Microscopes

For the visualisation of millimeter to nanometer structures

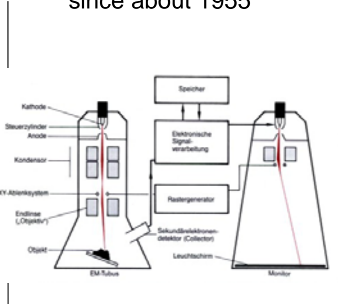
Light Microscope

since about 1750

geometric optics
resolution about 500 nm
Light-Intensity contrast

Electron Microscope (SEM)

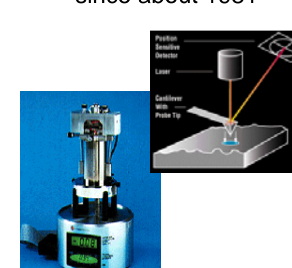
since about 1955



E-beam raster-scan
resolution 5 nm
secondary electron counting
projection image

Scanning Probe Microscope

since about 1981



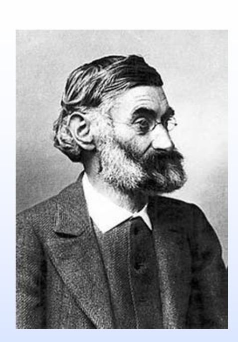
deflection sensor
piezo-scan
resolution 0.2 nm
3d topographic map

N.B.
Ein Bild sagt mehr als tausend Worte (Daten)

Es wird oft behauptet, es handele sich um ein chinesisches Sprichwort. Auch Konfuzius wird oft als Urheber genannt. Der erste gedruckte Nachweis findet sich jedoch im englischen Sprachraum. Am 8. Dezember 1921 veröffentlichete Fred R. Barnard in der Zeitschrift "Printers' Ink" eine Anzeige mit dem Slogan "One Look is Worth A Thousand Words." Es handelte sich um eine Fachzeitschrift der Werbebranche. Die Anzeige warb für den Gebrauch von Bildern in Werbeaufdrucken auf Autos. Am 10. März 1927 erschien eine zweite Anzeige mit der Phrase "One Picture is Worth Ten Thousand Words". Dort wird behaupted, es handele sich um ein chinesisches Sprichwort. Das Buch "The Home Book of Proverbs, Maxims, and Familiar Phrases" zitiert den Autor Barnard, der sagte, er habe den Slogan "als chinesisches Sprichwort betitelt, damit die Leute es ernst nehmen".

Teil 1:
Sekundär Elektronenmikroskopie
(SEM)

4



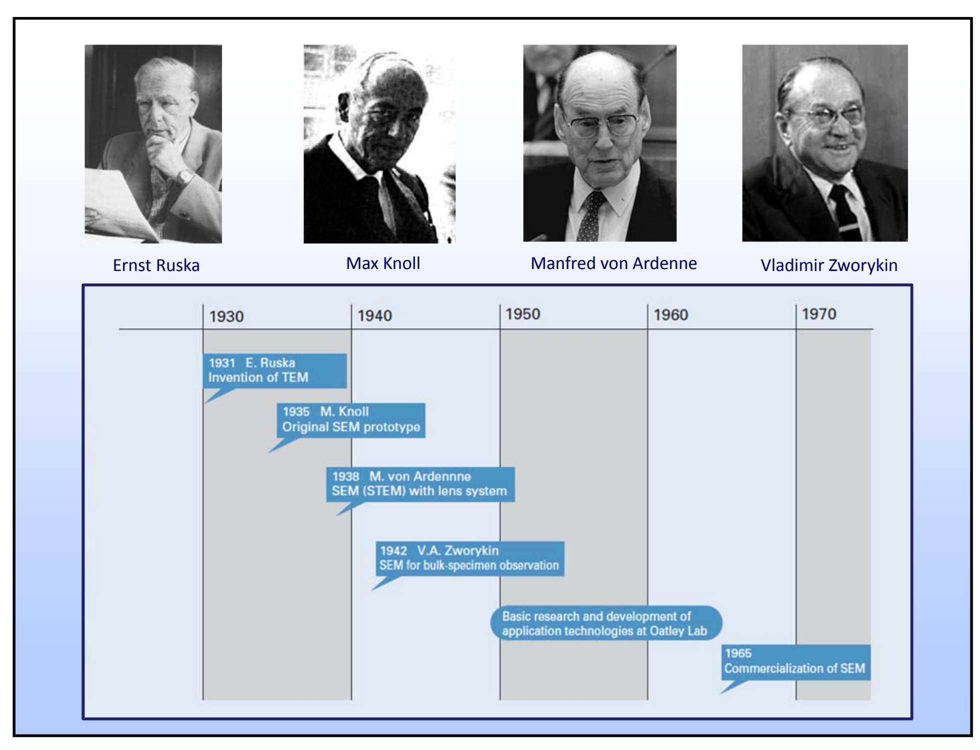
Ernst Karl Abbe
(1840 – 1905)

$$d = \frac{\lambda}{2n\sin\theta}$$

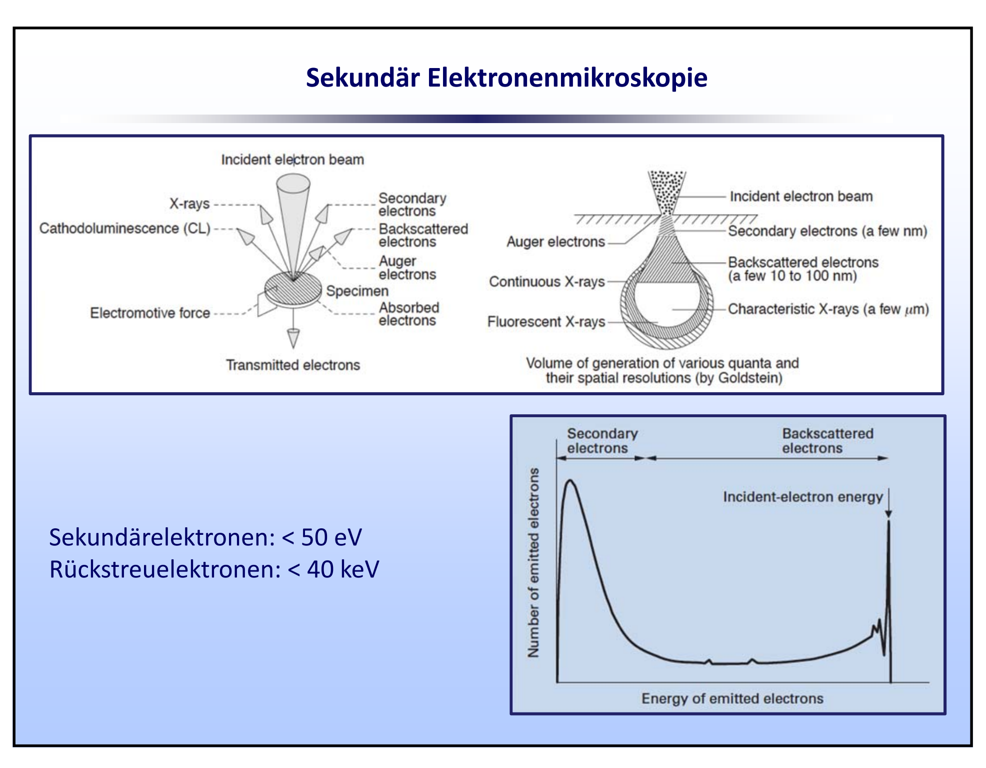
$$\lambda = \frac{1.22}{E^{1/2}}$$

Louis-Victor de Broglie
(1892 – 1987)

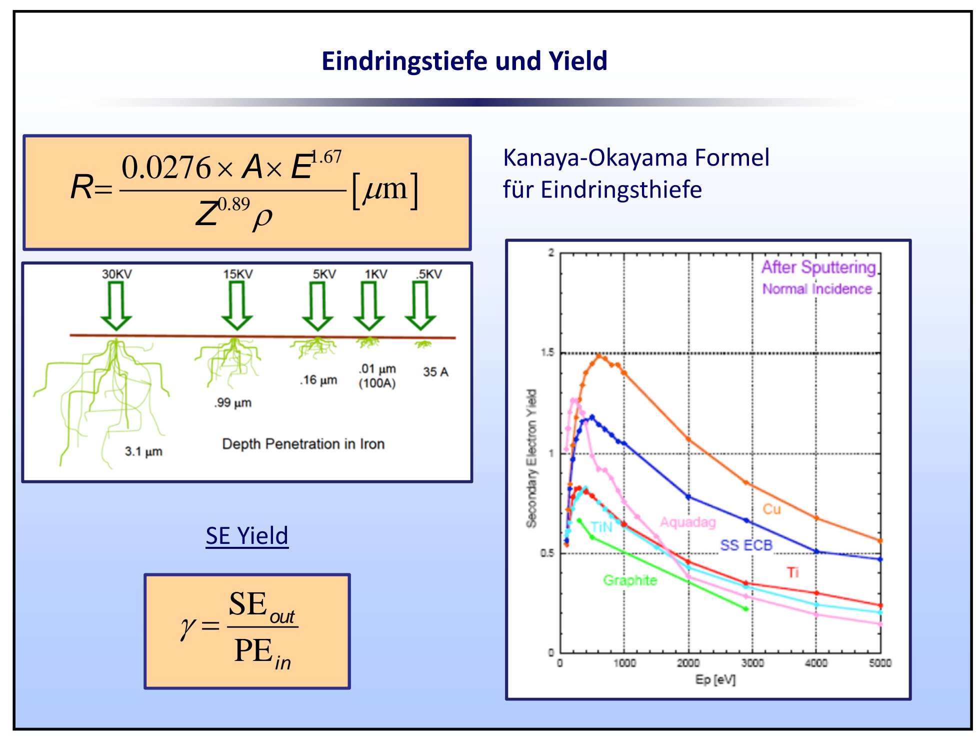
5



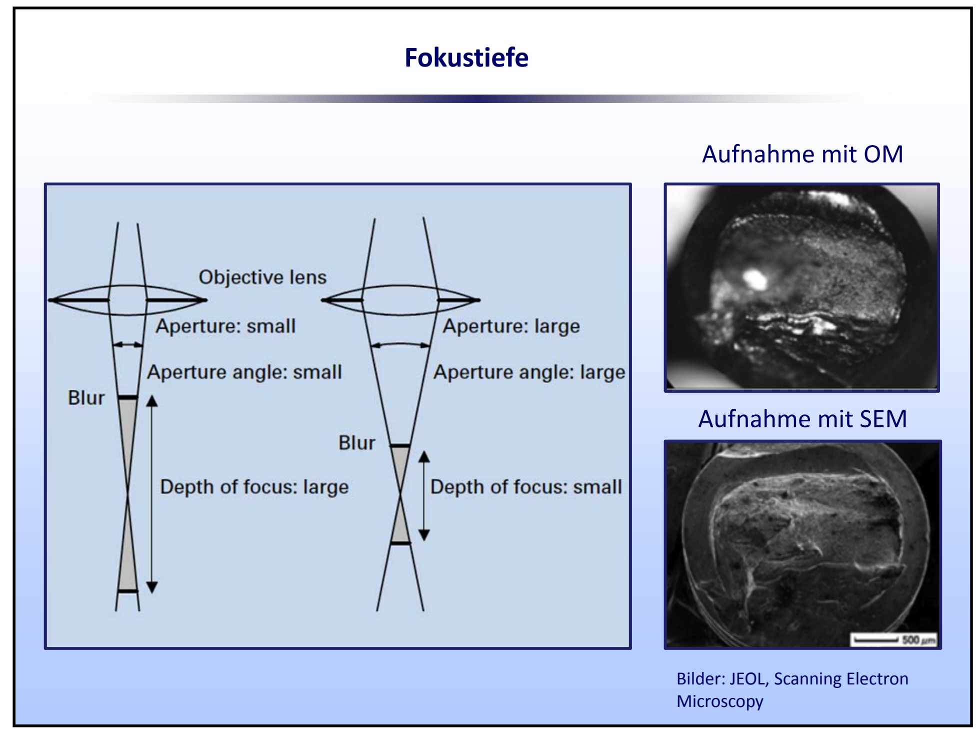
Ernst Ruska
Max Knoll
Manfred von Ardenne
Vladimir Zworykin
1930
1940
1950
1960
1970
1931 E. Ruska
Invention of TEM
1935 M. Knoll
Original SEM prototype
1938 M. von Ardennne
SEM (STEM) with lens system
1942 V.A. Zworykin
SEM for bulk-specimen observation
Basic research and development of
application technologies at Oatley Lab
1965
Commercialization of SEM



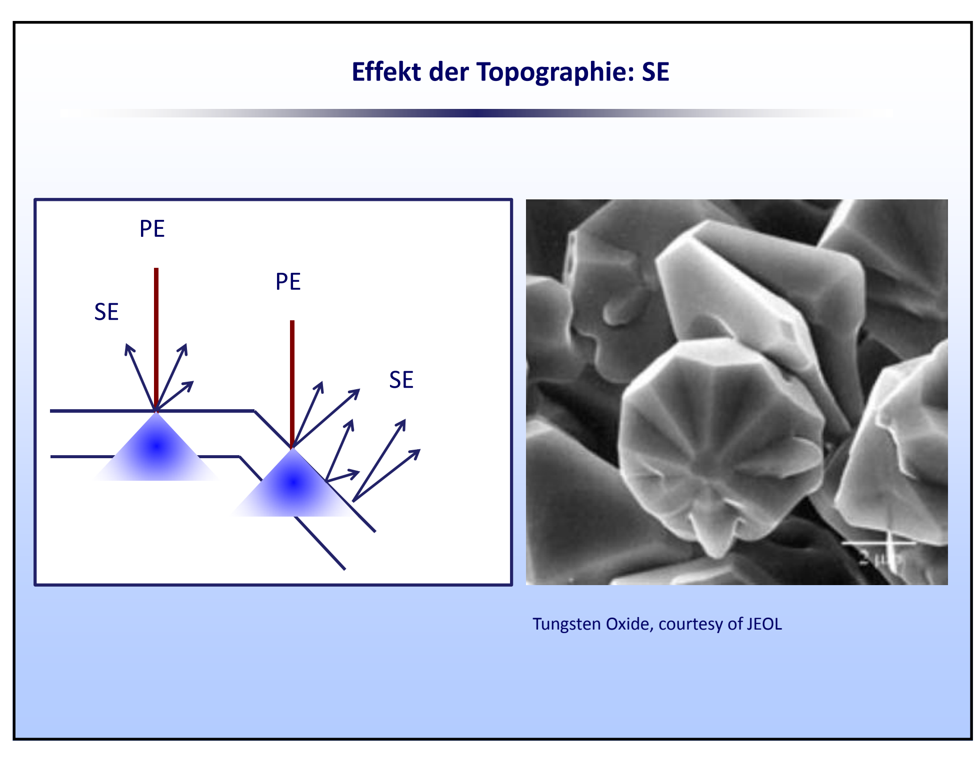
Sekundär Elektronenmikroskopie
Incident electron beam
X-rays
Cathodoluminescence (CL)
Secondary electrons
Backscattered electrons
Auger electrons
Specimen
Electromotive force
Absorbed electrons
Transmitted electrons
Incident electron beam
Auger electrons
Secondary electrons (a few nm)
Backscattered electrons (a few 10 to 100 nm)
Continuous X-rays
Characteristic X-rays (a few μm)
Fluorescent X-rays
Volume of generation of various quanta and their spatial resolutions (by Goldstein)
Sekundärelektronen: < 50 eV
Rückstreuelektronen: < 40 keV
Secondary electrons
Backscattered electrons
Incident-electron energy
Number of emitted electrons
Energy of emitted electrons

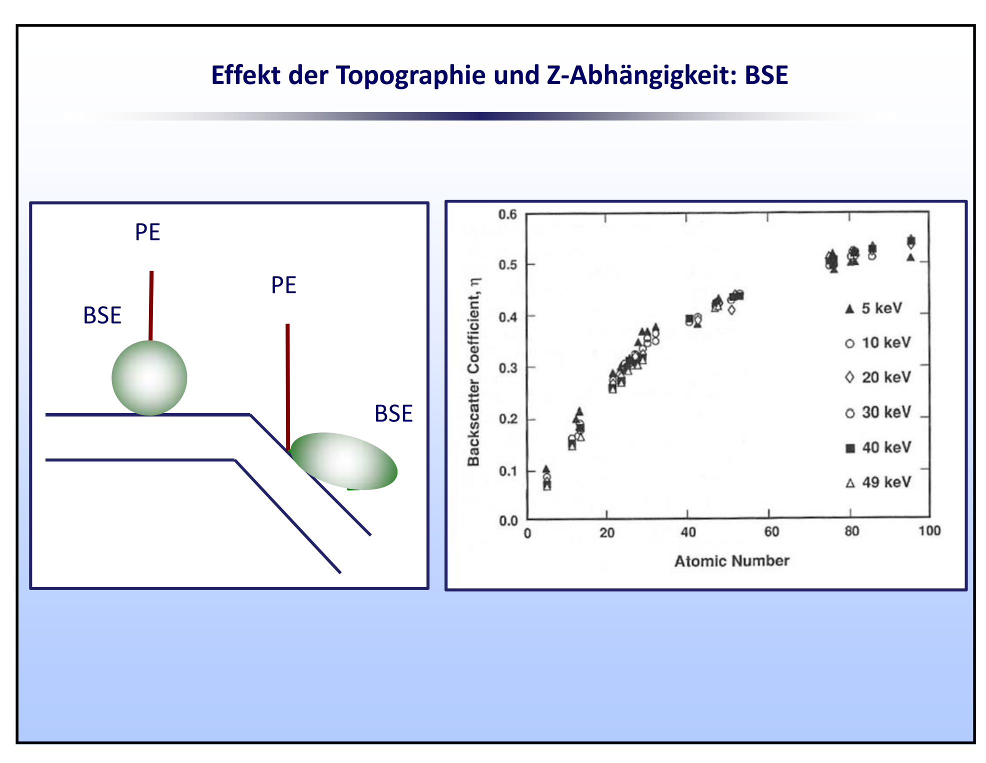


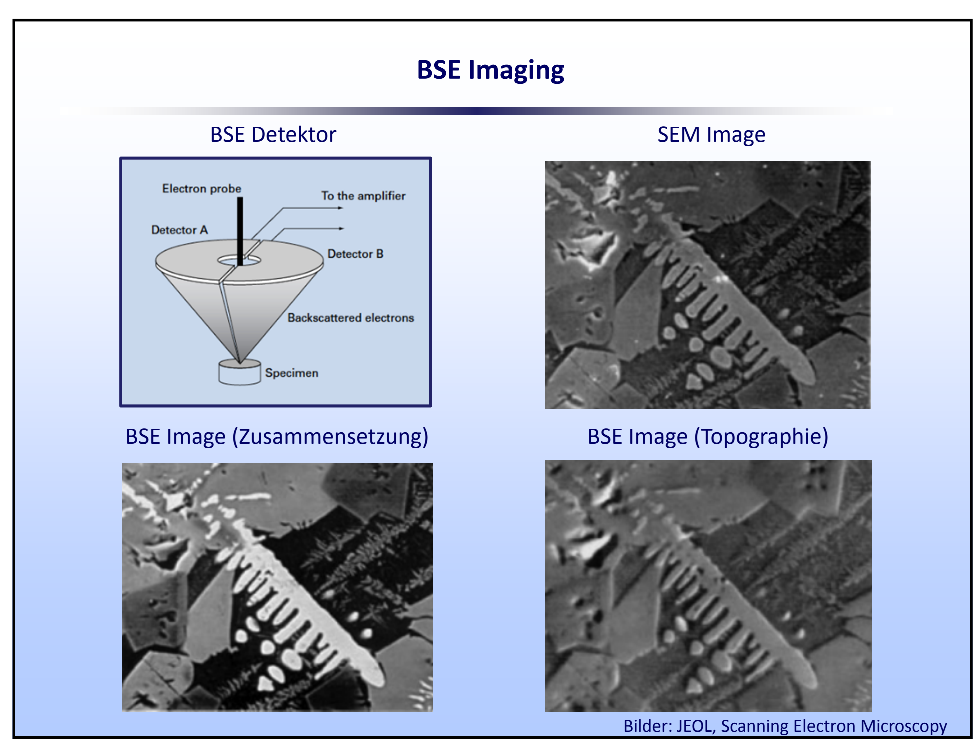
Eindringstiefe und Yield
$R = \frac{0.0276 \times A \times E^{1.67}}{Z^{0.89} \rho} [\mu m]$
Kanaya-Okayama Formel
für Eindringsthiefe
30KV
15KV
5KV
1KV
.5KV
3.1 µm
.99 µm
.16 µm
.01 µm
(100A)
35 A
Depth Penetration in Iron
SE Yield
$\gamma = \frac{SE_{out}}{PE_{in}}$
After Sputtering
Normal Incidence
Secondary Electron Yield
Ep [eV]
Cu
SS ECB
Aquadag
TiN
Ti
Graphite

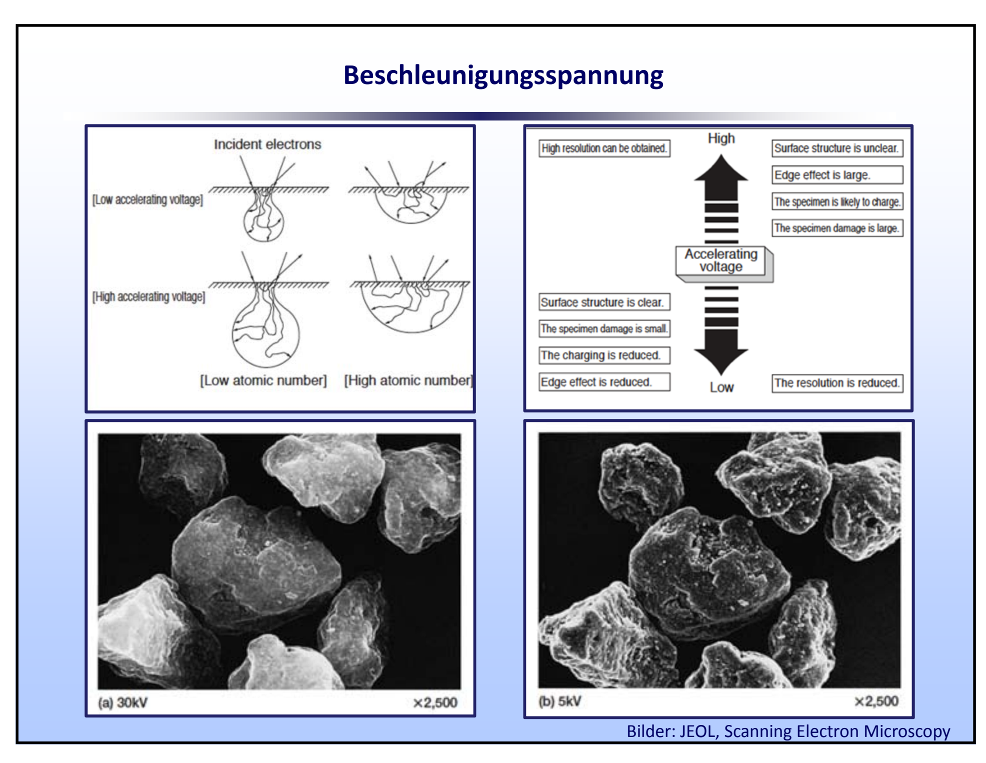


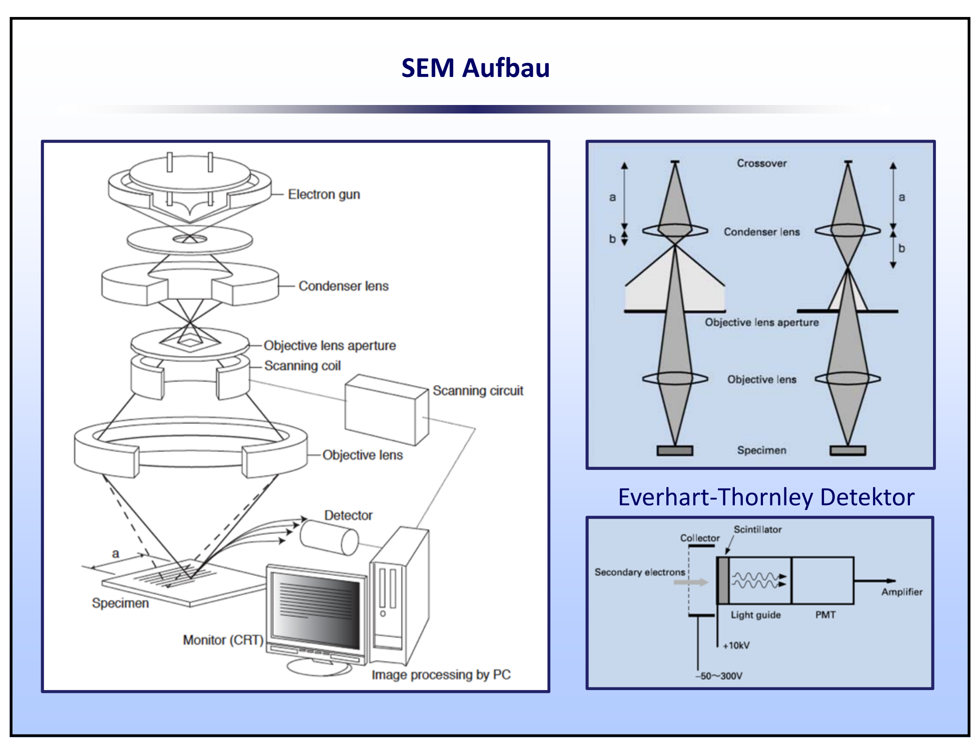
Fokustiefe
Objective lens
Aperture: small
Aperture angle: small
Blur
Depth of focus: large
Aperture: large
Aperture angle: large
Blur
Depth of focus: small
Aufnahme mit OM
Aufnahme mit SEM
Bilder: JEOL, Scanning Electron Microscopy


Effekt der Topographie: SE
PE
SE
PE
SE
Tungsten Oxide, courtesy of JEOL


Effekt der Topographie und Z-Abhängigkeit: BSE
PE
BSE
PE
BSE
Backscatter Coefficient, η
Atomic Number
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
20
40
60
80
100
5 keV
10 keV
20 keV
30 keV
40 keV
49 keV

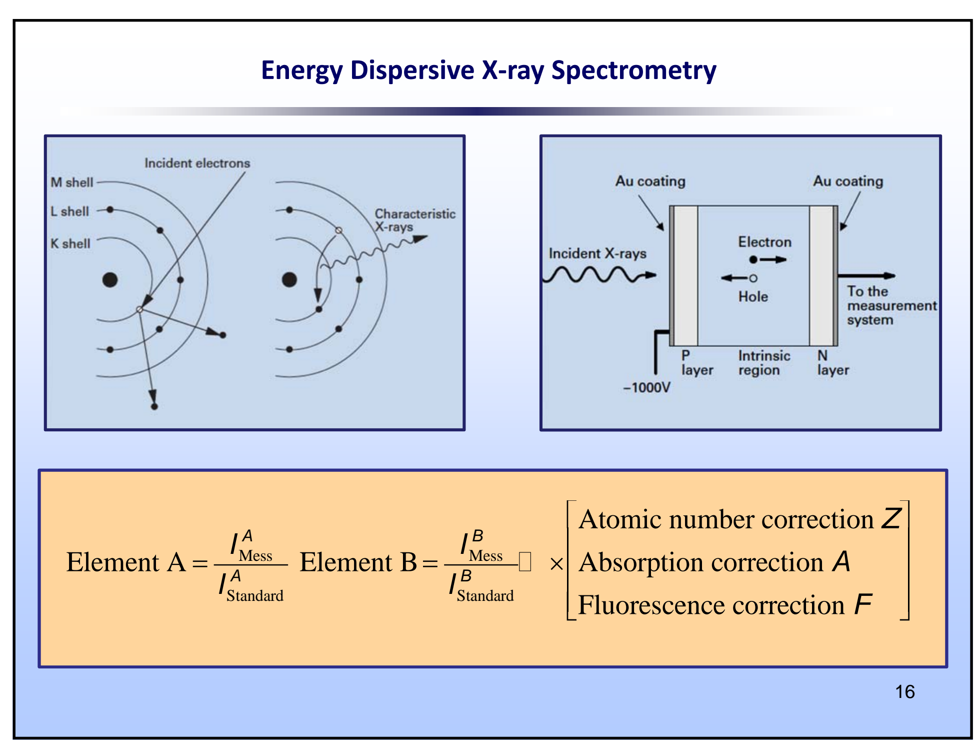

BSE Imaging
BSE Detektor
SEM Image
Electron probe
To the amplifier
Detector A
Detector B
Backscattered electrons
Specimen
BSE Image (Zusammensetzung)
BSE Image (Topographie)
Bilder: JEOL, Scanning Electron Microscopy

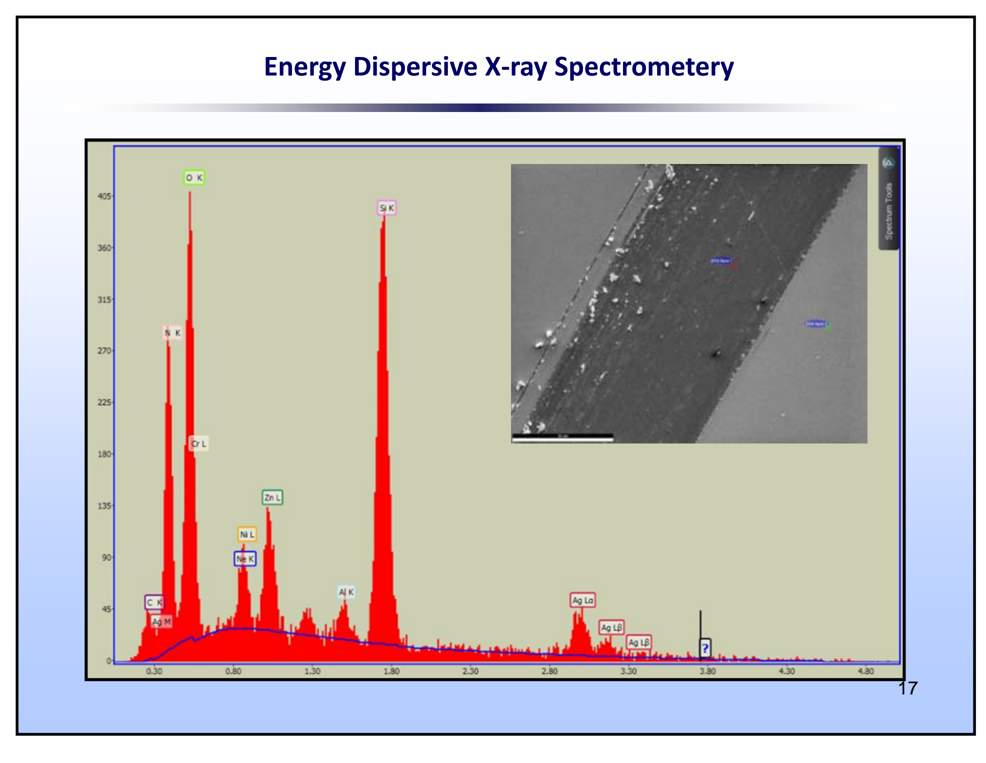

Beschleunigungsspannung
Incident electrons
[Low accelerating voltage]
[High accelerating voltage]
[Low atomic number]
[High atomic number]
High
High resolution can be obtained.
Surface structure is unclear.
Edge effect is large.
The specimen is likely to charge.
The specimen damage is large.
Accelerating voltage
Surface structure is clear.
The specimen damage is small.
The charging is reduced.
Edge effect is reduced.
Low
The resolution is reduced.
(a) 30kV
×2,500
(b) 5kV
×2,500
Bilder: JEOL, Scanning Electron Microscopy

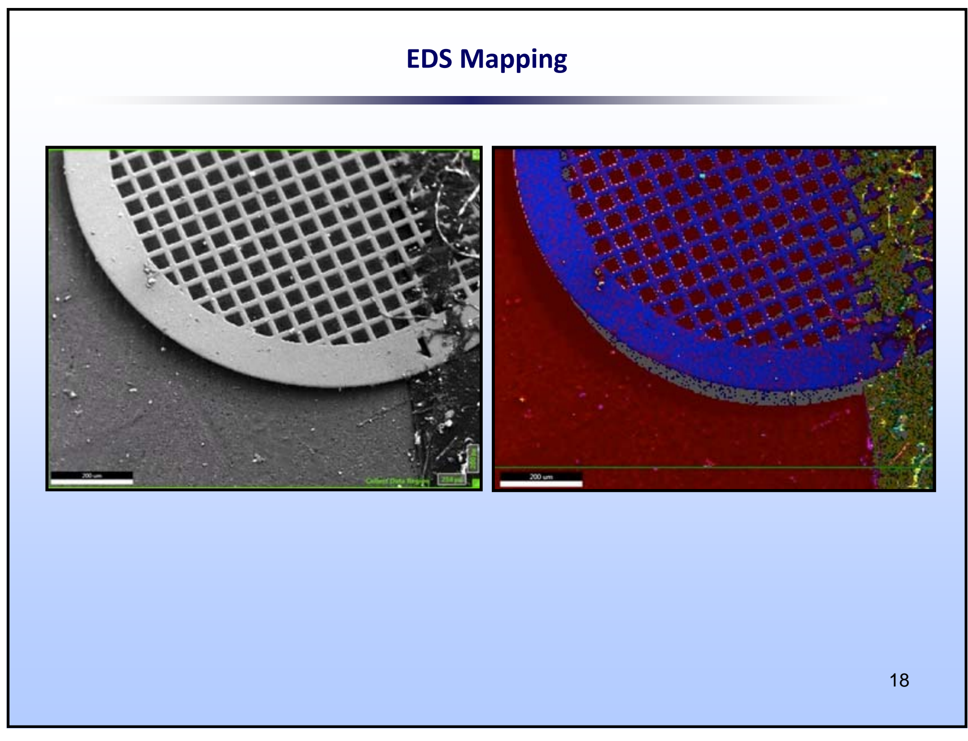


SEM Detektoren

Detector	Major Advantage or Uses
Secondary Electron (SED)	General Imaging
Backscattered Electron (BSE)	Difference in atomic number
Immersion Lens (in-lens)	Surface sensitive
X-Ray (EDS)	Elemental information from small area


Energy Dispersive X-ray Spectrometry
Incident electrons
M shell
L shell
K shell
Characteristic X-rays
Au coating
Au coating
Incident X-rays
Electron
Hole
To the measurement system
P layer
Intrinsic region
N layer
−1000V
Element A = $\frac{I^A_{Mess}}{I^A_{Standard}}$ Element B = $\frac{I^B_{Mess}}{I^B_{Standard}}$ ×
Atomic number correction Z
Absorption correction A
Fluorescence correction F
16


Energy Dispersive X-ray Spectrometery
O K
Si K
17



EDS Zusammenfassung

Stärken

- Schnelle Elementanalyse
- Kombination mit SEM => Mapping
- Spotsize < 1 µm (low kV)

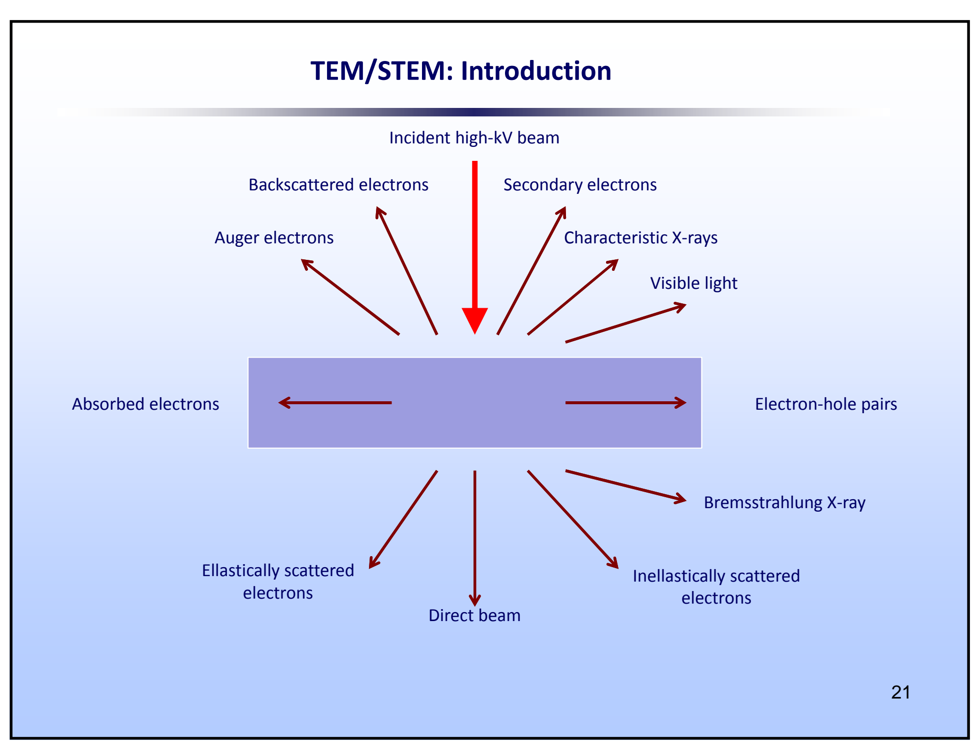
Limitierungen

- Quantifizierung
- Spektrale Interferenz
- Empfindlichkeit (1% - 0.1%), schlechter für kleine Z

=> schnellere Methode für Elementanalyse

19

20



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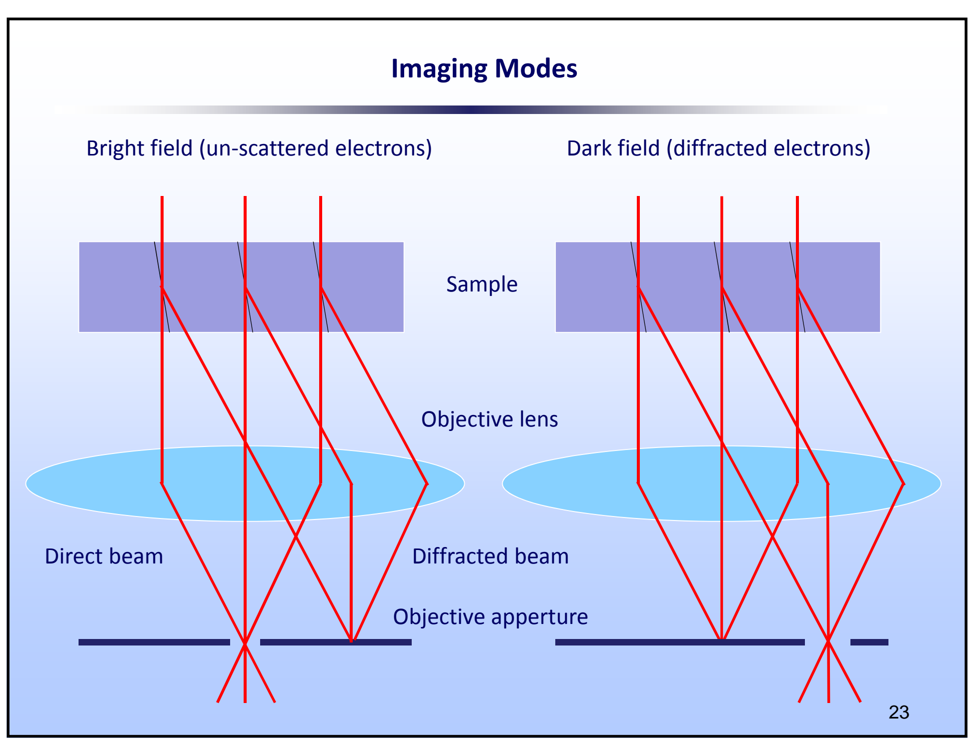
TEM/STEM: Key Anwendungen

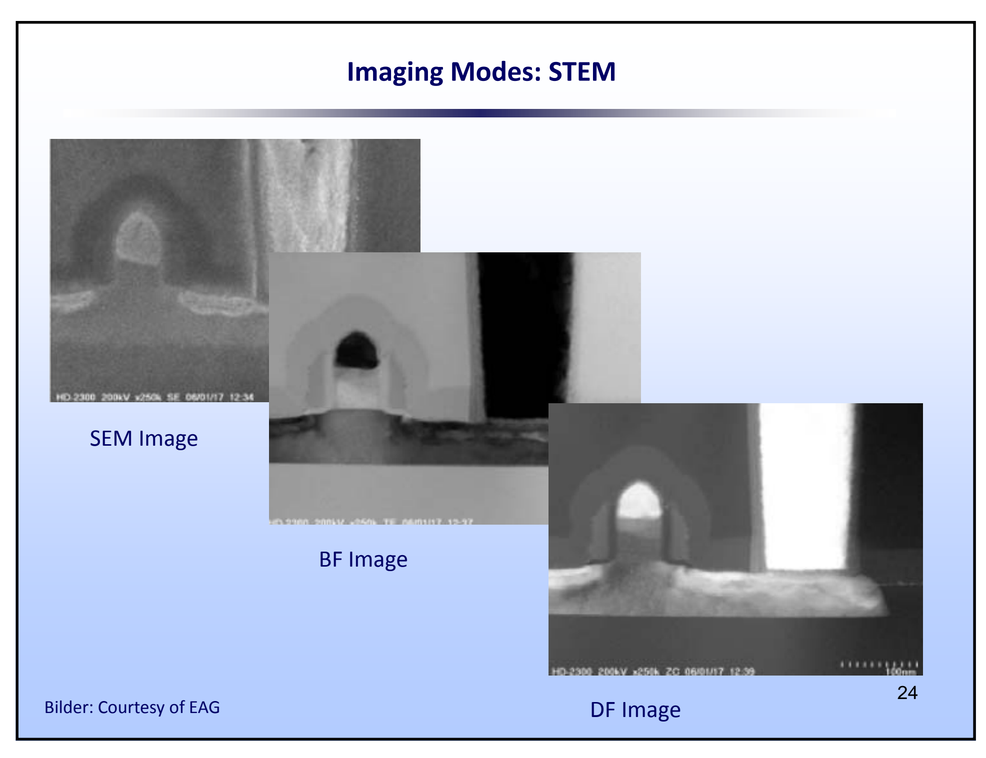
- Dünne Schichten (Dicke, Struktur)
- Failure Analysis
- Reverse Engineering
- Kristallographie (Defekten)
- Nanocluster (Grösser, Struktur)
- Elemental Mapping (EDS, EELS)

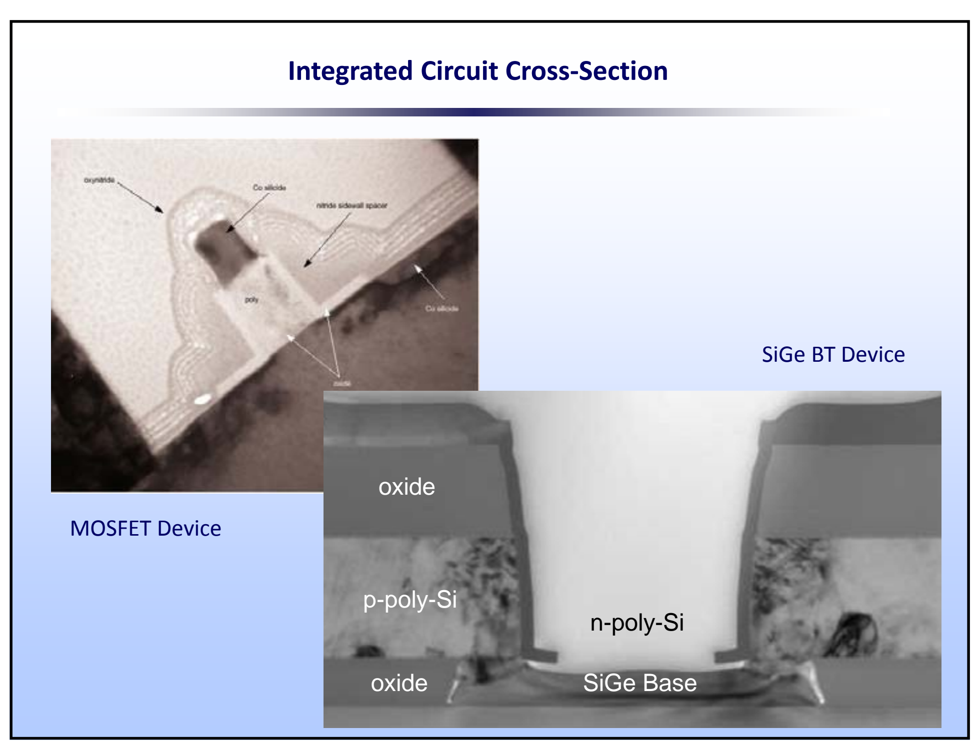
22

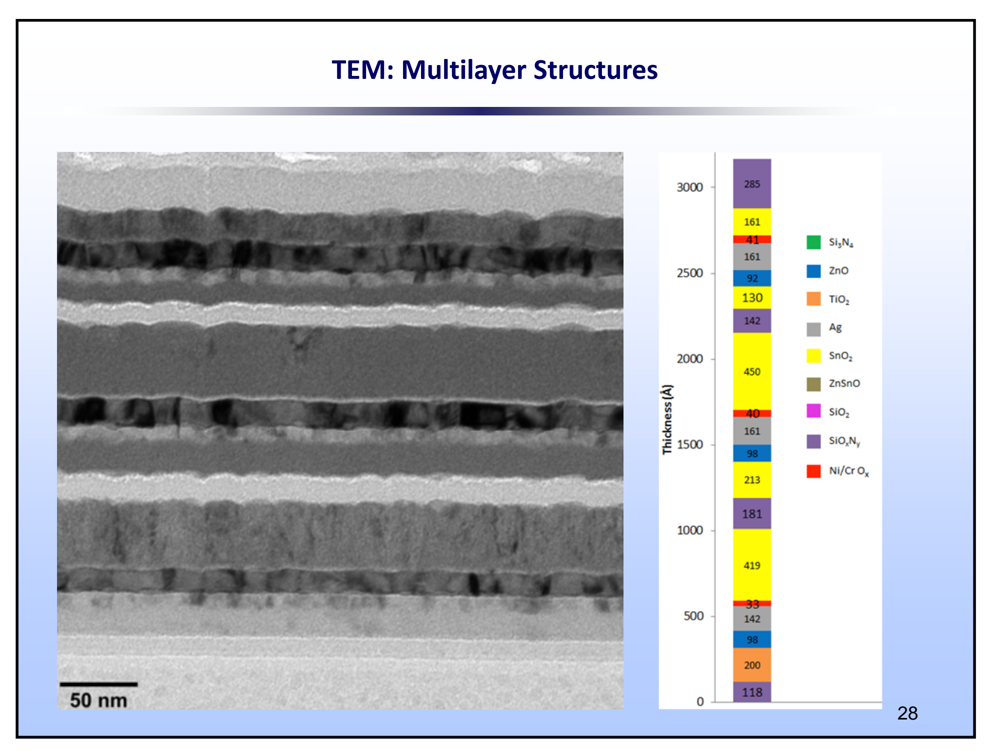
Imaging Modes

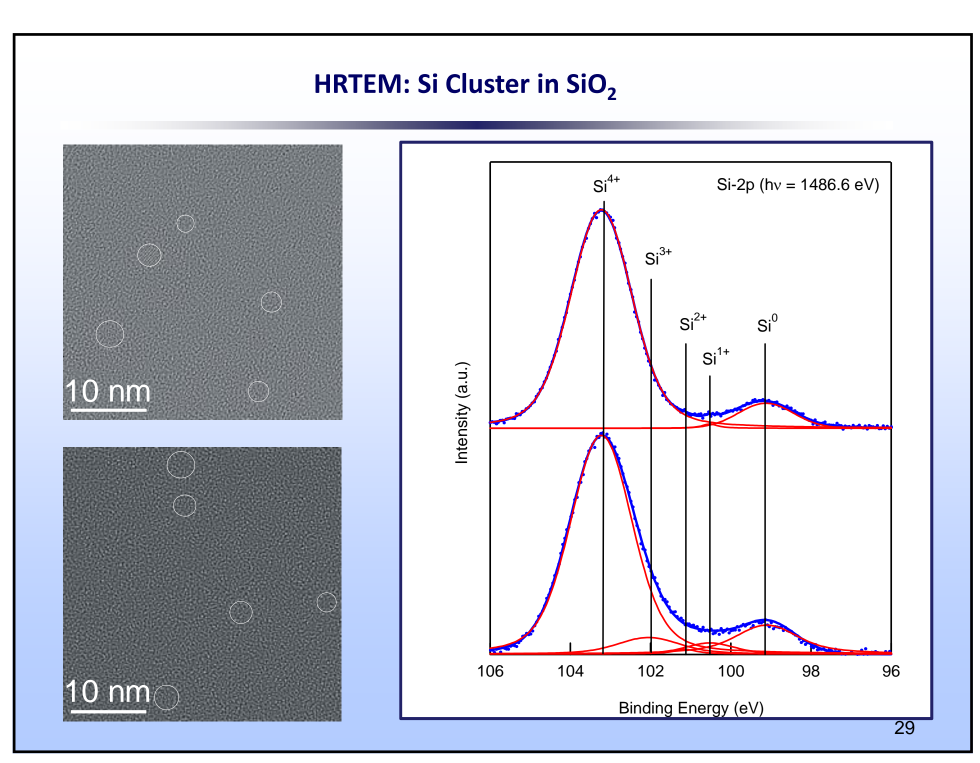


23


Imaging Modes: STEM
SEM Image
BF Image
DF Image
Bilder: Courtesy of EAG
24


Integrated Circuit Cross-Section
MOSFET Device
SiGe BT Device
oxide
p-poly-Si
n-poly-Si
oxide
SiGe Base


TEM: Multilayer Structures
50 nm
Thickness (A)
3000
2500
2000
1500
1000
500
0
285
161
41
161
92
130
142
450
40
161
98
213
181
419
33
142
98
200
118
Si_3N_4
ZnO
TiO_2
Ag
SnO_2
ZnSnO
SiO_2
SiO_xN_y
Ni/Cr O_x
28


HRTEM: Si Cluster in SiO_2
10 nm
10 nm
Si-2p (hν = 1486.6 eV)
Si^{4+}
Si^{3+}
Si^{2+}
Si^{1+}
Si^{0}
Intensity (a.u.)
106
104
102
100
98
96
Binding Energy (eV)
29

Wie mache ich 100 nm dünne Probe?

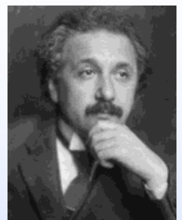
Ganz vorsichtig ...

30

Teil 1:
Photoemissionspektroskopie

Photoemission

Heinrich Hertz 1857 – 1894



Albert Einstein 1879 – 1955

Prozess der Photoemission
1887 – Heinrich Rudolf Hertz
1905 – Albert Einstein

Ultraviolettes Licht und electrische Entladung. 983

XIV. *Ueber einen Einfluss des ultravioletten Lichtes auf die electrische Entladung; von H. Hertz.*

(Hierzu Taf. VII Fig. 8–11.)

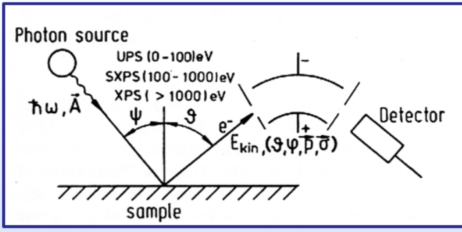
In einer Reihe von Versuchen, welche ich über die Resonanzerscheinungen zwischen sehr schnellen electrischen Schwingungen angestellt und kürzlich veröffentlicht habe[1]), wurden durch dieselbe Entladung eines Inductoriums, also genau gleichzeitig, zwei electrische Funken erregt. Der eine derselben, der Funke A, war der Entladungsfunke des In-

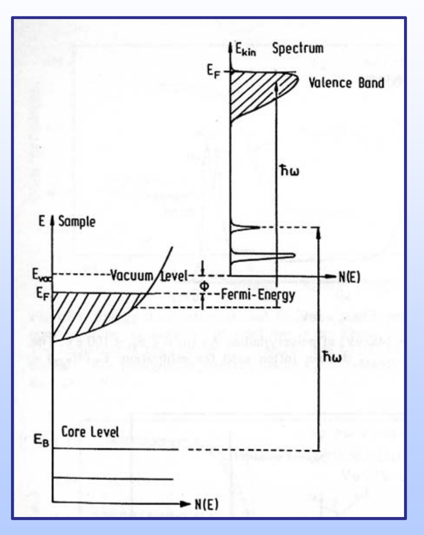
§ 8. Über die Erzeugung von Kathodenstrahlen durch Belichtung fester Körper.

Die übliche Auffassung, daß die Energie des Lichtes kontinuierlich über den durchstrahlten Raum verteilt sei, findet bei dem Versuch, die lichtelektrischen Erscheinungen zu erklären, besonders große Schwierigkeiten, welche in einer bahnbrechenden Arbeit von Hrn. Lenard dargelegt sind.[1])

Nach der Auffassung, daß das erregende Licht aus Energiequanten von der Energie $(R/N)\beta\nu$ bestehe, läßt sich die Erzeugung von Kathodenstrahlen durch Licht folgendermaßen auffassen. In die oberflächliche Schicht des Körpers dringen Energiequanten ein, und deren Energie verwandelt sich wenigstens zum Teil in kinetische Energie von Elektronen. Die einfachste Vorstellung ist die, daß ein Lichtquant seine ganze Energie an ein einziges Elektron abgibt; wir wollen annehmen, daß dies vorkomme. Es soll jedoch nicht ausgeschlossen sein,

Photoemission





$$E_{kin} = \hbar\omega - E_B - \varphi$$
$$E_B = \hbar\omega - E_{kin} - \varphi$$

Koopman's theorem

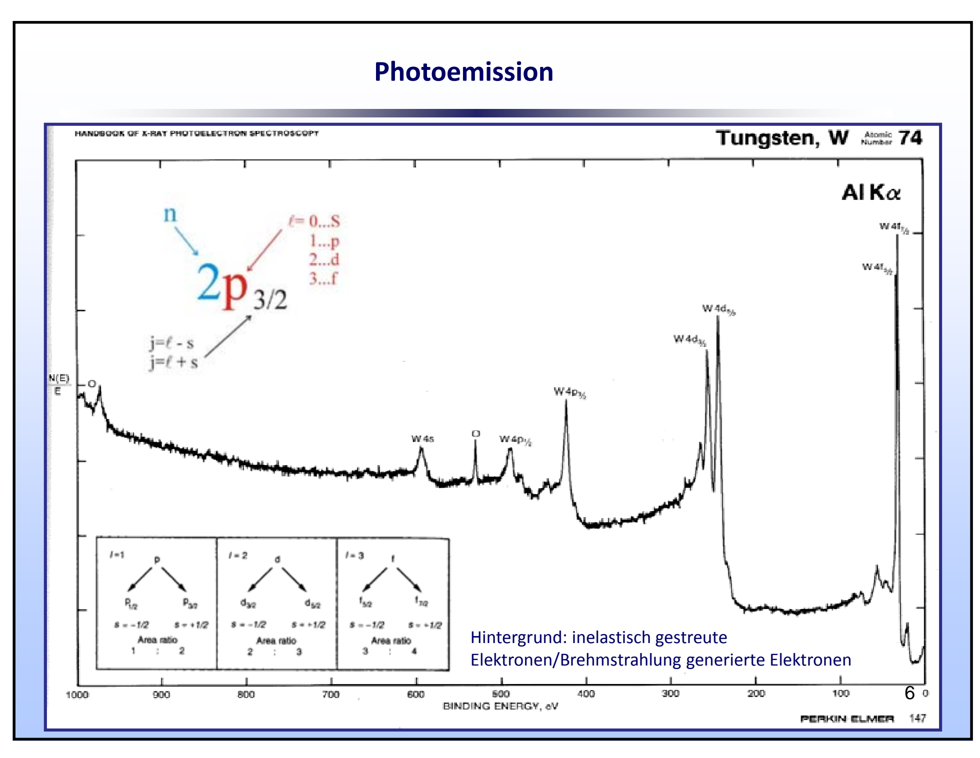
The binding energy of an electron is simply the difference between initial (atom with n electrons) and final state (atom with n-1 electrons and photoelectron)

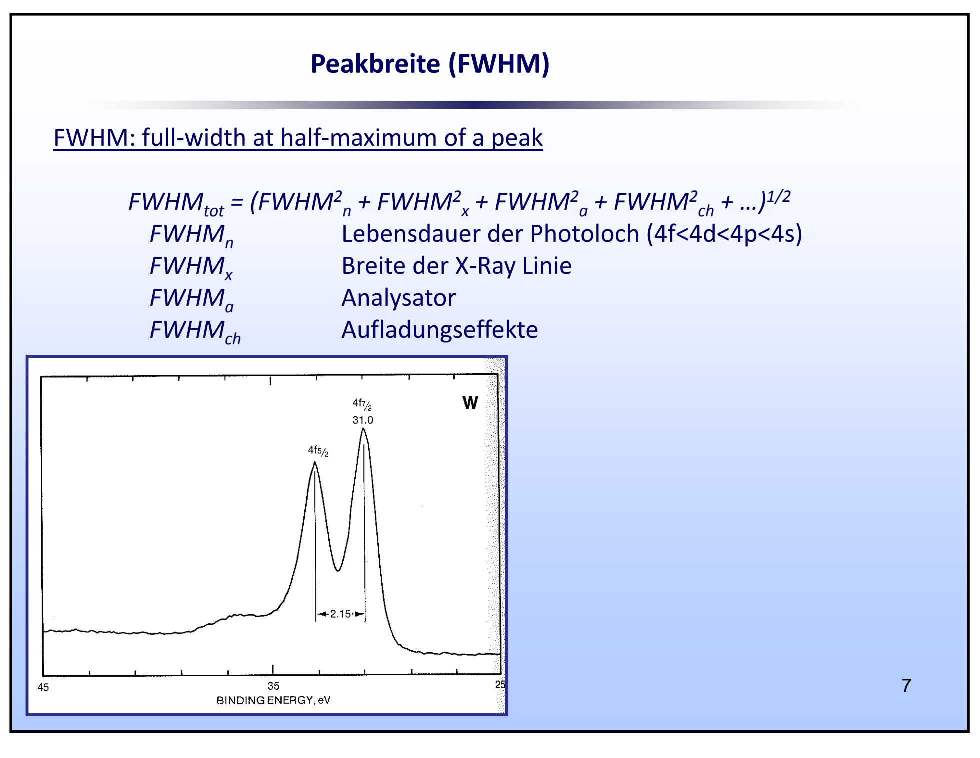
$$E_B = E_{\text{final}}(n-1) - E_{\text{initial}}(n)$$

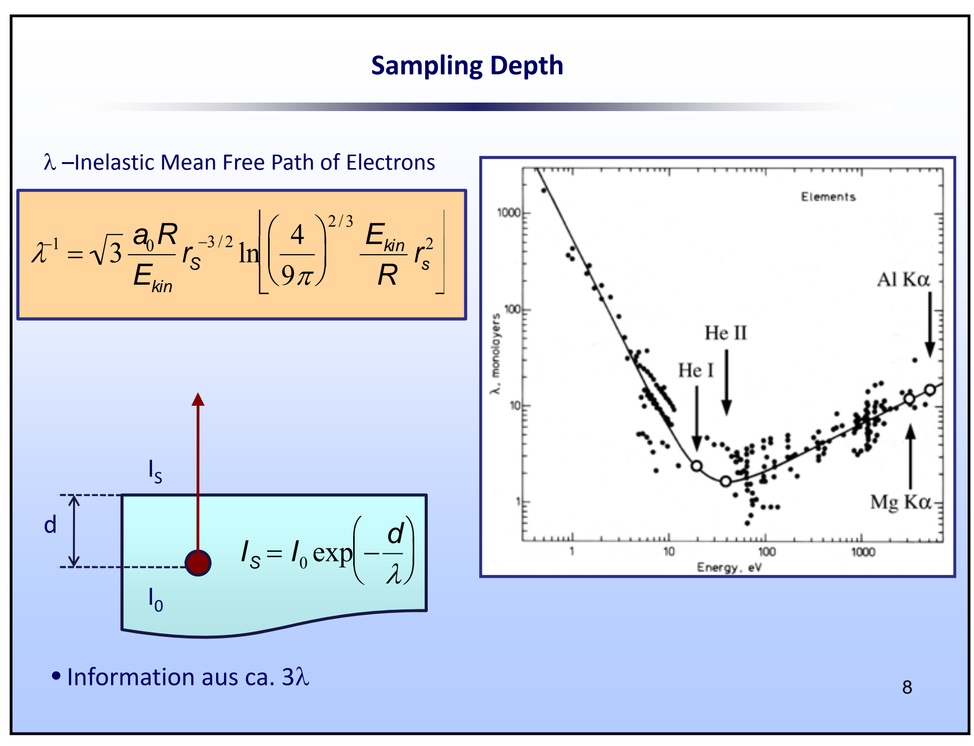
If no relaxation followed photoemission, binding energy = - orbital energy

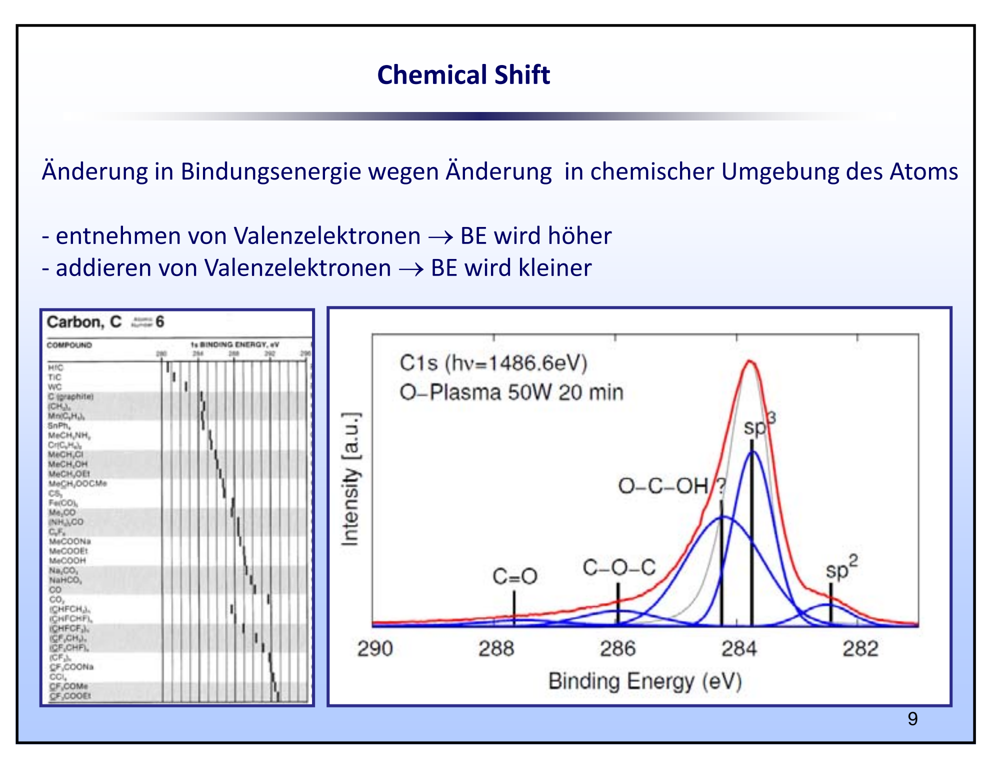
Difference between measurement and calculation due to:

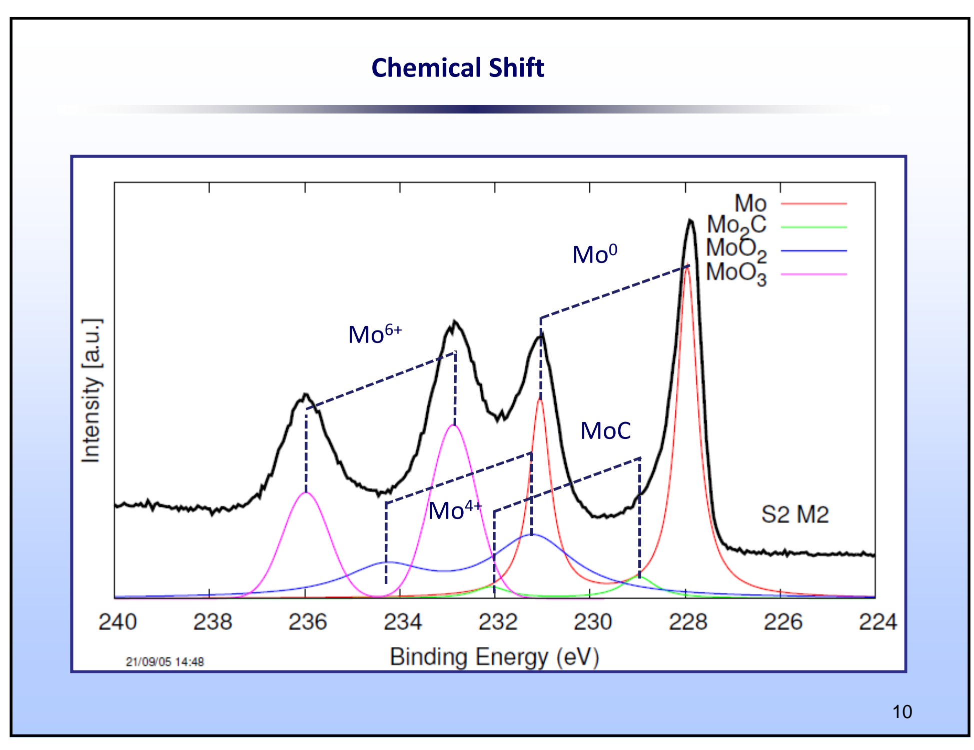
- Electron rearrangement to shield the core hole
- Electron correlation
- Relativistic effects

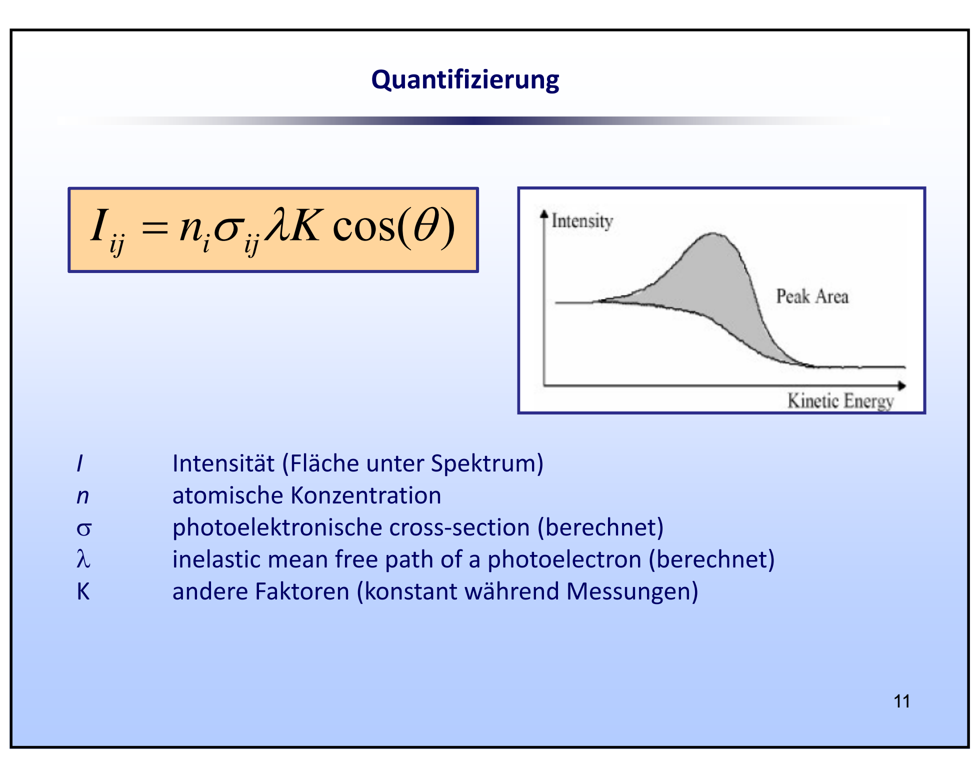

Photoemission
HANDBOOK OF X-RAY PHOTOELECTRON SPECTROSCOPY
Tungsten, W Atomic Number 74
Al Kα
n
2p3/2
ℓ= 0...S
1...p
2...d
3...f
j=ℓ - s
j=ℓ + s
W 4s
W 4p½
W 4p3/2
W 4d5/2
W 4d3/2
W 4f7/2
W 4f5/2
Hintergrund: inelastisch gestreute Elektronen/Brehmstrahlung generierte Elektronen
BINDING ENERGY, eV
PERKIN ELMER
6

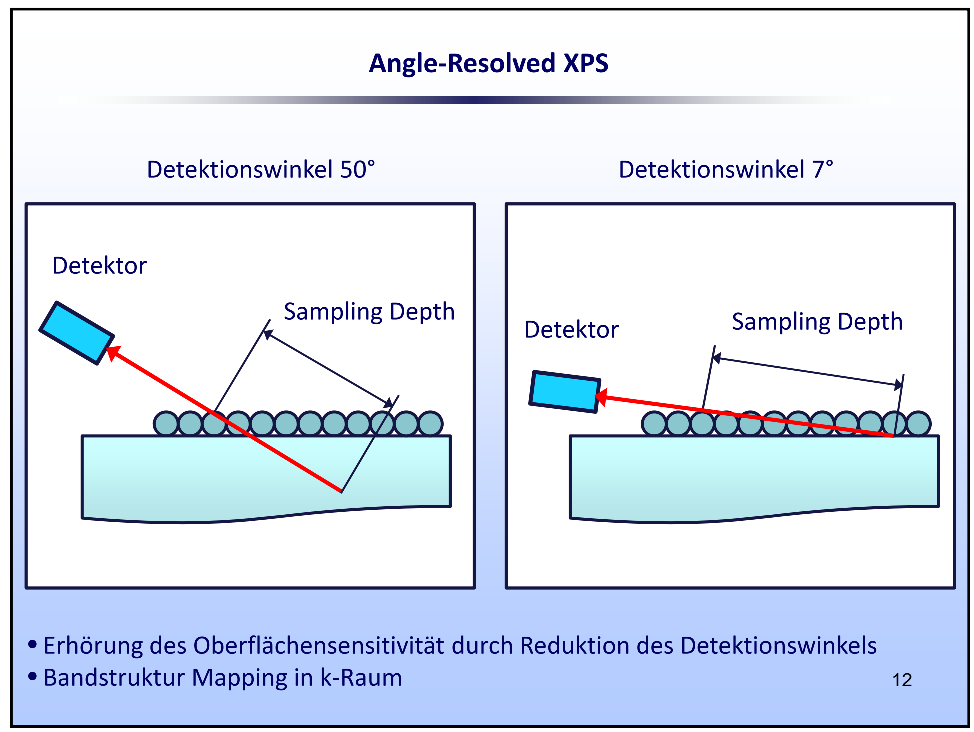

Peakbreite (FWHM)
FWHM: full-width at half-maximum of a peak
FWHMtot = (FWHM²n + FWHM²x + FWHM²a + FWHM²ch + ...)1/2
FWHMn Lebensdauer der Photoloch (4f<4d<4p<4s)
FWHMx Breite der X-Ray Linie
FWHMa Analysator
FWHMch Aufladungseffekte
W
4f7/2
31.0
4f5/2
2.15
BINDING ENERGY, eV
7

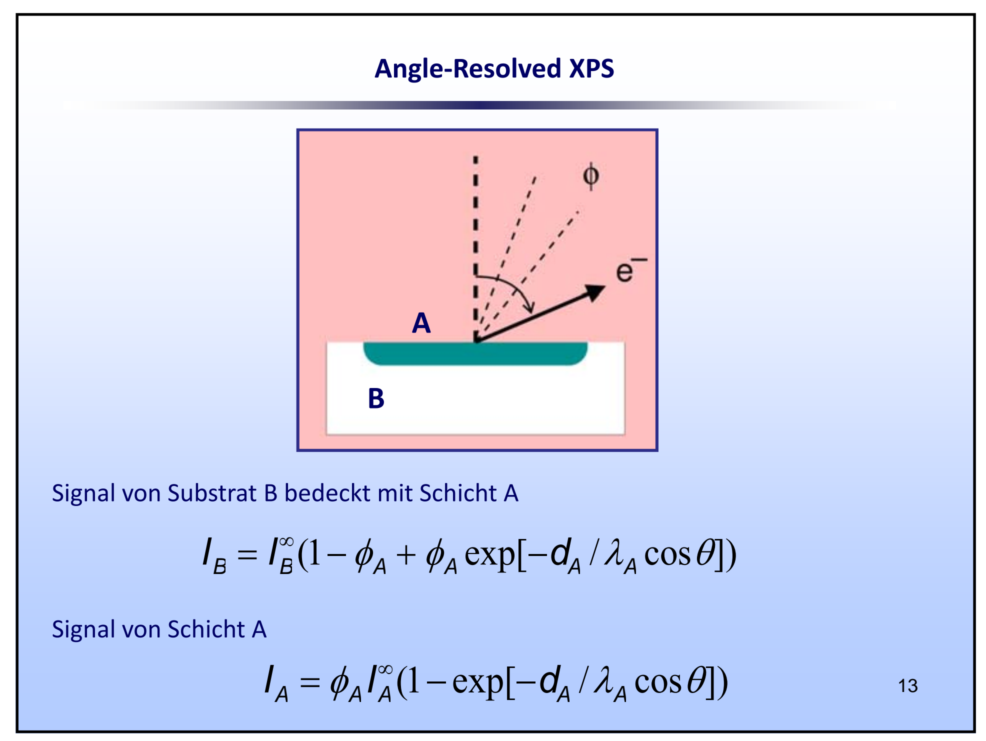

Sampling Depth
λ –Inelastic Mean Free Path of Electrons
$\lambda^{-1} = \sqrt{3}\,\frac{a_0 R}{E_{kin}}\, r_S^{-3/2} \ln\left[\left(\frac{4}{9\pi}\right)^{2/3} \frac{E_{kin}}{R}\, r_s^2\right]$
I_S
d
I_0
$I_S = I_0 \exp\left(-\frac{d}{\lambda}\right)$
• Information aus ca. 3λ
Elements
Al Kα
He II
He I
Mg Kα
λ, monolayers
Energy, eV
8

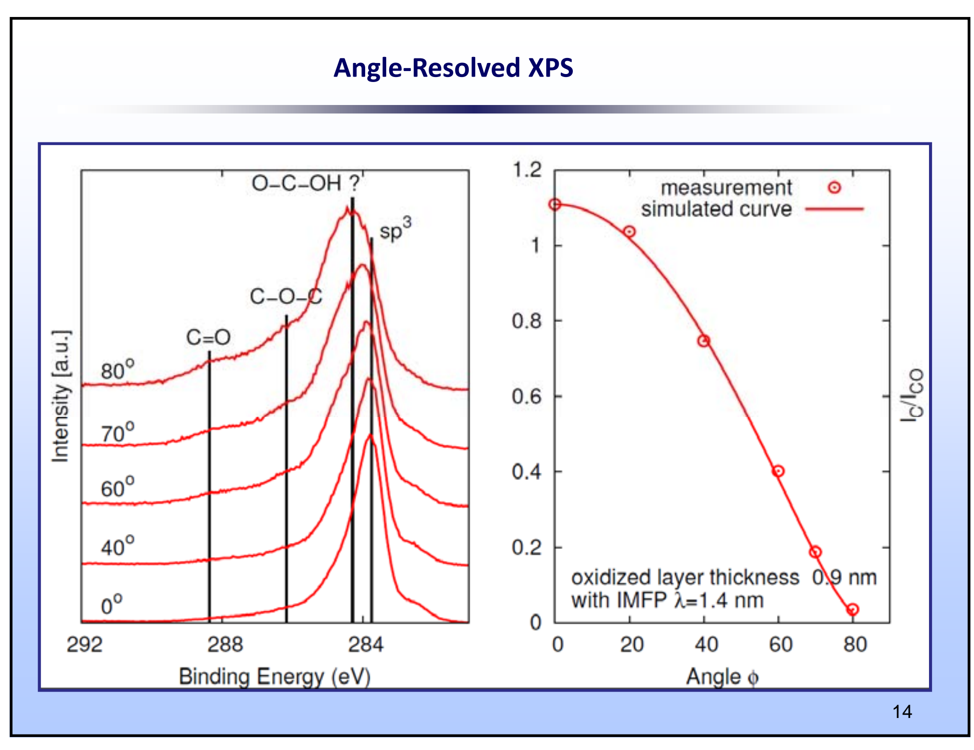

Chemical Shift
Änderung in Bindungsenergie wegen Änderung in chemischer Umgebung des Atoms
- entnehmen von Valenzelektronen → BE wird höher
- addieren von Valenzelektronen → BE wird kleiner
Carbon, C 6
C1s (hν=1486.6eV)
O–Plasma 50W 20 min
Intensity [a.u.]
sp3
O–C–OH ?
C–O–C
C=O
sp2
290
288
286
284
282
Binding Energy (eV)
9

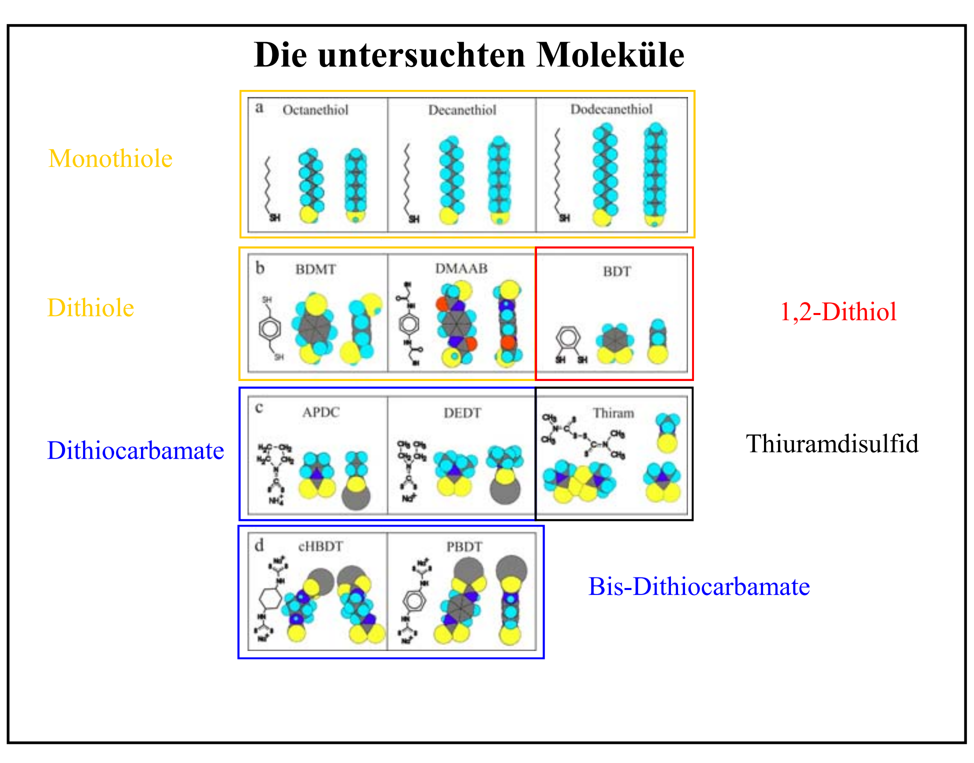

Chemical Shift
Intensity [a.u.]
Binding Energy (eV)
240
238
236
234
232
230
228
226
224
Mo
Mo2C
MoO2
MoO3
Mo0
Mo6+
MoC
Mo4+
S2 M2
21/09/05 14:48
10


Quantifizierung
$I_{ij} = n_i \sigma_{ij} \lambda K \cos(\theta)$
Intensity
Peak Area
Kinetic Energy
I Intensität (Fläche unter Spektrum)
n atomische Konzentration
σ photoelektronische cross-section (berechnet)
λ inelastic mean free path of a photoelectron (berechnet)
K andere Faktoren (konstant während Messungen)
11


Angle-Resolved XPS
Detektionswinkel 50°
Detektionswinkel 7°
Detektor
Sampling Depth
Detektor
Sampling Depth
• Erhörung des Oberflächensensitivität durch Reduktion des Detektionswinkels
• Bandstruktur Mapping in k-Raum
12


Angle-Resolved XPS
ϕ
e⁻
A
B
Signal von Substrat B bedeckt mit Schicht A
$I_B = I_B^\infty(1 - \phi_A + \phi_A \exp[-d_A / \lambda_A \cos\theta])$
Signal von Schicht A
$I_A = \phi_A I_A^\infty(1 - \exp[-d_A / \lambda_A \cos\theta])$
13


Angle-Resolved XPS
O–C–OH ?
sp3
C–O–C
C=O
80°
70°
60°
40°
0°
Intensity [a.u.]
292
288
284
Binding Energy (eV)
measurement
simulated curve
oxidized layer thickness 0.9 nm
with IMFP λ=1.4 nm
1.2
1
0.8
0.6
0.4
0.2
0
20
40
60
80
Angle ϕ
IC/ICO
14


Die untersuchten Moleküle
Monothiole
Octanethiol
Decanethiol
Dodecanethiol
Dithiole
BDMT
DMAAB
BDT
1,2-Dithiol
Dithiocarbamate
APDC
DEDT
Thiram
Thiuramdisulfid
cHBDT
PBDT
Bis-Dithiocarbamate

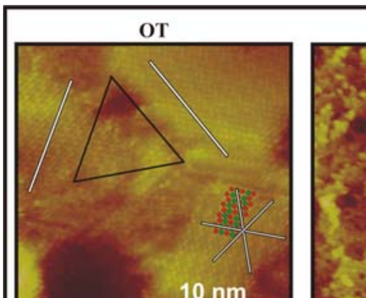
STM 2D Self-assembled Monolayer

- etch pits
- domain boundaries
- $(\sqrt{3}\times\sqrt{3})R30°$
- 0.5 nm dot distance

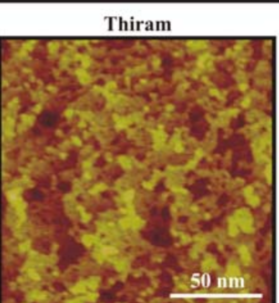
- jagged step edges
- no molecular resolution

- etch pits
- chiral domains
- $(2\sqrt{3}\times2\sqrt{3})R30°$
- 0.96 nm dot distance

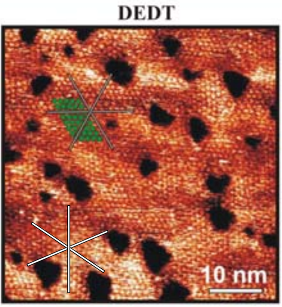
OT



Thiram



DEDT



1 Schwefel/Punkt **6 Schwefel/Punkt**

Untersuchung der Chemisorption

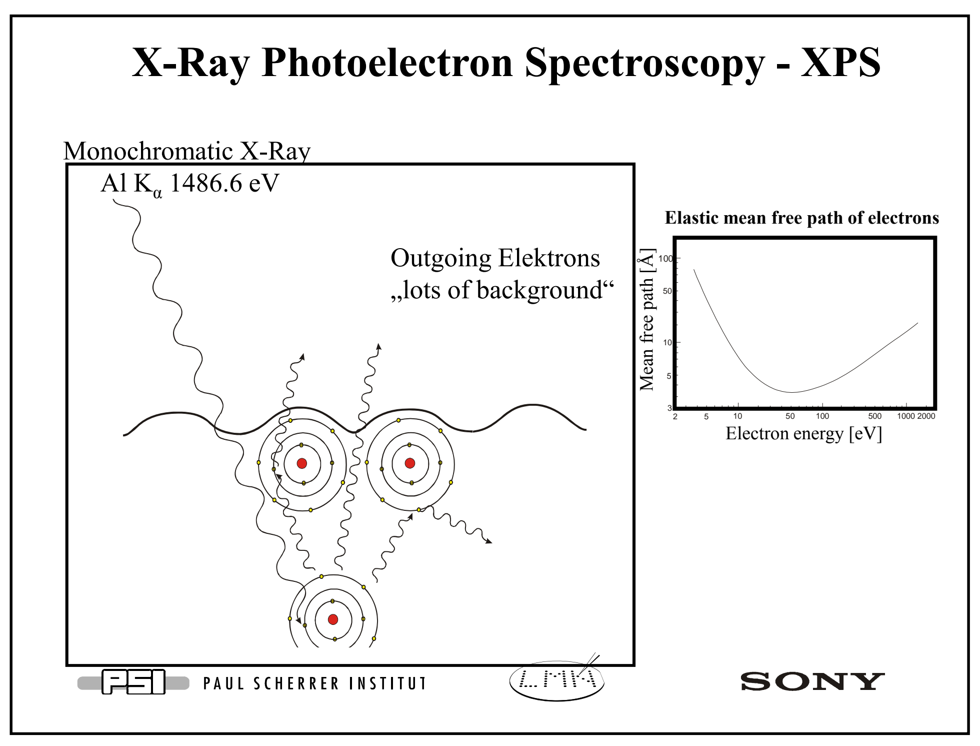
XPS - ESCA

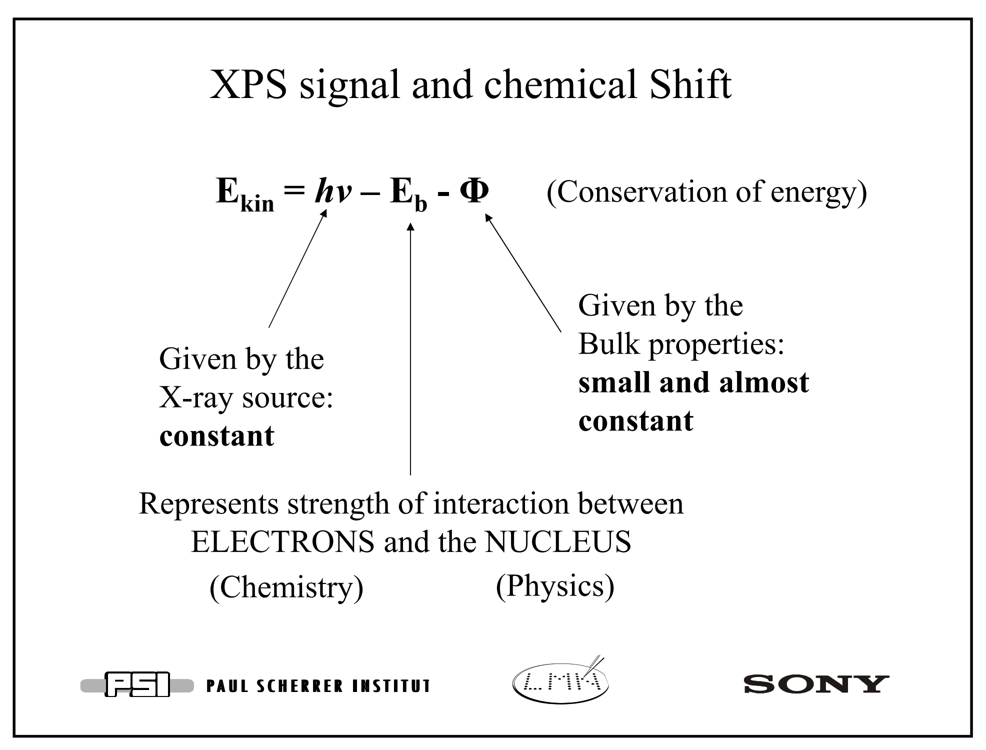
x-Ray photoelectron spectroscopy

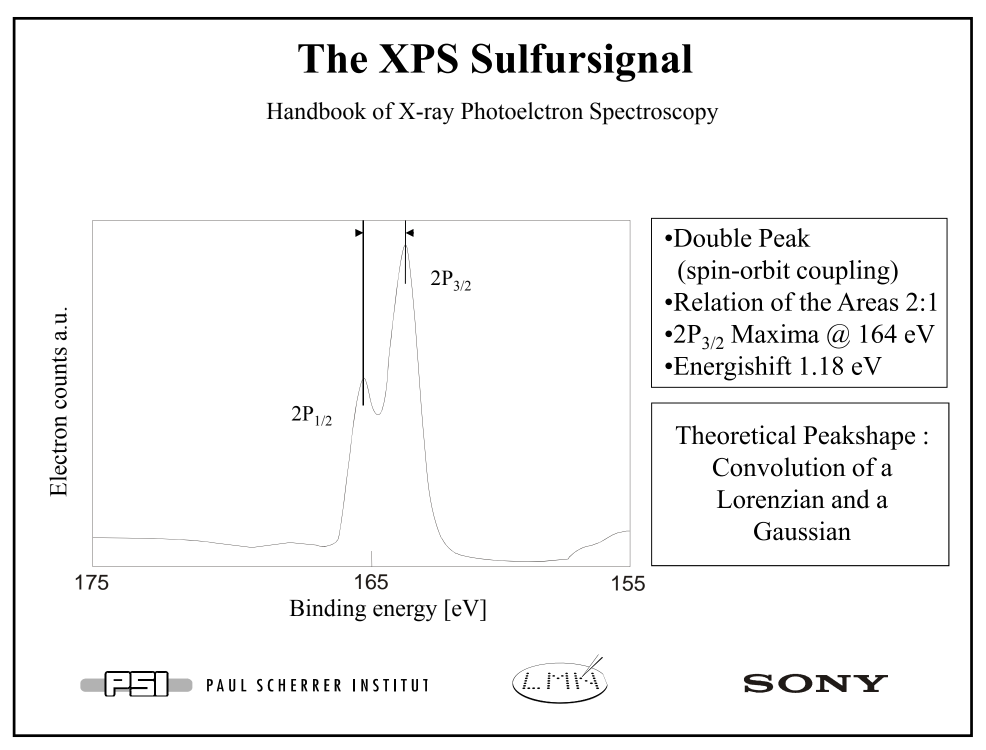
Electron spectroscopy for chemical analysis

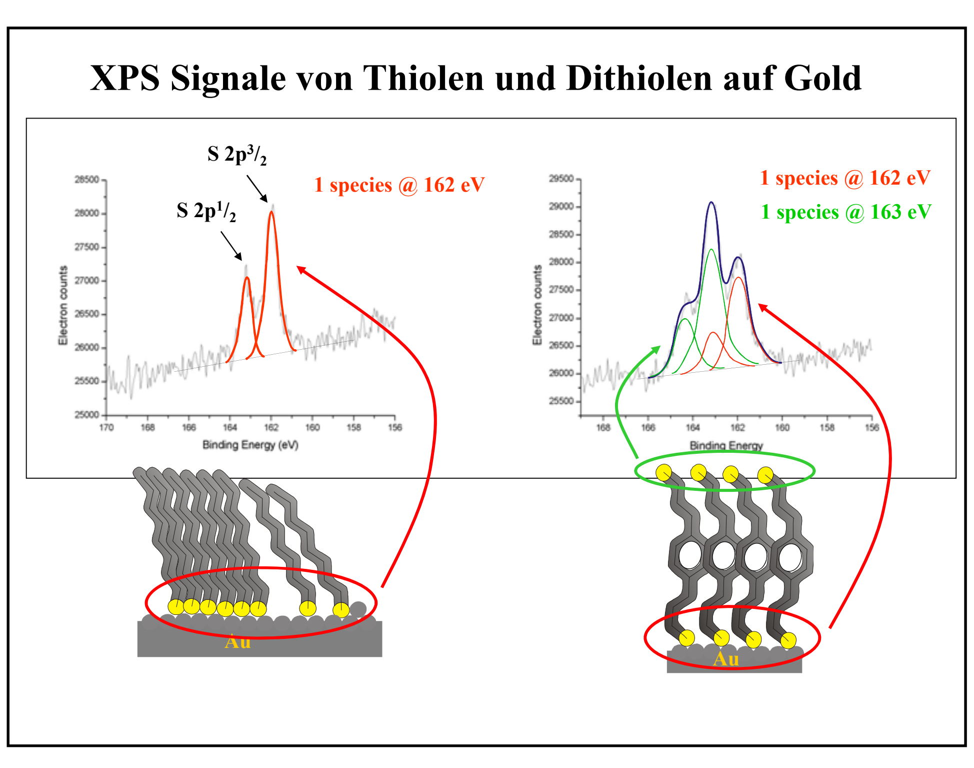
CV

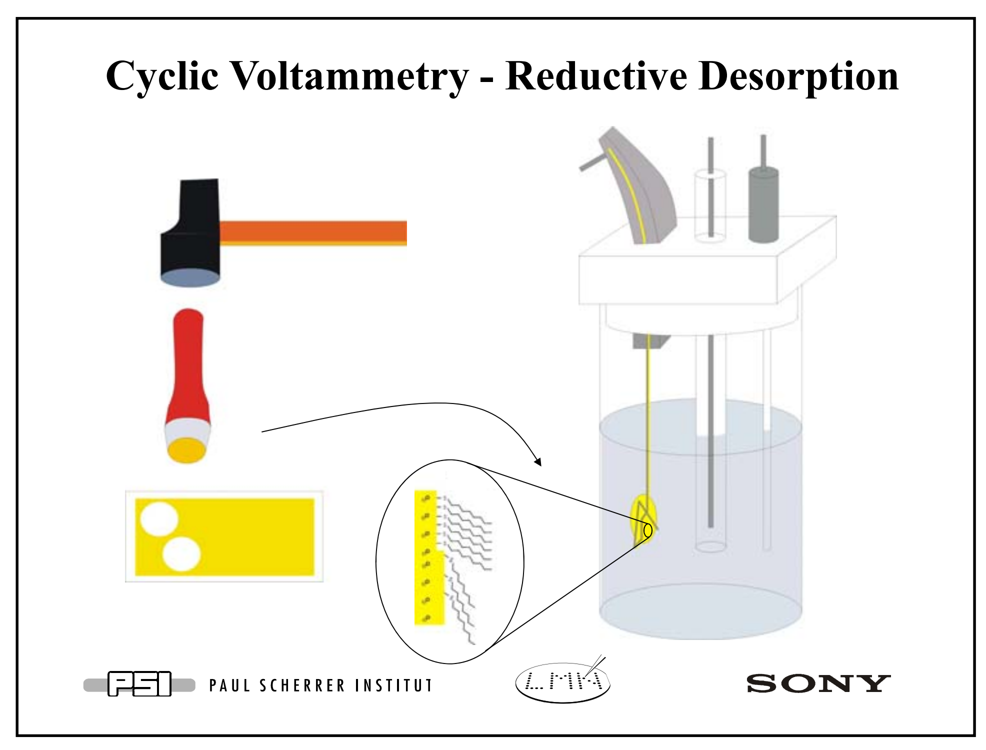
Cyclic voltammetry

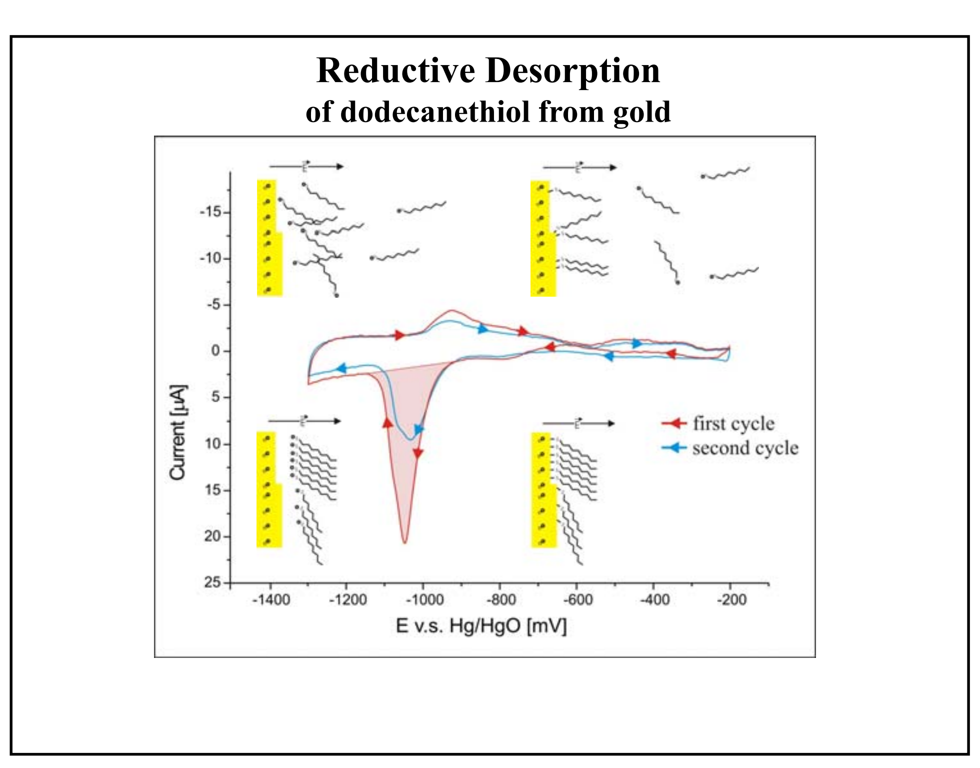

X-Ray Photoelectron Spectroscopy - XPS
Monochromatic X-Ray
Al Kα 1486.6 eV
Outgoing Elektrons
„lots of background“
Elastic mean free path of electrons
Mean free path [Å]
Electron energy [eV]
PAUL SCHERRER INSTITUT
SONY

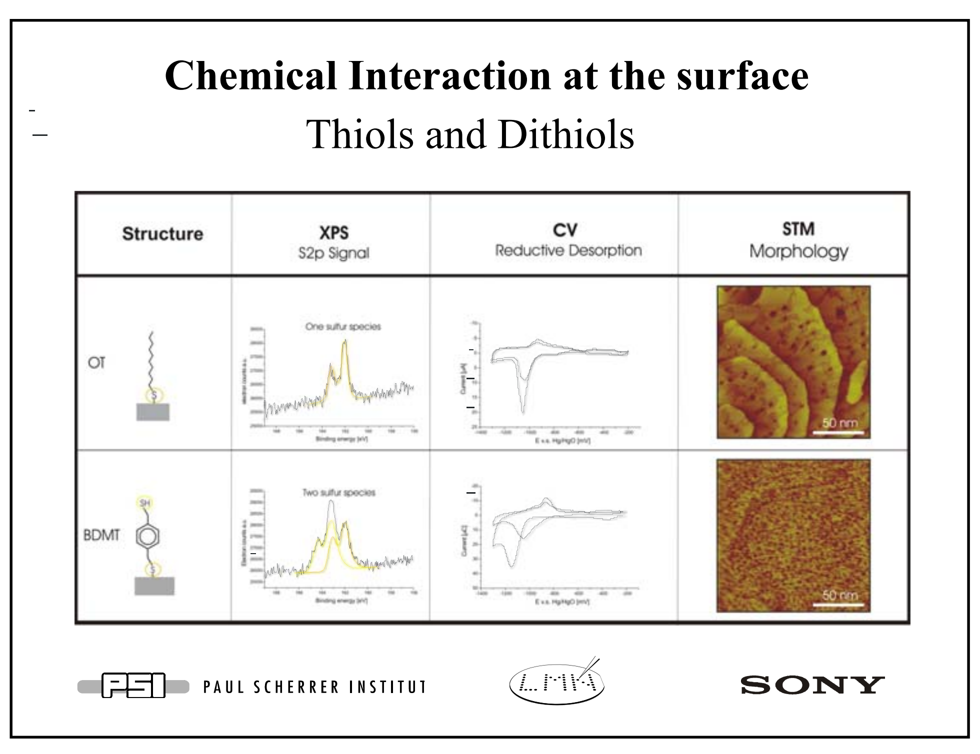

XPS signal and chemical Shift
E_kin = hv – E_b - Φ
(Conservation of energy)
Given by the
X-ray source:
constant
Given by the
Bulk properties:
small and almost
constant
Represents strength of interaction between
ELECTRONS and the NUCLEUS
(Chemistry)
(Physics)
PAUL SCHERRER INSTITUT
SONY

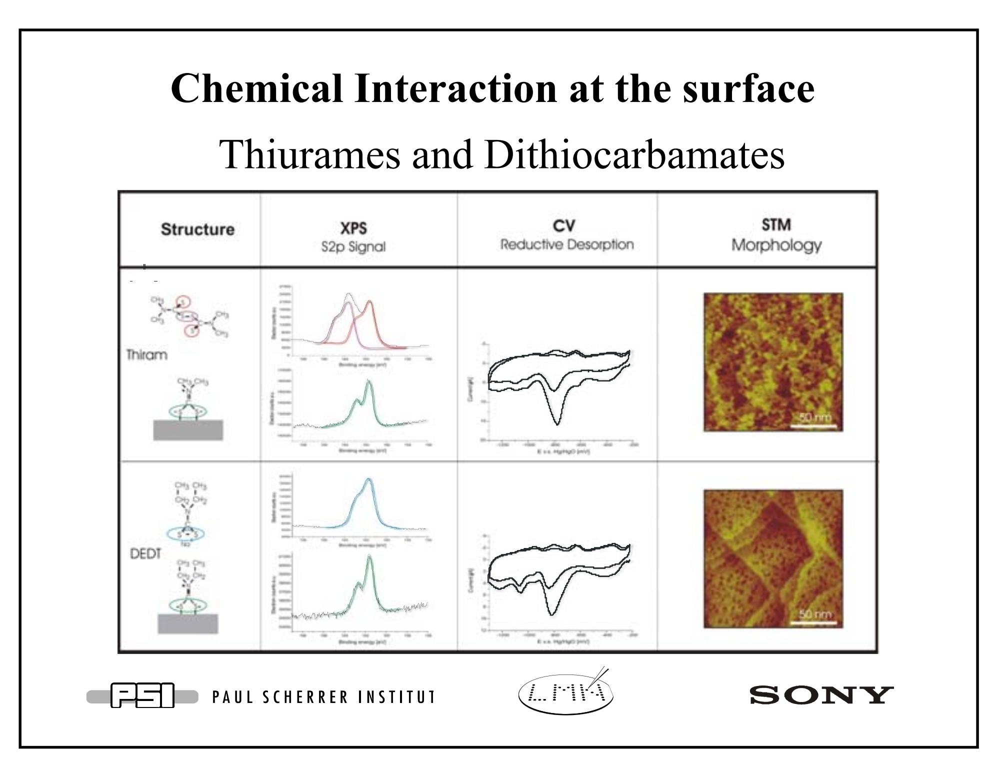

The XPS Sulfursignal
Handbook of X-ray Photoelctron Spectroscopy
Electron counts a.u.
2P3/2
2P1/2
175
165
155
Binding energy [eV]
•Double Peak
(spin-orbit coupling)
•Relation of the Areas 2:1
•2P3/2 Maxima @ 164 eV
•Energishift 1.18 eV
Theoretical Peakshape :
Convolution of a
Lorenzian and a
Gaussian
PAUL SCHERRER INSTITUT
SONY

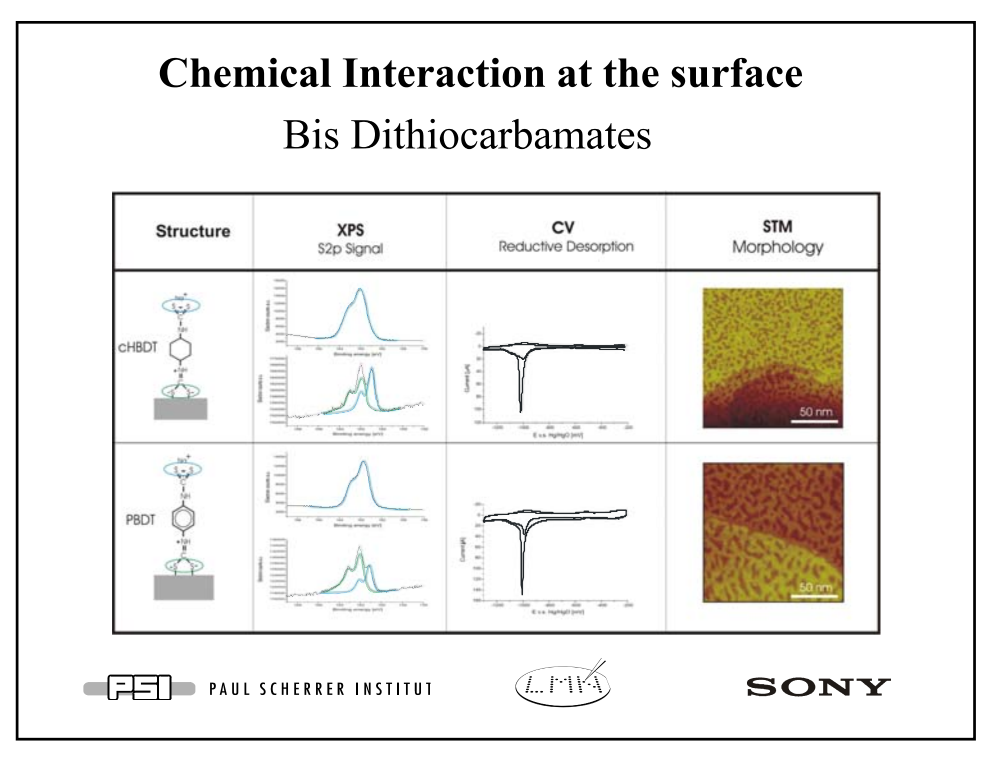

XPS Signale von Thiolen und Dithiolen auf Gold
S 2p3/2
S 2p1/2
1 species @ 162 eV
Electron counts
Binding Energy (eV)
1 species @ 162 eV
1 species @ 163 eV
Binding Energy
Au
Au


Cyclic Voltammetry - Reductive Desorption
PAUL SCHERRER INSTITUT
SONY

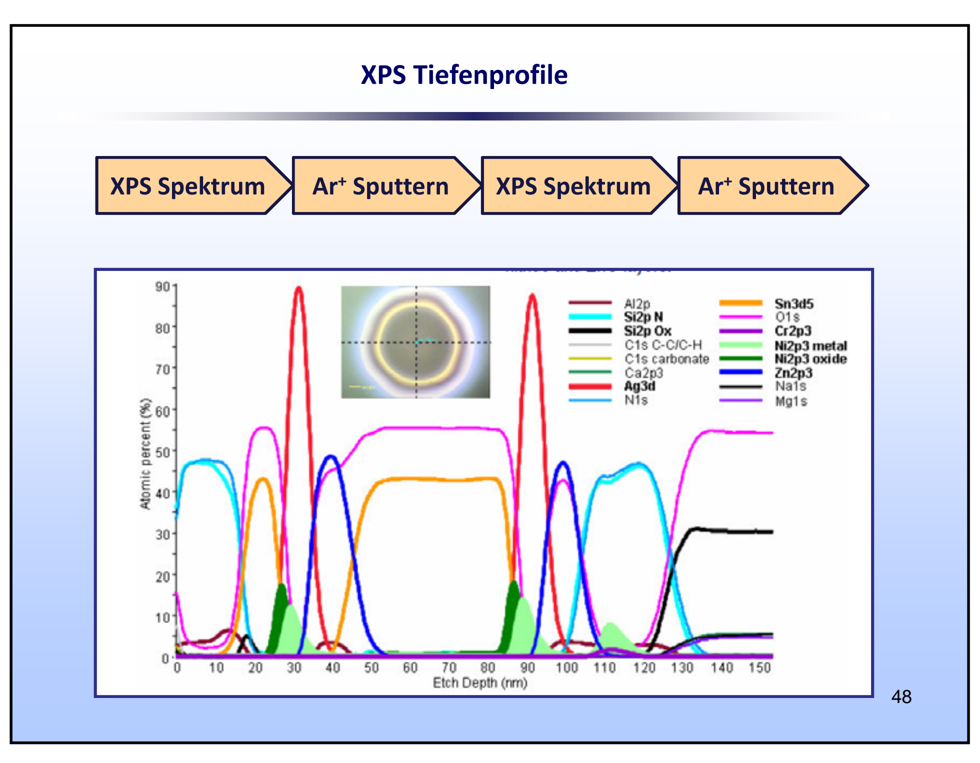

Reductive Desorption
of dodecanethiol from gold
Current [µA]
E v.s. Hg/HgO [mV]
first cycle
second cycle


Chemical Interaction at the surface
Thiols and Dithiols
Structure
XPS
S2p Signal
CV
Reductive Desorption
STM
Morphology
OT
One sulfur species
50 nm
BDMT
Two sulfur species
50 nm
PAUL SCHERRER INSTITUT
SONY

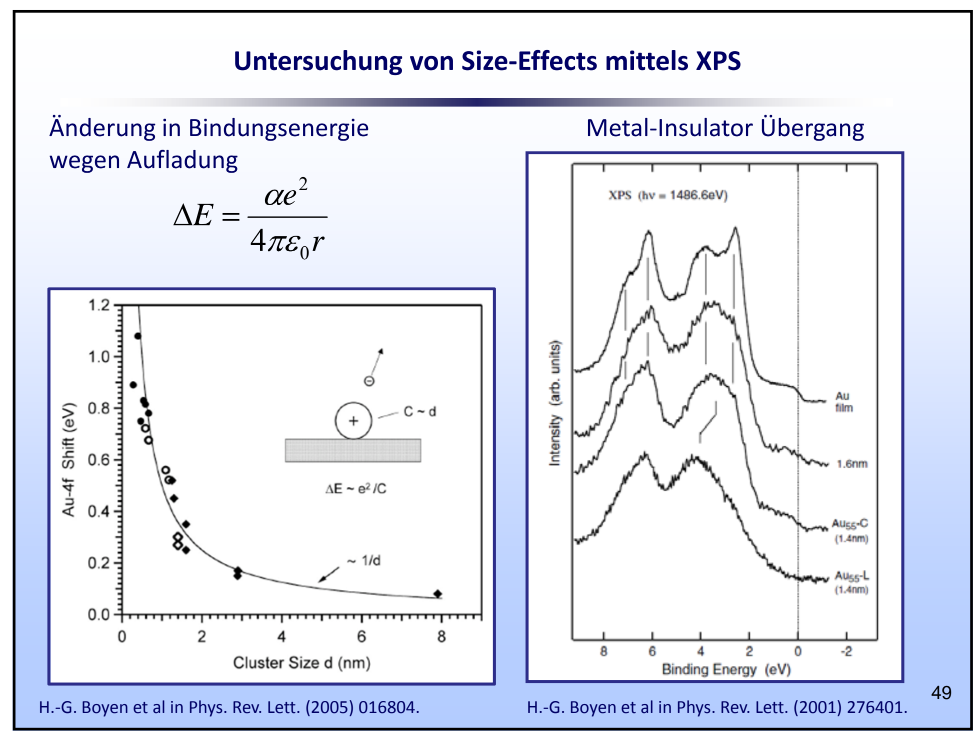

Chemical Interaction at the surface
Thiurames and Dithiocarbamates
Structure
XPS
S2p Signal
CV
Reductive Desorption
STM
Morphology
Thiram
50 nm
DEDT
50 nm
PAUL SCHERRER INSTITUT
SONY



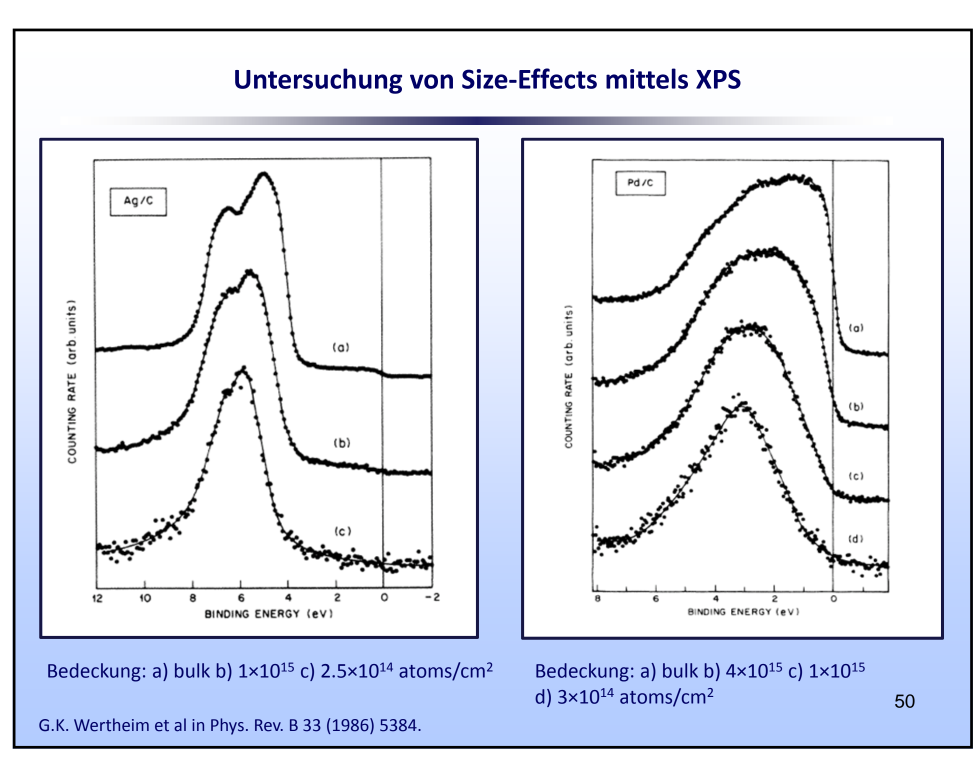
Chemical Interaction at the surface
Bis Dithiocarbamates
Structure
XPS
S2p Signal
CV
Reductive Desorption
STM
Morphology
cHBDT
PBDT
50 nm
PAUL SCHERRER INSTITUT
SONY



XPS Tiefenprofile
XPS Spektrum
Ar+ Sputtern
XPS Spektrum
Ar+ Sputtern
Atomic percent (%)
Etch Depth (nm)
Al2p
Si2p N
Si2p Ox
C1s C-C/C-H
C1s carbonate
Ca2p3
Ag3d
N1s
Sn3d5
O1s
Cr2p3
Ni2p3 metal
Ni2p3 oxide
Zn2p3
Na1s
Mg1s
48



Untersuchung von Size-Effects mittels XPS
Änderung in Bindungsenergie wegen Aufladung
$$\Delta E = \frac{\alpha e^2}{4\pi\varepsilon_0 r}$$
Metal-Insulator Übergang
Au-4f Shift (eV)
Cluster Size d (nm)
C ~ d
ΔE ~ e²/C
~ 1/d
XPS (hν = 1486.6eV)
Intensity (arb. units)
Binding Energy (eV)
Au film
1.6nm
Au55-C (1.4nm)
Au55-L (1.4nm)
H.-G. Boyen et al in Phys. Rev. Lett. (2005) 016804.
H.-G. Boyen et al in Phys. Rev. Lett. (2001) 276401.
49



Untersuchung von Size-Effects mittels XPS
Ag/C
COUNTING RATE (arb units)
BINDING ENERGY (eV)
Pd/C
Bedeckung: a) bulk b) 1×10¹⁵ c) 2.5×10¹⁴ atoms/cm²
Bedeckung: a) bulk b) 4×10¹⁵ c) 1×10¹⁵ d) 3×10¹⁴ atoms/cm²
G.K. Wertheim et al in Phys. Rev. B 33 (1986) 5384.
50

Ultraviolett Photoelektronenspektroskopie

Ionisationsquellen:

- Ne I (16.6 eV) und Ne II (26.8 eV)
- He I (21.2 eV) und He II (40.8 eV)
  - I – Emission neutrale Atomen
  - II – Emission ionisierte Atomen

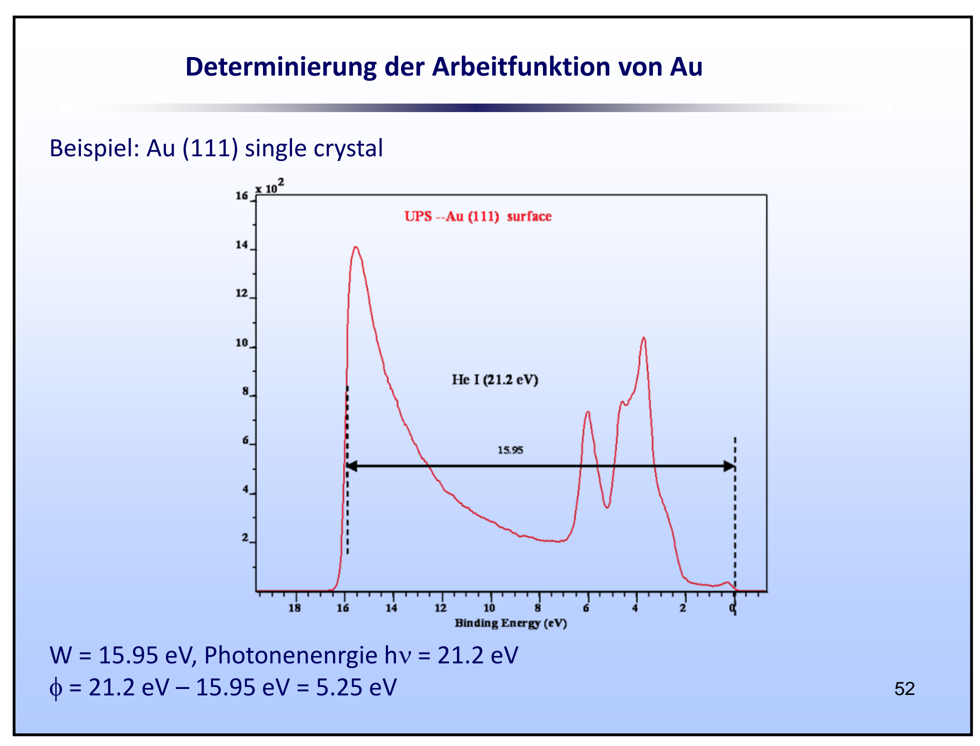
Hauptanwendungsgebiete:
- Elektronische Struktur der Festkörper
- Absorbierte Moleküle

Spezifische Beispiele:
- Determinierung der Arbeitsfunktion von Festkörper
- Messung der orbitalen Energien der Molekülen
- Bandstruktur Mapping in k-Raum (mit AR-UPS)

51

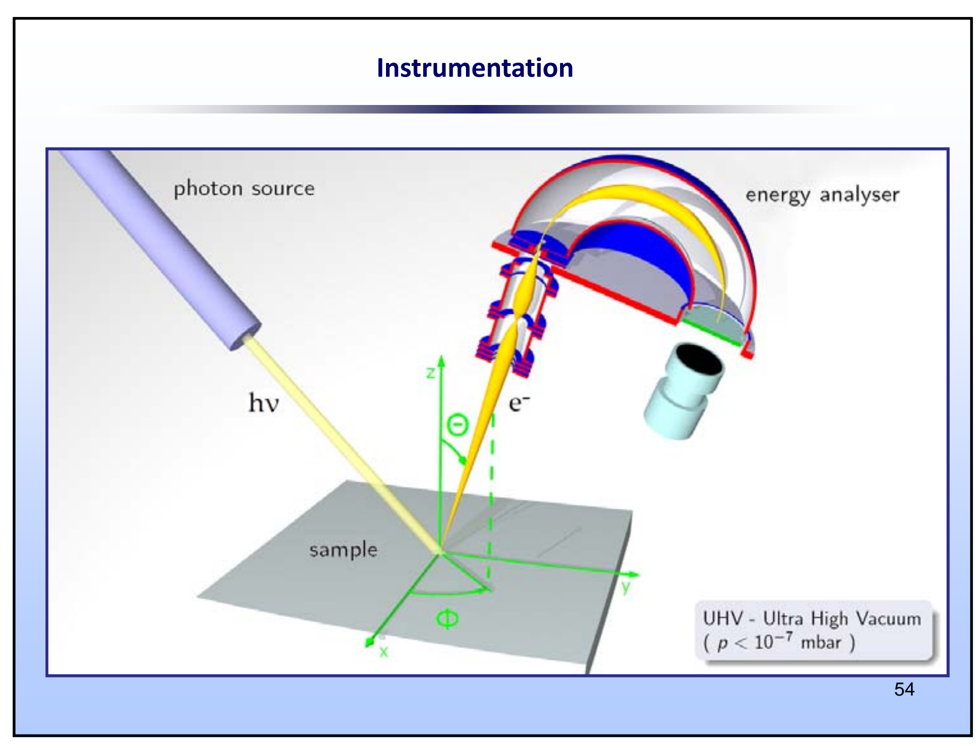
Determinierung der Arbeitfunktion von Au

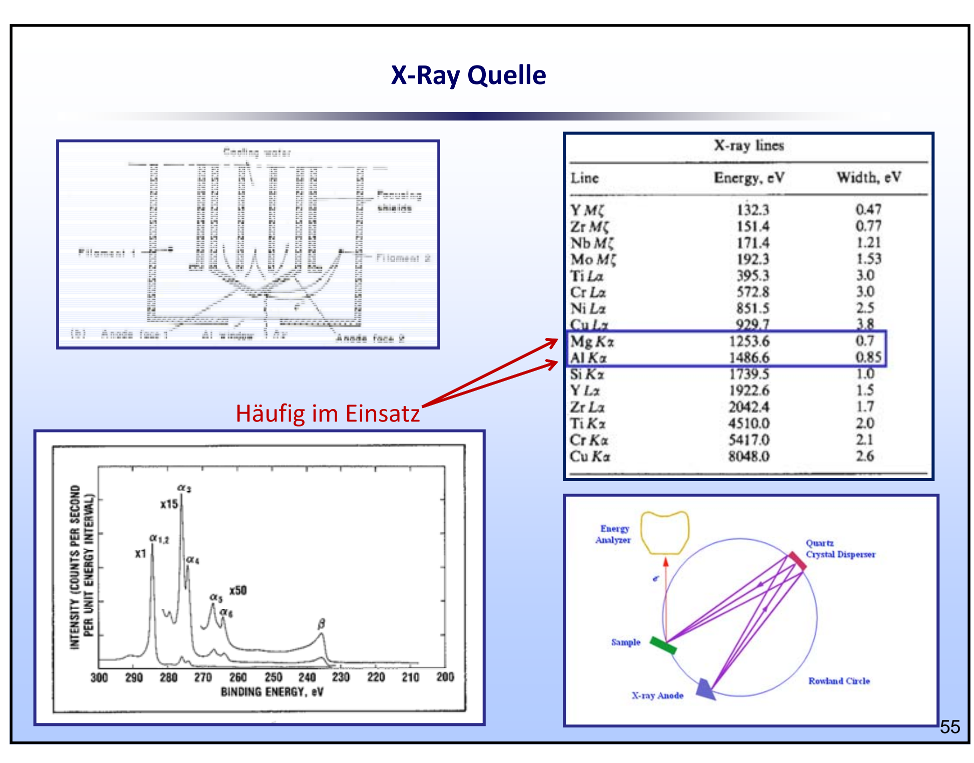
Beispiel: Au (111) single crystal



W = 15.95 eV, Photonenenrgie $h\nu$ = 21.2 eV
ϕ = 21.2 eV – 15.95 eV = 5.25 eV

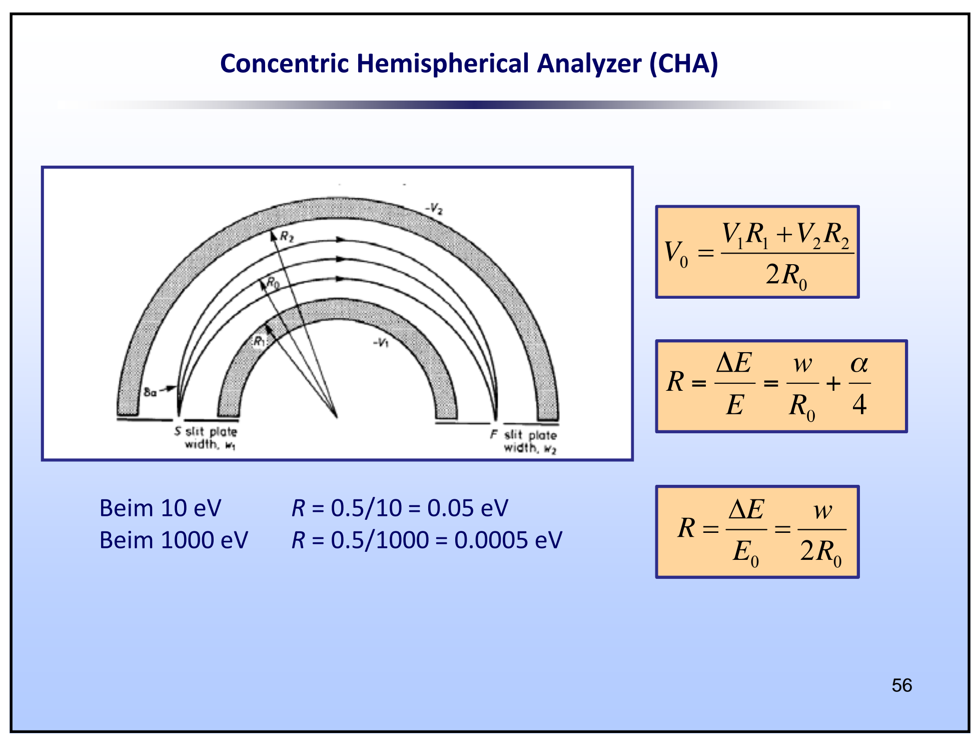
52



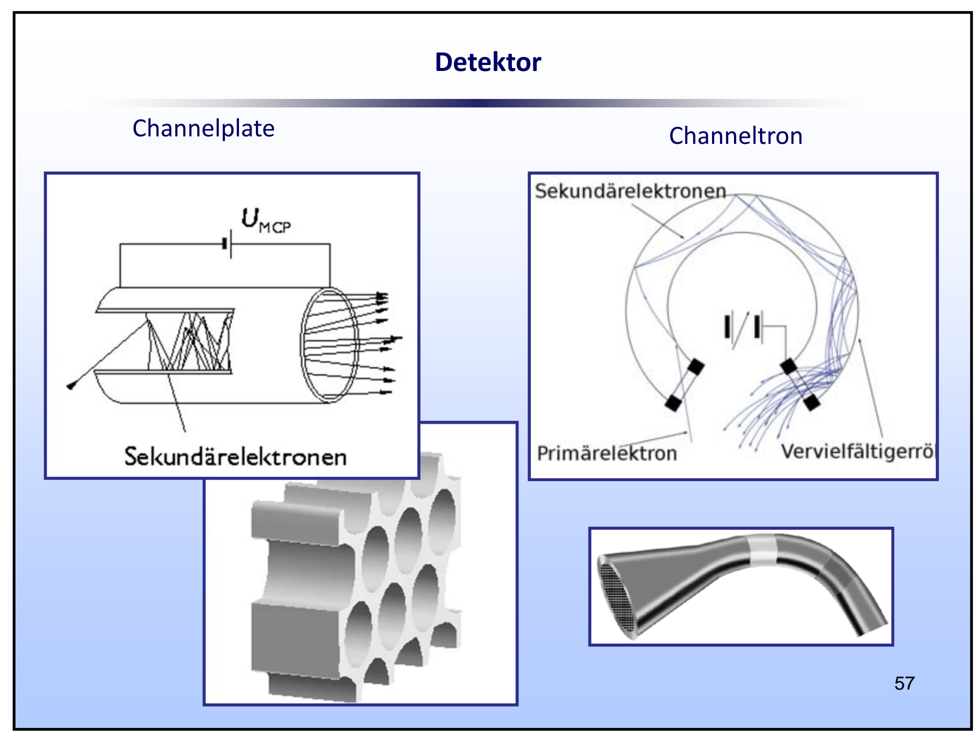


X-ray lines

Line	Energy, eV	Width, eV
Y $M\zeta$	132.3	0.47
Zr $M\zeta$	151.4	0.77
Nb $M\zeta$	171.4	1.21
Mo $M\zeta$	192.3	1.53
Ti $L\alpha$	395.3	3.0
Cr $L\alpha$	572.8	3.0
Ni $L\alpha$	851.5	2.5
Cu $L\alpha$	929.7	3.8
Mg $K\alpha$	1253.6	0.7
Al $K\alpha$	1486.6	0.85
Si $K\alpha$	1739.5	1.0
Y $L\alpha$	1922.6	1.5
Zr $L\alpha$	2042.4	1.7
Ti $K\alpha$	4510.0	2.0
Cr $K\alpha$	5417.0	2.1
Cu $K\alpha$	8048.0	2.6

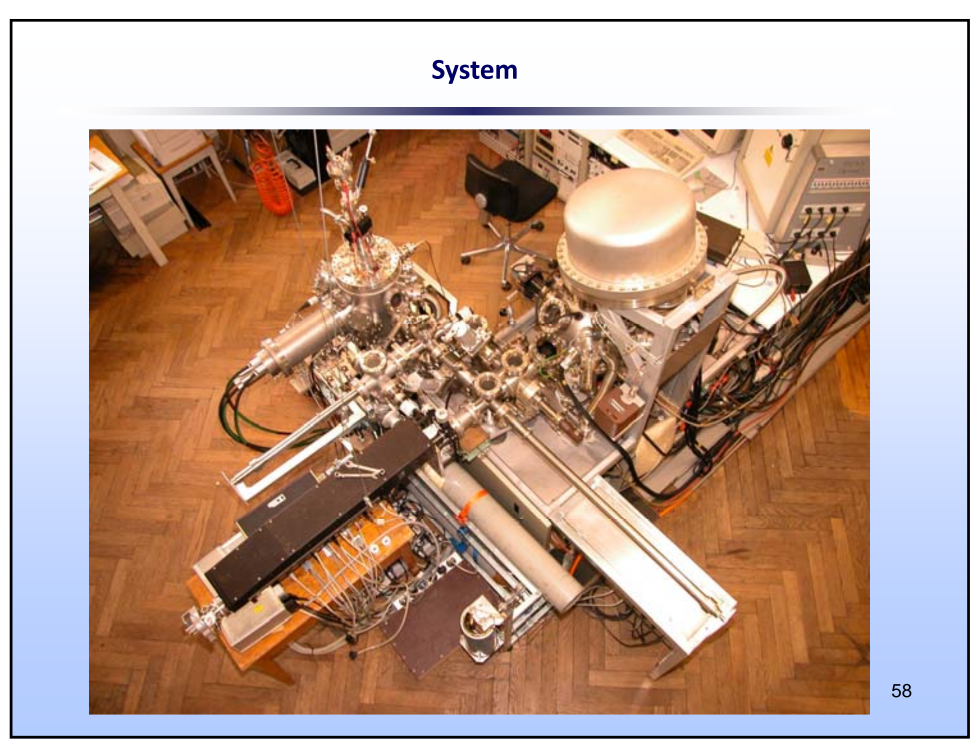


Concentric Hemispherical Analyzer (CHA)
$V_0 = \frac{V_1 R_1 + V_2 R_2}{2R_0}$
$R = \frac{\Delta E}{E} = \frac{w}{R_0} + \frac{\alpha}{4}$
$R = \frac{\Delta E}{E_0} = \frac{w}{2R_0}$
Beim 10 eV R = 0.5/10 = 0.05 eV
Beim 1000 eV R = 0.5/1000 = 0.0005 eV
56



Detektor
Channelplate
Channeltron
U_{MCP}
Sekundärelektronen
Sekundärelektronen
Primärelektron
Vervielfältigerrö
57

System



58

Teil 2:
Auger Spektroskopie

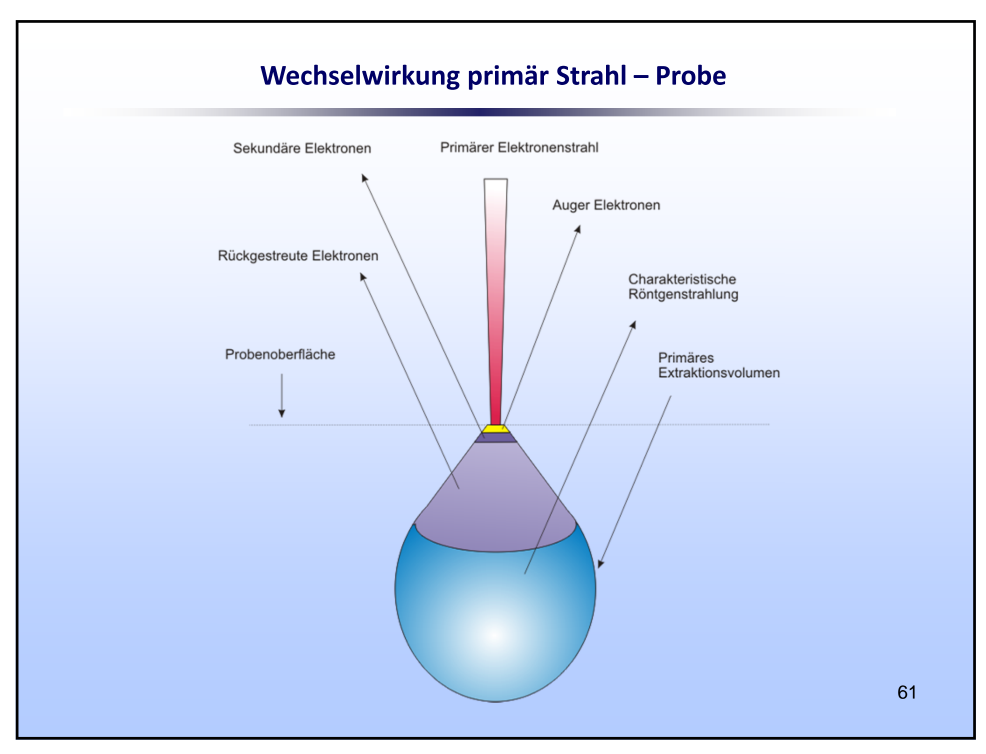
59

X-Ray Bezeichnungen

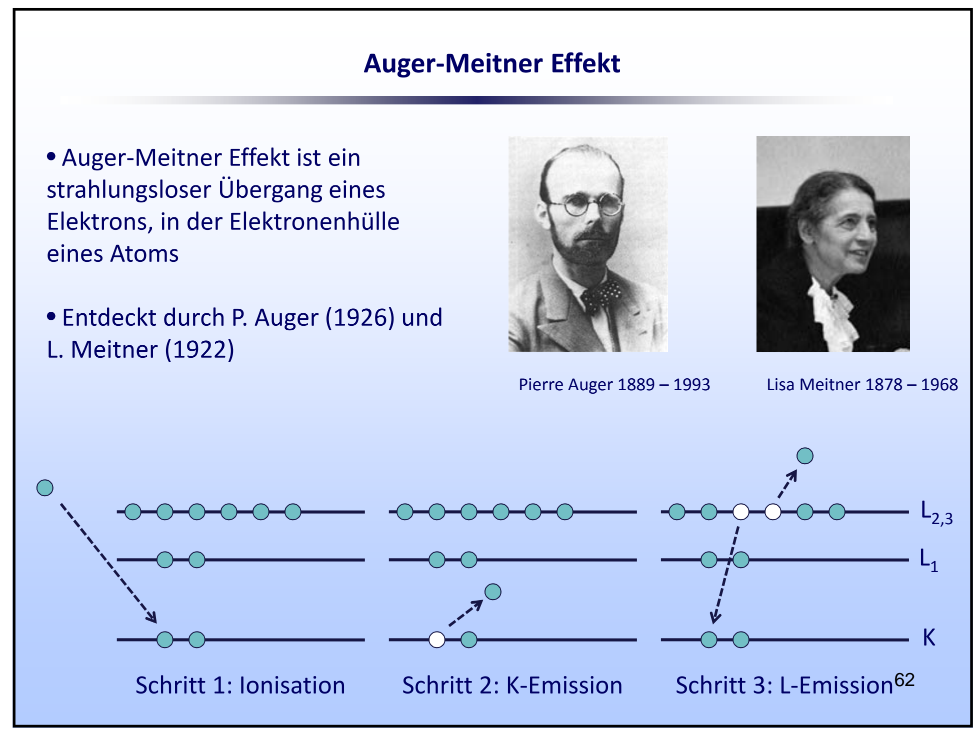
Quantum numbers					
n	l	j	X-ray suffix	X-ray level	Spectroscopic level
1	0	$\frac{1}{2}$	1	K	$1s_{1/2}$
2	0	$\frac{1}{2}$	1	L_1	$2s_{1/2}$
2	1	$\frac{1}{2}$	2	L_2	$2p_{1/2}$
2	1	$\frac{3}{2}$	3	L_3	$2p_{3/2}$
3	0	$\frac{1}{2}$	1	M_1	$3s_{1/2}$
3	1	$\frac{1}{2}$	2	M_2	$3p_{1/2}$
3	1	$\frac{3}{2}$	3	M_3	$3p_{3/2}$
3	2	$\frac{3}{2}$	4	M_4	$3d_{3/2}$
3	2	$\frac{5}{2}$	5	M_5	$3d_{5/2}$
	etc.		etc.	etc.	etc.

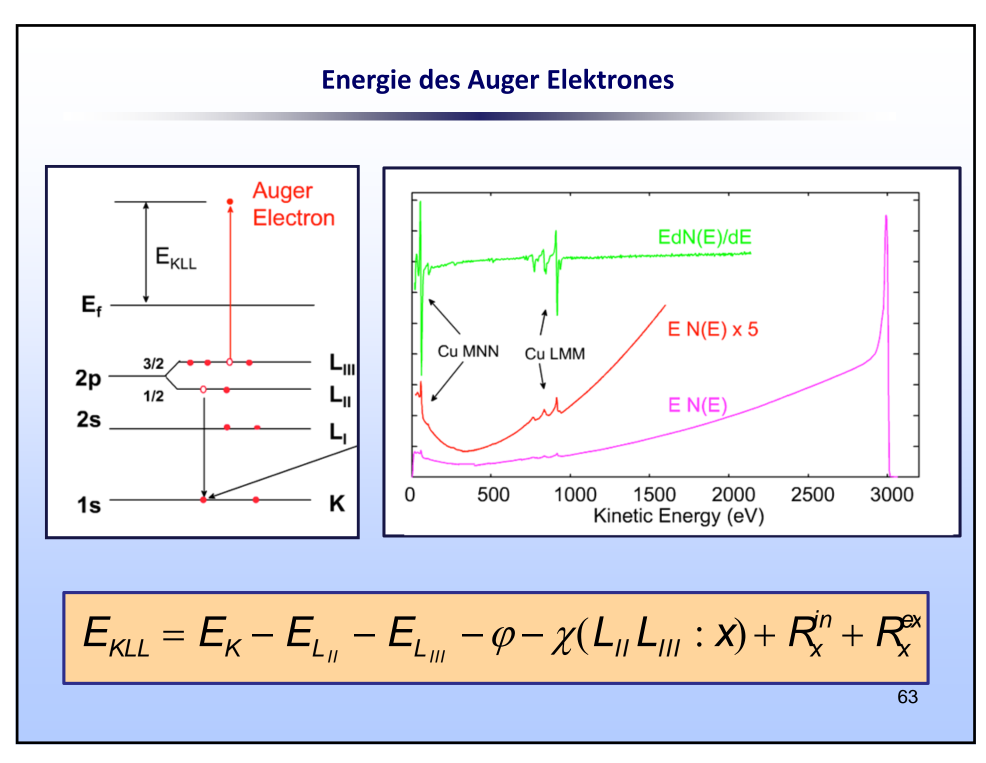
60

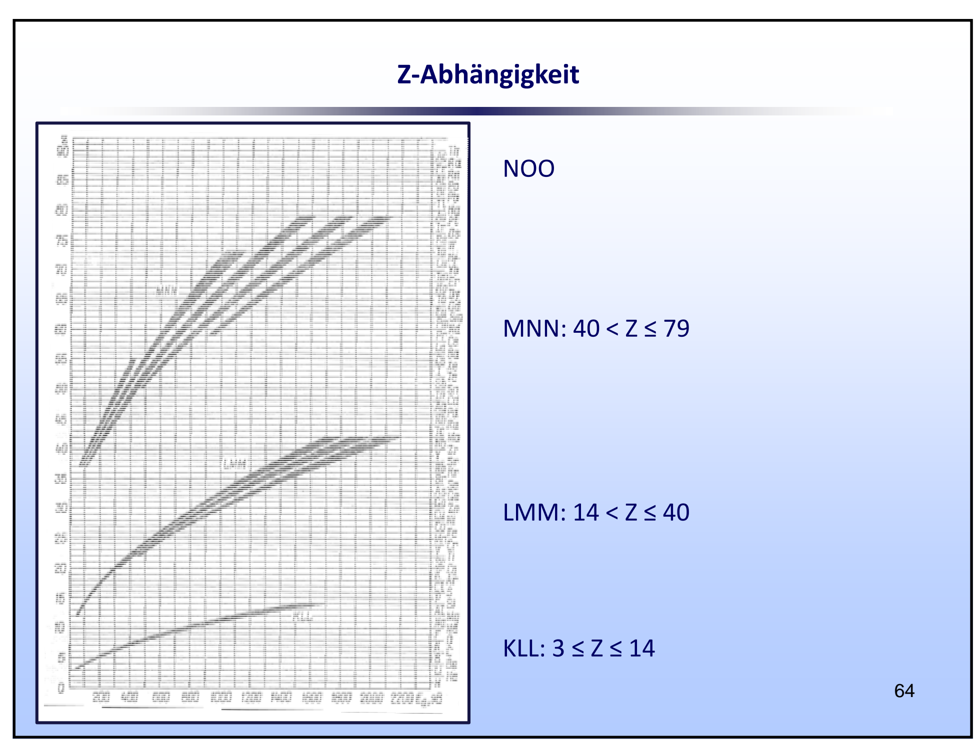
Wechselwirkung primär Strahl – Probe

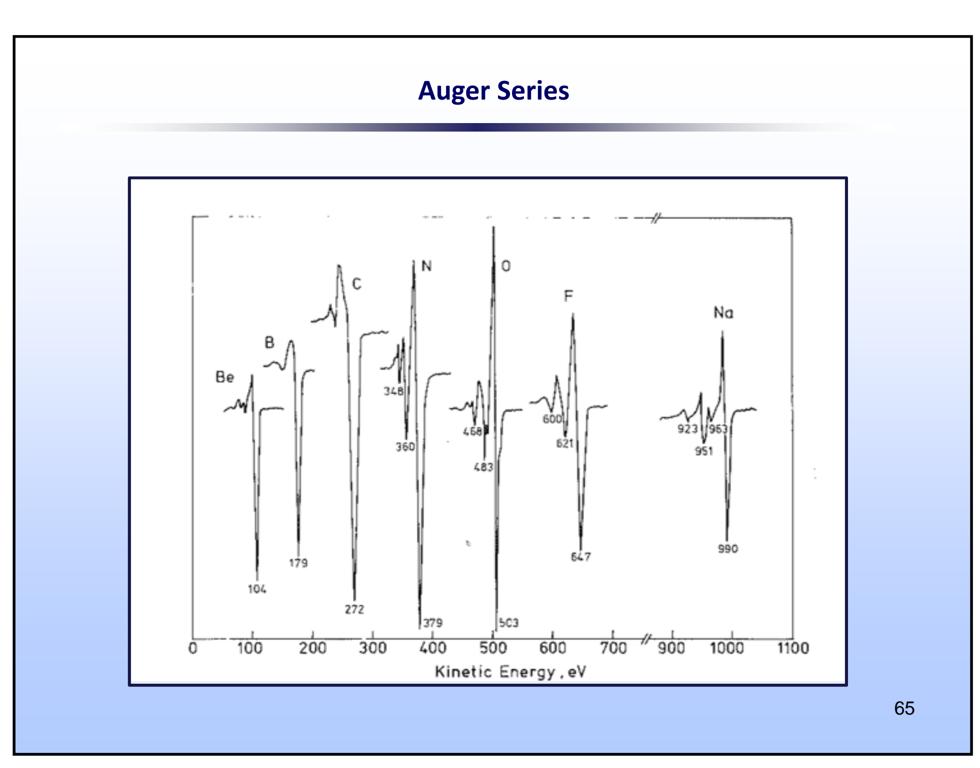


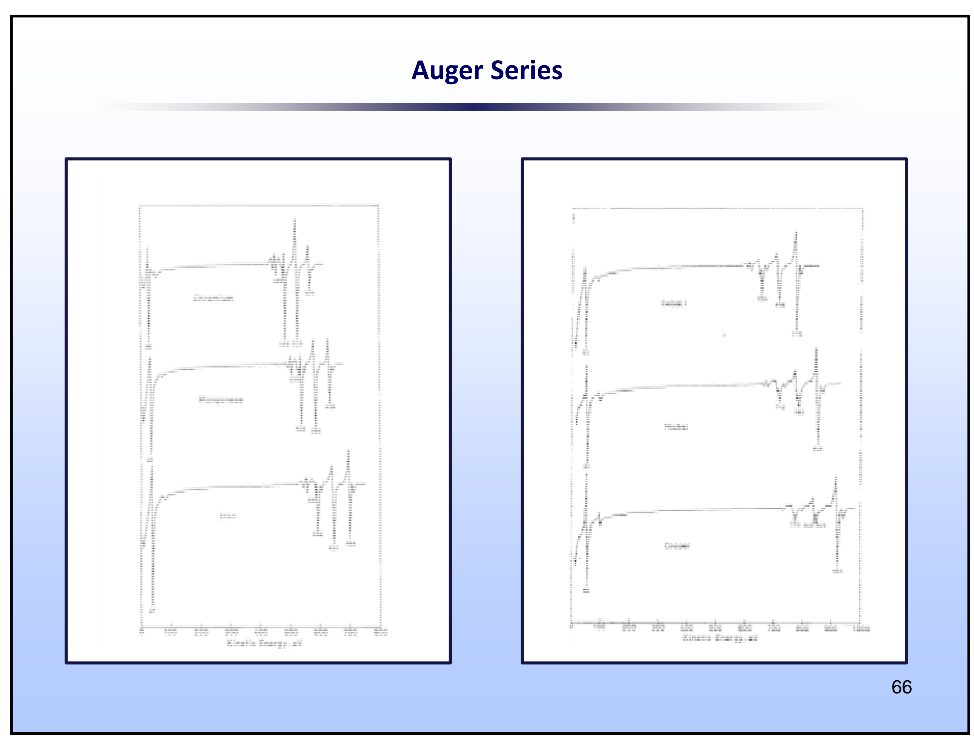
61

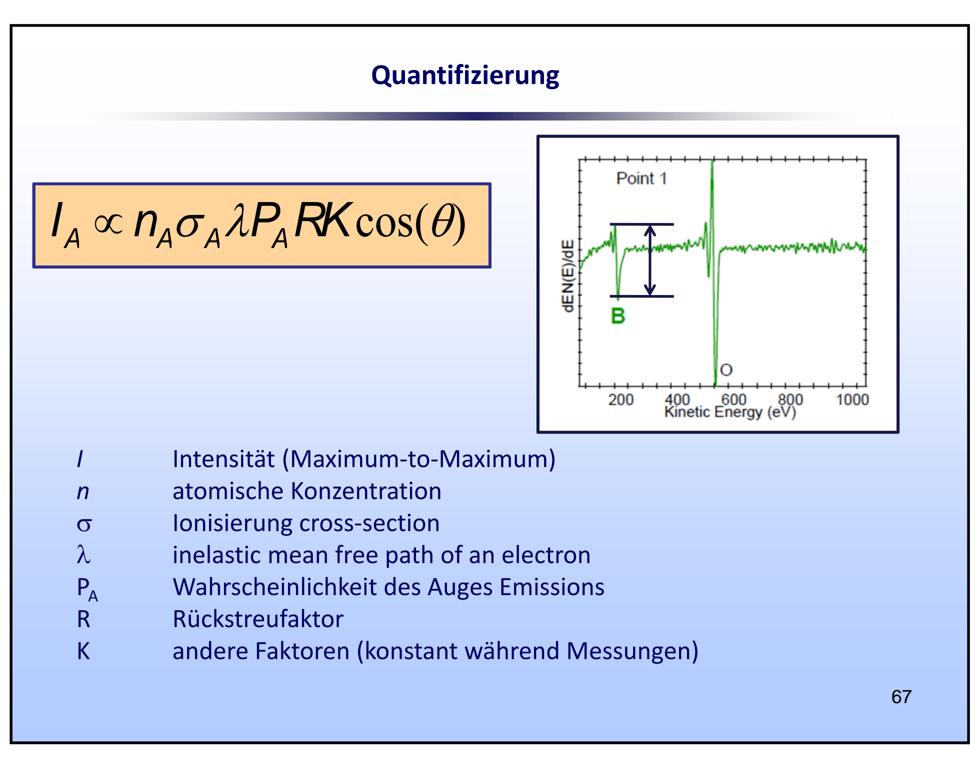

Auger-Meitner Effekt
• Auger-Meitner Effekt ist ein strahlungsloser Übergang eines Elektrons, in der Elektronenhülle eines Atoms
• Entdeckt durch P. Auger (1926) und L. Meitner (1922)
Pierre Auger 1889 – 1993
Lisa Meitner 1878 – 1968
L2,3
L1
K
Schritt 1: Ionisation
Schritt 2: K-Emission
Schritt 3: L-Emission
62

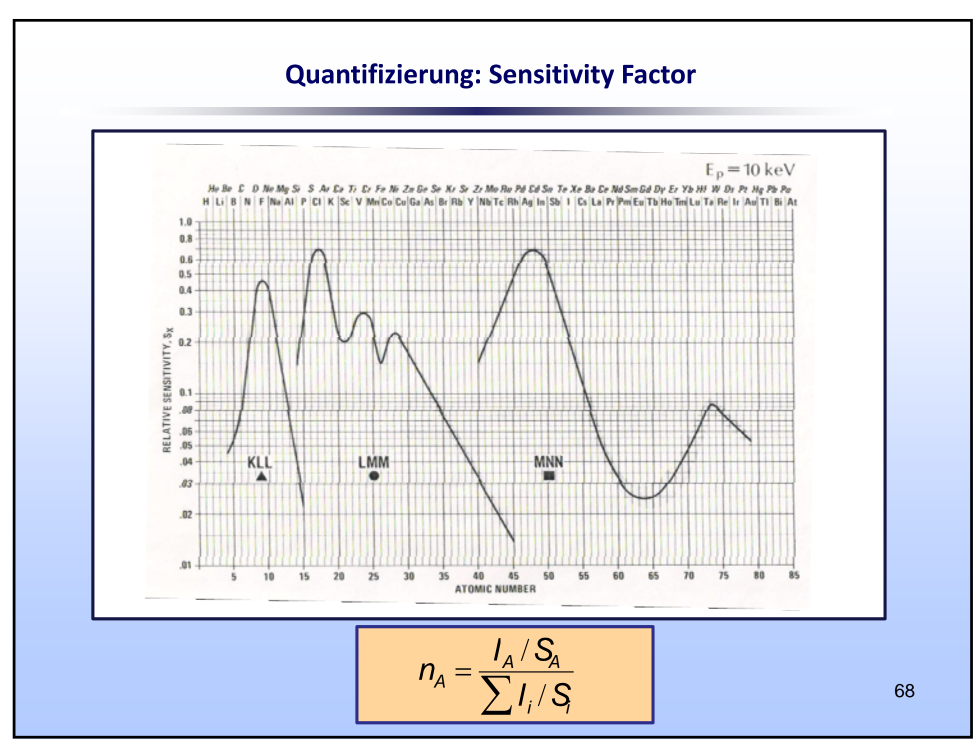

Energie des Auger Elektrones
Auger Electron
EKLL
Ef
2p
3/2
1/2
2s
1s
LIII
LII
LI
K
EdN(E)/dE
Cu MNN
Cu LMM
E N(E) x 5
E N(E)
0
500
1000
1500
2000
2500
3000
Kinetic Energy (eV)
$E_{KLL} = E_K - E_{L_{II}} - E_{L_{III}} - \varphi - \chi(L_{II} L_{III} : x) + R_x^{in} + R_x^{ex}$
63

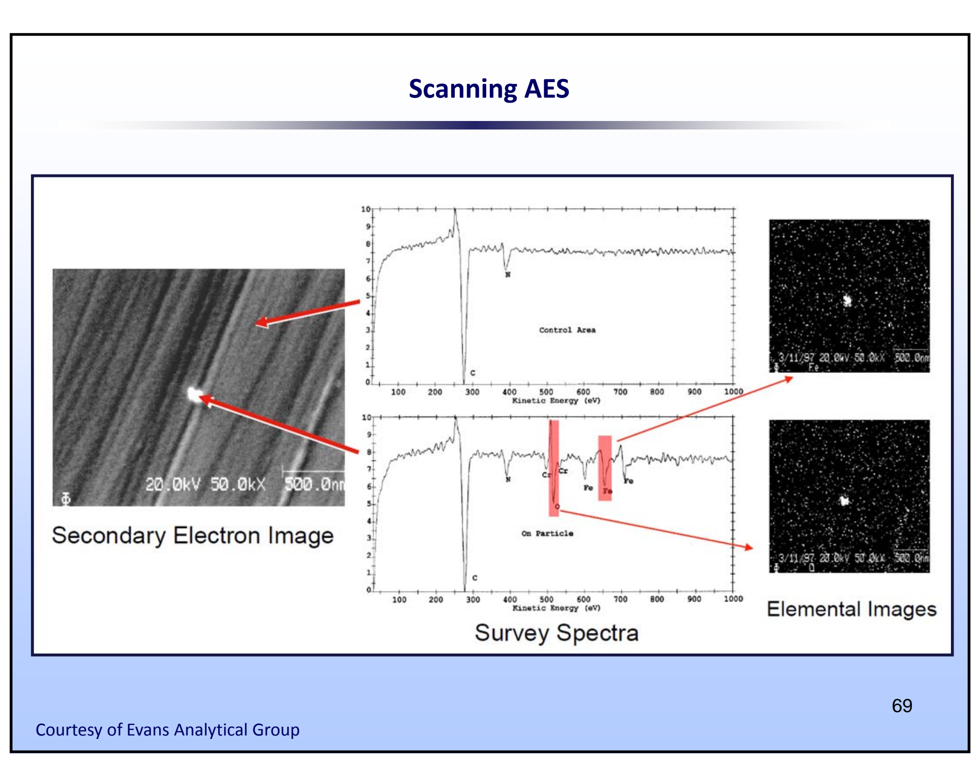

Z-Abhängigkeit
NOO
MNN: 40 < Z ≤ 79
LMM: 14 < Z ≤ 40
KLL: 3 ≤ Z ≤ 14
64

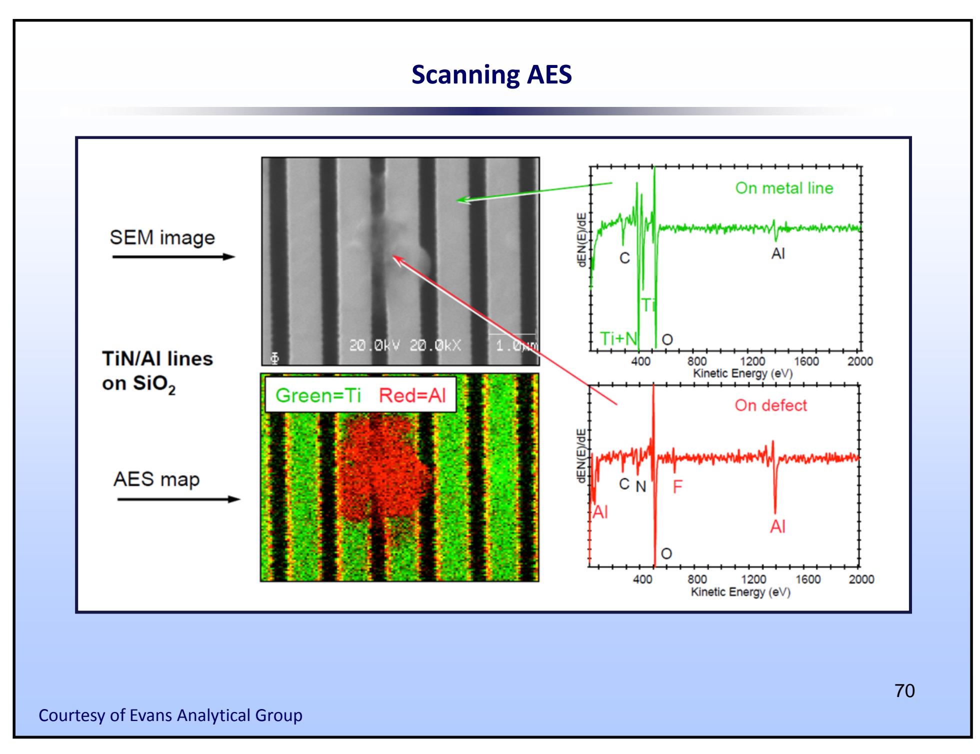

Auger Series
Be
B
C
N
O
F
Na
104
179
272
348
360
379
468
483
503
600
621
647
923
951
963
990
Kinetic Energy, eV
65


Auger Series
66

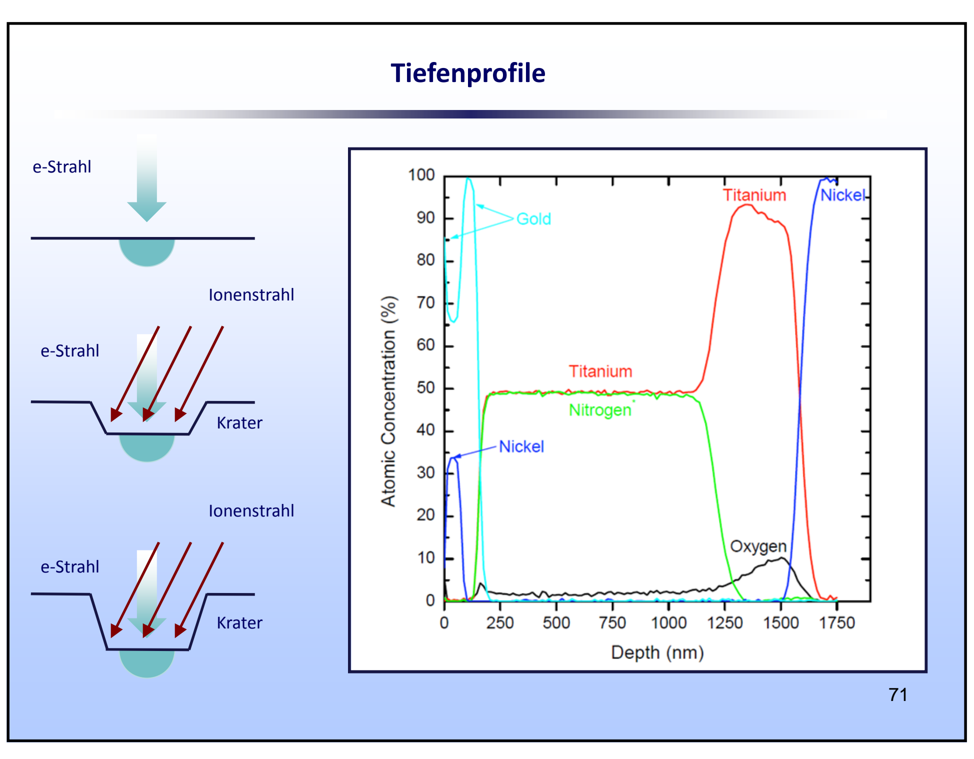

Quantifizierung
$I_A \propto n_A \sigma_A \lambda P_A R K \cos(\theta)$
Point 1
dEN(E)/dE
B
O
200 400 600 800 1000
Kinetic Energy (eV)
I Intensität (Maximum-to-Maximum)
n atomische Konzentration
σ Ionisierung cross-section
λ inelastic mean free path of an electron
P_A Wahrscheinlichkeit des Auges Emissions
R Rückstreufaktor
K andere Faktoren (konstant während Messungen)
67


Quantifizierung: Sensitivity Factor
$E_p = 10$ keV
RELATIVE SENSITIVITY, S_X
ATOMIC NUMBER
KLL
LMM
MNN
$$n_A = \frac{I_A / S_A}{\sum I_i / S_i}$$
68


Scanning AES
Secondary Electron Image
Control Area
On Particle
Kinetic Energy (eV)
Survey Spectra
Elemental Images
69
Courtesy of Evans Analytical Group



Scanning AES
SEM image
TiN/Al lines on SiO2
AES map
Green=Ti Red=Al
On metal line
dEN(E)/dE
C
Ti
Ti+N
O
Al
400 800 1200 1600 2000
Kinetic Energy (eV)
On defect
C N
F
Al
O
Al
400 800 1200 1600 2000
Kinetic Energy (eV)
70
Courtesy of Evans Analytical Group



Tiefenprofile
e-Strahl
Ionenstrahl
e-Strahl
Krater
Ionenstrahl
e-Strahl
Krater
Atomic Concentration (%)
Gold
Titanium
Nickel
Titanium
Nitrogen
Nickel
Oxygen
Depth (nm)
0 250 500 750 1000 1250 1500 1750
0 10 20 30 40 50 60 70 80 90 100
71

Elektronenquellen

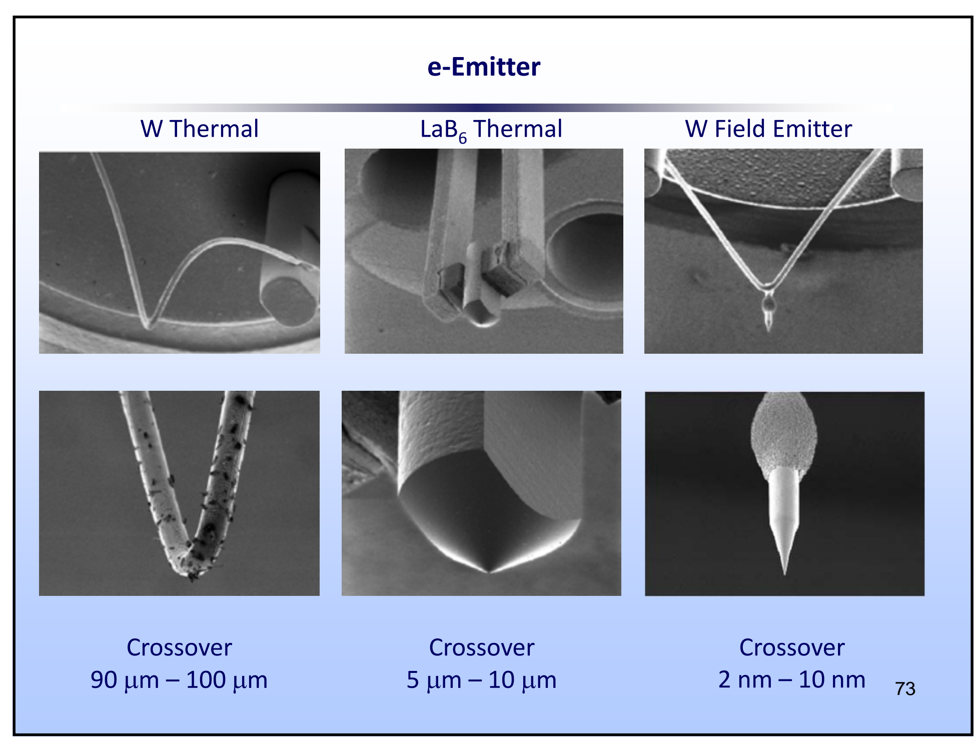
Thermoinonische Quellen:
(Richardson Gleichung)

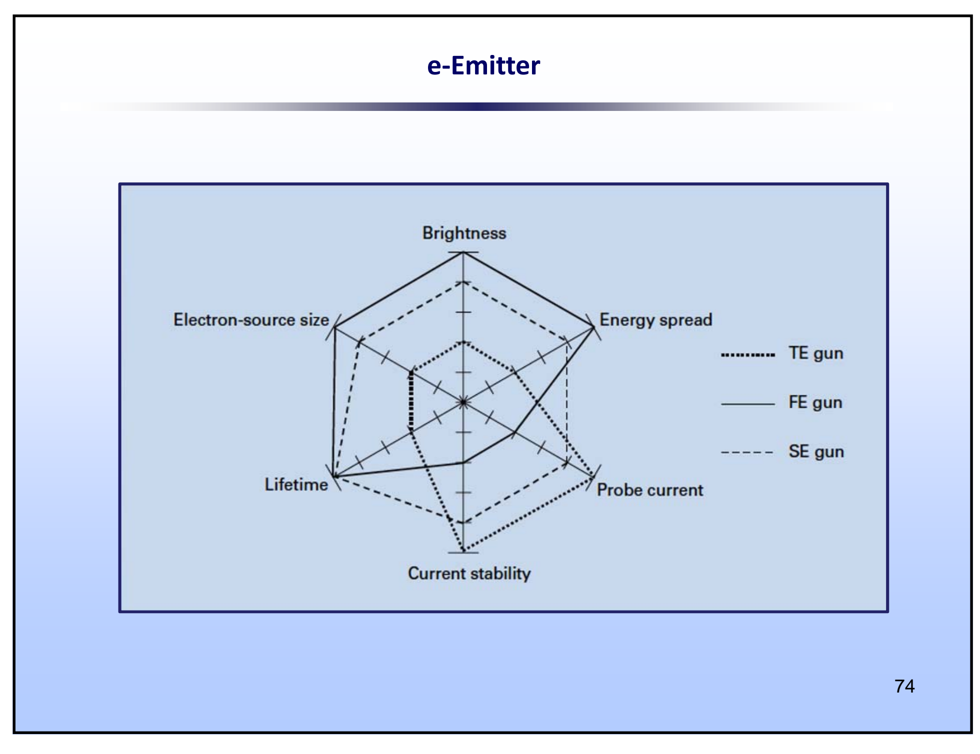
$$J = A(1-r)T^2 \exp(-e\phi / kT)$$

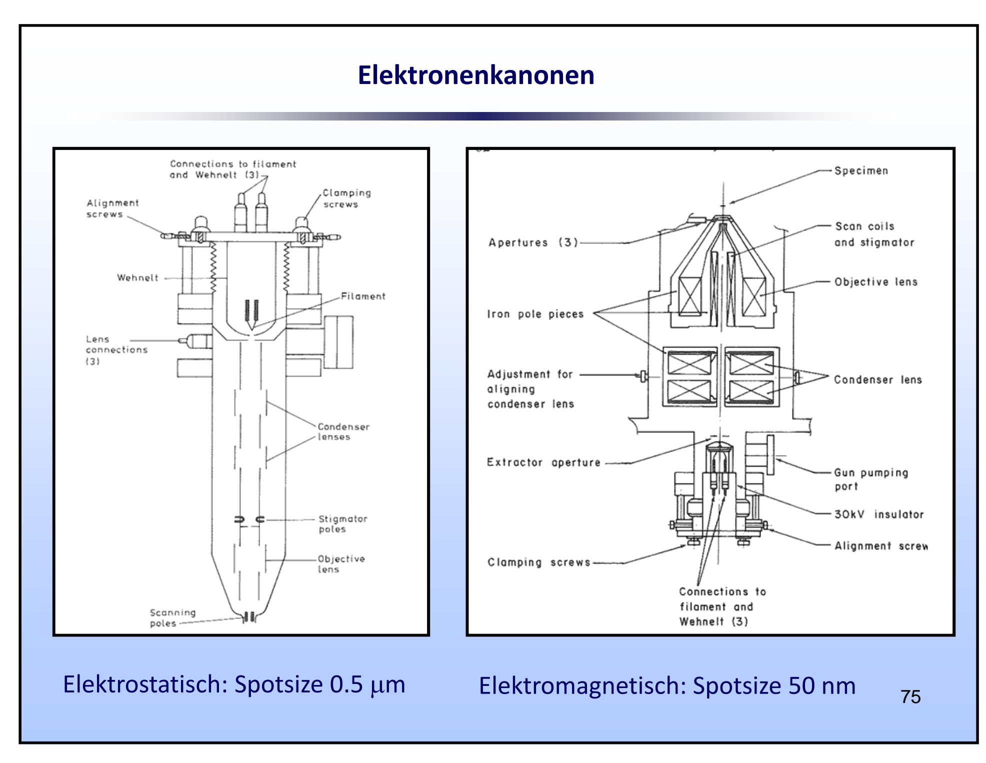
Feldemissionsquellen:
(Fower-Nordheim Gleichung)

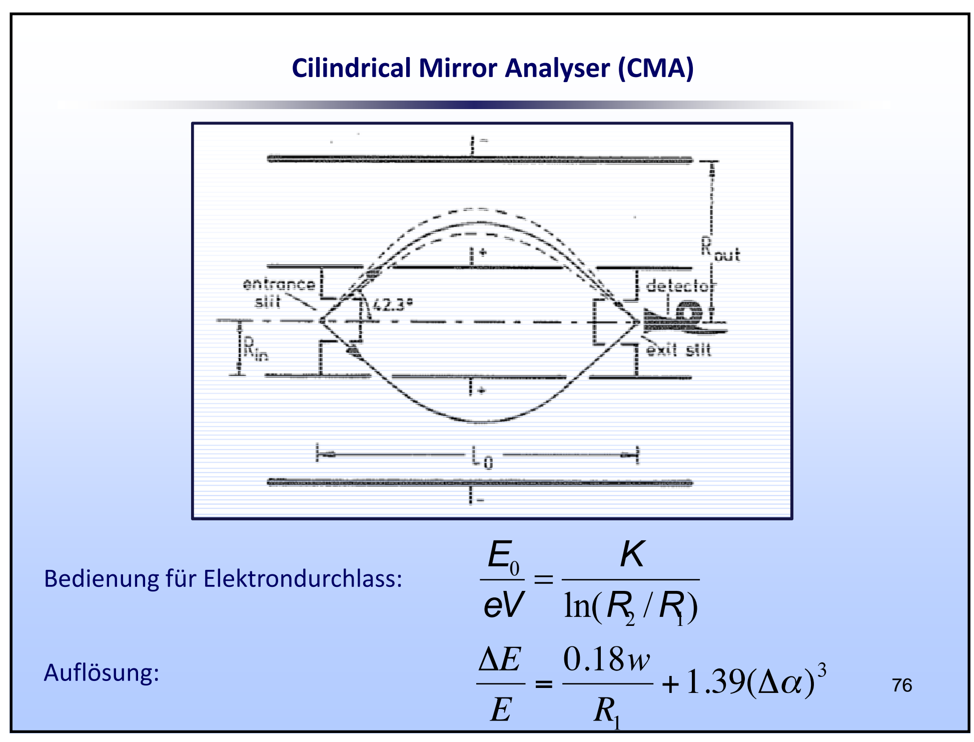
$$J = (1.55 \times 10^{-6} E^2 / \phi) \exp\left[-6.86 \times 10^7 \phi^{3/2} \theta(x) / E\right]$$

72

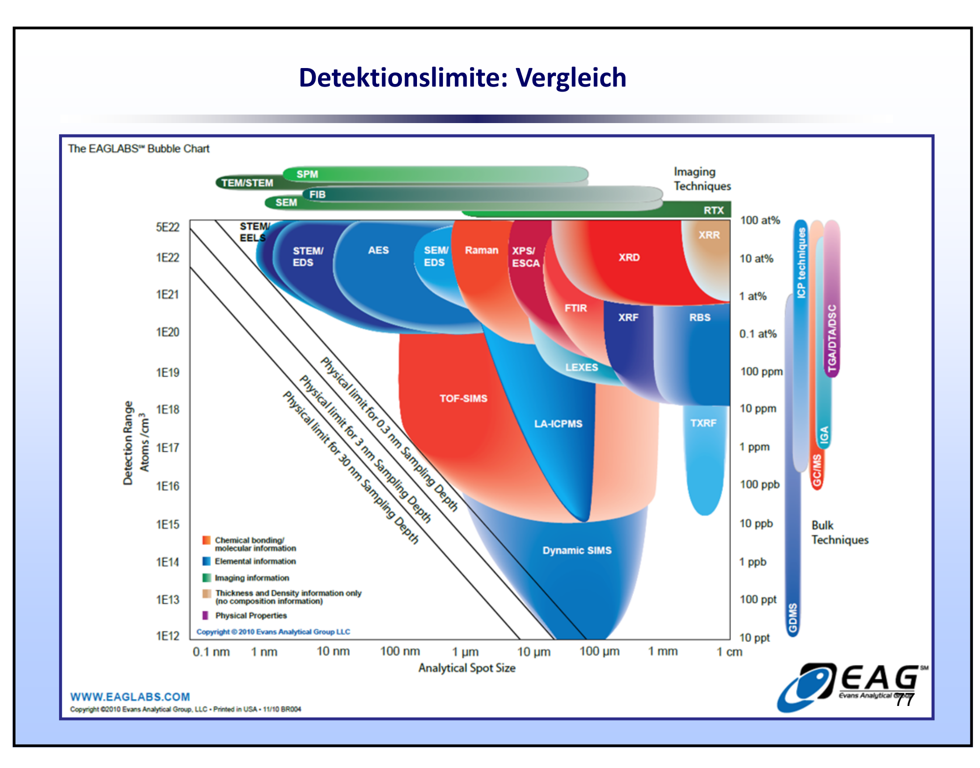



e-Emitter
Brightness
Electron-source size
Energy spread
TE gun
FE gun
SE gun
Lifetime
Probe current
Current stability
74


Elektronenkanonen
Connections to filament and Wehnelt (3)
Clamping screws
Alignment screws
Wehnelt
Filament
Lens connections (3)
Condenser lenses
Stigmator poles
Objective lens
Scanning poles
Specimen
Apertures (3)
Scan coils and stigmator
Objective lens
Iron pole pieces
Adjustment for aligning condenser lens
Condenser lens
Extractor aperture
Gun pumping port
30kV insulator
Alignment screw
Clamping screws
Connections to filament and Wehnelt (3)
Elektrostatisch: Spotsize 0.5 μm
Elektromagnetisch: Spotsize 50 nm
75



Cilindrical Mirror Analyser (CMA)
entrance slit
42.3°
R_{in}
R_{out}
detector
exit slit
L_0
Bedienung für Elektrondurchlass:
$\frac{E_0}{eV} = \frac{K}{\ln(R_2/R_1)}$
Auflösung:
$\frac{\Delta E}{E} = \frac{0.18w}{R_1} + 1.39(\Delta\alpha)^3$
76



Detektionslimite: Vergleich
The EAGLABS™ Bubble Chart
TEM/STEM
SPM
FIB
SEM
RTX
Imaging Techniques
STEM/ EELS
STEM/ EDS
AES
SEM/ EDS
Raman
XPS/ ESCA
XRD
XRR
FTIR
XRF
RBS
LEXES
TOF-SIMS
LA-ICPMS
TXRF
Dynamic SIMS
ICP techniques
TGA/DTA/DSC
IGA
GC/MS
GDMS
Bulk Techniques
Physical limit for 0.3 nm Sampling Depth
Physical limit for 3 nm Sampling Depth
Physical limit for 30 nm Sampling Depth
Detection Range Atoms /cm³
5E22
1E22
1E21
1E20
1E19
1E18
1E17
1E16
1E15
1E14
1E13
1E12
100 at%
10 at%
1 at%
0.1 at%
100 ppm
10 ppm
1 ppm
100 ppb
10 ppb
1 ppb
100 ppt
10 ppt
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
Analytical Spot Size
Chemical bonding/ molecular information
Elemental information
Imaging information
Thickness and Density information only (no composition information)
Physical Properties
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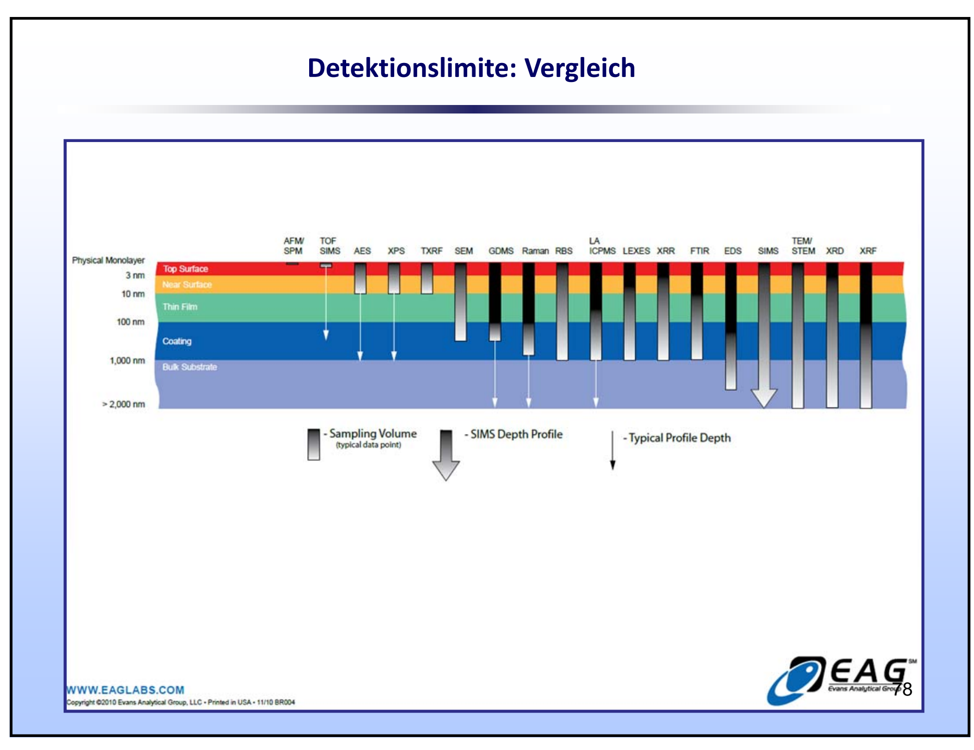

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