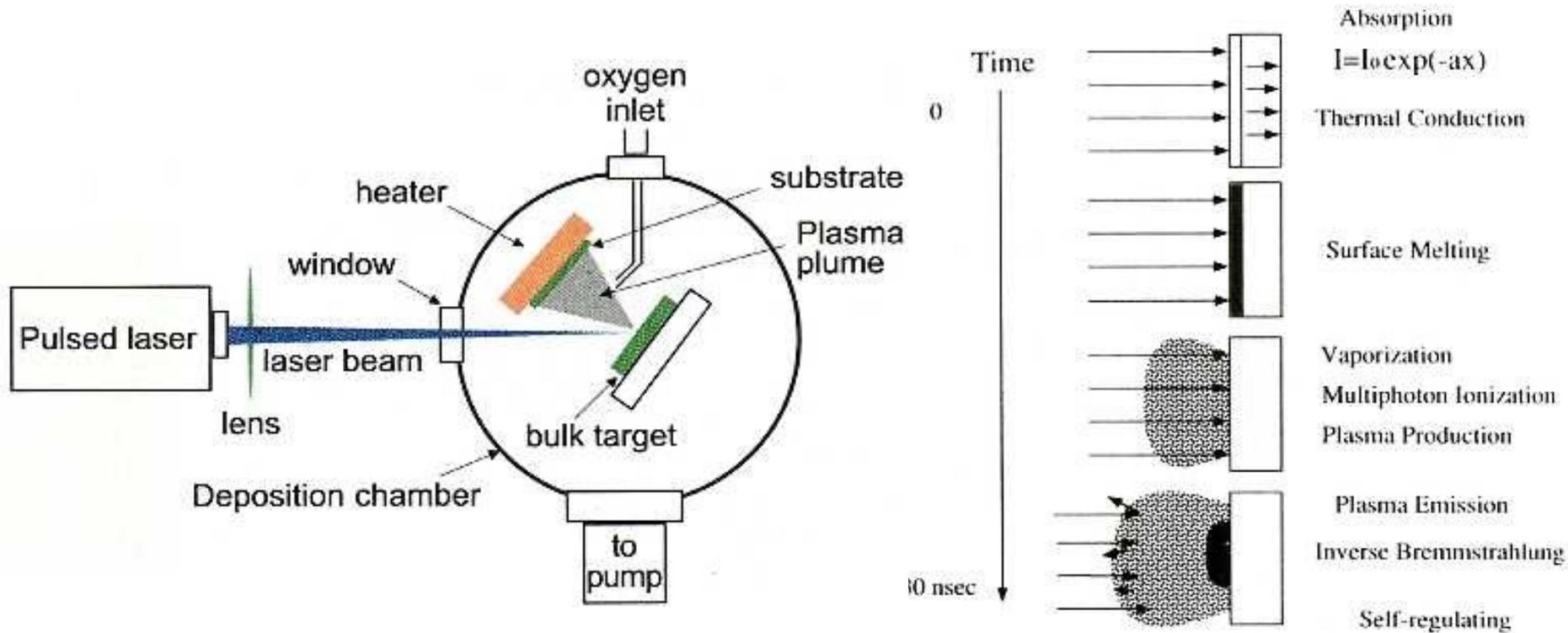


Figure 18: Growth and re-evaporation of GaAs as observed by RHEED [3].

Abscheidetechniken: 6.2.2 Pulsed Laser Deposition (PLD)



Pulsenergie ~ 1 J/Puls \rightarrow hohe Energiedichte $3-5$ J/cm² \rightarrow Plasmabildung

Bsp.: • Hochtemperatursupraleiter: Pulsfrequenz 50 Hz, $\Delta t = 25$ ns, $\lambda = 248/193$ nm
 Substrattemperatur 750°C
 Sauerstoffpartialdruck 0.3-1 mbar

• elektrooptische Anwendungen, z. B. Wellenleiter aus LiNbO₃, KNbO₃ oder BaTiO₃

6.2.3. Sputtern (Kathodenzerstäubung/Sputterdeposition)

Man unterscheidet:

- DC Sputter: Gleichstrom-Gasentladung, nur leitfähige Materialien
- DC Magnetron Sputtern: zur Verbesserung der Ionisationsrate
Magnet unter Target,
Anwendung: Beschichtung großer Flächen wie
Glasscheiben, Sonnenkollektoren, etc.
- RF Sputtern: für nichtleitende Materialien, Wechselfeld 13,6 MHz
+ überlagerte negativer Offset

Bem.: Partialdruck des Sputtergases ist ein wichtiger Prozessparameter

--> freie Weglänge der Atome

--> Wachstumskonditionen des Films

6.3.1. Chemical Vapor Deposition

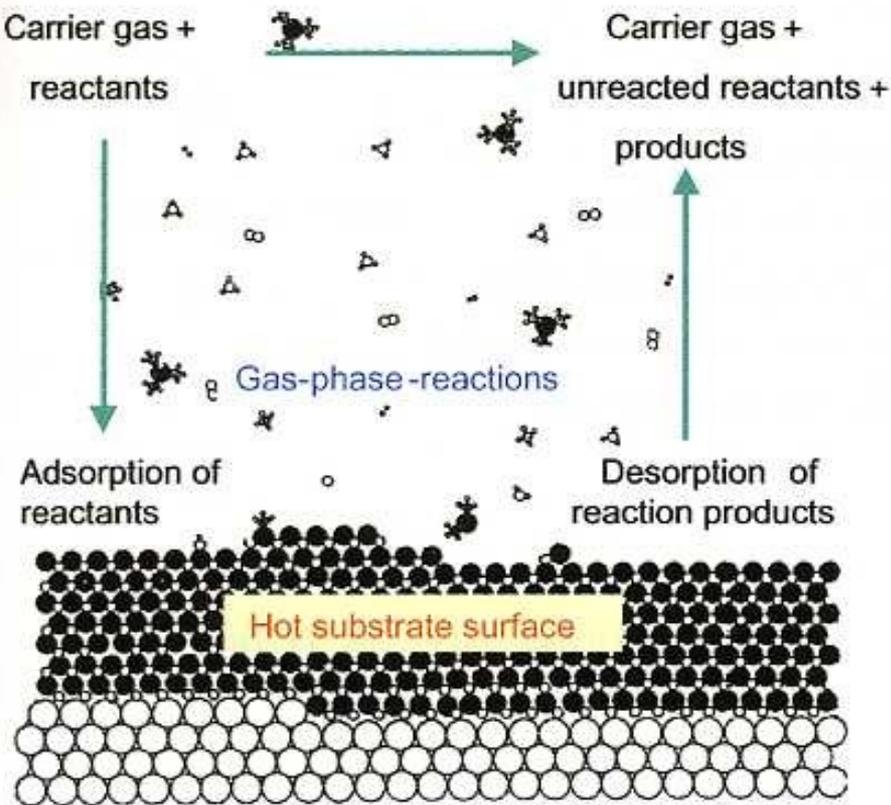


Figure 30: Schematics of the gas flow and the atomic scale chemical environment in the region of the growing film surface during a MOCVD process.

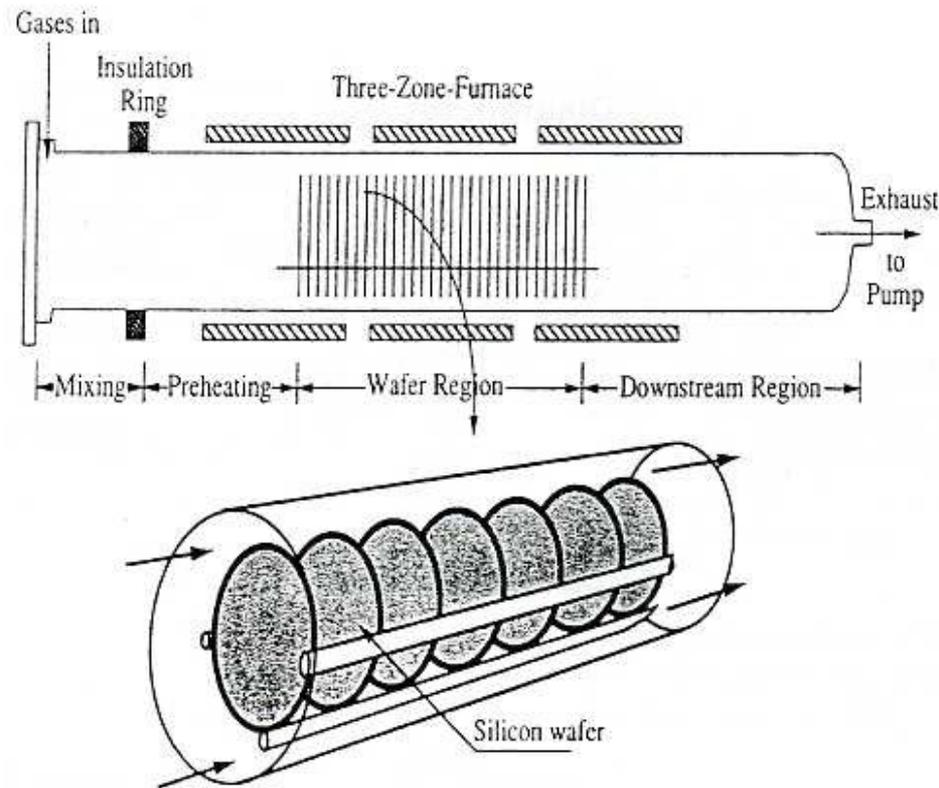
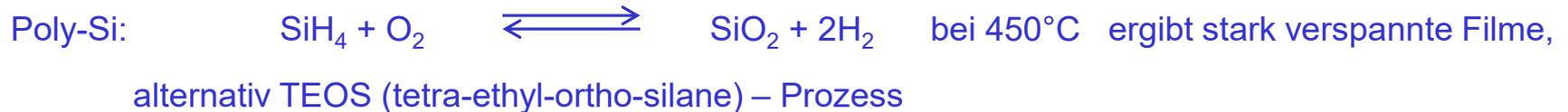


Figure 31: Schematic representation of a hot-wall multiple-wafer in-tube CVD reactor [20].

Anwendung: Standardprozess in der CMOS-Technologie zur Abscheidung von Isolatoren wie poly-Si, Si-Nitrid und SiO₂ durch thermische Zersetzung von SiH₄ (Silan)

6.3.1. Chemical Vapor Deposition

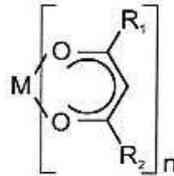


Beispiele:

- Herstellung metallischer Filme: Precursor = organo-metallische Verbindungen --> MOCVD
- Herstellung komplexer Oxid-Filme: Precursor = metall-organische Verbindungen --> M – O – R
z.B. Alkoxide, Ketonate, Karboxylate

Chemische Abscheidung: Chemical Vapor Deposition

β -Diketonates



$R_1=R_2=CH_3$ (acetylacetonate)

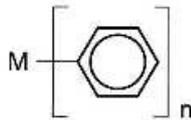
$R_1=R_2=C(CH_3)_3$ (tetramethylheptadionate) **Ba(thd)₂, Sr(thd)₂**

$R_1=C(CH_3)_3, R_2=CF_3$ (trifluorodimethylhexanedionate)

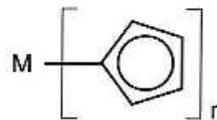
$R_1=C(CH_3)_3, R_2=C_3F_7$ (heptafluorodimethyloctanedionate)

$R_1=R_2=CF_3$ (hexafluoroacetylacetonate)

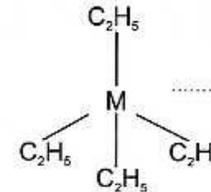
Organometallics



phenyl



cyclopentadienide

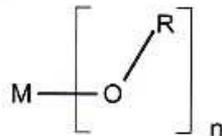


..... tetra-ethyl-lead

tetraethyl

..... triphenyl-Bi

Alkoxides



$R=CH_3$ (methoxide)

$R=C_2H_5$ (ethoxide)

$R=CH(CH_3)_2$ (isopropoxide) **Ti: TIP, Zr: ZIP**

$R=C(CH_3)_3$ (t-butoxide) **Zr -tert -butoxide**

CVD- Reaktor zur PZT-Abscheidung

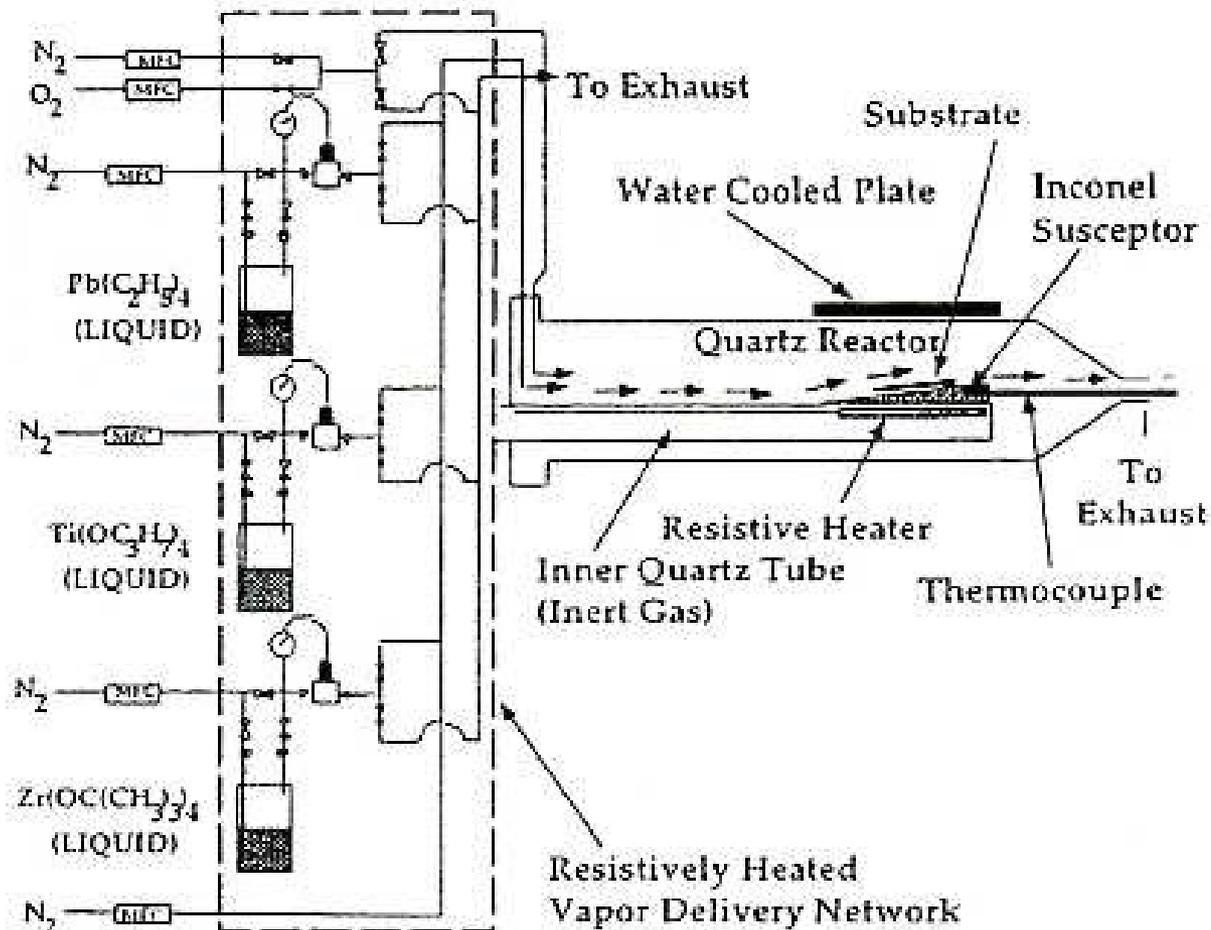


Figure 33: MOCVD research reactor with bubbler system and quartz tube horizontal flow reactor used for PZT deposition [25].

CVD- Reaktor zur BST-Abscheidung

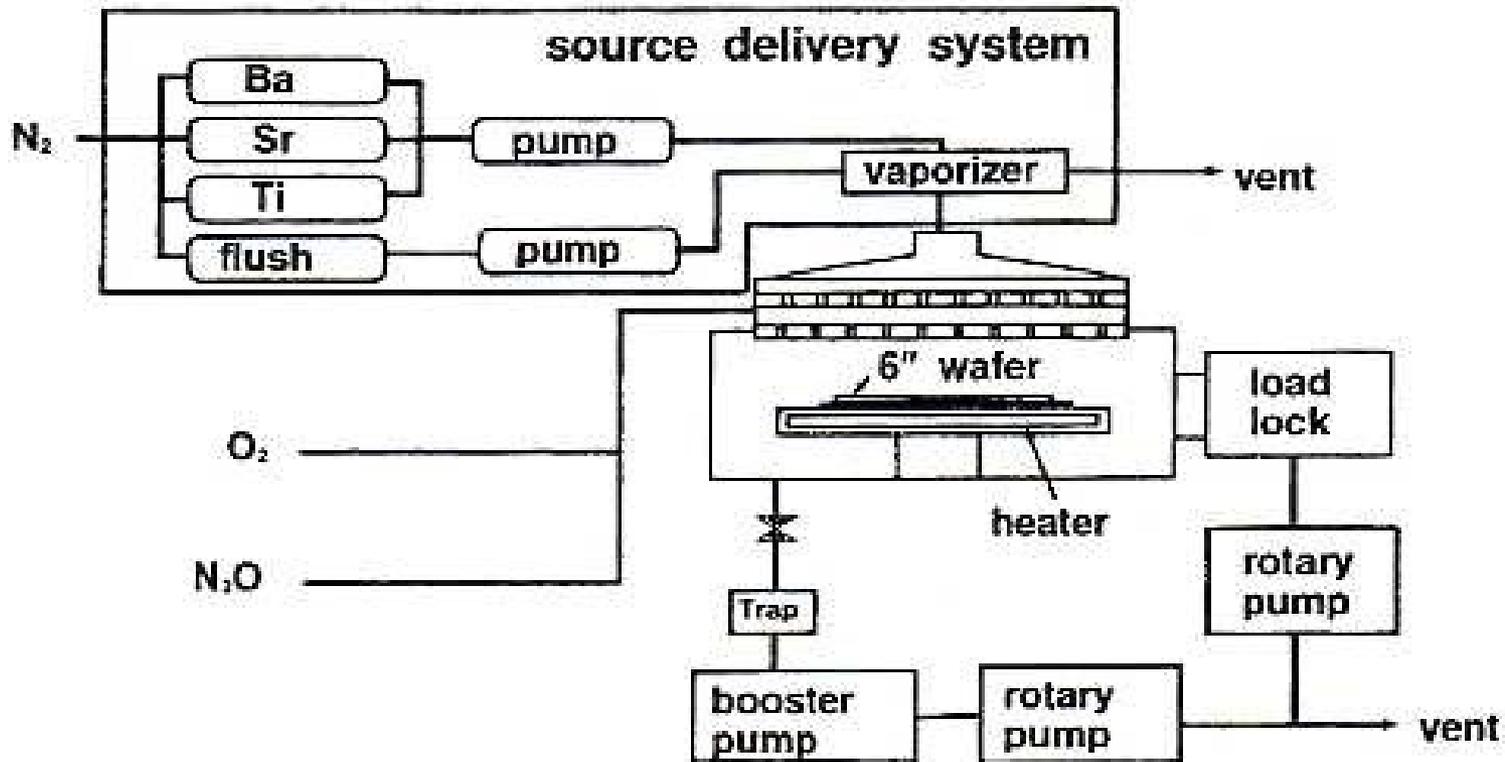
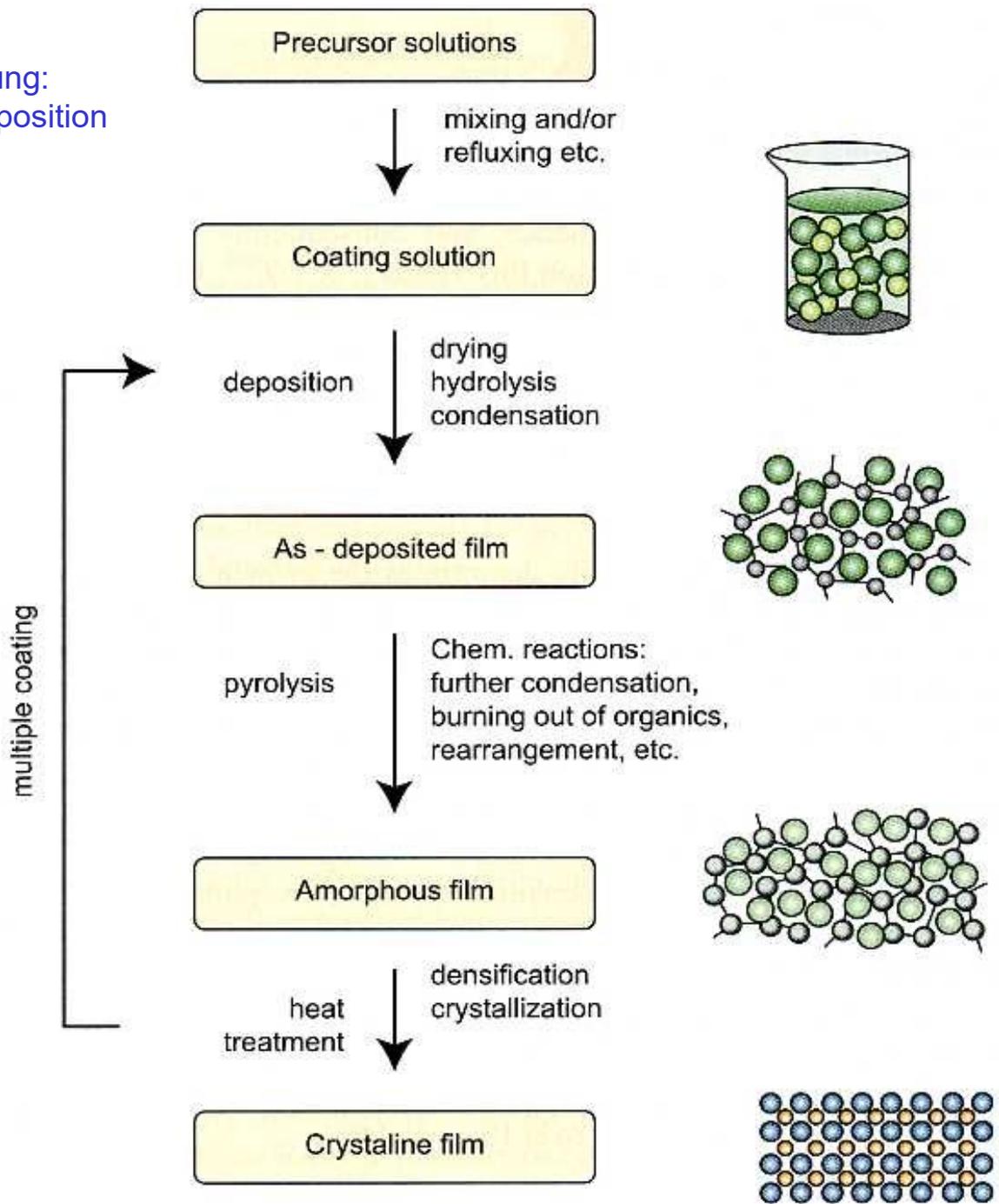


Figure 34: MOCVD production tool with liquid source delivery system showerhead reactor and load lock used for BST deposition [26].

Chemische Abscheidung:
Chemical Solution Deposition



Themen im Sommersemester:

C. Ausgewählte Kapitel zur Nanotechnologie

7. Nanostrukturen durch Selbstorganisation

7.1 Voraussetzungen für Selbstanordnung

7.2 Thermodynamische Aspekte der Selbstanordnung

7.3 Weitere Beispiele

8. Partikuläre Nanostrukturen

8.1 Festkörper in reduzierter Dimension

8.2 Elektronische Eigenschaften eindimensionaler Strukturen

8.3 Kohlenstoff-Nanoröhrchen

8.4 Cluster und Kolloide

8.5 Einzelladungseffekte

9. Nanoelektronik

9.1 Der Einzelladungstransistor (SET)

9.2 Quanten-Computing

9.3 Molekulare Elektronik

10. Nanooptik

10.1 Photonische Bandlückenmaterialien (PBG)

10.2 Plasmonen

11. Nanotribologische Systeme

11.1 Der Lotus-Effekt

11.2 Der Gecko-Effekt

12. Biologische Nanostrukturen

12.1 Abbildung und mechanische Eigenschaften lebender Zellen

12.2 Biologische Nanostrukturen