Semiconductor X-Ray Detectors

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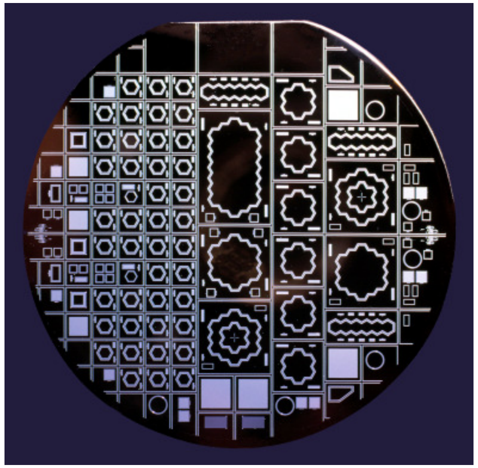
Ketek GmbH

Semiconductor X-Ray Detectors

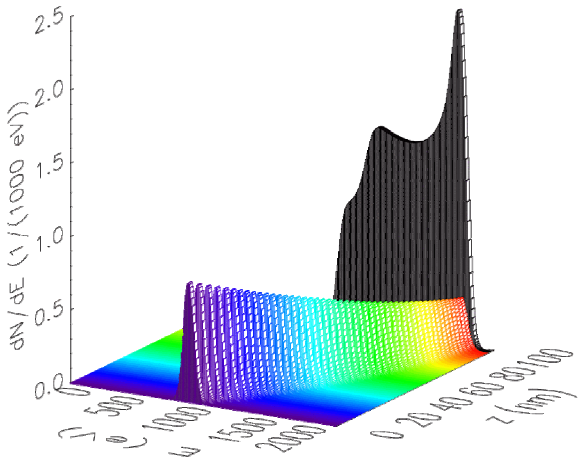


Part A Principles of Semiconductor Detectors

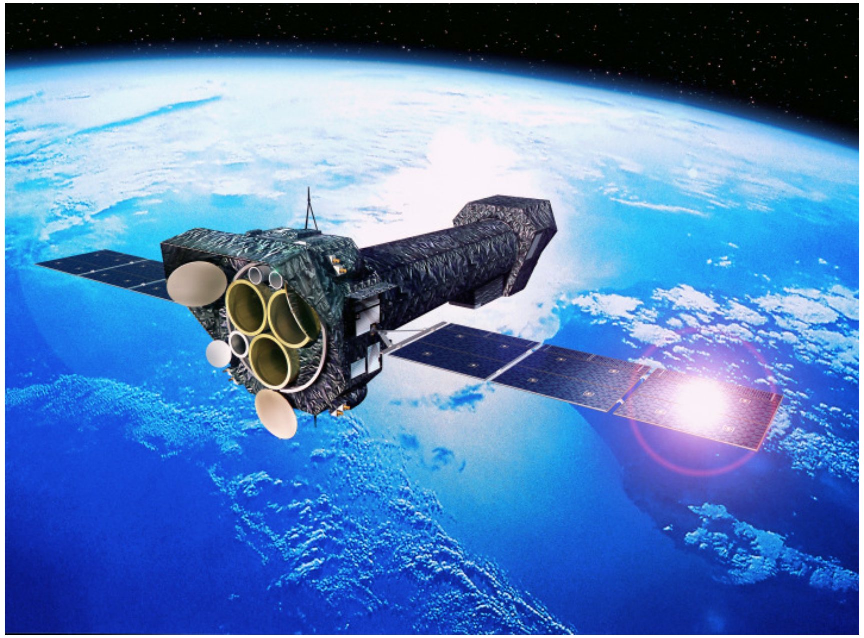
1. Basic Principles
2. Typical Applications
3. Planar Technology
4. Read-out Electronics

Part B Silicon Drift Detectors

1. Silicon Drift Detectors
2. GaAs Detectors
3. Outlook
4. Resume

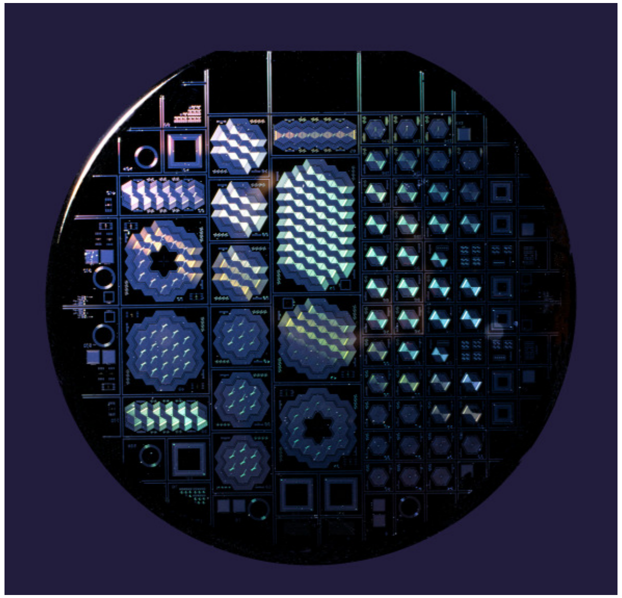


Motivation



- Many discoveries and results of fundamental research are closely related to the quality of the instruments used
- Telescopes, Microscopes, Cameras
- New detector concepts enabled the discovery of many elementary particles (e^+, ν, J/ψ)
- X-ray astronomy → detectors with spatial and energy resolution
- Fully depleted pn-CCD

Why Semiconductor Detectors?



- Photons and charged particles ionize matter
- Gases: electron ion pairs are produced
- Semiconductors: electron hole pairs are produced
- Measurement of position and energy
- Pair creation energy in semiconductors is much lower than ionization energy in gases
- High density of solids → high interaction probability
- Integration of transistors and read-out electronics

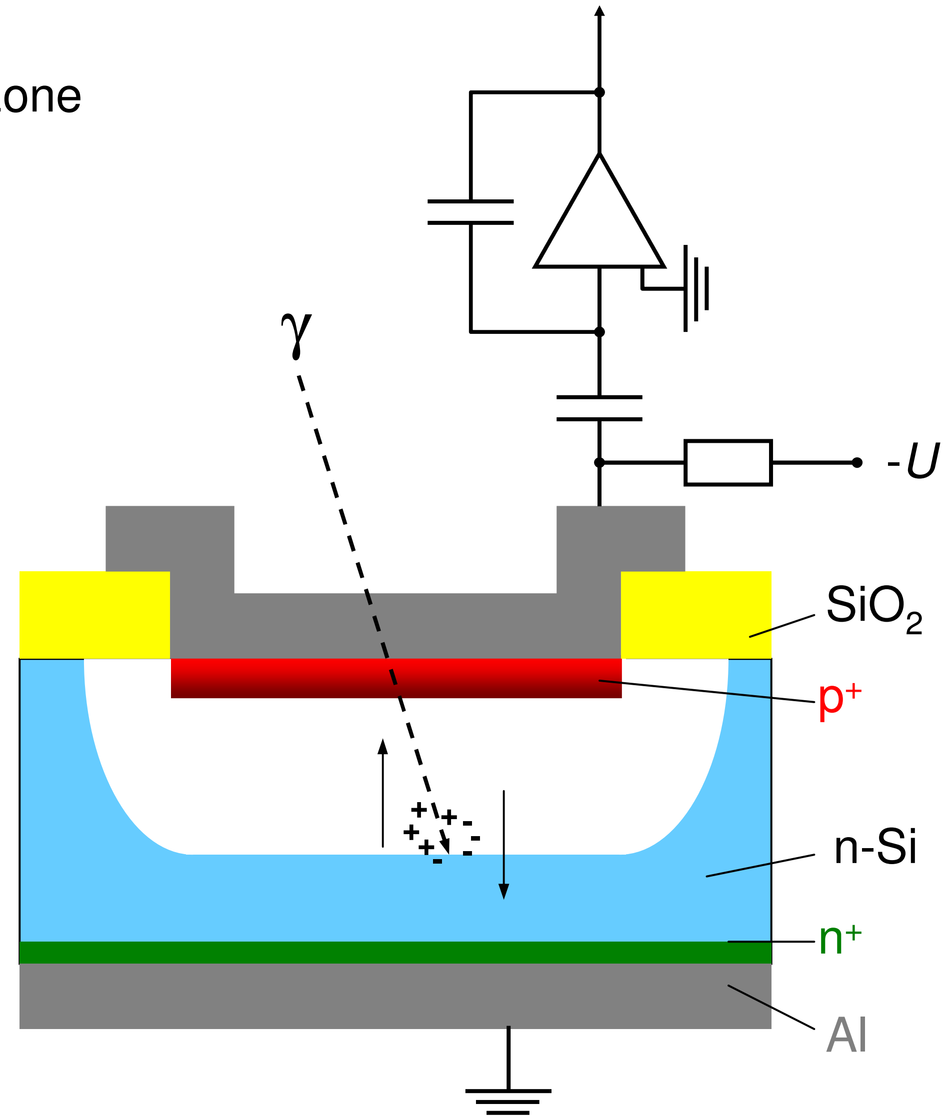
Semiconductor Detectors

p-i-n configuration → depletion zone

Al → saturation of free bonds
→ contacts p^+
→ reflects visible light

p^+ → maximum at the surface
→ no dead layer
→ high electric field strength

- e^--hole pairs generated by radiation
- charge separated and collected
- current mode: current prop. to flux and energy
- single photon counting: signal amplitude prop. to deposited charge



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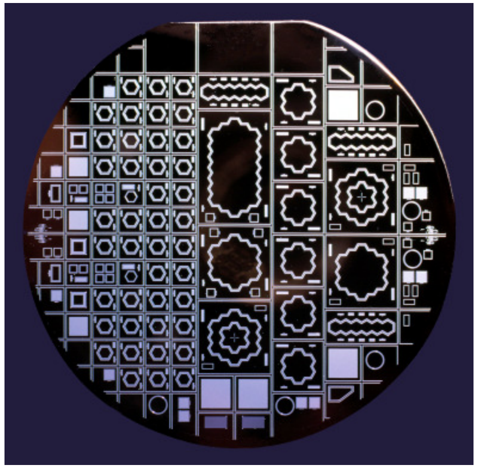

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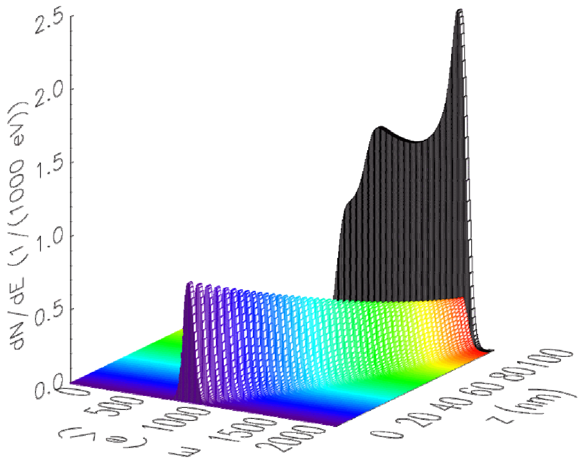

Part B Silicon Drift Detectors

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2. GaAs
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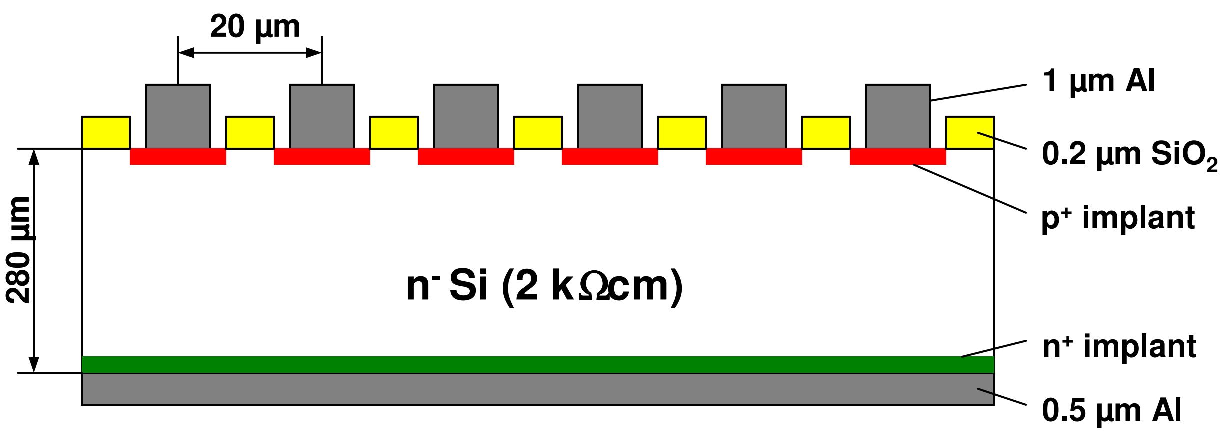
Applications in Basic Research

High Energy Physics

Silicon Strip detectors

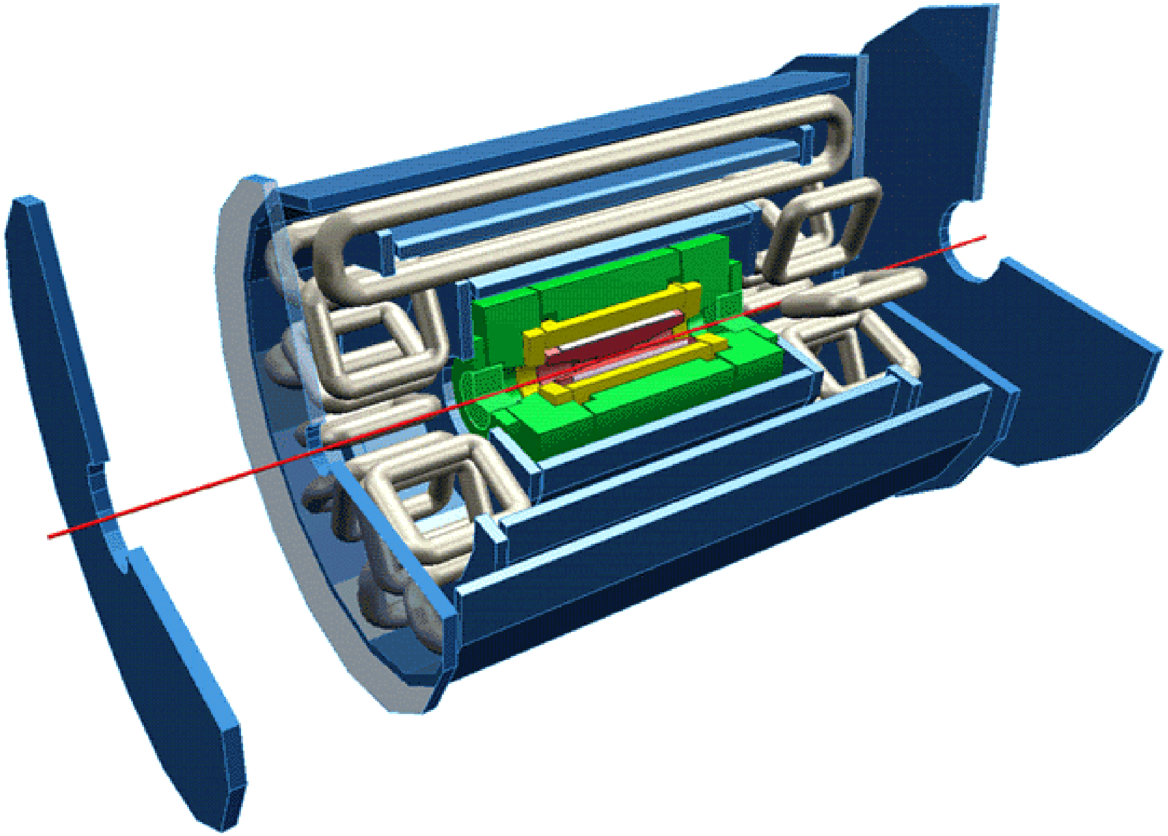


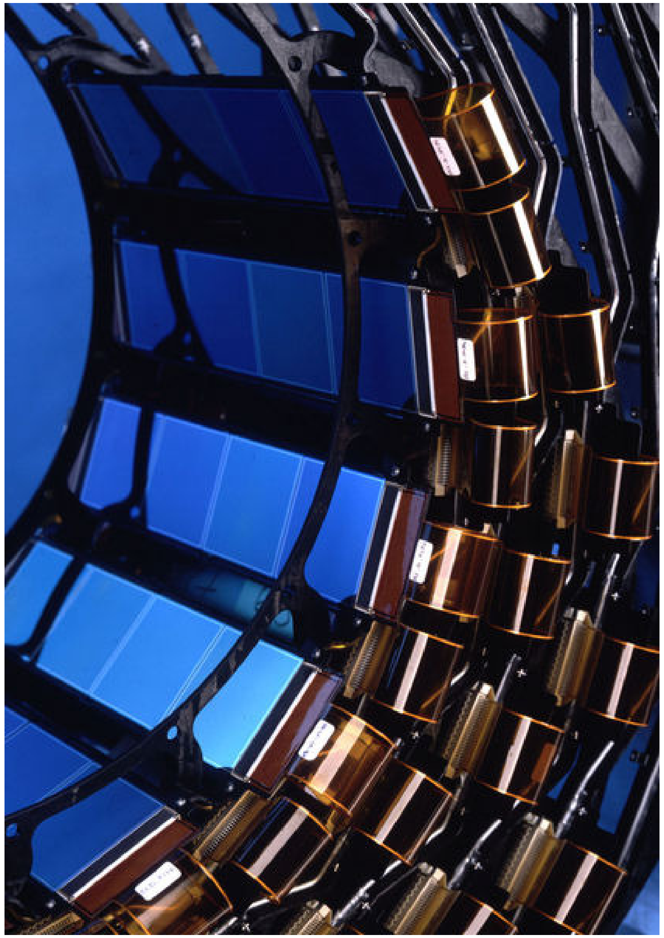
position resolution: pitch $/\sqrt{12}$

Diode array for position measurement

Applications in Basic Research

High Energy Physics

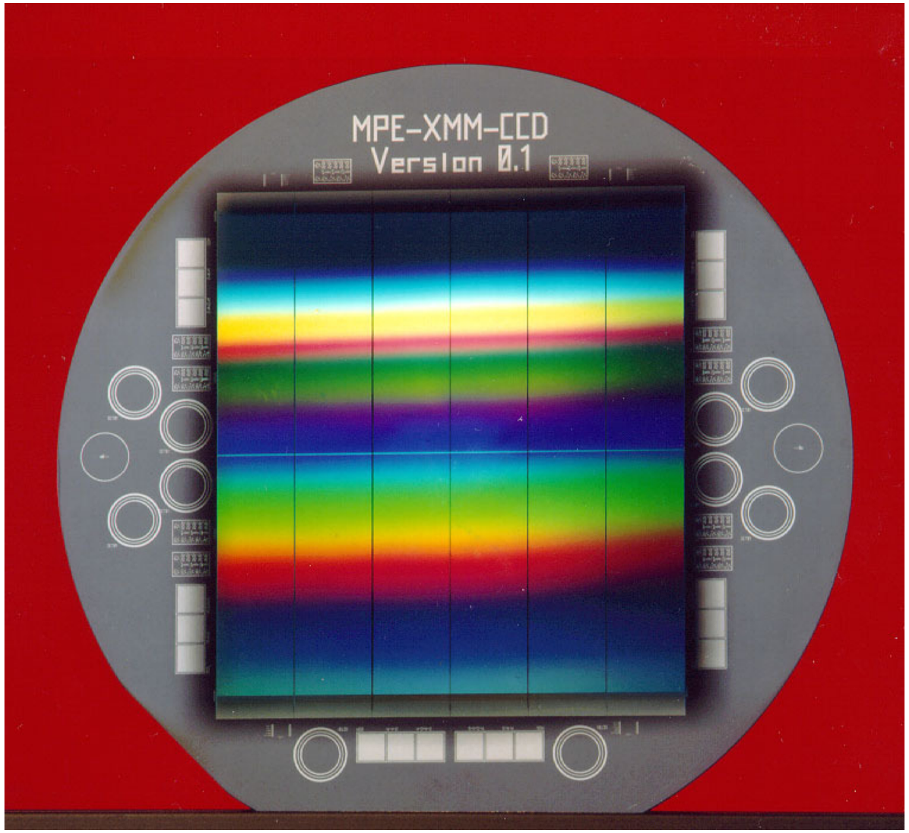


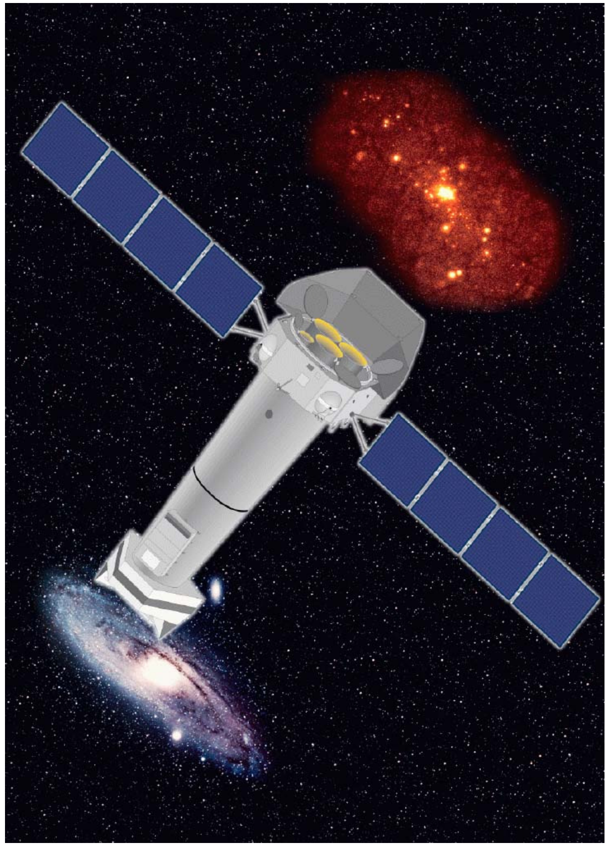


Strip or pixel detectors as inner trackers → position resolution

Applications in Basic Research

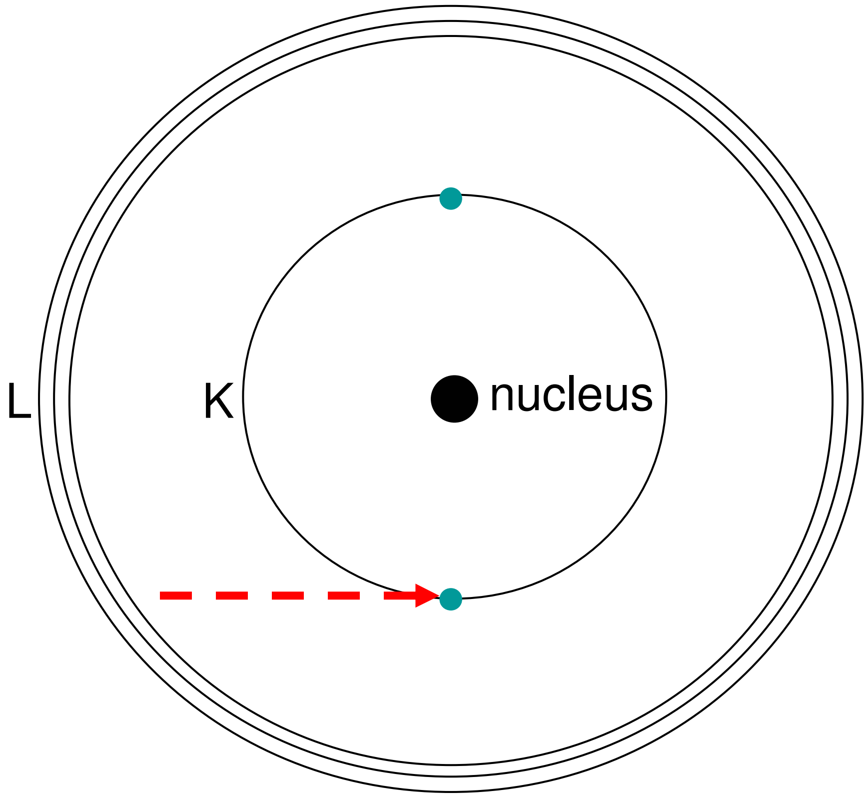
X-Ray Astronomy



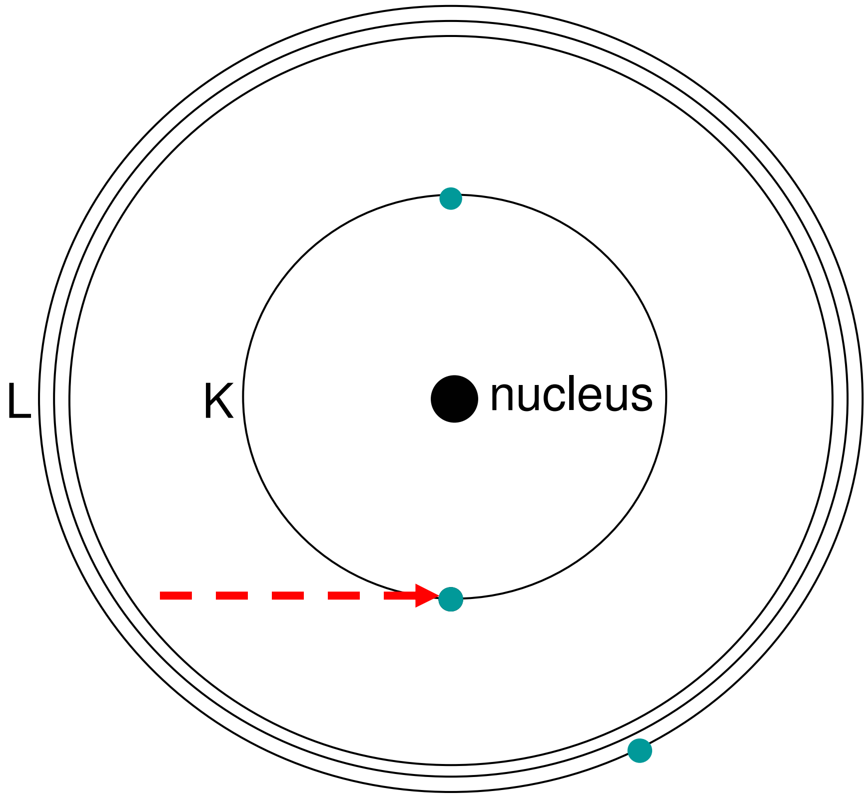


Spectroscopy of cosmic x-ray sources
Fully depleted pn-CCD on ESA's x-ray multi-mirror mission (XMM)

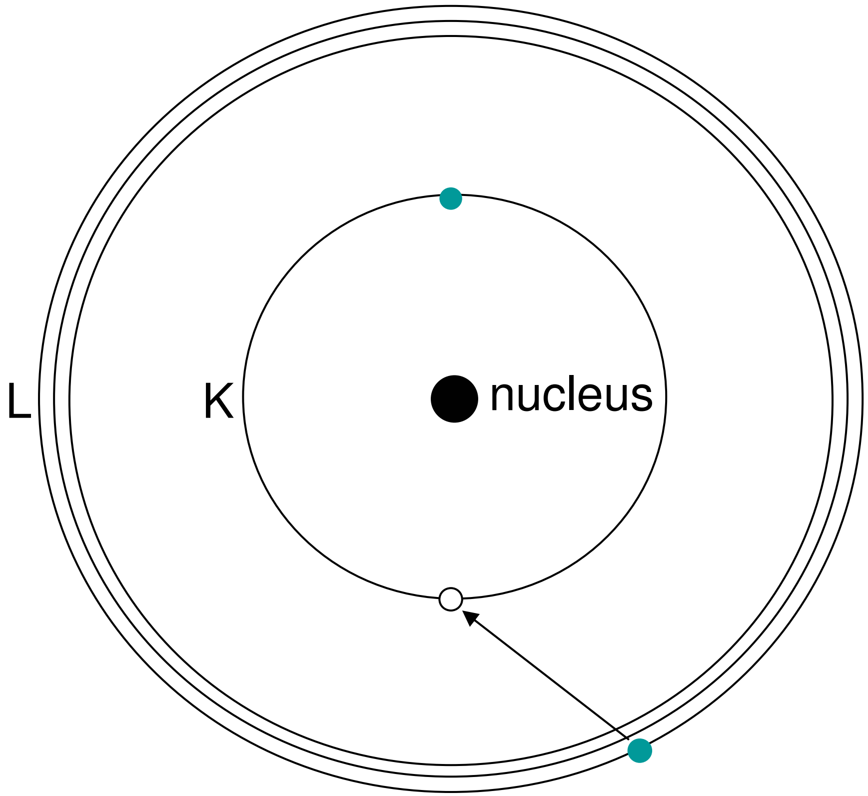
X-Ray Fluorescence



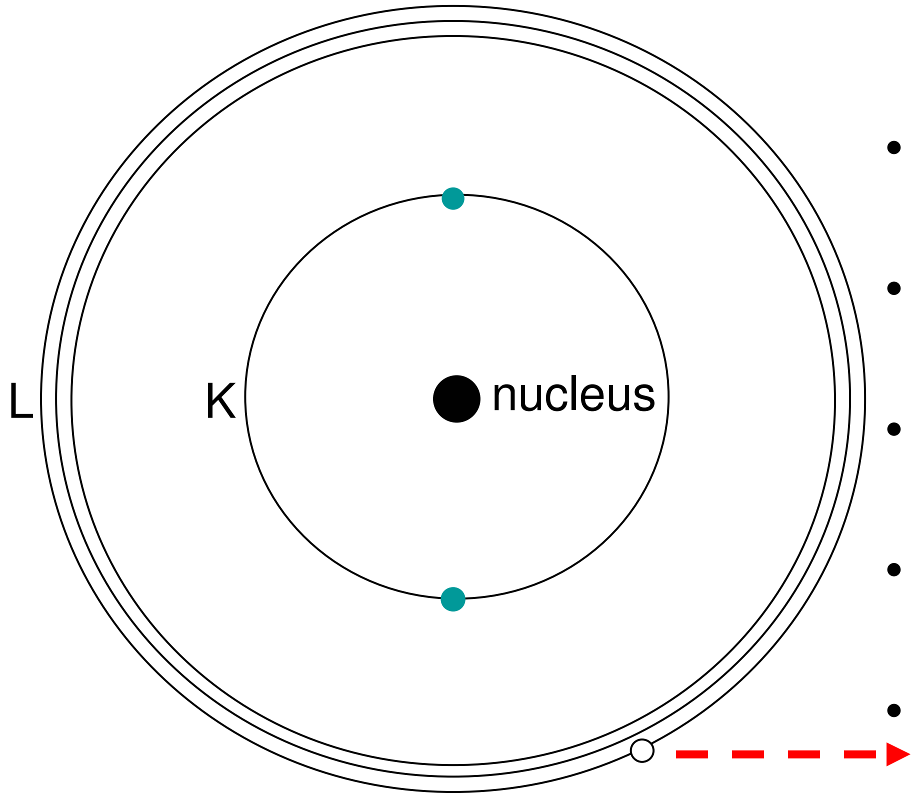
X-Ray Fluorescence



X-Ray Fluorescence



X-Ray Fluorescence

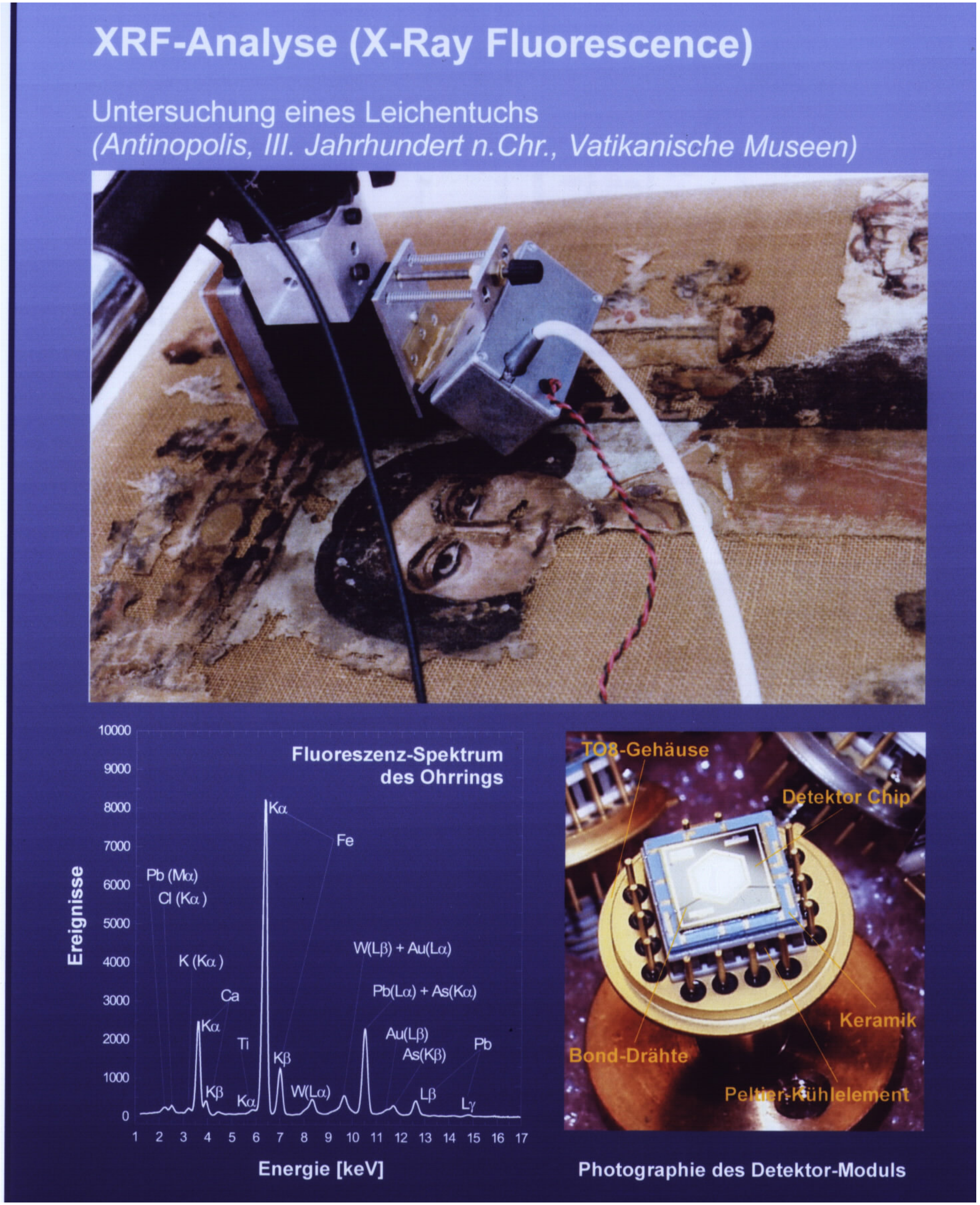


- Energy of fluorescence photon = difference of binding energies
- Moseleys Law: E_F prop. to Z^2
- Many transitions possible
- Transitions into K-shell: $K_{\alpha, \beta}$ photons ("peaks")
- Transitions into L-shell: $L_{\alpha, \beta, \gamma, \eta, L}$ photons
- Higher fluorescence yield for high Z elements

Application

X-Ray Fluorescence Analysis (XRF)

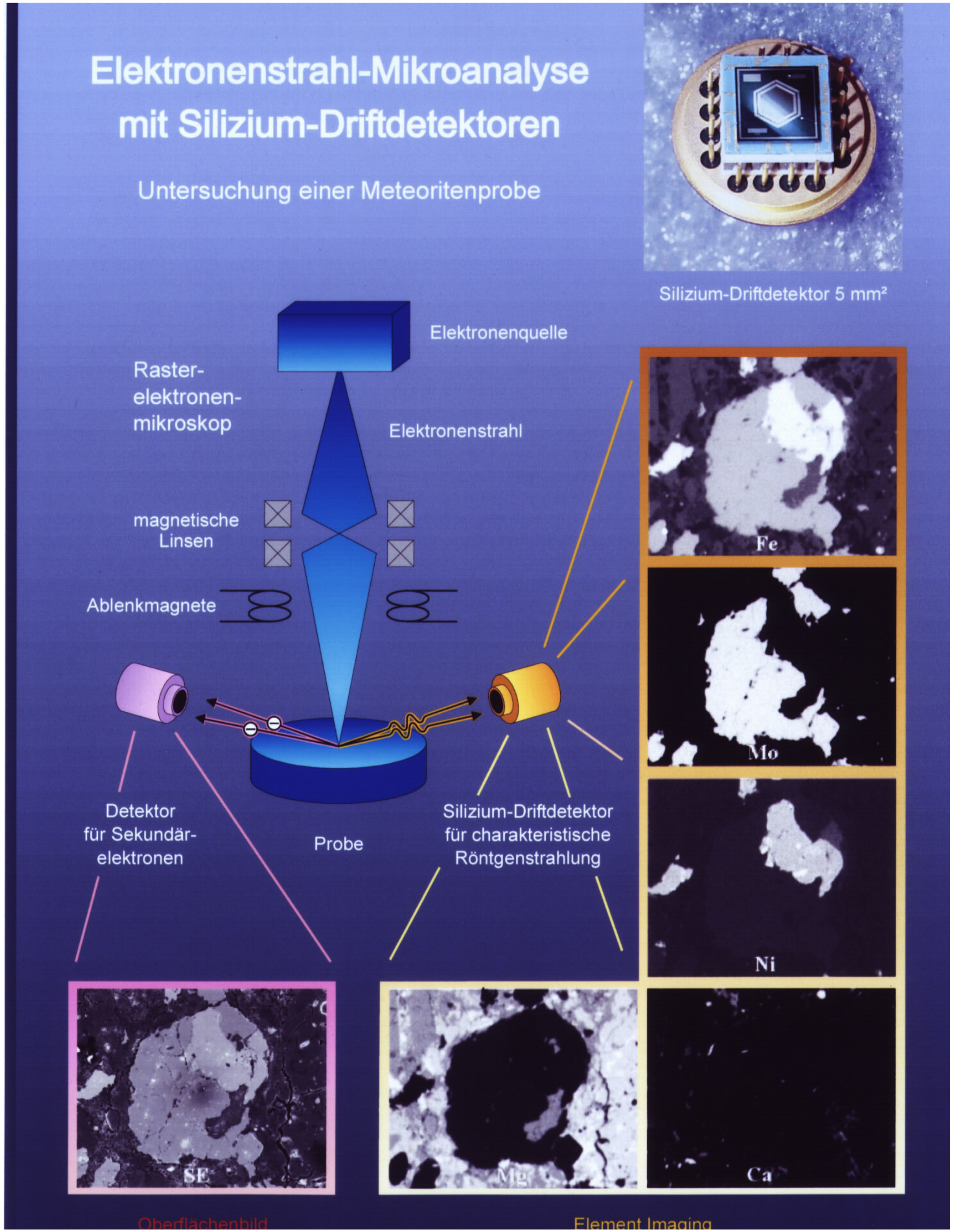
Excitation of sample with X-rays

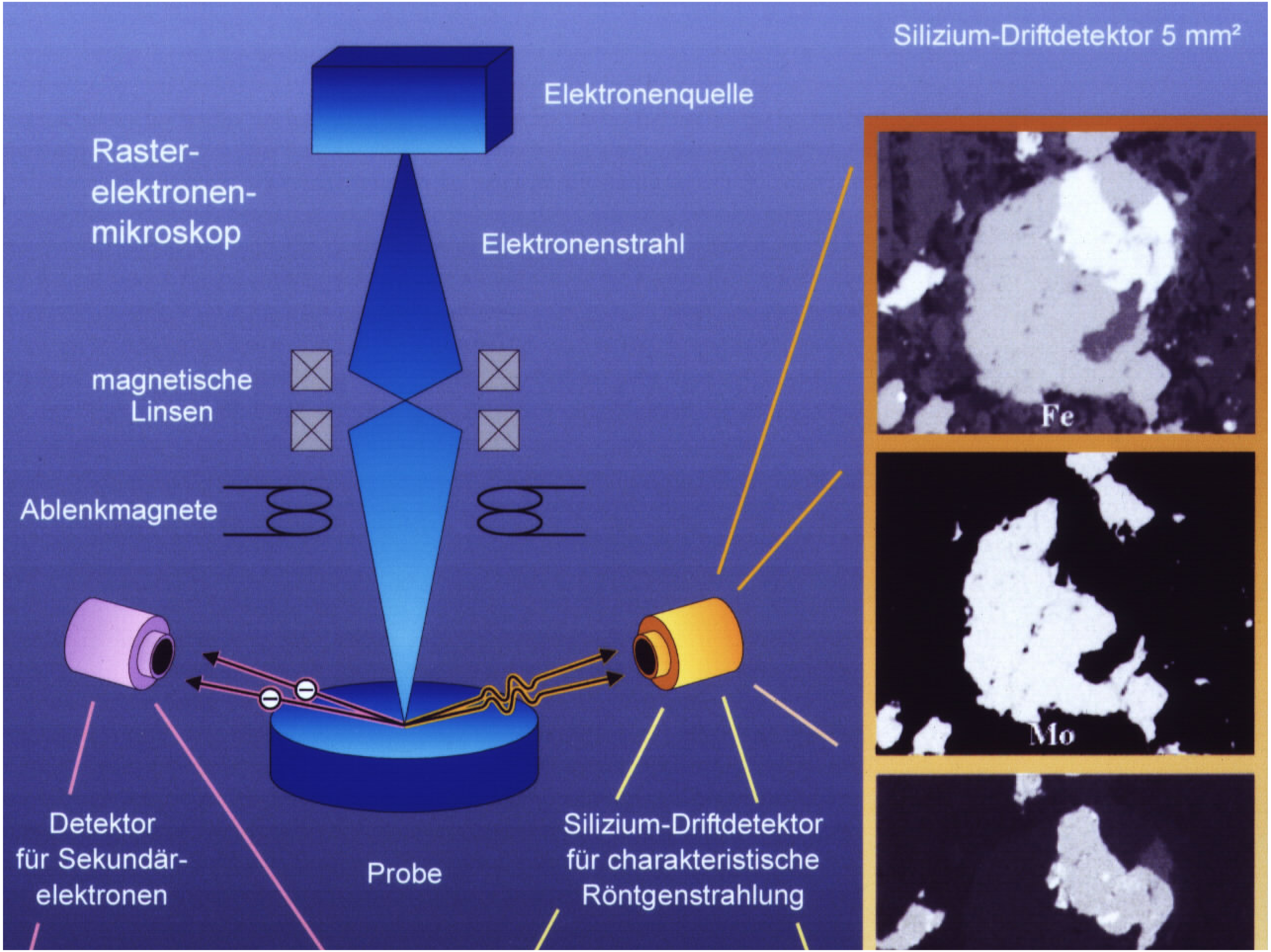


Application

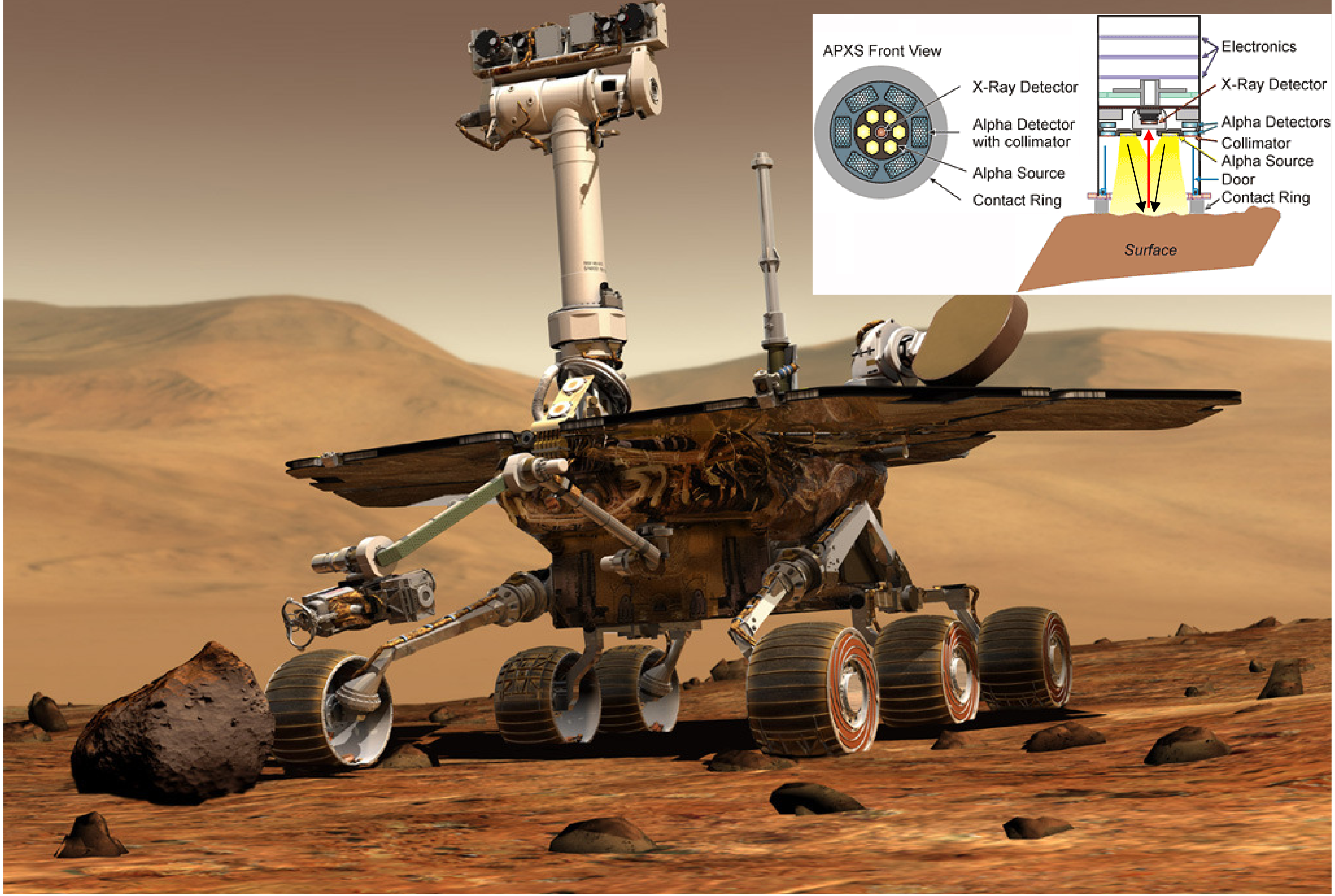
XRF with scanning electron microscopes

Excitation of sample with electrons

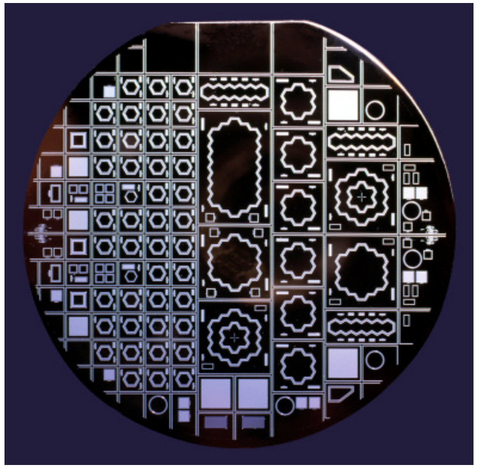



Silizium-Driftdetektor 5 mm²
Elektronenquelle
Raster-
elektronen-
mikroskop
Elektronenstrahl
magnetische
Linsen
Ablenkmagnete
Fe
Mo
Detektor
für Sekundär-
elektronen
Probe
Silizium-Driftdetektor
für charakteristische
Röntgenstrahlung

NASA Mars Rovers



Semiconductor X-Ray Detectors



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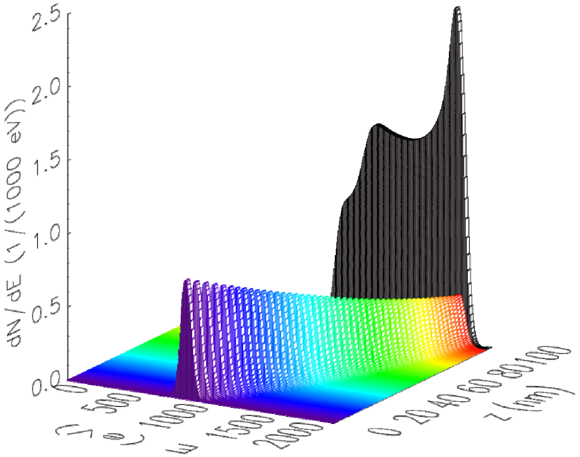
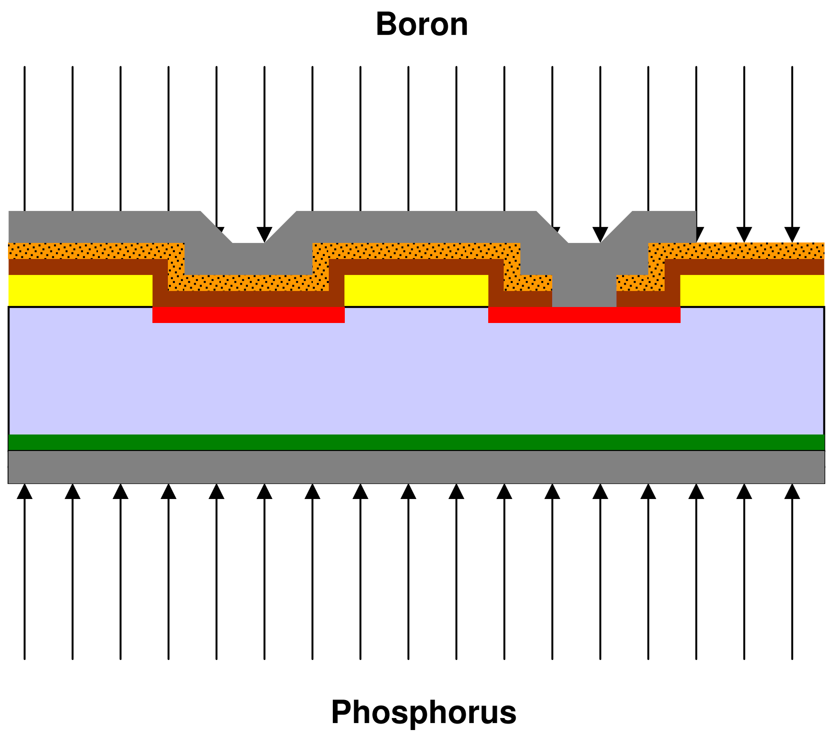


Planar Technology



Doping by ion implantation
and annealing at 600 °C

P: 30 keV, $5\cdot10^{15}$ cm^{-2}

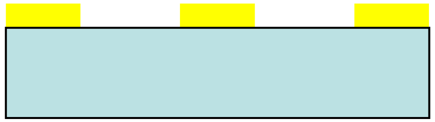
Differences to conventional planar technology

→ Wafer structured on both sides
→ Larger structures
→ Low temperature processes
→ Less diffusion of impurities
→ Low leakage currents and high charge carrier life-times

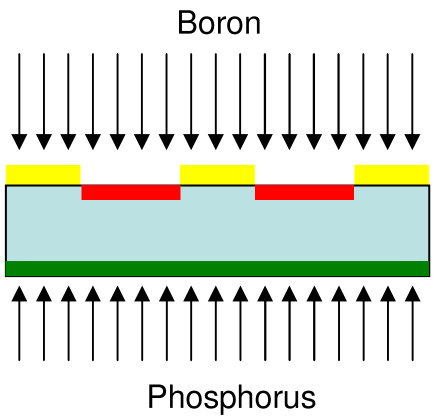
Planar Technology

n-Si wafer

Thermal oxidation

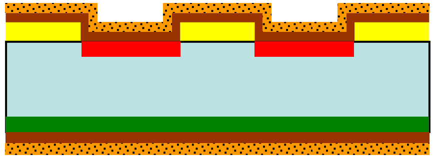


Opening of windows

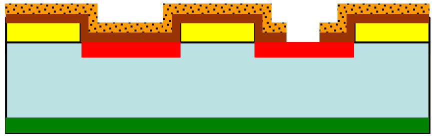


Doping by ion implantation and annealing at 600°C

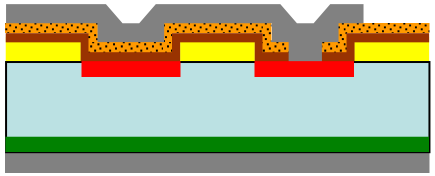
B: 15 keV, 5×10^{14} cm^{-2} P: 30 keV, 5×10^{15} cm^{-2}



Deposition of
LPCVD-Nitride and
LPCVD-Oxide



Opening of
contact holes

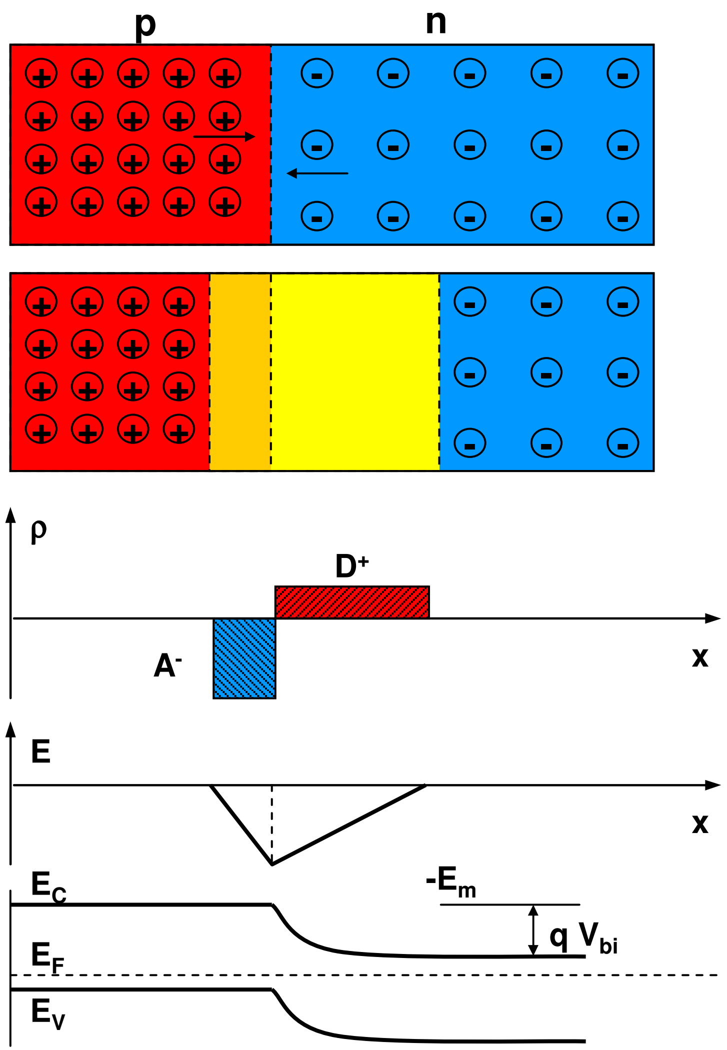


Metal deposition
and patterning

Important Semiconductor Properties

		Si	Ge	GaAs	SiC
atomic number		14	32	31 / 33	14 /12
atomic weight		28.09	72.59	144.63	40
density	g/cm^3	2.33	5.33	5.32	3.21
band gap (RT)	eV	1.12	0.66	1.42	3.0
av. energy for e-h pair	eV	3.65	2.85	4.2	~ 8.5
electron mobility μ_e	cm^2/Vs	1500	3900	8500	~ 1000
hole mobility μ_h	cm^2/Vs	450	1900	400	~ 100
minority carrier lifetime τ	s	$2.5 \cdot 10^{-3}$	10^{-3}	$\sim 10^{-8}$	$\sim 10^{-6}$
$\mu\tau$ – product (e)	cm^2/V	2 – 5	5	$\sim 10^{-4}$	$\sim 10^{-3}$
$\mu\tau$ – product (h)	cm^2/V	1 – 2	2	$\sim 10^{-5}$	$\sim 10^{-4}$
intrinsic resistivity	Ω cm	$2.3 \cdot 10^5$	47	10^8	$> 10^{12}$
intrinsic carrier conc.	cm^{-3}	$1.45 \cdot 10^{10}$	$2.5 \cdot 10^{13}$	$1.8 \cdot 10^6$	10^{-6}

pn-Junction for Detector Applications



diffusion of majority carriers

formation of depletion layers

fixed space charge of
acceptors (A^-) and donors (D^+)

electric field due to space charge

band bending of the junction
built in voltage

Properties of Si pn-Junction Detectors

Depletion layer thickness d

$d/\mathrm{cm} = 5 \cdot 10^{-3} \, (\rho \; U/(\Omega\mathrm{cmV}))^{1/2}$

ρ resistivity
U bias voltage

Capacitance C

$C/\mathrm{pF} = 2 \cdot 10^{4} \; A/\mathrm{cm}^2 (\rho \; U/(\Omega\mathrm{cmV}))^{-1/2}$

A junction area

Reverse current I_R

$I_R = I_D + I_S + I_G$

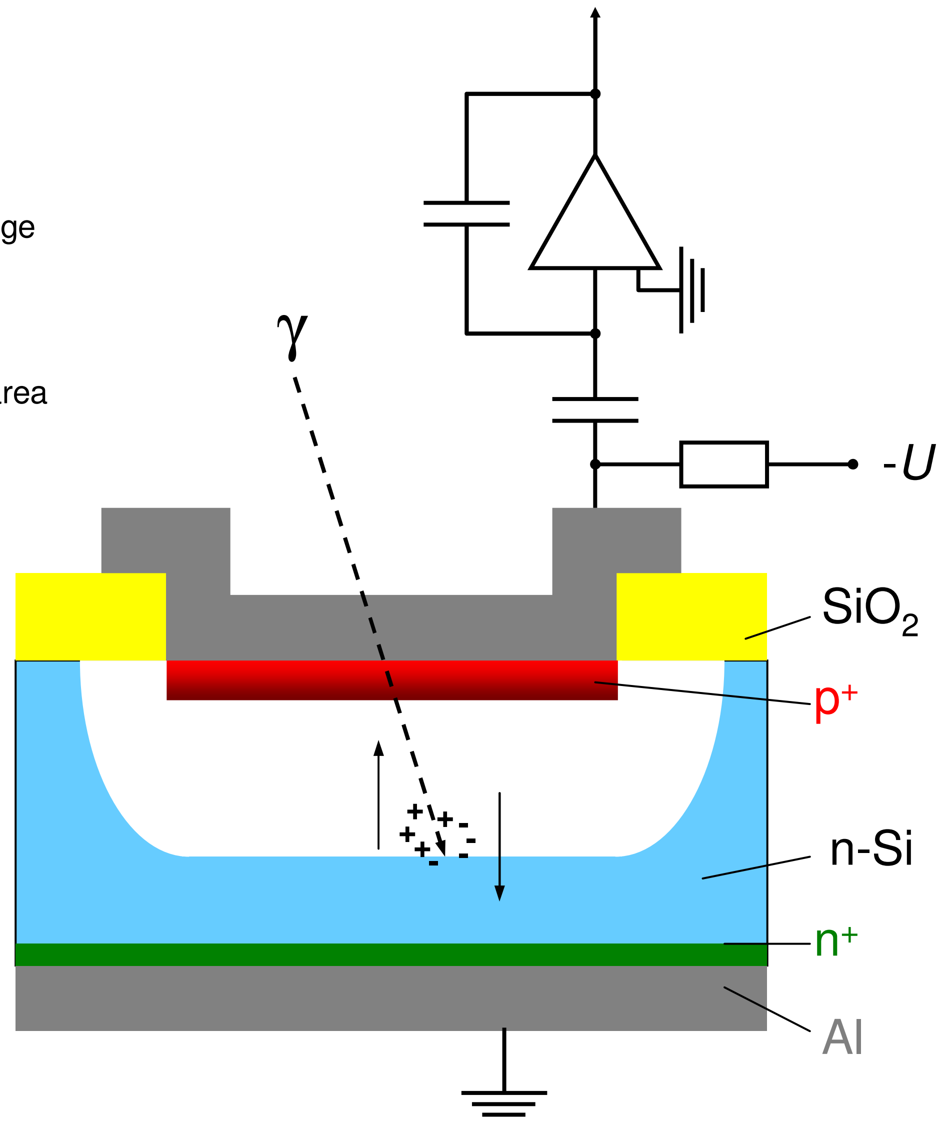
I_D diffusion current
I_S surface leakage c.
I_G generation current

For thick depletion layers

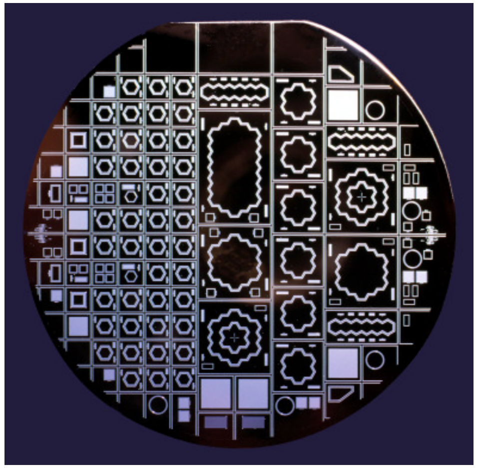
$I_R = I_G = q \, (n_i/\tau) A \, 5 \cdot 10^{-3} \, (\rho \; U)^{1/2}$

$I_R \sim U^{1/2}/\tau$

n_i $1.5 \cdot 10^{10}$ cm^{-3} intrinsic carrier conc.
τ minority carrier lifetime
q 1.6×10^{-19} As



The Response of Energy Dispersive X-Ray Detectors



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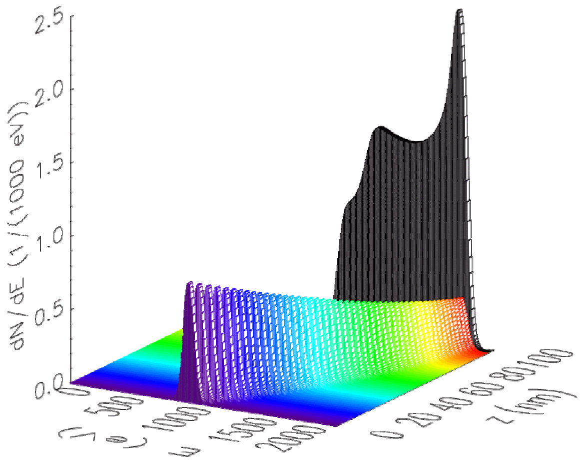
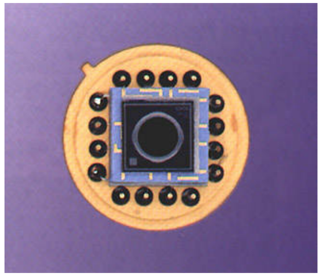
1. Basic Principles
2. Typical Applications
3. Planar Technology
4. Read-out Electronics, Spectra, Efficiency Limits

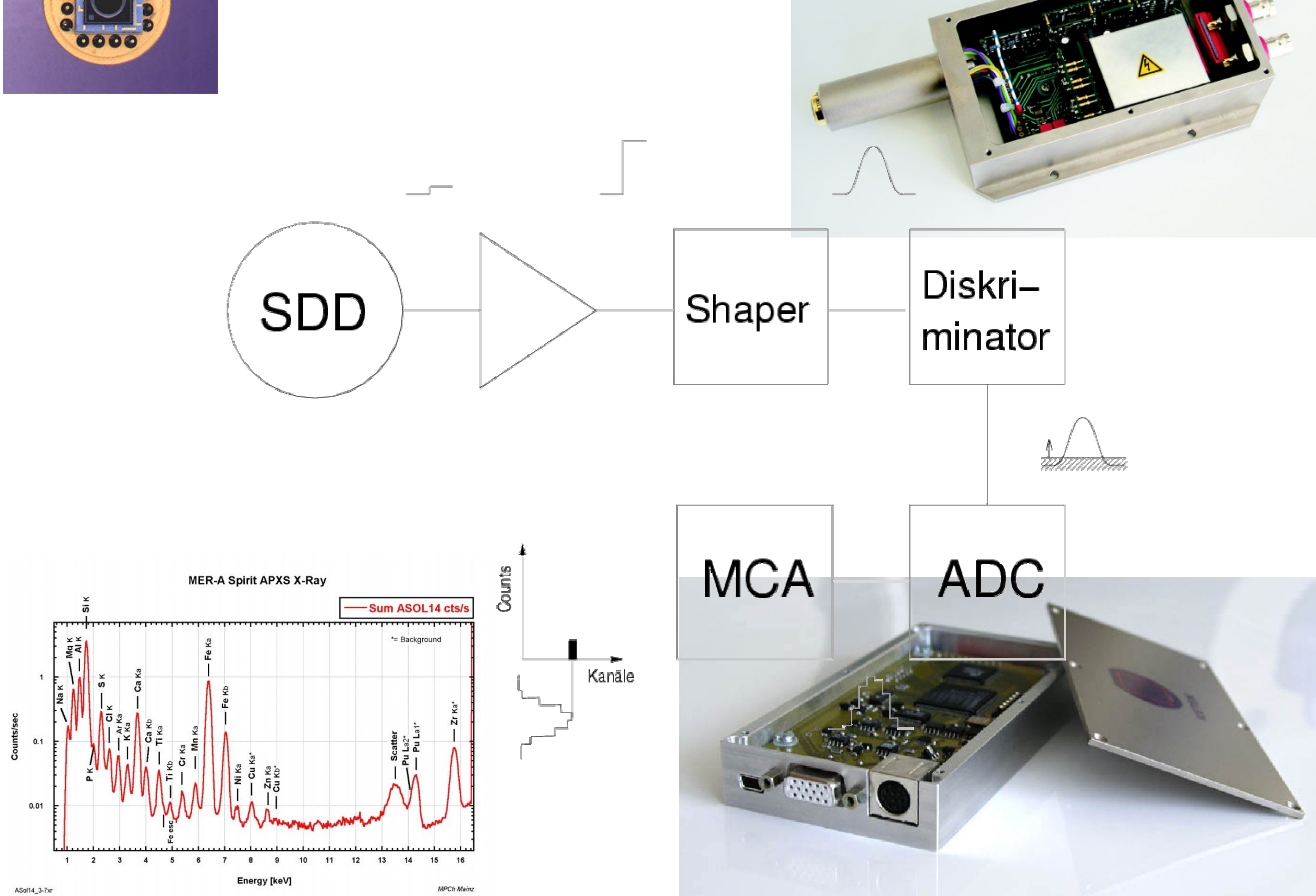


Part B Silicon Drift Detectors

1. SDD structure
2. Low Energy Measurements/Experimental Setup
3. Calculation of Spectral Contributions
4. Results
5. Resume

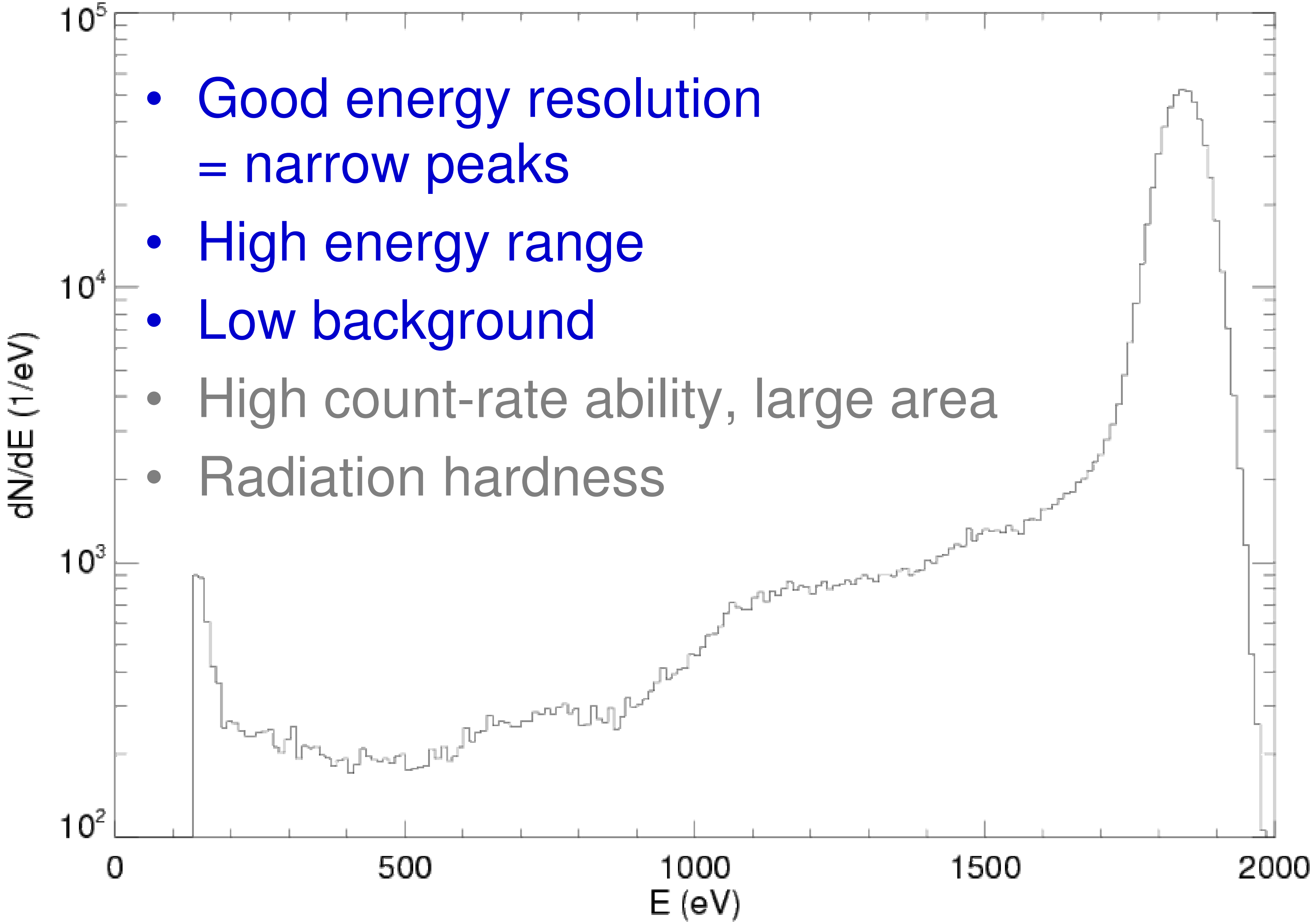


Read Out Electronics

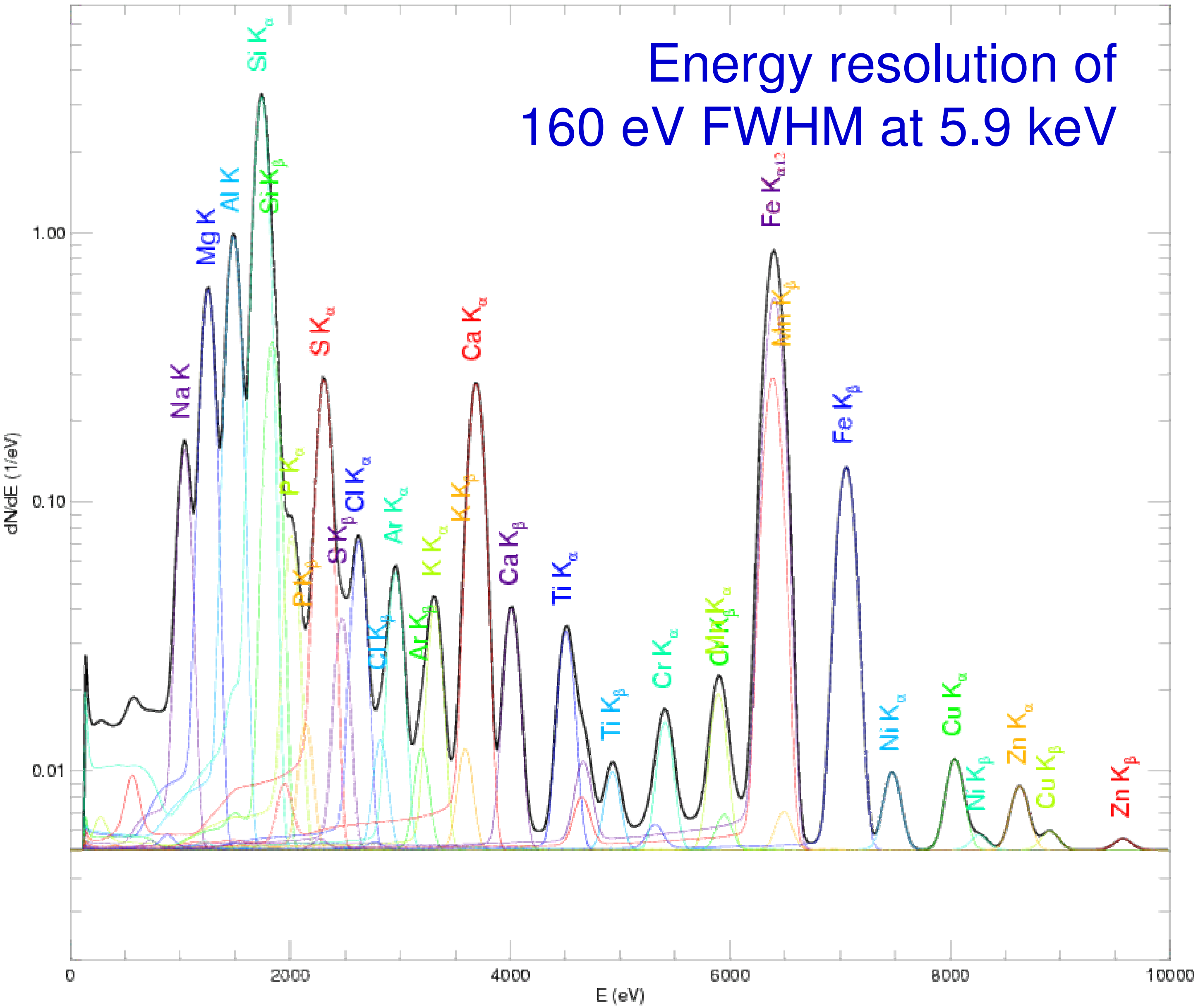


Requirements on Spectrometers

- Good energy resolution
  = narrow peaks
- High energy range
- Low background
- High count-rate ability, large area
- Radiation hardness



Spectrum of Martian Soil



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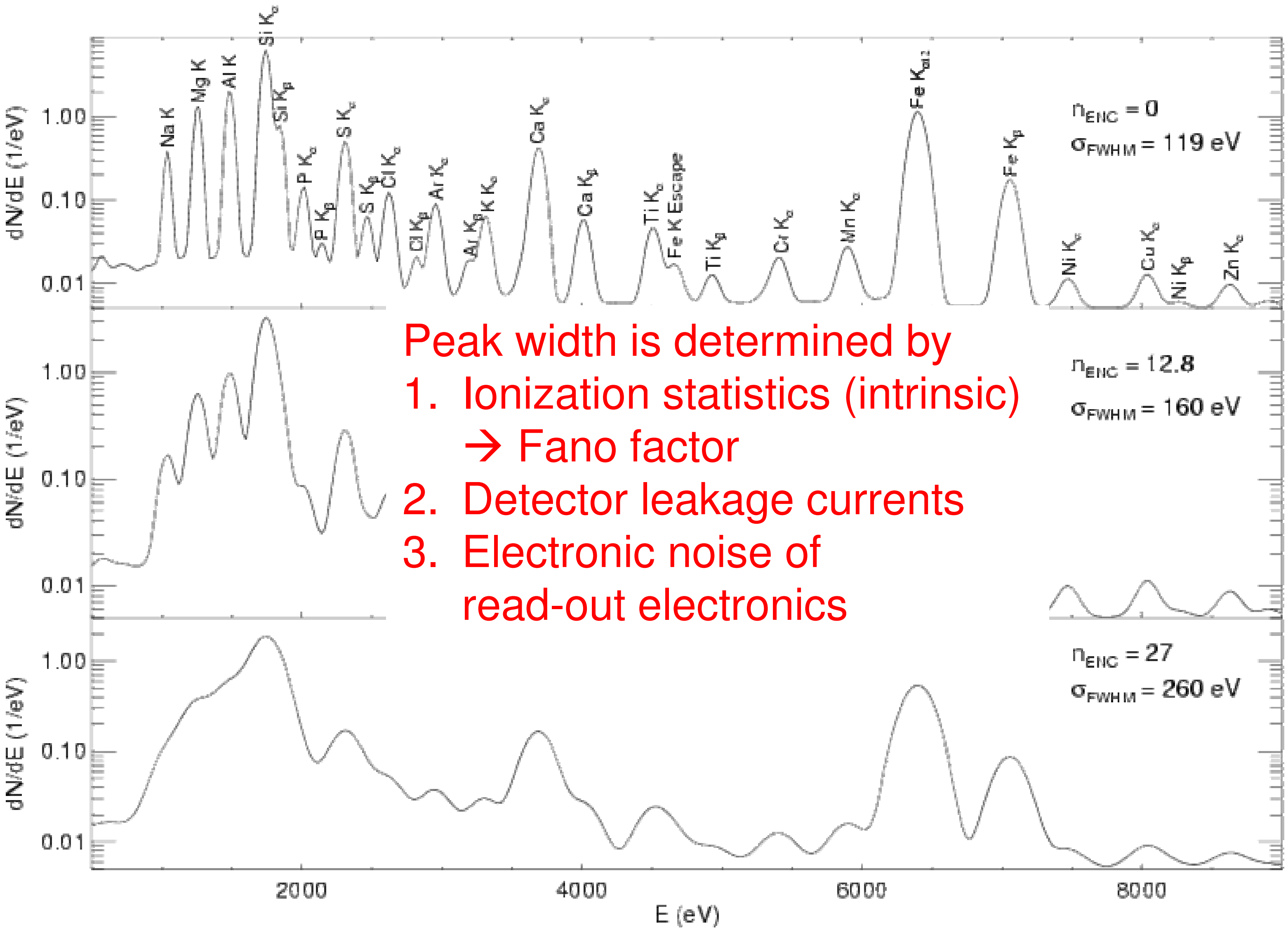
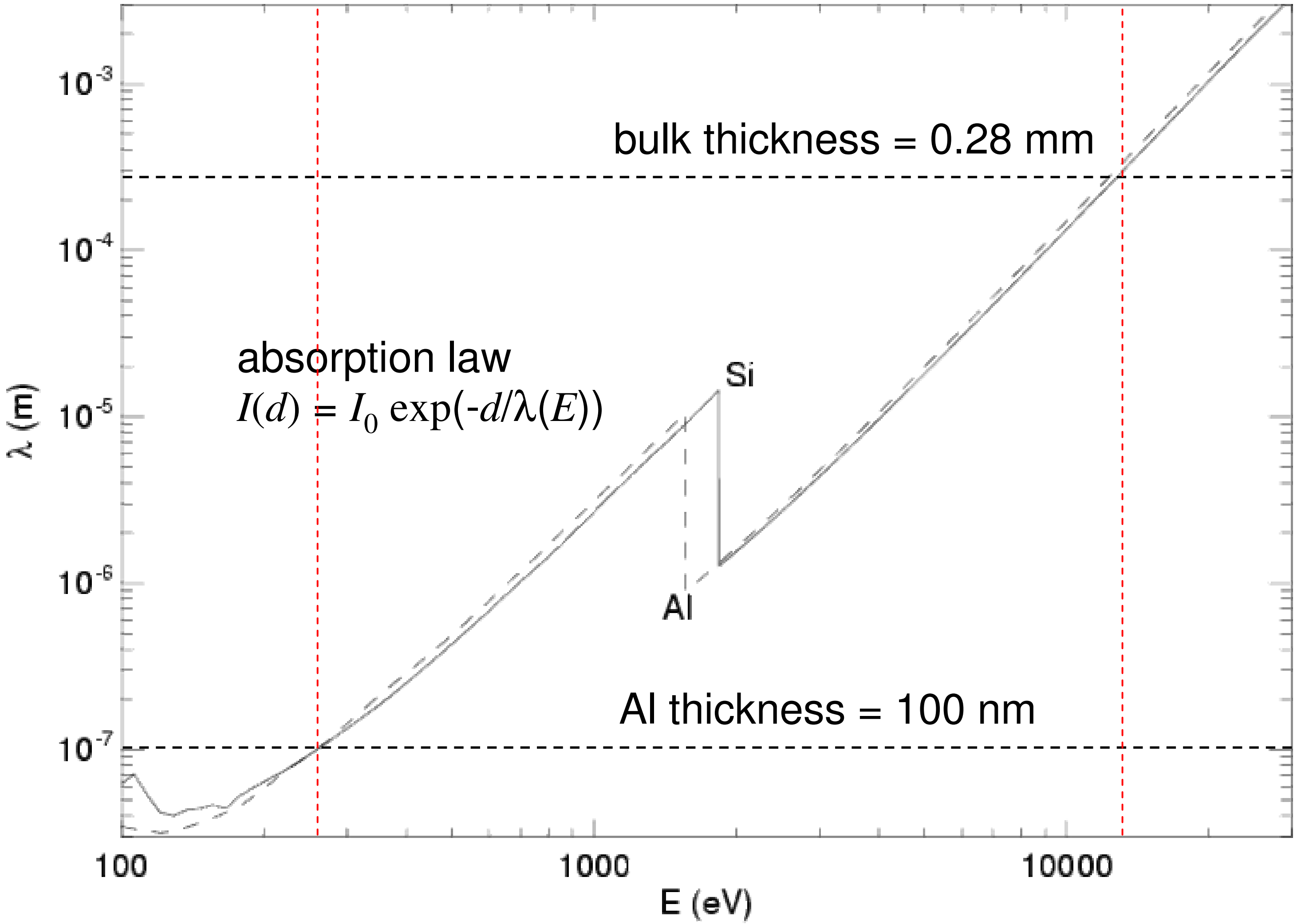


Peak width is determined by

1. Ionization statistics (intrinsic)
   → Fano factor
2. Detector leakage currents
3. Electronic noise of read-out electronics

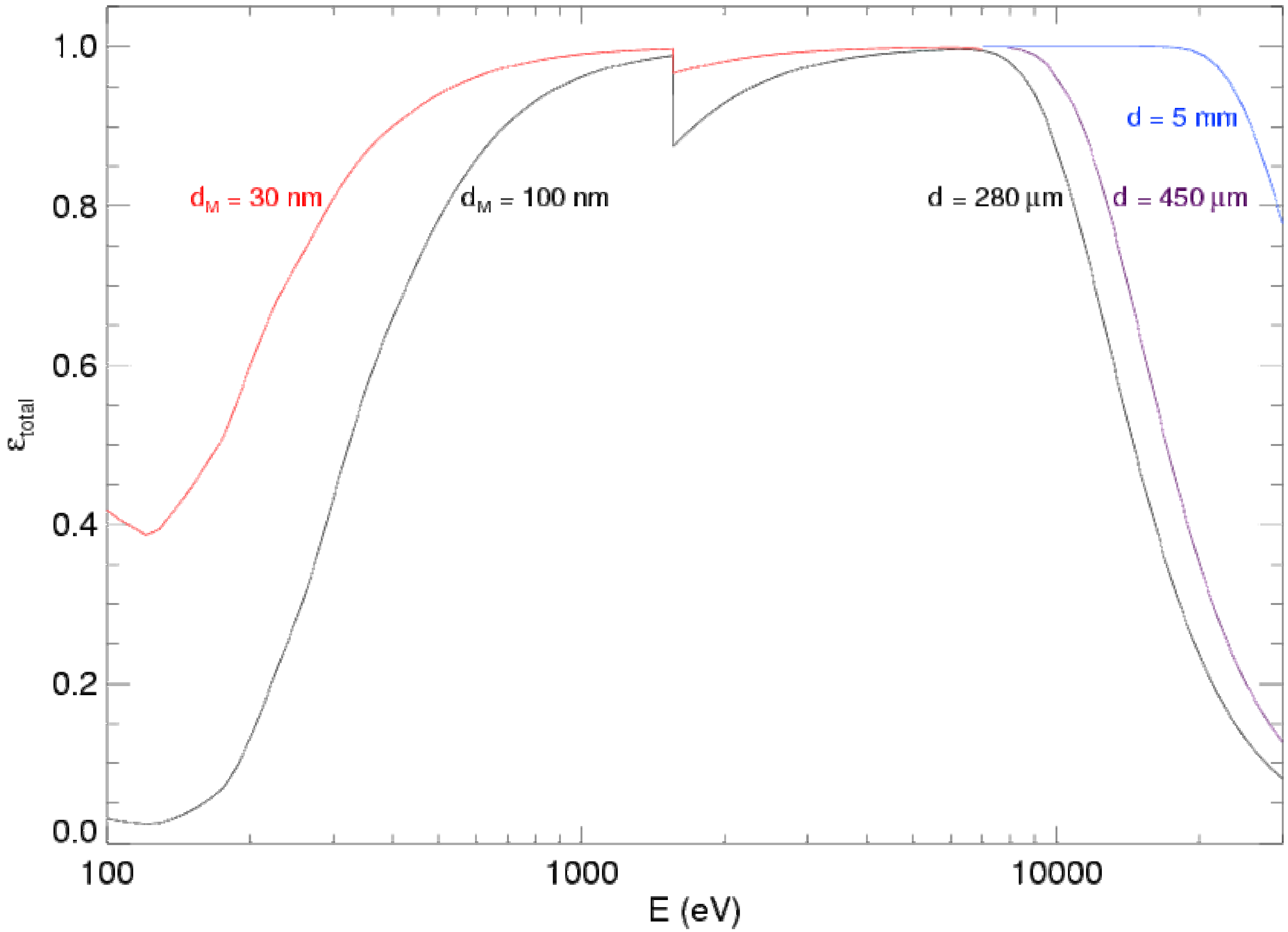
Absorption Lengths of Si + Al



Good efficiency from 250 eV to 11 keV
(20 keV)

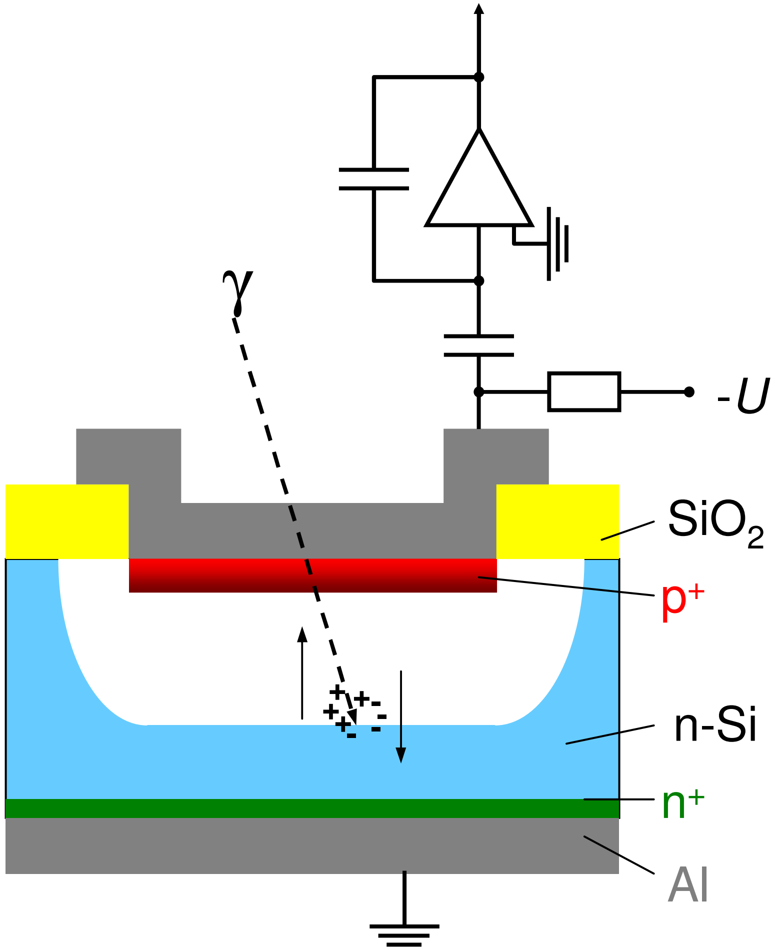
Quantum Efficiency

ε = interaction probability



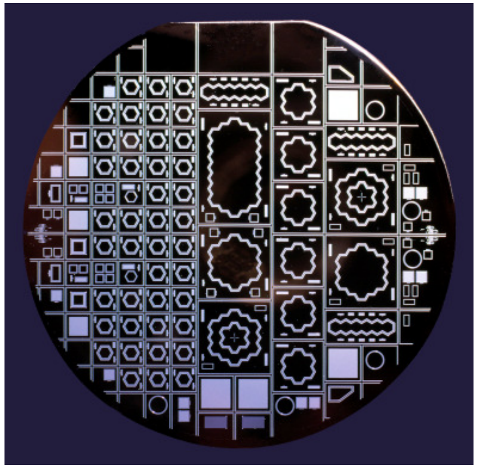
Soft X-Rays from 100 eV – 30 keV

Conventional Radiation Detectors



- Main problem of pin diodes and conventional Si(Li)s:
- Capacitance prop. to area
- Large active area required for high sensitivity
- Low capacitance required for low noise
- The drift principles allows both, large area and low capacitance

The Response of Energy Dispersive X-Ray Detectors



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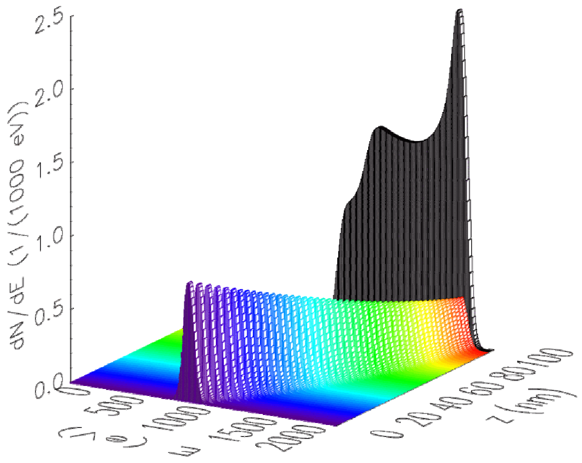
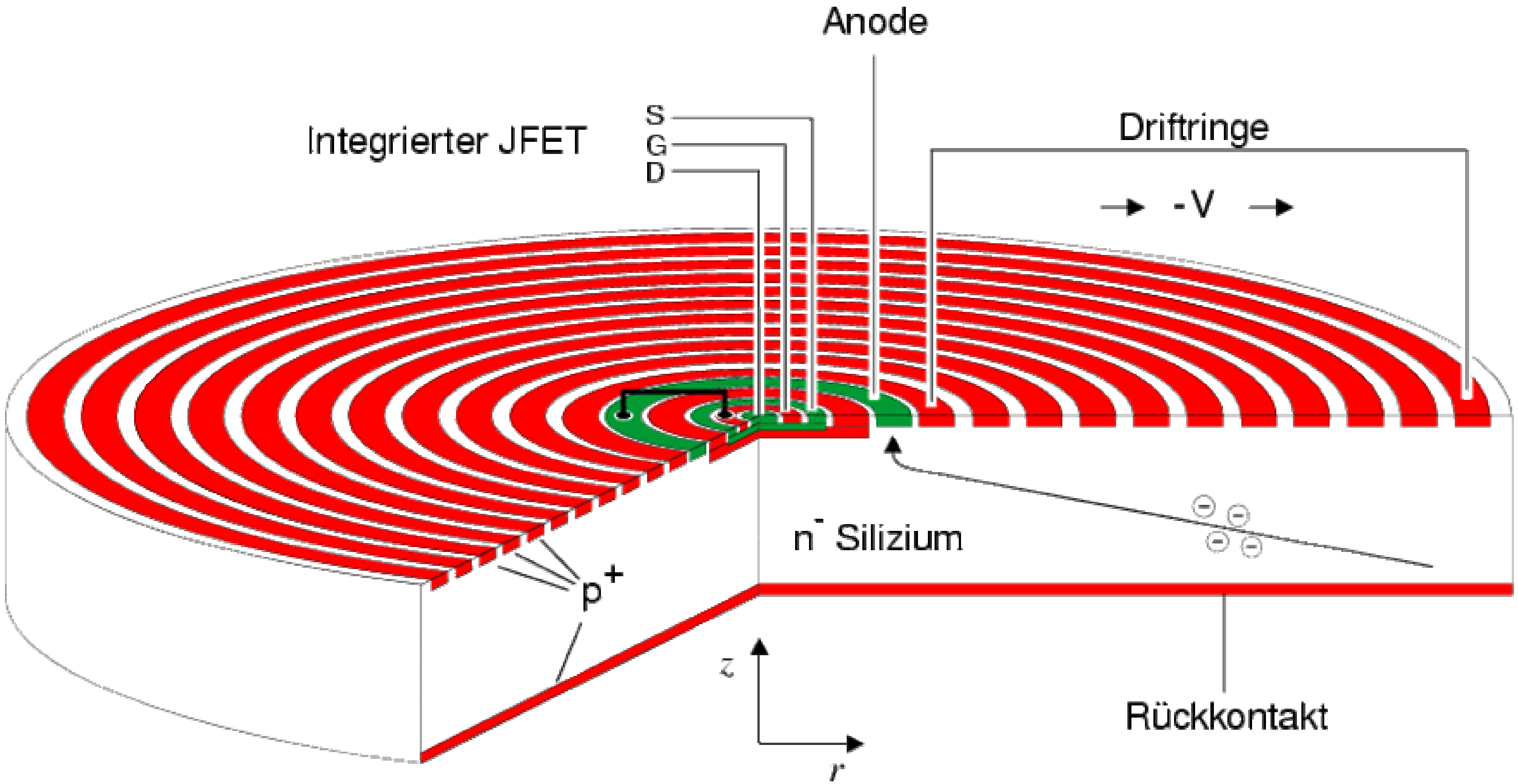


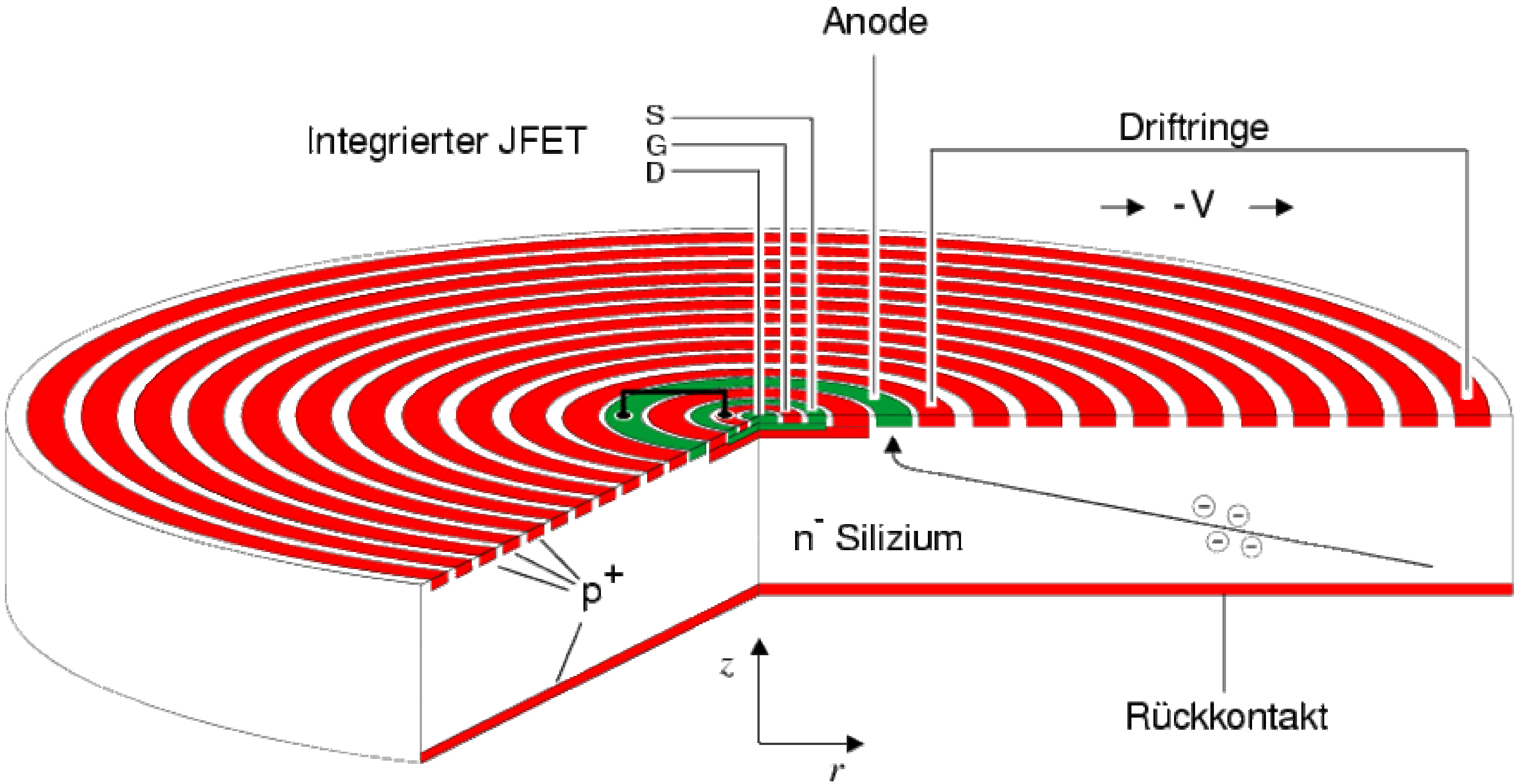
Silicon Drift Detector (SDD)

- High resistivity, high purity n-type silicon ($10^{12}/cm^3$)
- pn junctions on both sides
- Drift rings at the front side, integrated voltage dividers
- Homogeneous entrance window at the back side



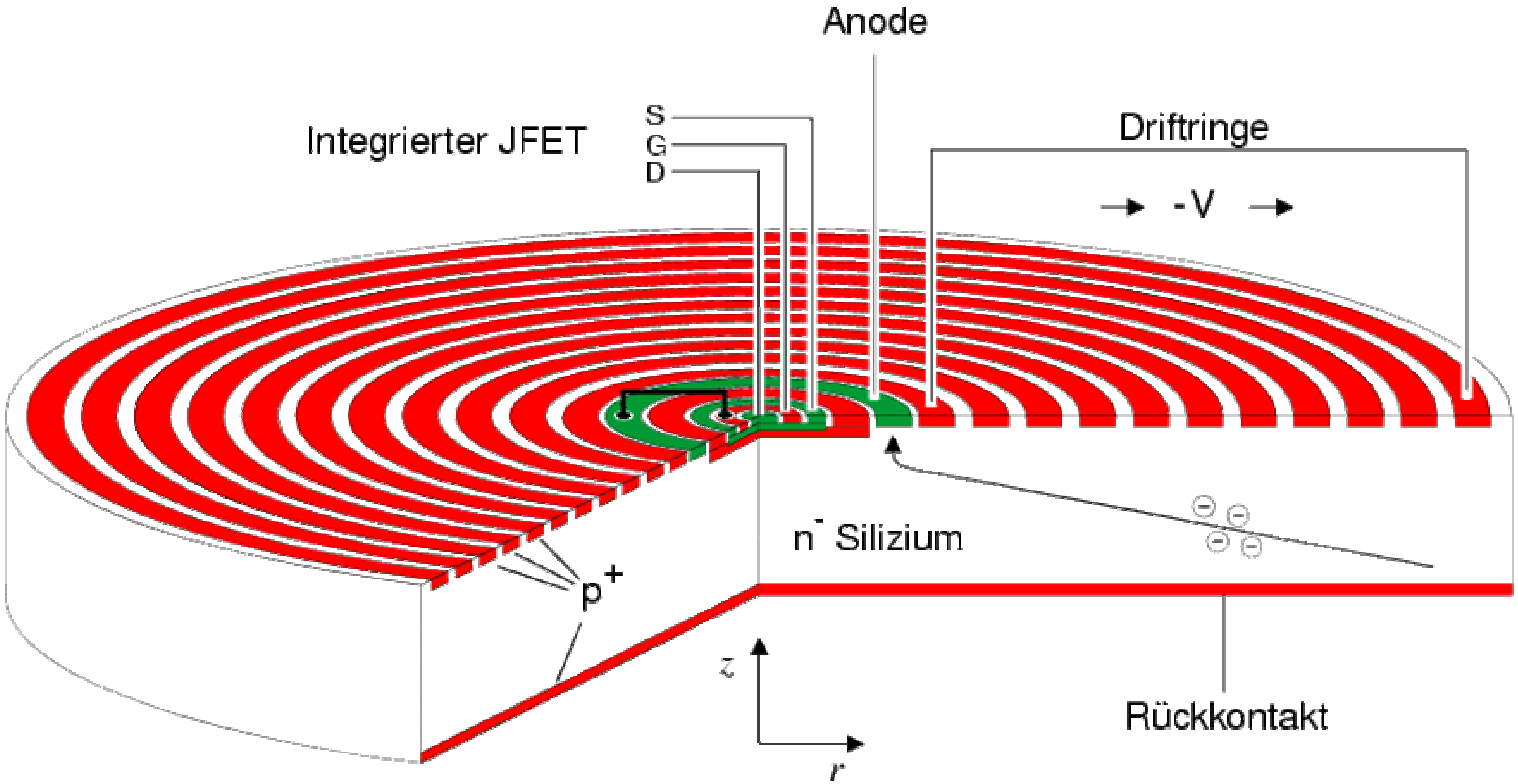
Silicon Drift Detector (SDD)

- Depletion from back contact towards bulk contact (n^+, not shown)
- Vertical and lateral drift field → small anode size → low capacitance
- Low leakage currents, low noise, high energy resolution
- Thermoelectrically cooled to –20 °C (other detectors need 77 K)
- Current entrance window: large background for energies < 300 eV

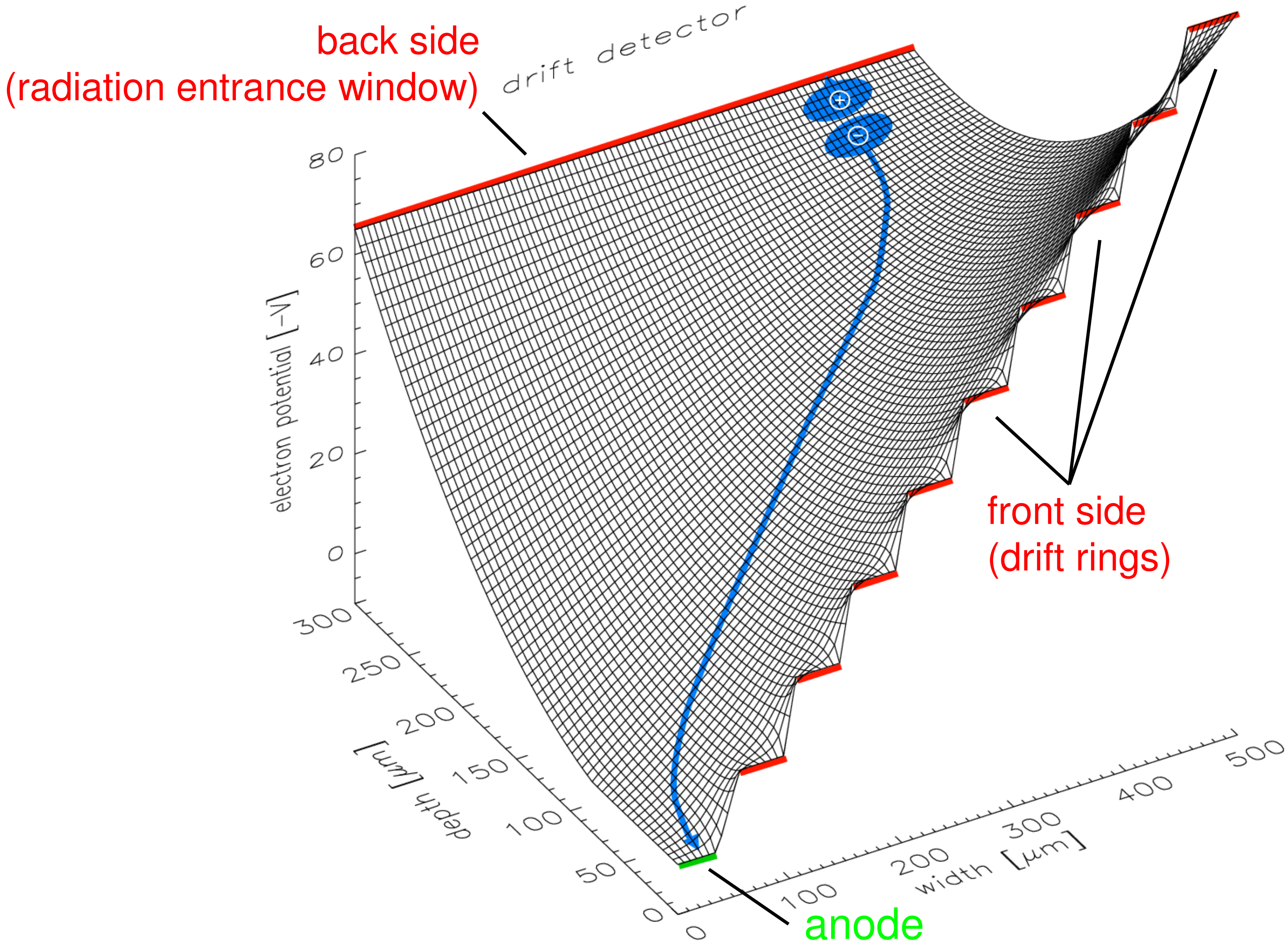


Silicon Drift Detector (SDD)

- Integrated Junction Field Effect Transistor
- Energy resolution down to 135 eV (FWHM) at 5.9 keV
- No pickup noise, no microphony, low overall noise
- Shaping times 250 ns … 1 µs (other detectors: 20 µs)
- Count-rate ability up to 10^6/s, suited for high X-ray intensities



Drift Field Configuration

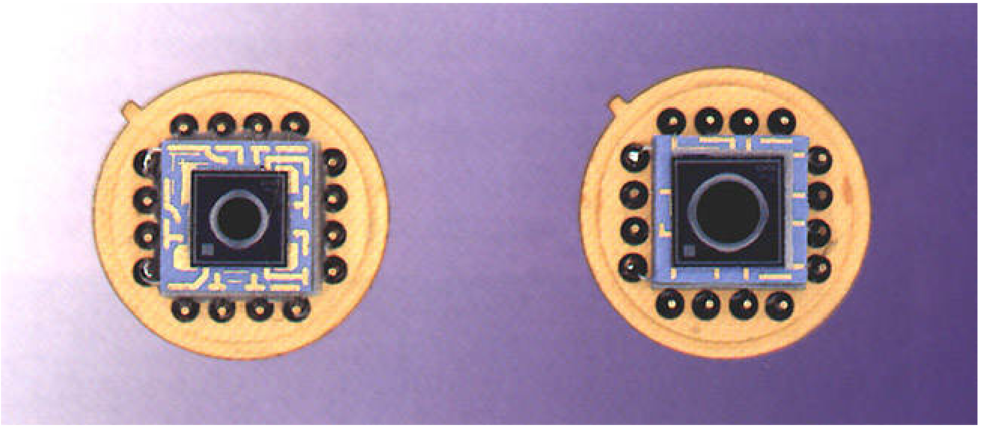


History

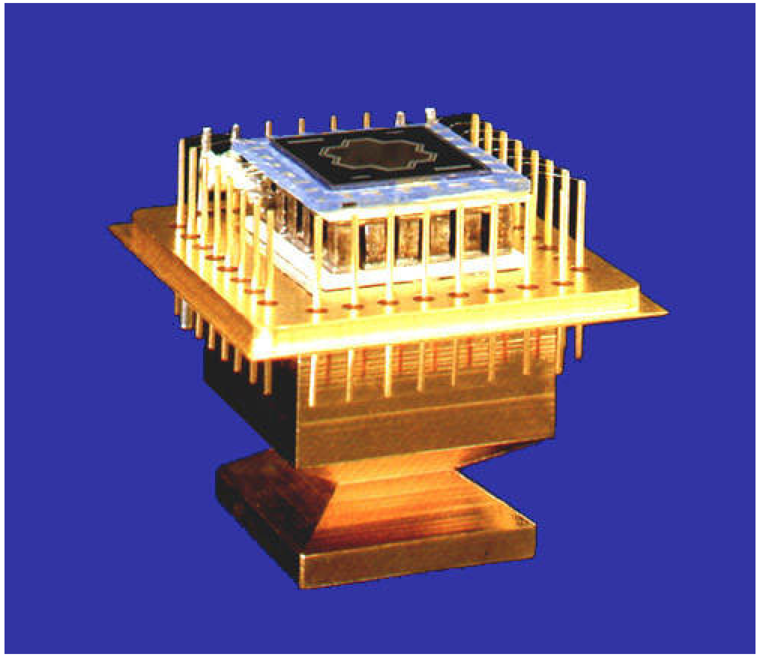
- 1970-76 Josef Kemmer develops planar technology for semiconductor detectors
- 1983 E. Gatti and P. Rehak introduce principle of silicon drift detector
- 1983 Cooperation between J. Kemmer, P. Rehak and MPI, first SDDs produced at TU München
- 1985-2001 Cooperation with MPI to develop new detector concepts: SDD with homogeneous entrance window, completely depleted pn-CCD for XMM X-ray telescope, DEPMOS, DEPFET
- 1991 Qualification of Kemmer‘s planar process for the MPI semiconductor laboratory completed
- 1998 First commercial SDD systems available
- 2003 2000th SDD system sold

Mounted Devices

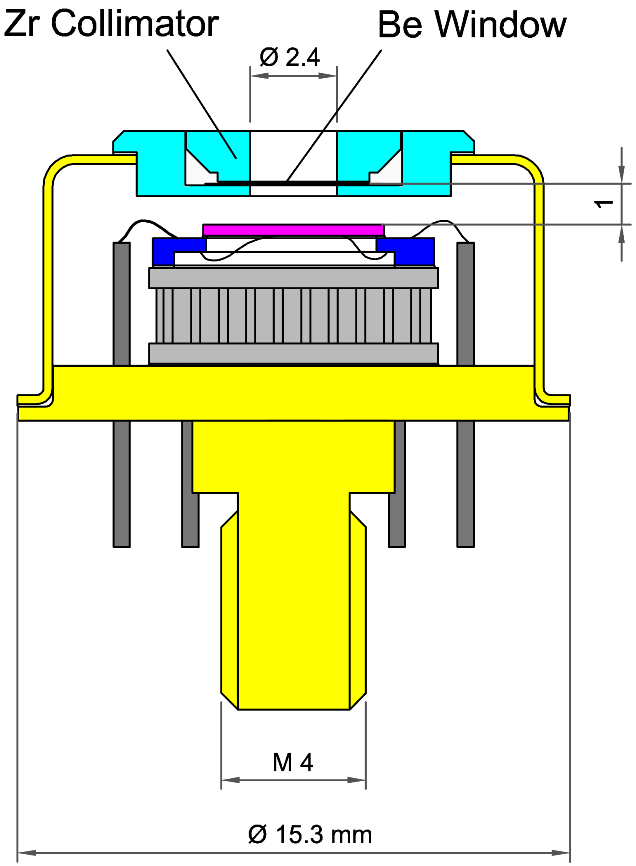
- 5 mm², 10 mm²

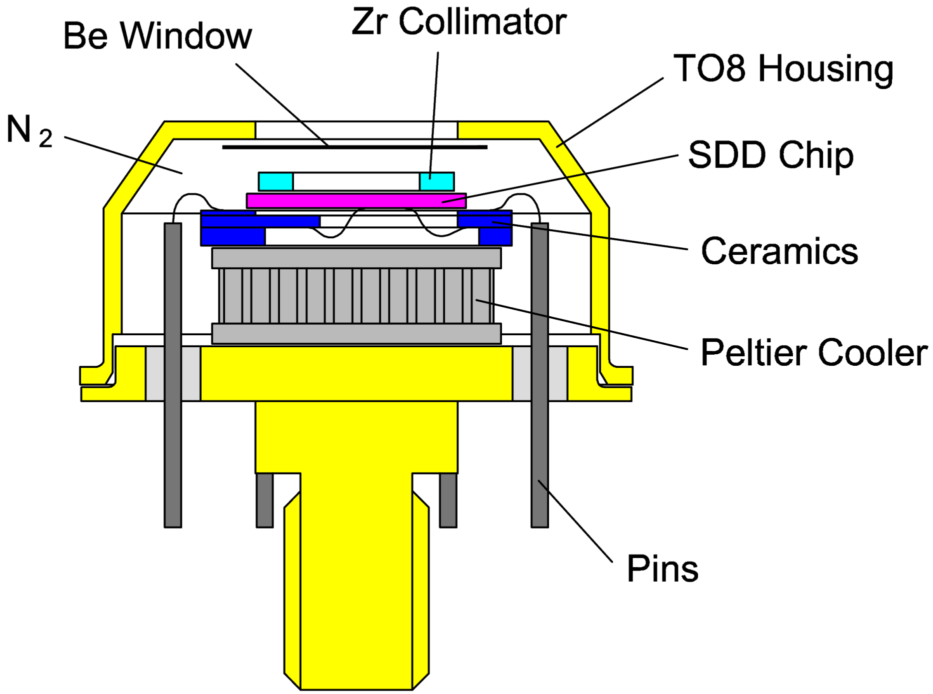


- 7 channel detector with 35 mm²

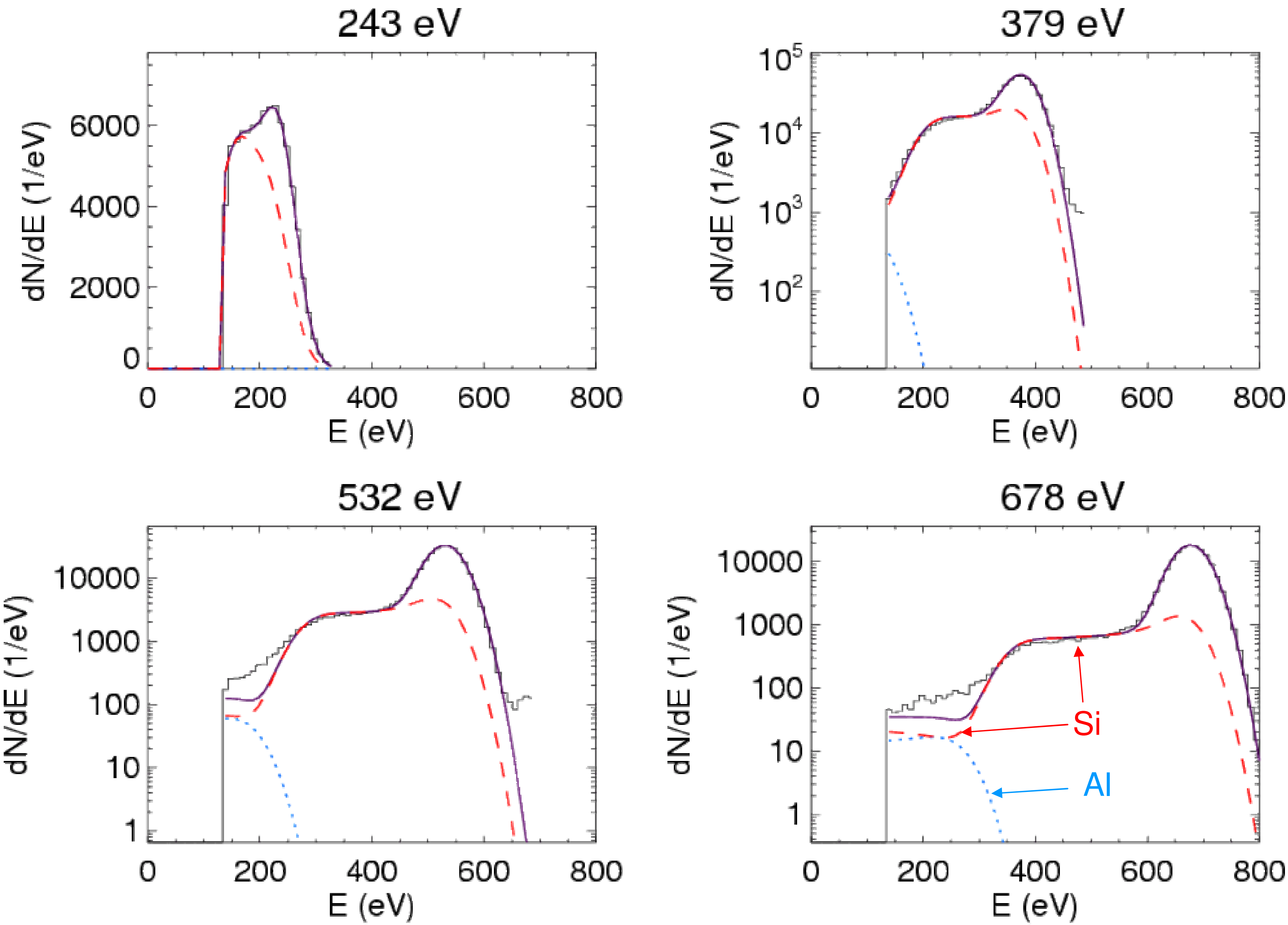


Mounted Devices

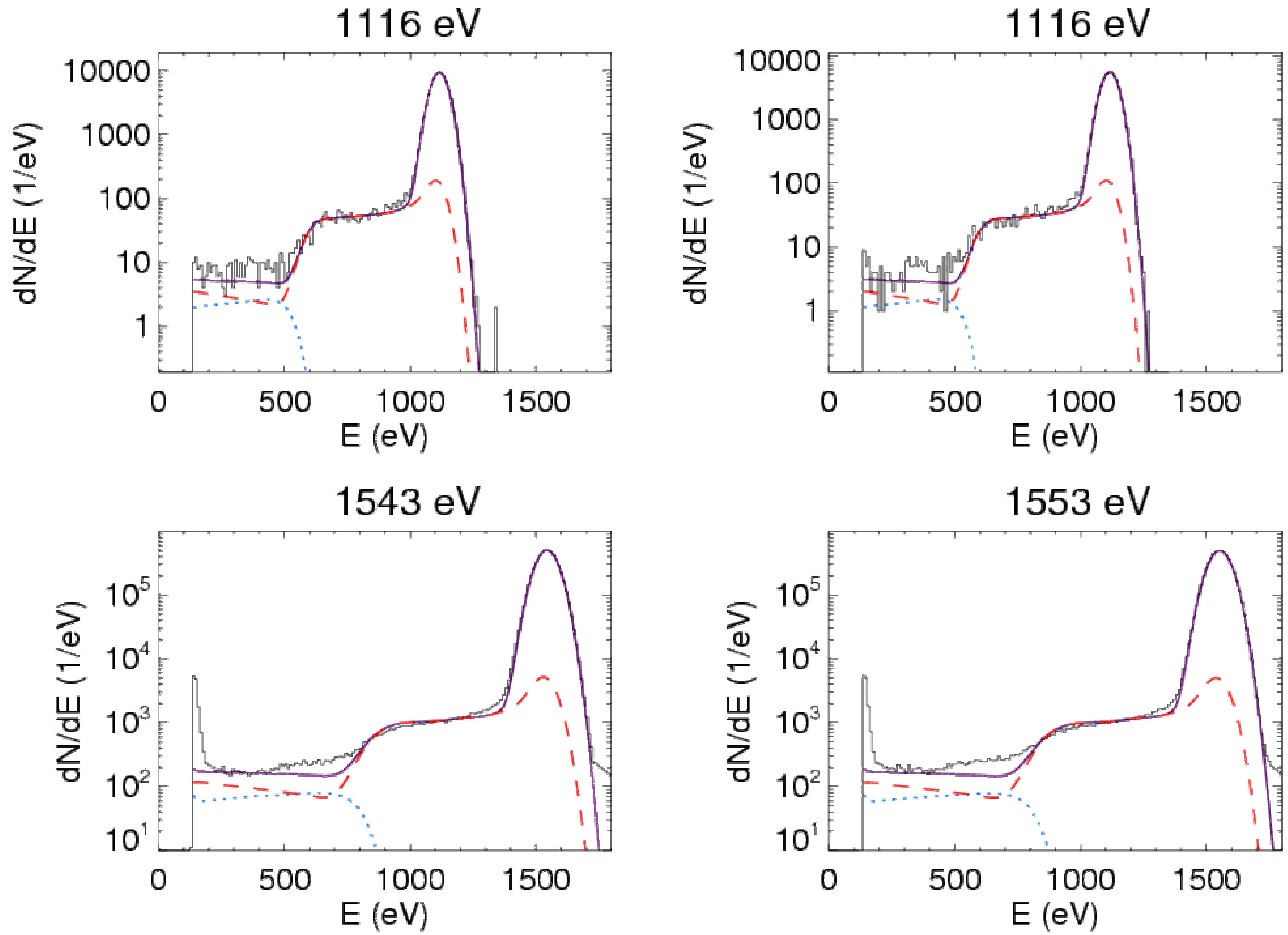




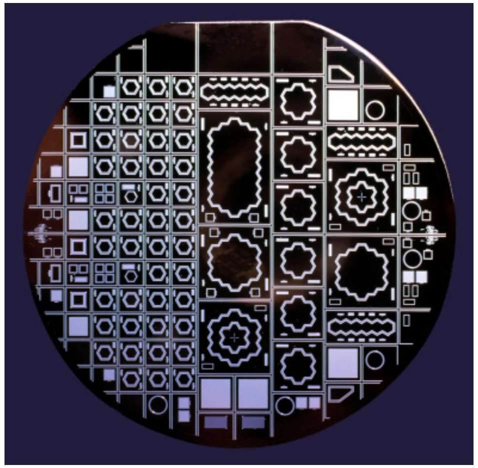
- Illuminated from back-side
- Anode continuously discharged → no reset clock
- Standard: 8 µm Be window
- Polyimide window with Si grid also available
- N_2 filled housing (1 bar or 100 mbar)

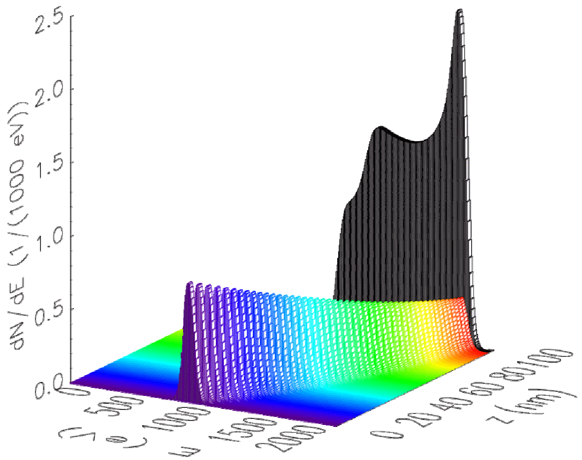


243 eV
379 eV
532 eV
678 eV
dN/dE (1/eV)
E (eV)
0
2000
4000
6000
200
400
600
800
10^2
10^3
10^4
10^5
1
10
100
1000
10000
Si
Al


1116 eV
10000
1000
100
10
1
0
500
1000
1500
dN/dE (1/eV)
E (eV)
1116 eV
10000
1000
100
10
1
0
500
1000
1500
dN/dE (1/eV)
E (eV)
1543 eV
10^5
10^4
10^3
10^2
10^1
0
500
1000
1500
dN/dE (1/eV)
E (eV)
1553 eV
10^5
10^4
10^3
10^2
10^1
0
500
1000
1500
dN/dE (1/eV)
E (eV)

Semiconductor X-Ray Detectors





Part A Principles of Semiconductor Detectors

1. Basic Principles
2. Typical Applications
3. Planar Technology
4. Read-out Electronics

Part B Silicon Drift Detectors

1. Silicon Drift Detectors
2. GaAs Detectors
3. Outlook
4. Resume

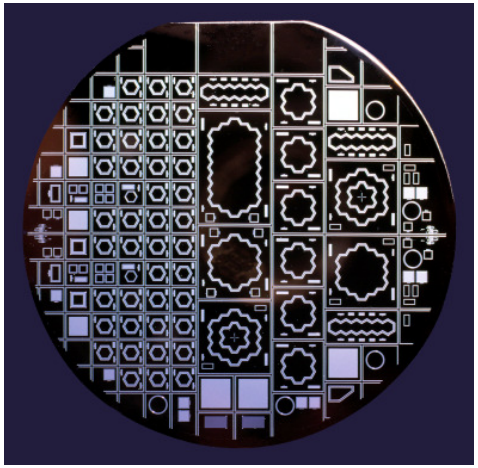
GaAs Detectors

- Silicon detectors with reasonable thicknesses (< 5 mm) are mainly sensitive to soft X-rays
- GaAs has higher *Z* and higher ρ → high absorption probability
- XRF application: detection of X-rays > 30 keV elements have higher fluorescence yield
- Hard X-rays (≈ 100 keV) used in medicine: radiography, fluoroscopy, and nuclear medicine
- Detector with high efficiency → reduces dose on patient
- Band gap of GaAs (1.42 eV) is high enough → operation at room temperature operation possible
- Band gap is low enough for good resolution (Fano limit 140 eV FWHM at 5.9 keV, pair creation energy 4.2 eV)
- Large bulk resistivity → high fields for charge collection
- Electron mobilities 6 x higher than Si → Fast signal

Production of GaAs Detectors

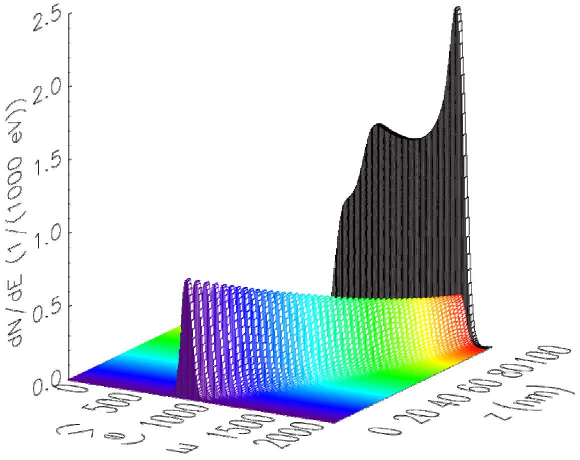
- No natural oxide → Production not as easy as in Si planar technology
- Thickness > 100 μm required for high efficiency detection of hard X-rays and γ-rays and low detector capacitance
- Not possible with molecular beam epitaxy
- Maximum thickness with chemical vapor phase deposition epitaxy: 60 – 100 μm
- Most promising: liquid phase technology (Prof. Andreev, Ioffe Institute)
- Energy resolution of 220 eV obtained with 0.04 mm² pixels @ 5.9 keV and -30℃
- Drift principle required to reduce capacitance
- Very important: high purity epitaxial layer

Semiconductor X-Ray Detectors



Part A Principles of Semiconductor Detectors

1. Basic Principles
2. Typical Applications
3. Planar Technology
4. Read-out Electronics



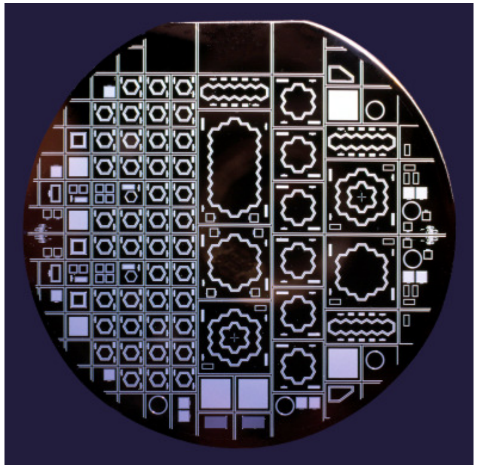
Part B Silicon Drift Detectors

1. Silicon Drift Detectors
2. GaAs Detectors
3. Outlook
4. Resume

Outlook

- Focus in the past: Silicon drift detectors and read-out electronics → spectrometer
- Competitors: High-end: Si(Li)s, HPGe (for γ)
  Low-end: pin-Diodes
- Future Targets:
  - SDDs with larger areas (> 10 mm^2)
  - Less charge low at $E_0 < 300$eV
  - Scintillator-covered SDDs for γ-rays
  - GaAs detectors for hard X-rays ($E_0 > 50$ keV)

The Response of Energy Dispersive X-Ray Detectors



Part A Principles of Semiconductor Detectors

1. Basic Principles
2. Typical Applications
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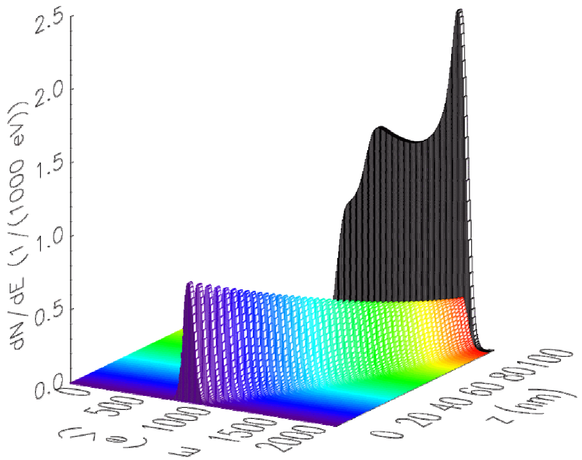
4. Read-out Electronics

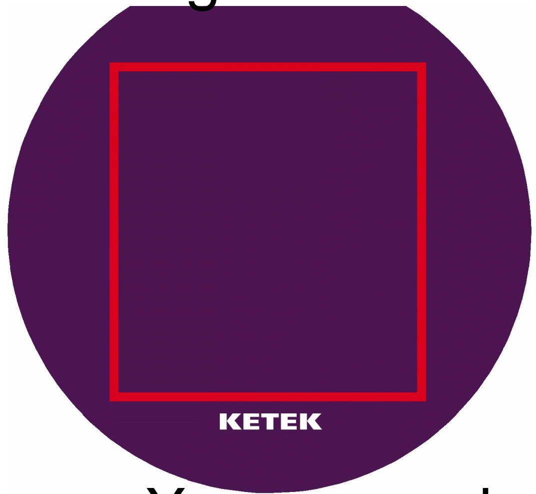


Part B Silicon Drift Detectors

1. Silicon Drift Detectors
2. Low Energy Measurements/Experimental Setup
3. Calculation of Spectral Contributions
4. Results
5. Resume

Resume

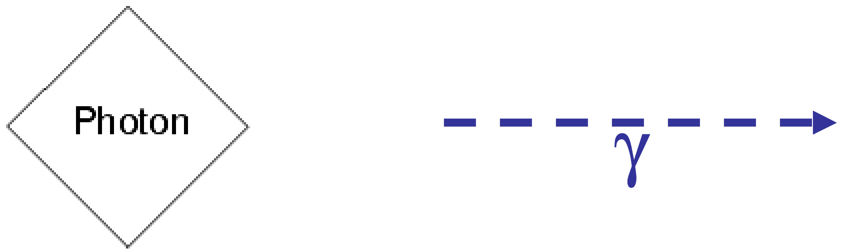
- Ketek’s Silicon Drift Detector is a unique and established product for XRF and SEM applications
- Highly optimized production process → low leakage currents
- Drift priciple → low capacitance
- → Low overall noise
- → very good energy resolution
- → high count-rate ability
- Future tasks:
  Expand energy range to both, higher and lower X-ray energies
  High *E*: GaAs detectors
  Low *E*: SDD with optimized entrace window



KETEK

- www.ketek.biz / www.ketek.net
- Спасибо!

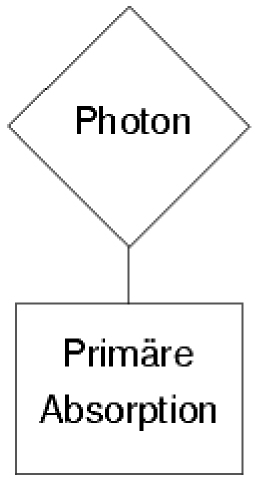
X-ray photon hits detector

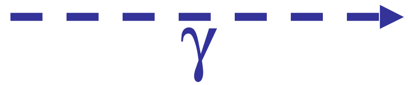


Interaction always by
photoelectric effect

Compton effect unlikely

e^-e^+ pair creation impossible



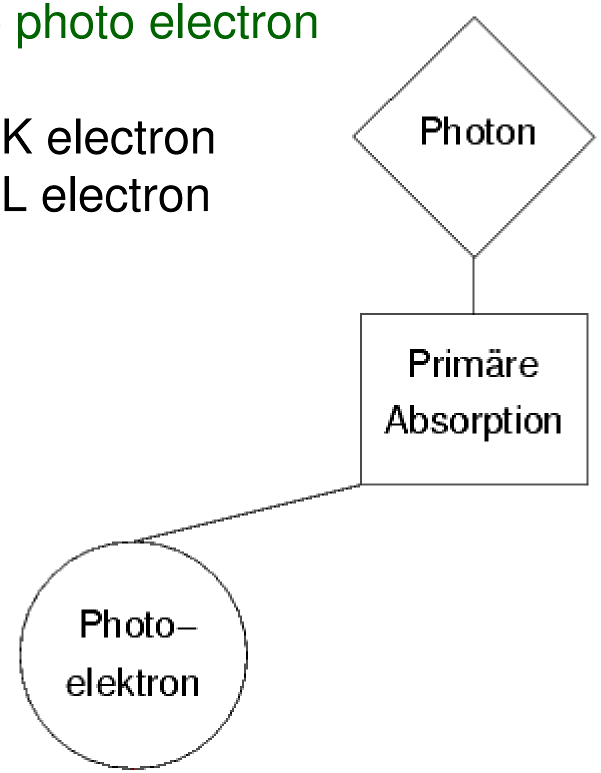


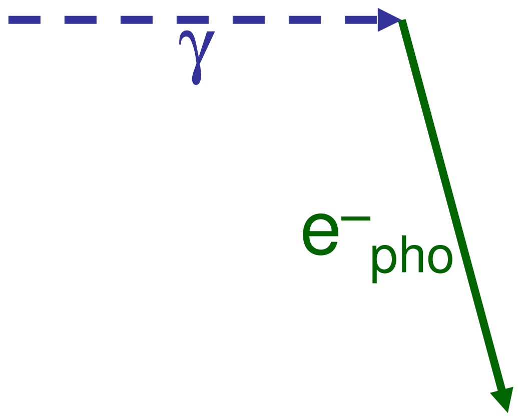
Creation of one photo electron

$E = E_0 - E_B$

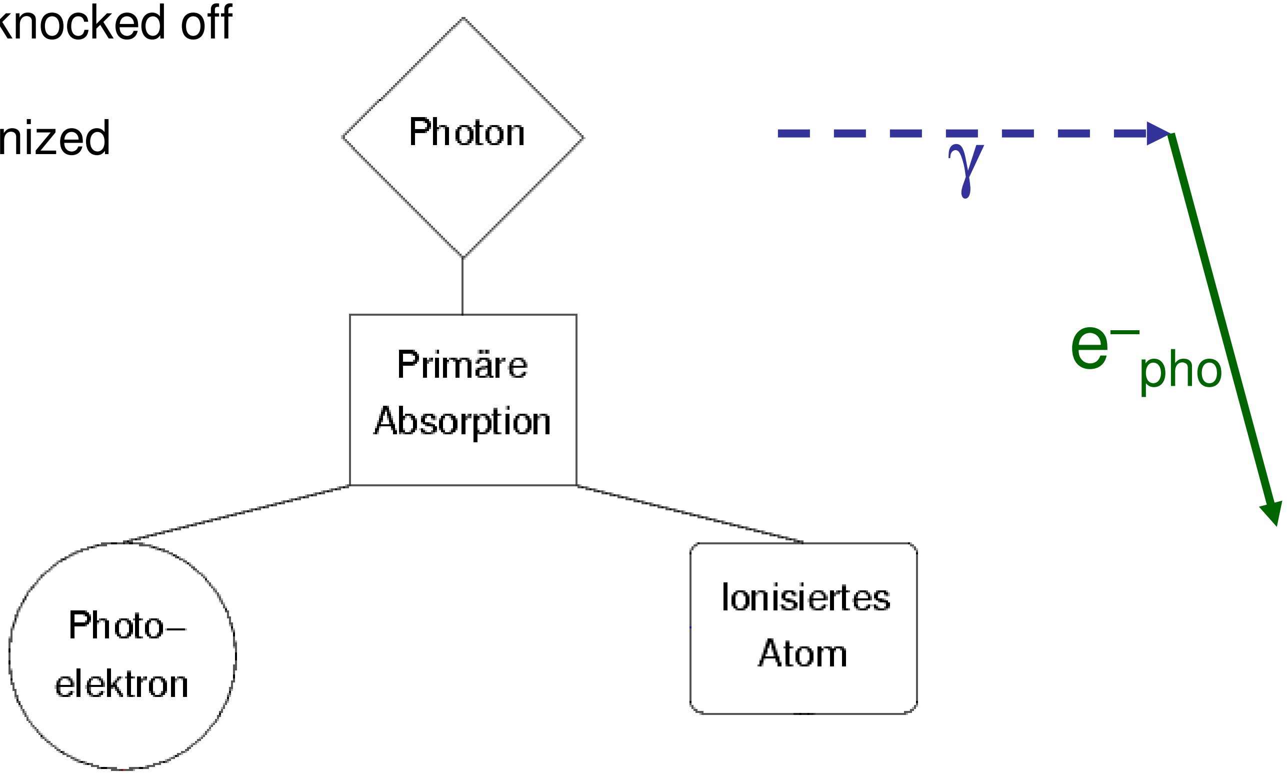
E_0 > Si K shell: K electron

E_0 < Si K shell: L electron



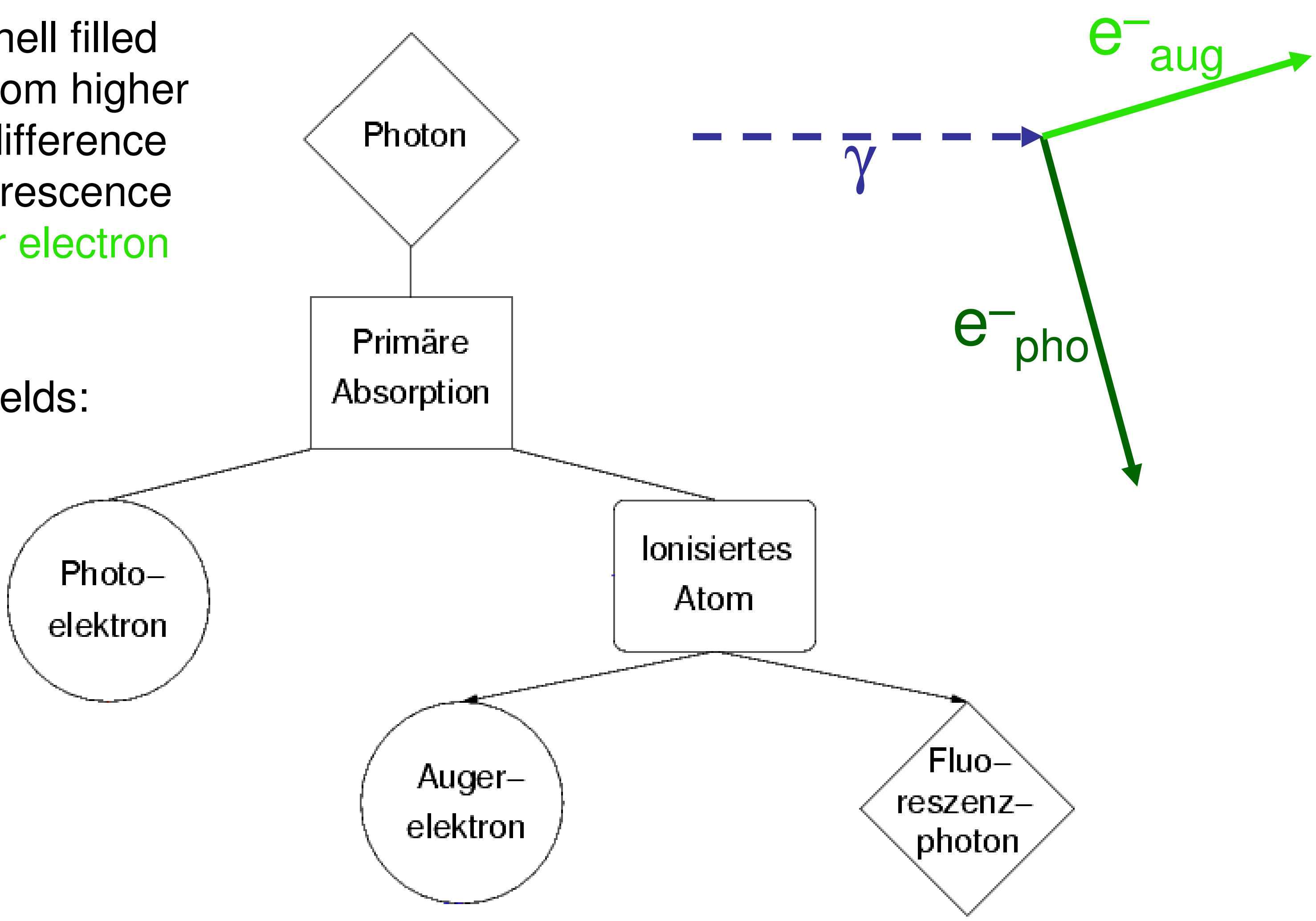


K or L electron knocked off its shell
- ➢atom single ionized

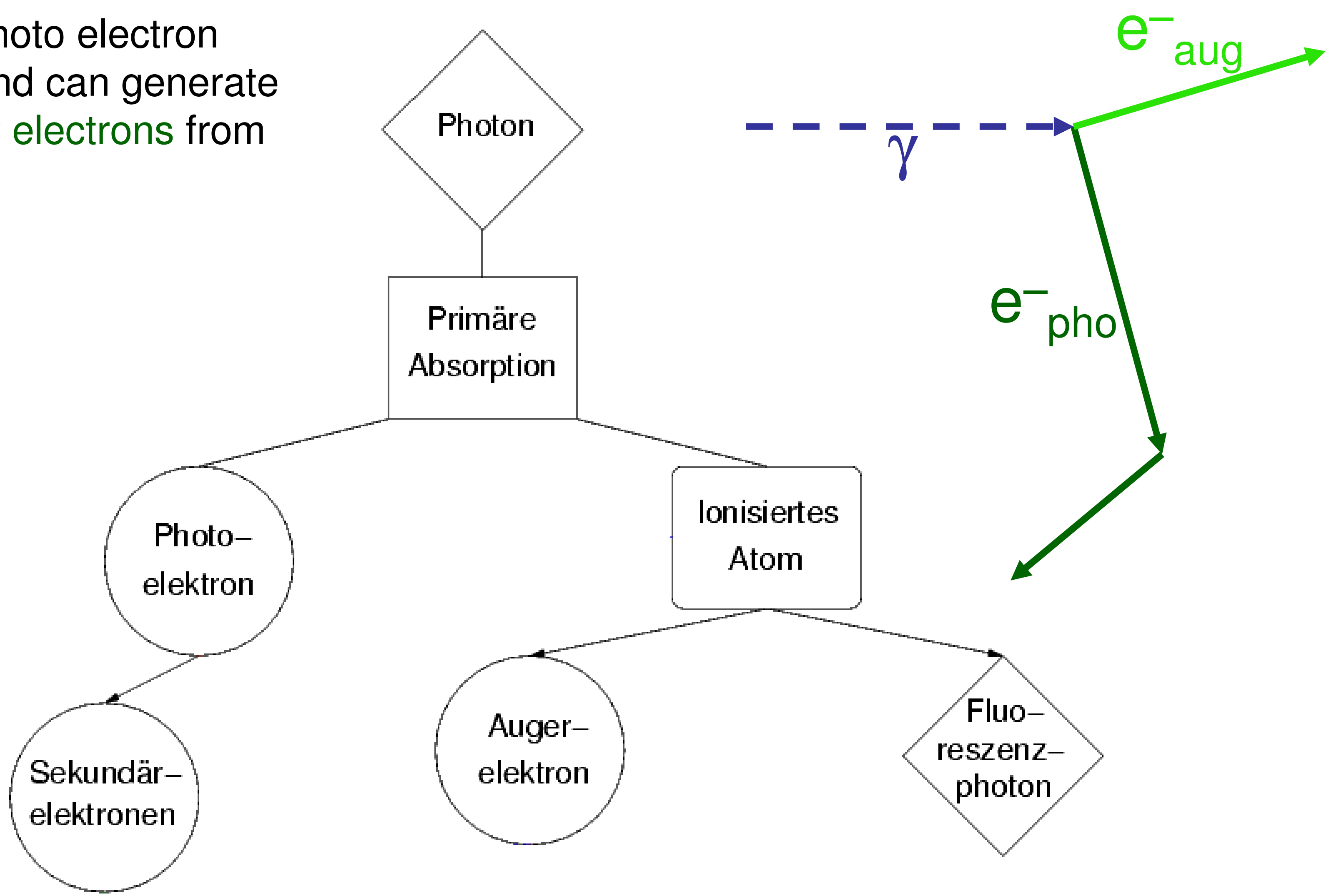


Hole in K or L shell filled with electrons from higher shells. Energy difference assigned to fluorescence photon or Auger electron of fixed energy

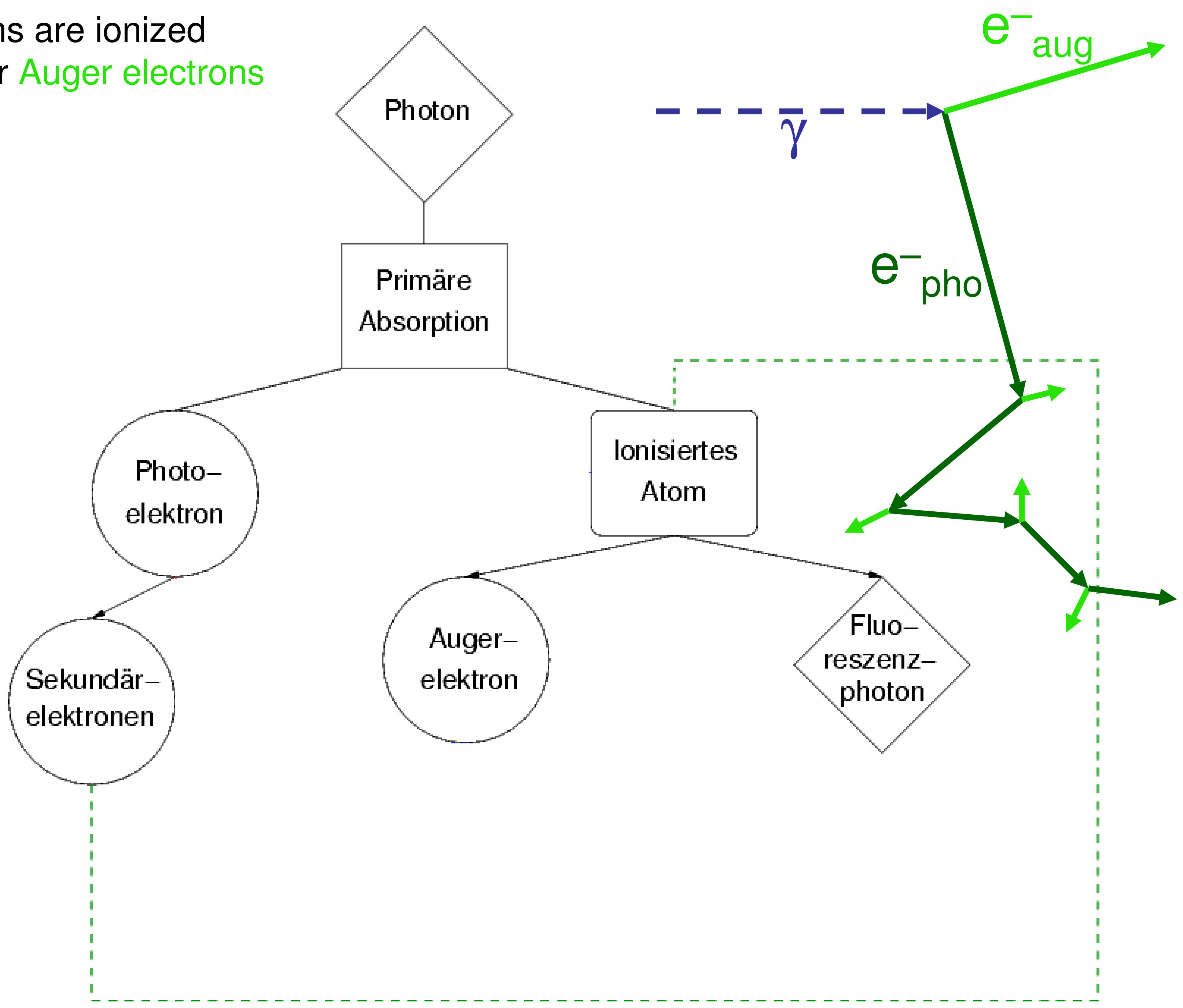
Fluorescence yields:
L shell: 0%
K shell: 4%



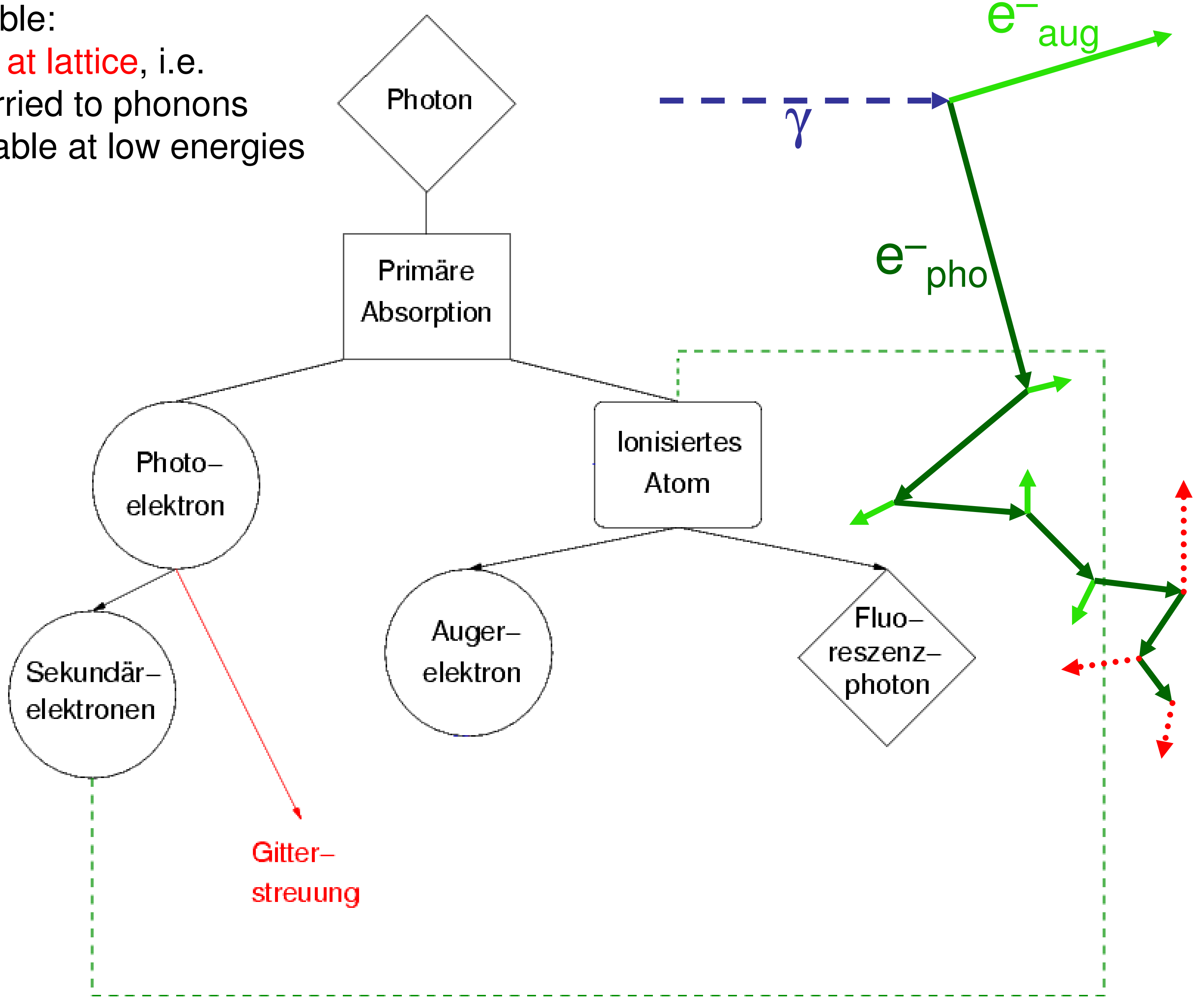
Primary photo electron scatters and can generate secondary electrons from Si atoms



More atoms are ionized and further Auger electrons emerge

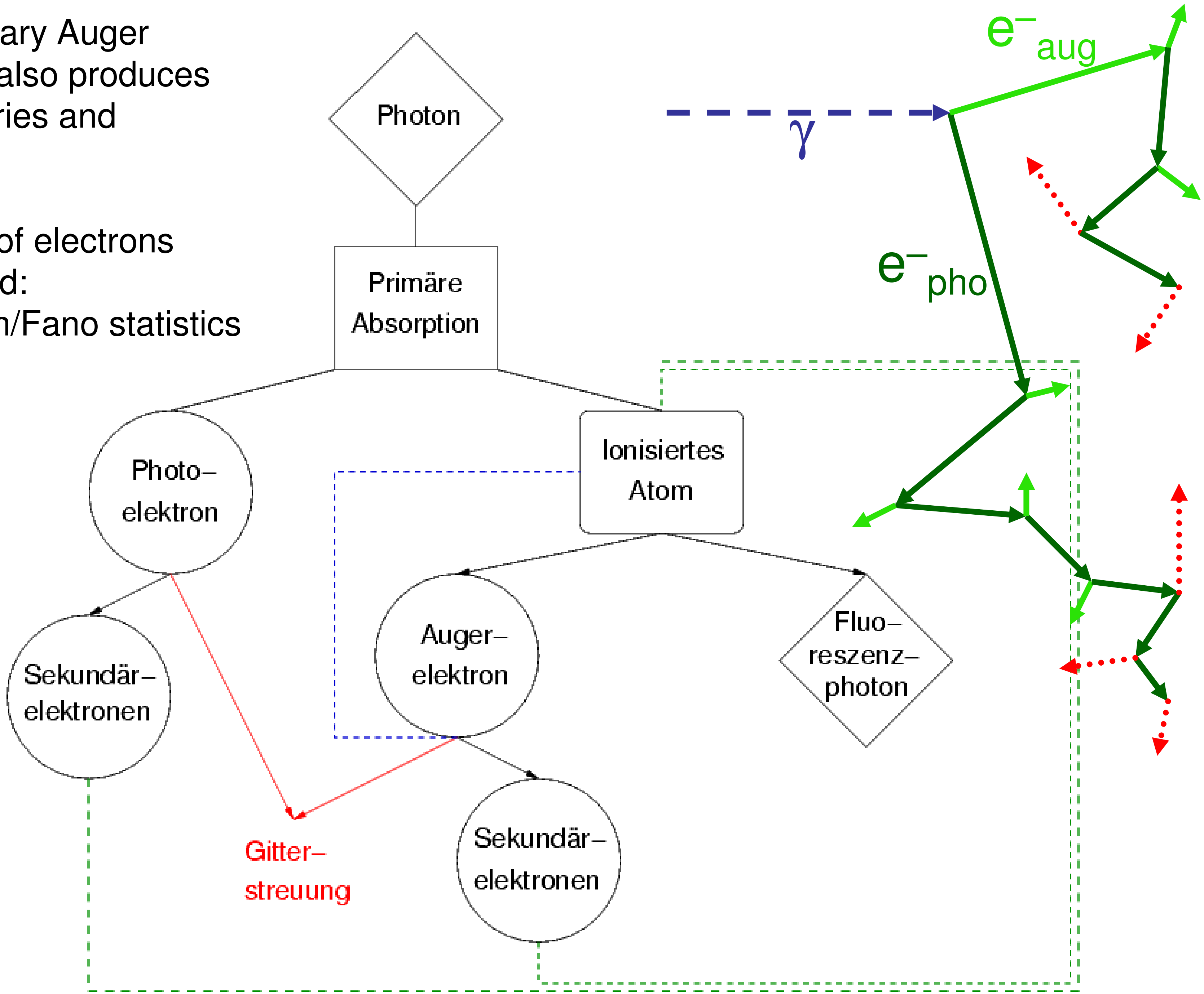


Also possible:
Scattering at lattice, i.e.
energy carried to phonons
Very probable at low energies



The primary Auger electron also produces secondaries and phonons

Number of electrons generated: Ionization/Fano statistics



K shell fluorescence:
X-ray can escape or is
reabsorbed inside detector