Experimentelle Methoden der Teilchenphysik

Sommersemester 2011/2012

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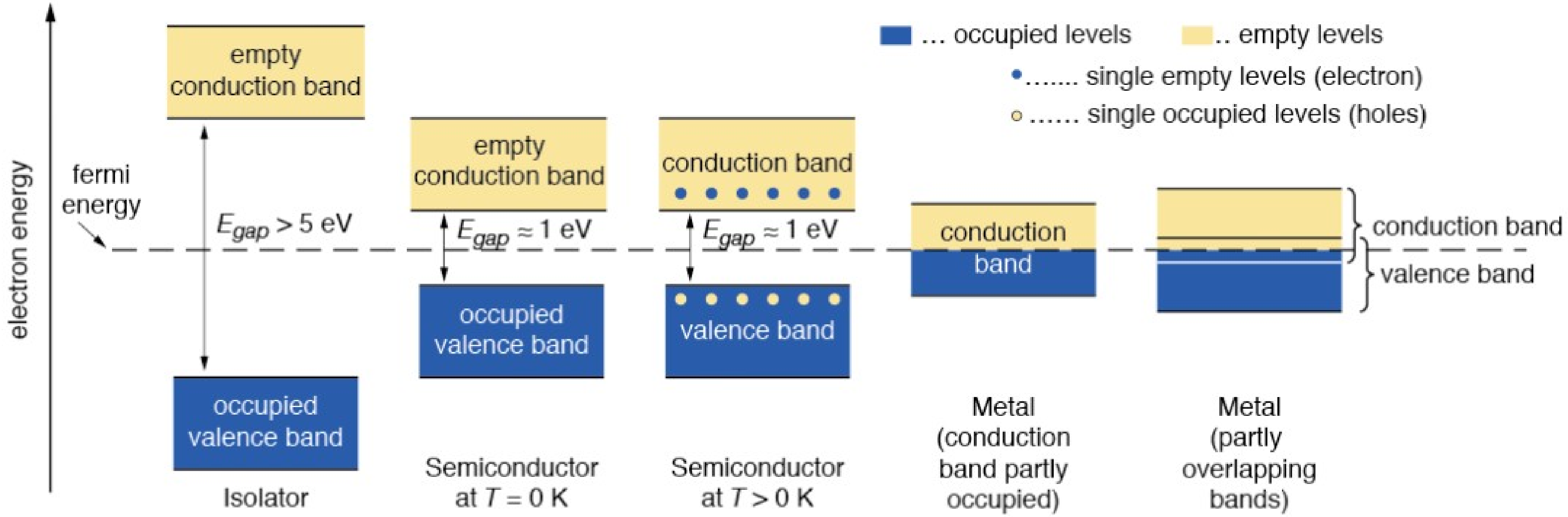
Kapitel 6: Halbleiterdetektoren

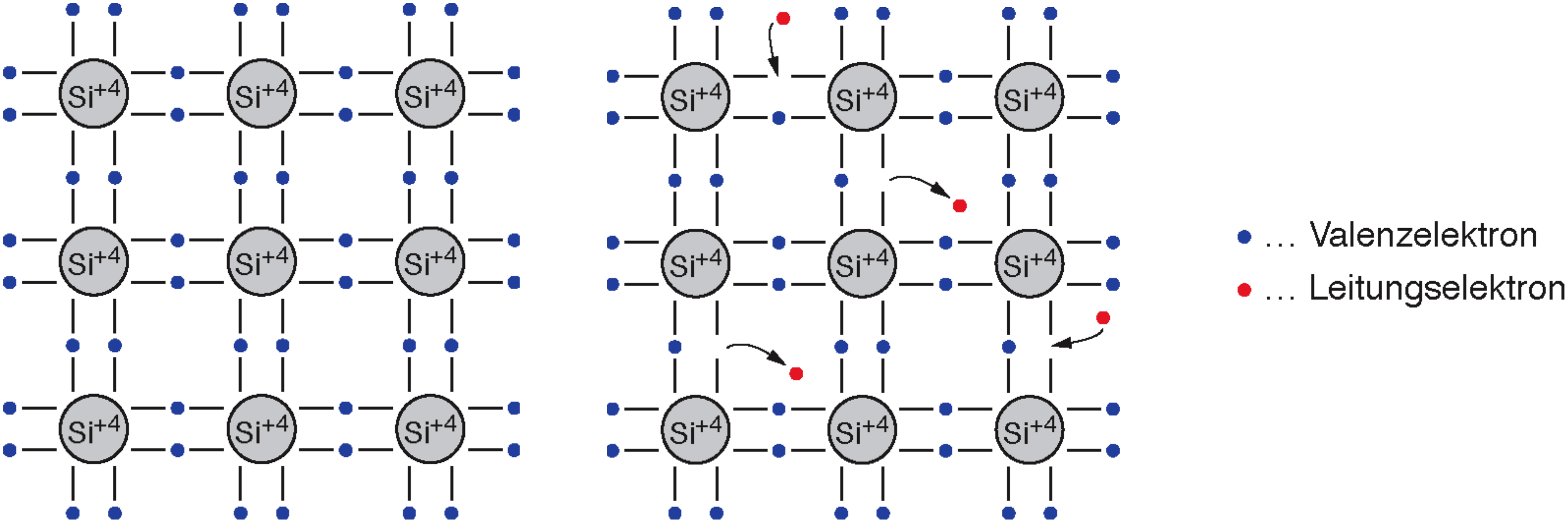
http://terascale.physik.uni-freiburg.de/lehre/Sommersemester%202012

Bandstruktur in Festkörpern



Elektronenstruktur von Silizium

Group IV Semiconductor: 4 valence electrons

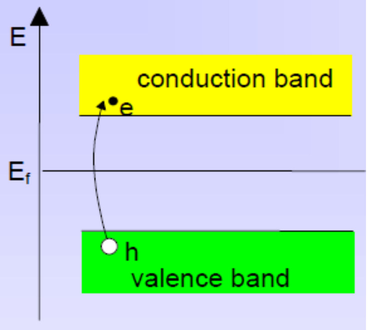

T = 0K

T > 0K

Thermal excitation → conductivity for T > 0 K

Elektronenstruktur von Silizium

- Small band gap → electrons in conduction band
- Recombination with holes

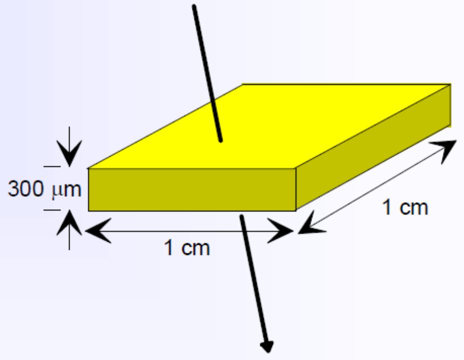


- Intrinsic charge carrier concentration in thermal equilibrium (intrinsic semiconductor):

$$n_i \propto T^{3/2} \cdot \mathrm{e}^{-\frac{E_g}{2\mathrm{kT}}}$$

At room temparature in pure silicon:

$n_i \approx 1.45 \times 10^{10}\ \mathrm{cm}^{-3}$



≈ 4.5 x 10^8 free charge carriers in this volume
>> 32000 e-h pairs created by a MIP!

→ Reduce numbe of free charge carriers

→ Deplete detector

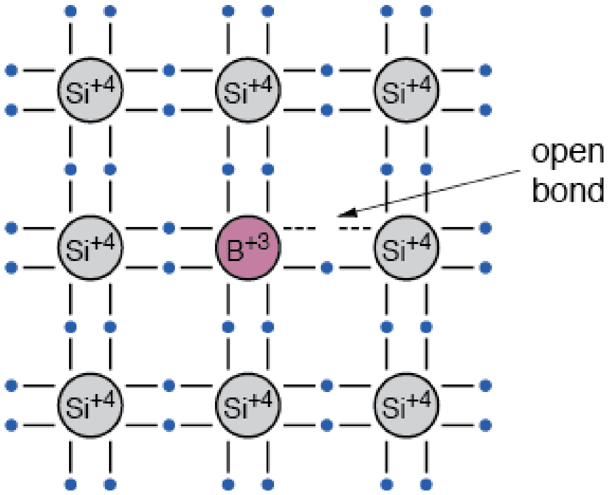
→ Need *Doping* :

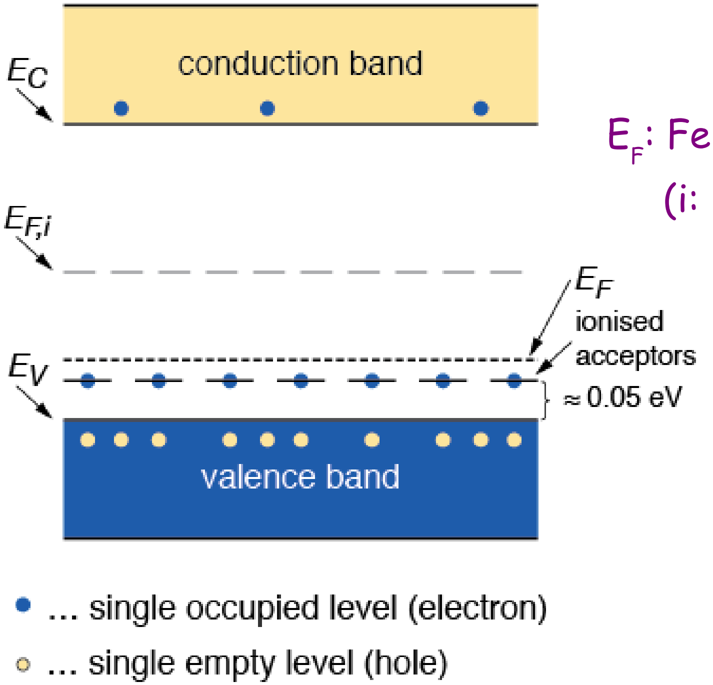
Replace small fraction of atoms by atoms of neighboring columns of periodic table (from group III or V) → extrinsic semiconductor

p-Dotierung mit 3-wertigen Atomen → Akzeptoren

- p doping:
  Add *acceptor* atoms from Group III (e.g. B, Al, Ga, In)

Open valence bond attracts electrons from neighbor atoms





E_F: Fermi Level

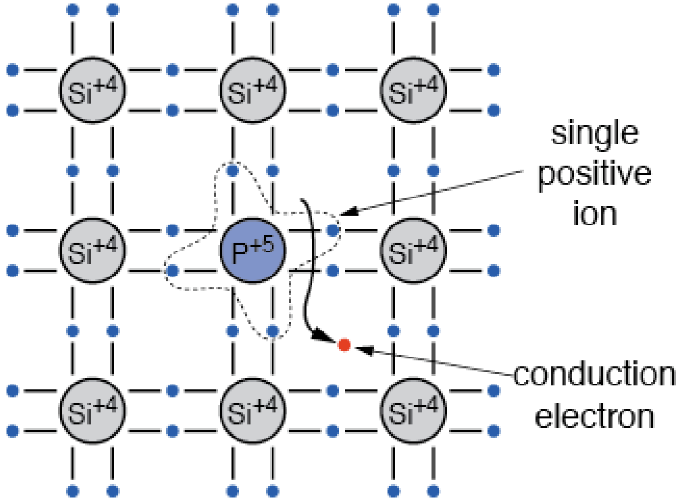
(i: intrinsic)

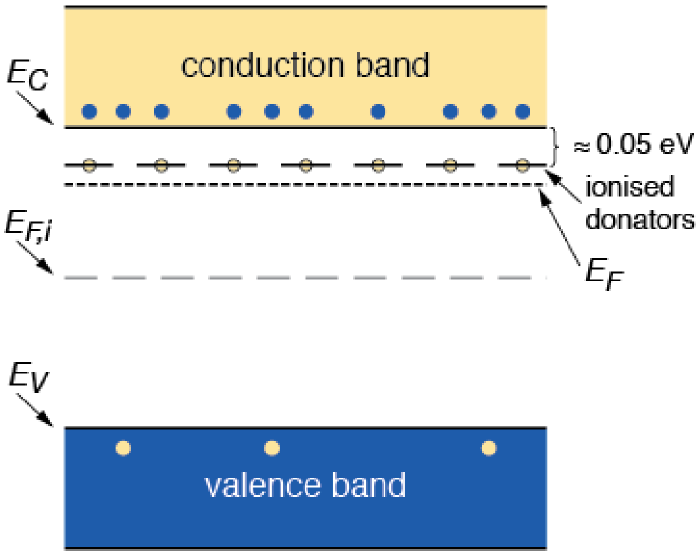
n-Dotierung mit 5-wertigen Atomen → Donatoren

- n doping:
  Add *donor* atoms from Group V
  (e.g. P, As, Sb)

Typical doping concentration
~5 x 10^{13} atoms/cm^3
(compared to Si concentration
~5 x 10^{22} atoms/cm^3)

Additional valence electron
weakly bound

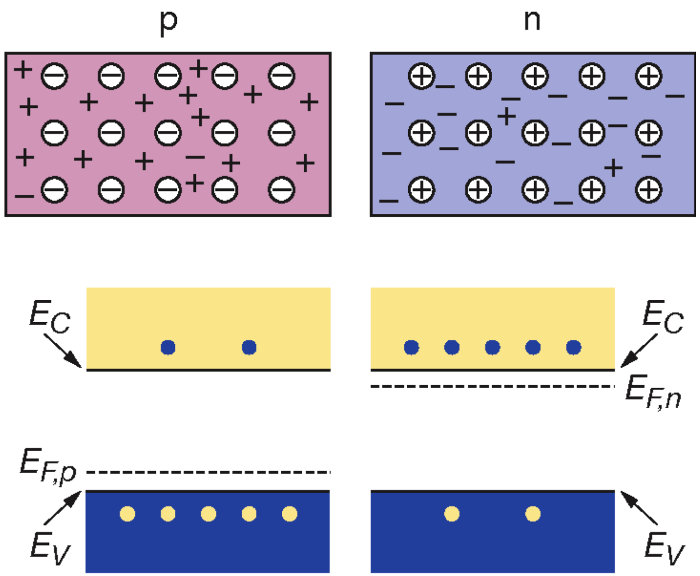


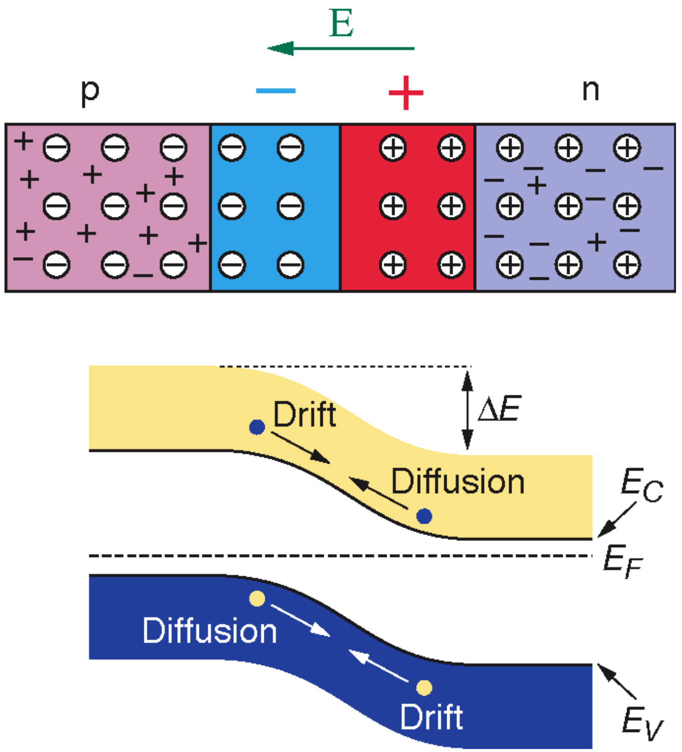


● ... single occupied level (electron)
○ ... single empty level (hole)

Der p-n-Übergang

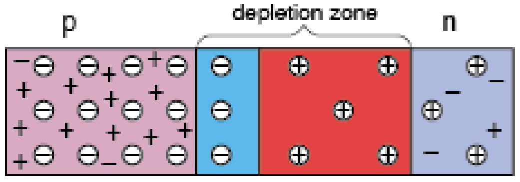
- Connect p- and n-doped silicon
- Electrons from n-type diffuse towards p-type and fill holes (recombination)
- Fermi levels have to adapt
  → Diffusion of charge carriers until equilibrium is reached
  → Potential difference at junction (contact potential)
  → creates space charge → electric field
- *Depletion zone:* Free of charge carriers



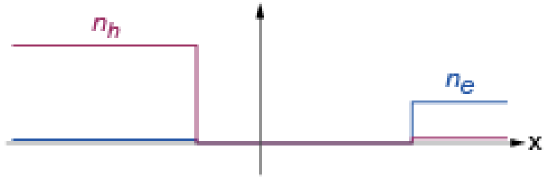


Der p-n-Übergang

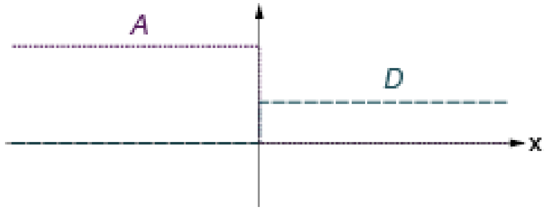
pn junction scheme



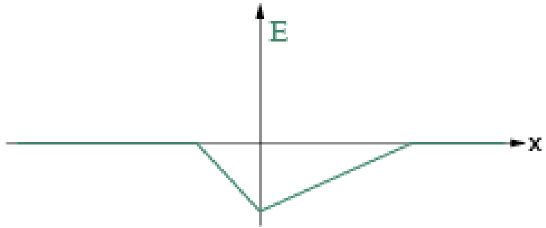
concentration of free charge carriers



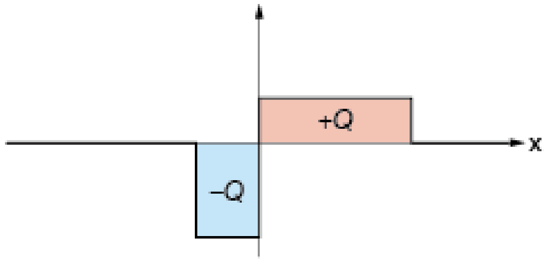
acceptor and donator concentration



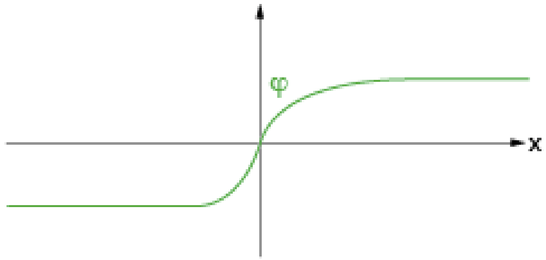
electric field



space charge density



electric potential



⊖ … acceptor

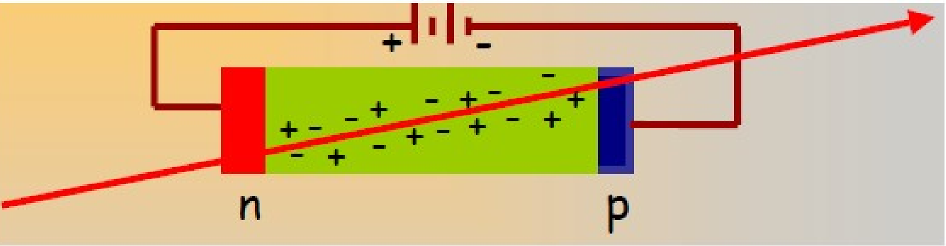
⊕ … donator

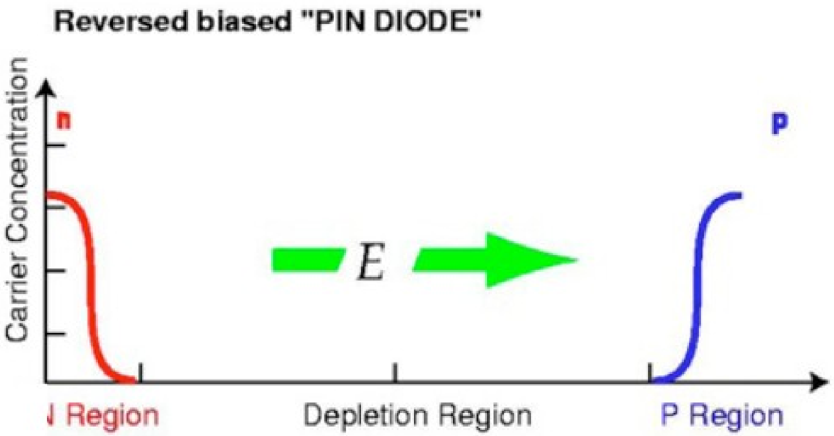
+ … empty hole

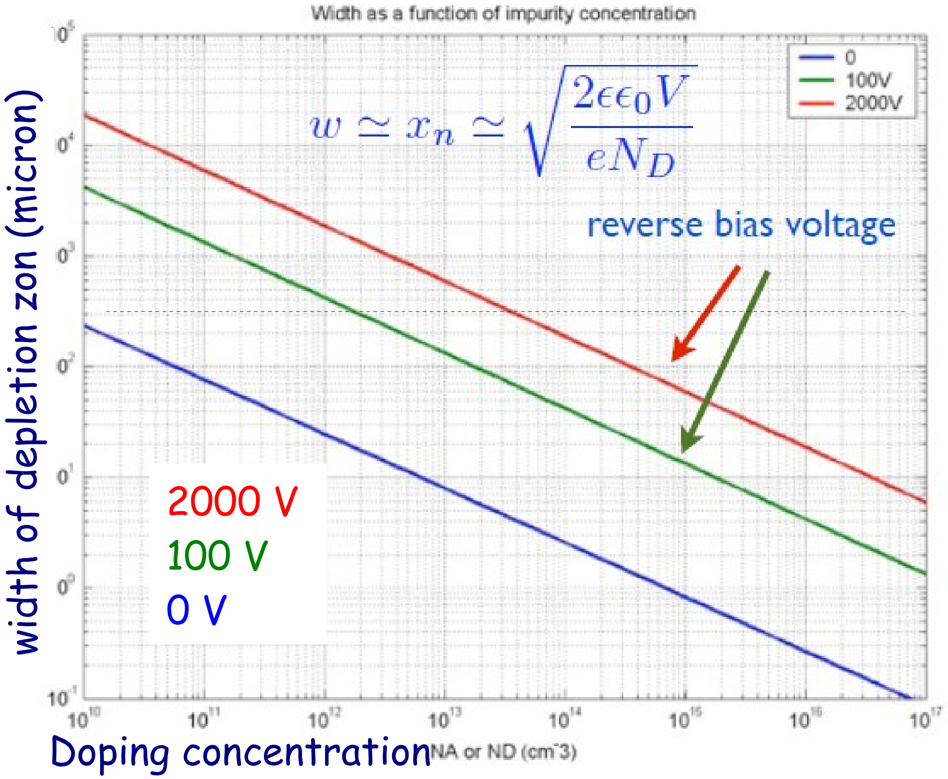
− … conduction electron

Verarmungszone bei äußerer Sperrspannung

Increase depletion width with reversed bias







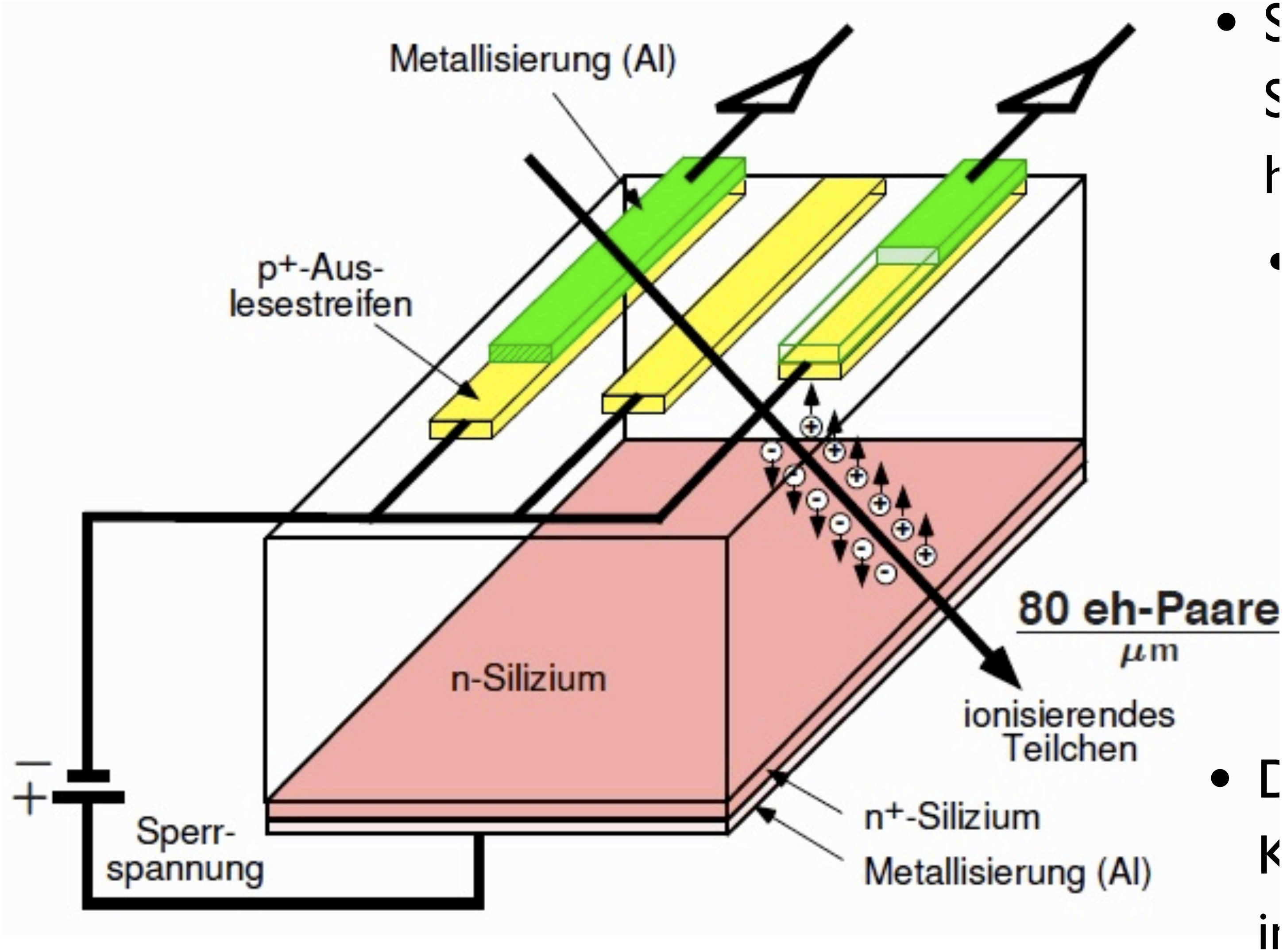
$$w \simeq x_n \simeq \sqrt{\frac{2\epsilon\epsilon_0 V}{eN_D}}$$

Electron - hole pairs,
created in the depletion region
by the ionizing particle,
drift in the electric field.

typical ionization: 100 e-h pairs/μm
typical noise: 1000 electrons

Large S/N requires large depletion region, i.e. large reverse bias voltage.

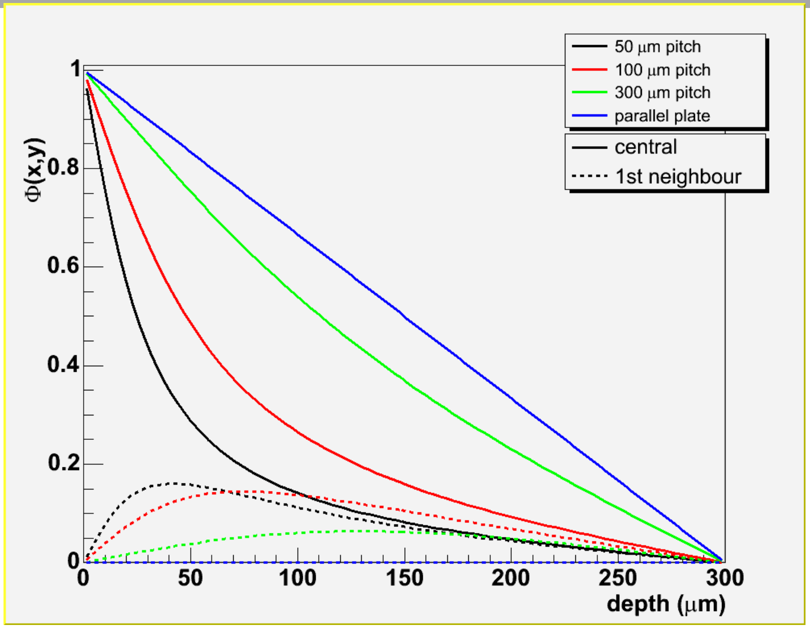
Silizium-Streifendetektoren



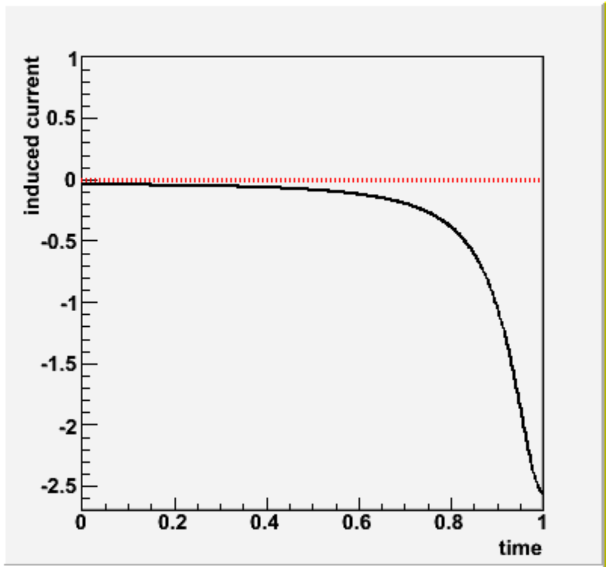
- S
  S
  h
  -
- D
  K
  i

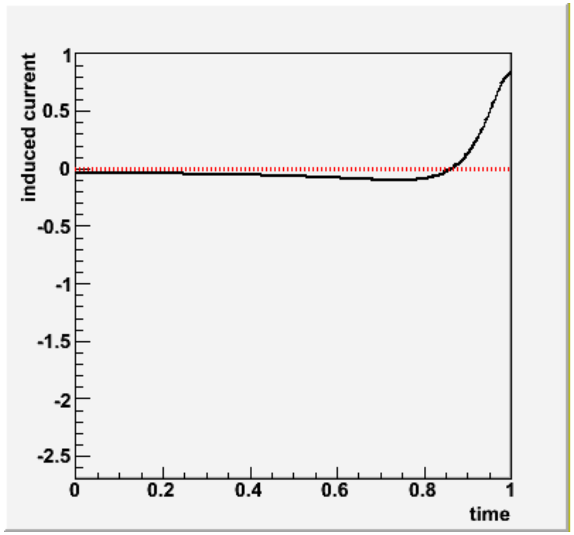
Potentialverlauf und Zeitentwicklng des Signal

Potentialverlauf auf zentralen und Nachbarstreifen

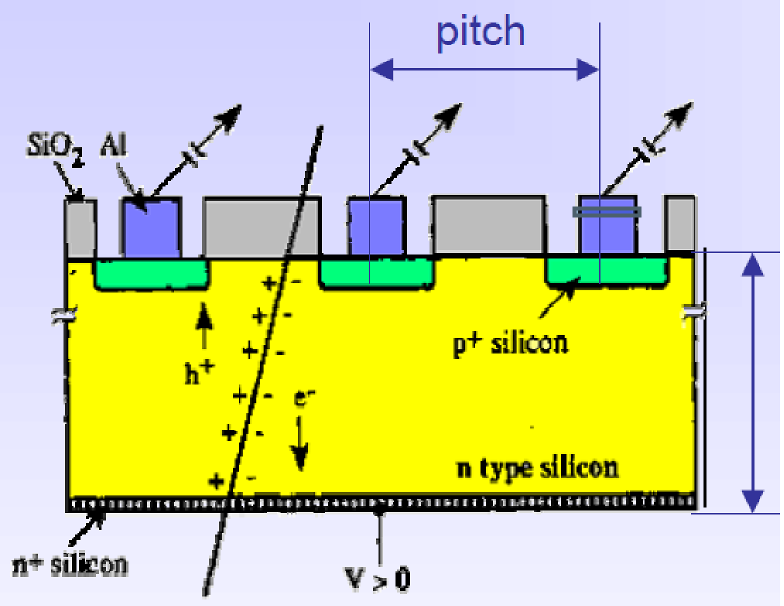


Zeitentwicklung auf Zentral- (links) und Nachbarstreifen (rechts)





Silizium-Streifendetektoren



typically:
d ≈ 300 µm

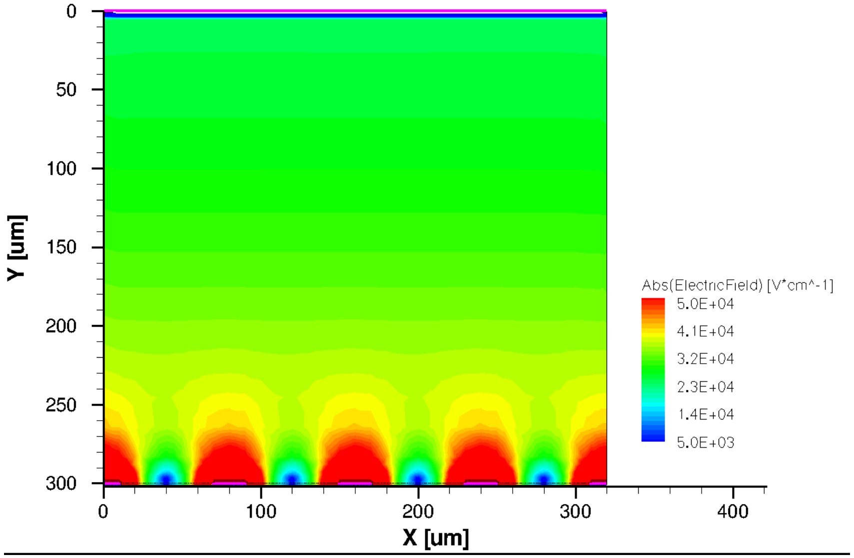
Segmentation of p layer into strips
→ spatial information

Pitch typically 20-150 µm

Position resolution
= pitch / √12 (14 µm for 50 µm pitch)

(can be improved by centre-of gravity and analogue readout)

E field configuration



Silizium-Streifendetektoren

Charge collection time:

Drift velocity of charge carriers $v \simeq \mu E$ and drift time $t_d = d/v = d/\mu E$.

Typical values: d=300 µm, E=2.5 kV/cm (μ_e=1350 cm²/Vs and μ_h=450 cm²/Vs).

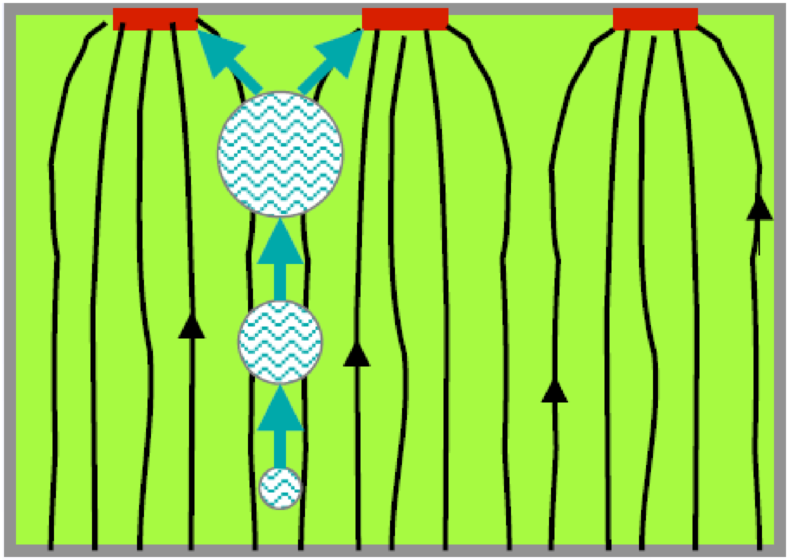
Drift times: $t_d(e) = 9$ ns, $t_d(h) = 27$ ns

Diffusion:

Diffusion of charge cloud caused by scattering of charge carriers. Width of distribution increases with drift time t_d. Using the diffusion constant $D = \mu kT/e$ one finds:

$$\sigma = \sqrt{2Dt_d} = \sqrt{\frac{2dkT}{eE}}$$

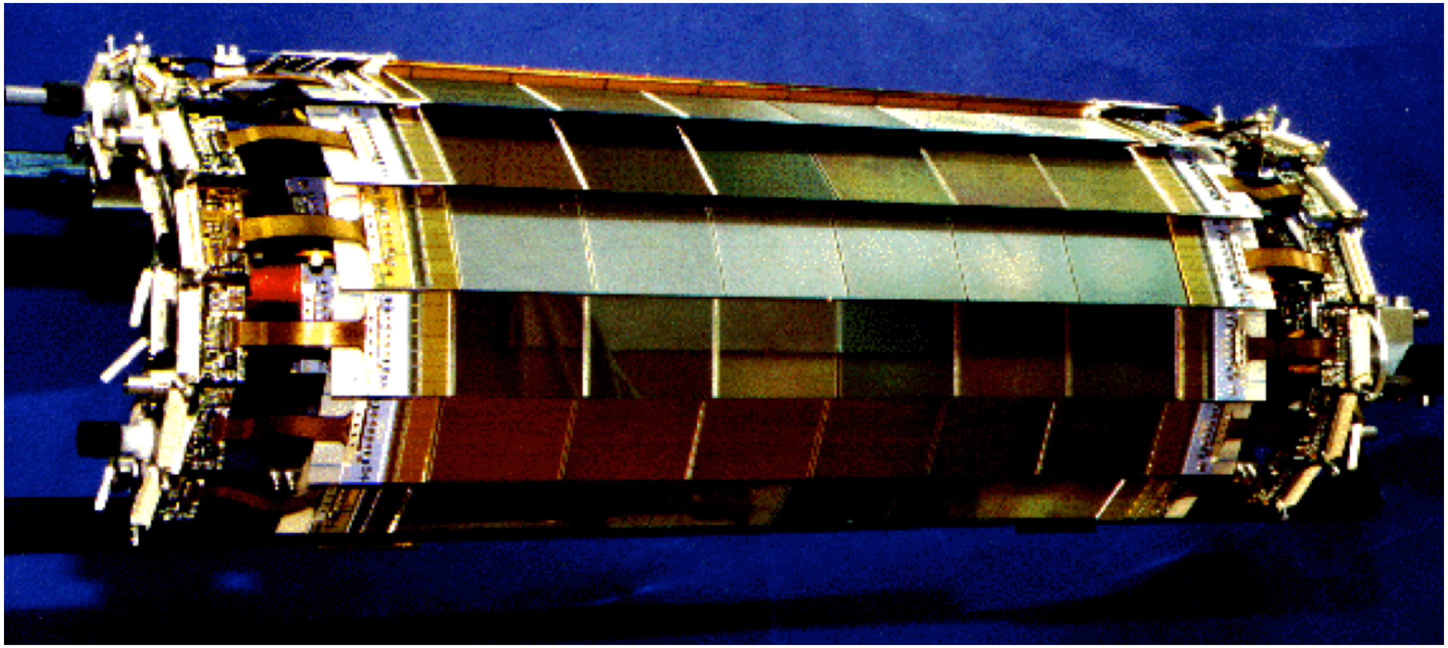
Note that diffusion is the same for electrons and holes, since the mobility drops out.



from M. Moll

Typical charge width: 8-10 µm in 300 µm thick silicon. Width of charge cloud could be exploited to obtain better position resolution due to charge sharing between strips (charge centroid finding).

ALEPH-Silizium-Streifendetektor



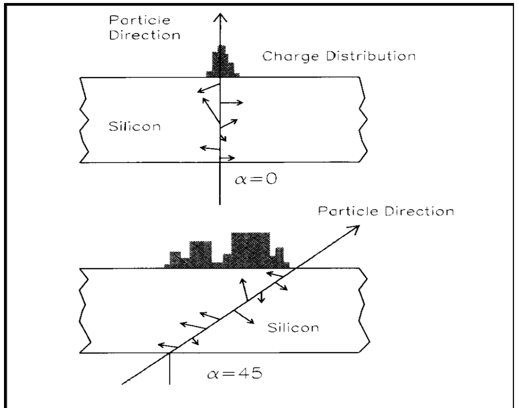
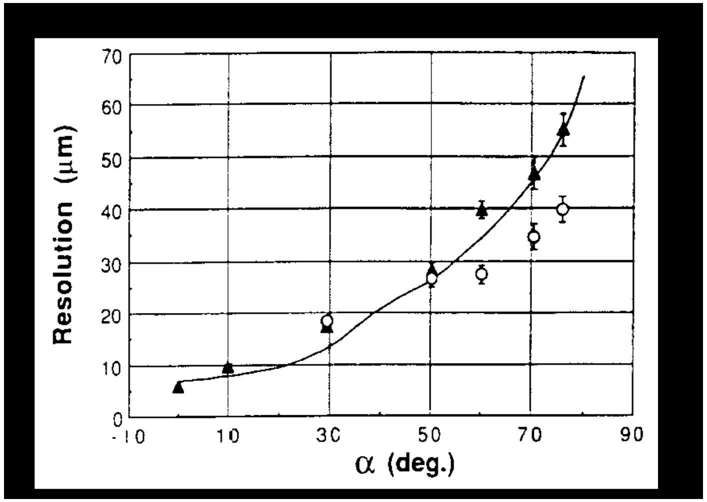
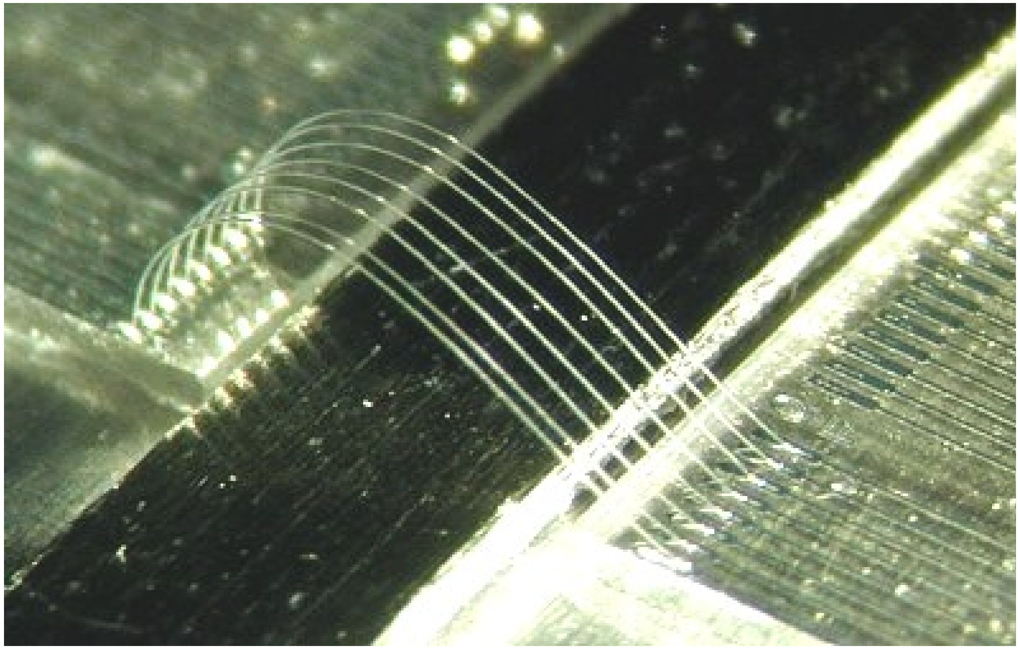
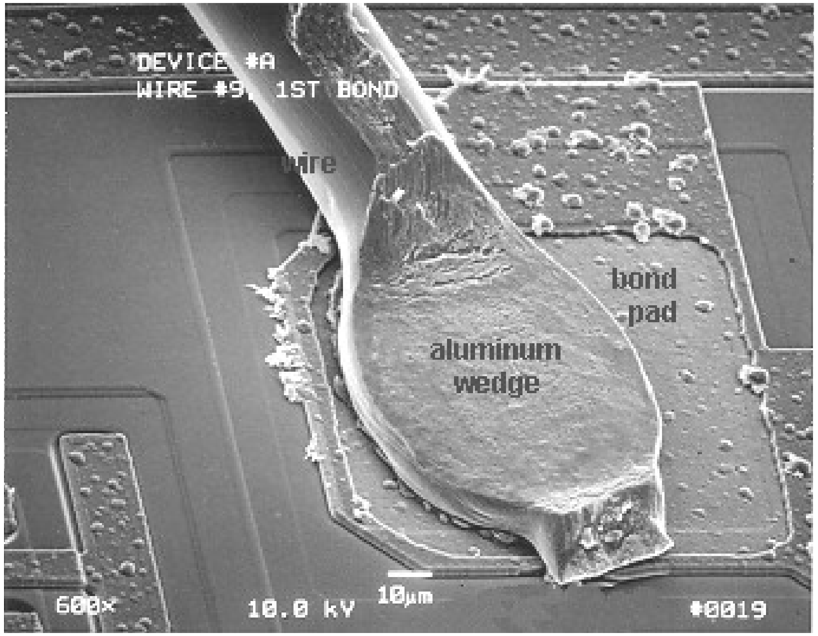


Fig. 3.13. An illustration of the effect of energy loss fluctuations on the projected charge distribution for tracks of normal incidence and tracks inclined at an angle α.



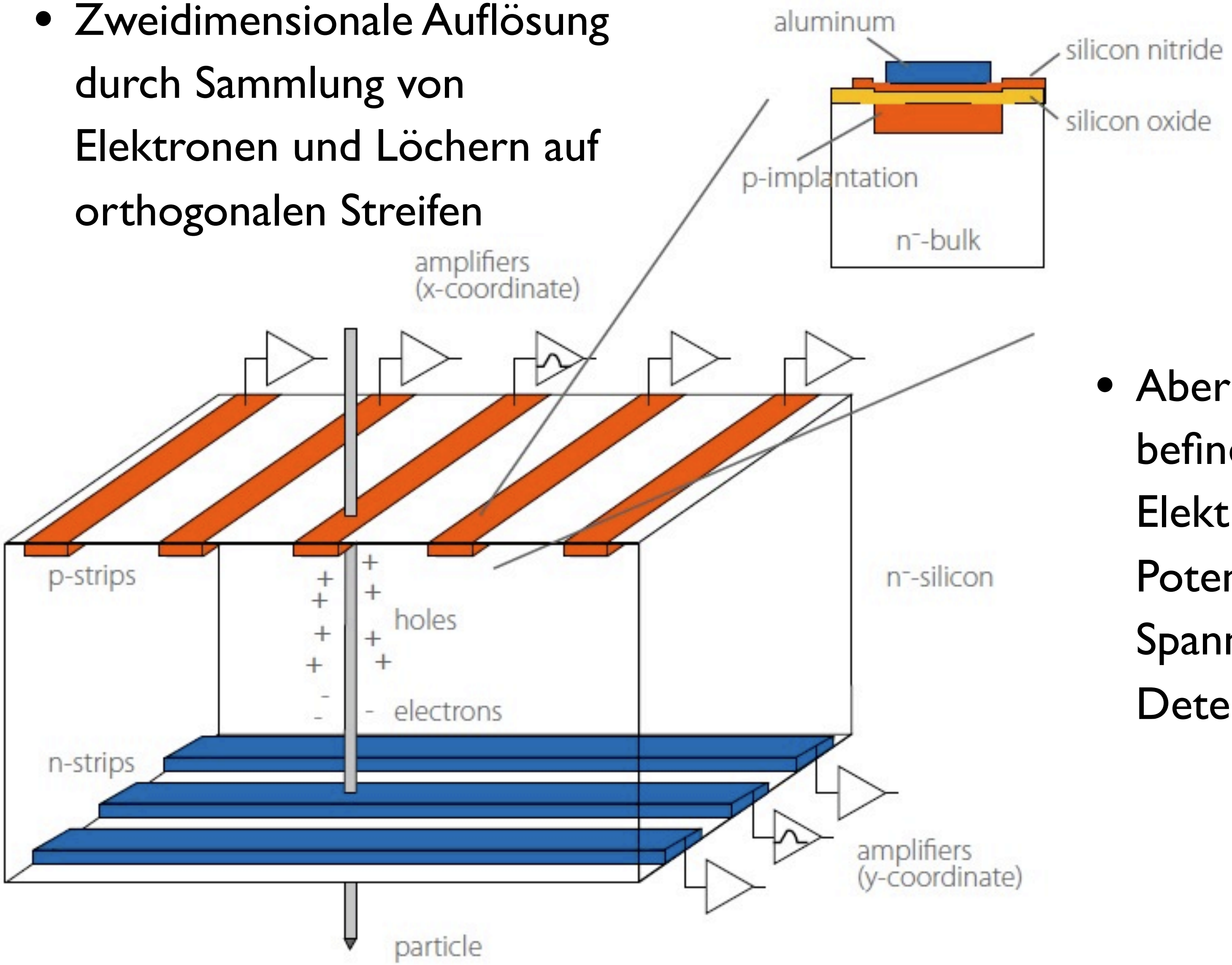
Silizium-Streifendetektor: “Wire bonds”





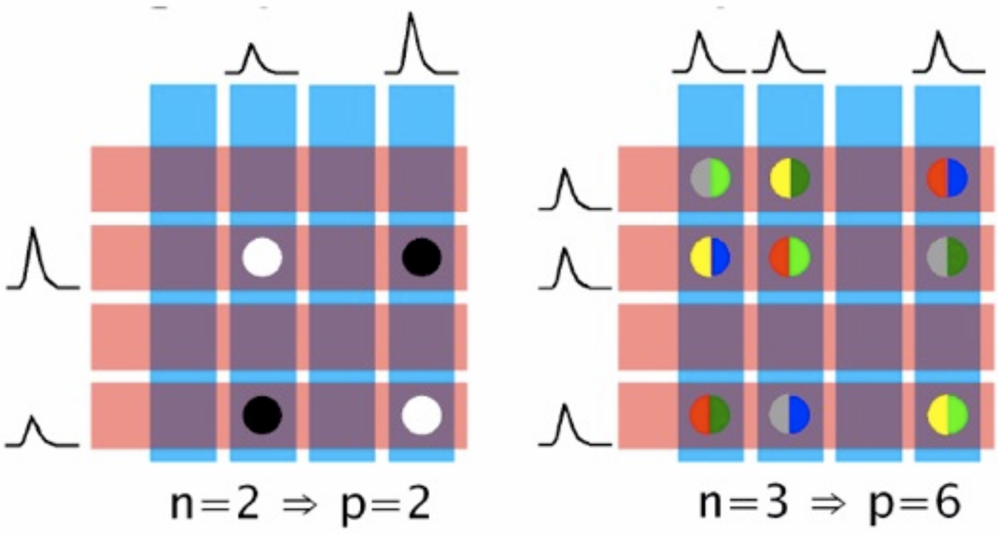
Silizium-Streifendetektoren

- Zweidimensionale Auflösung durch Sammlung von Elektronen und Löchern auf orthogonalen Streifen



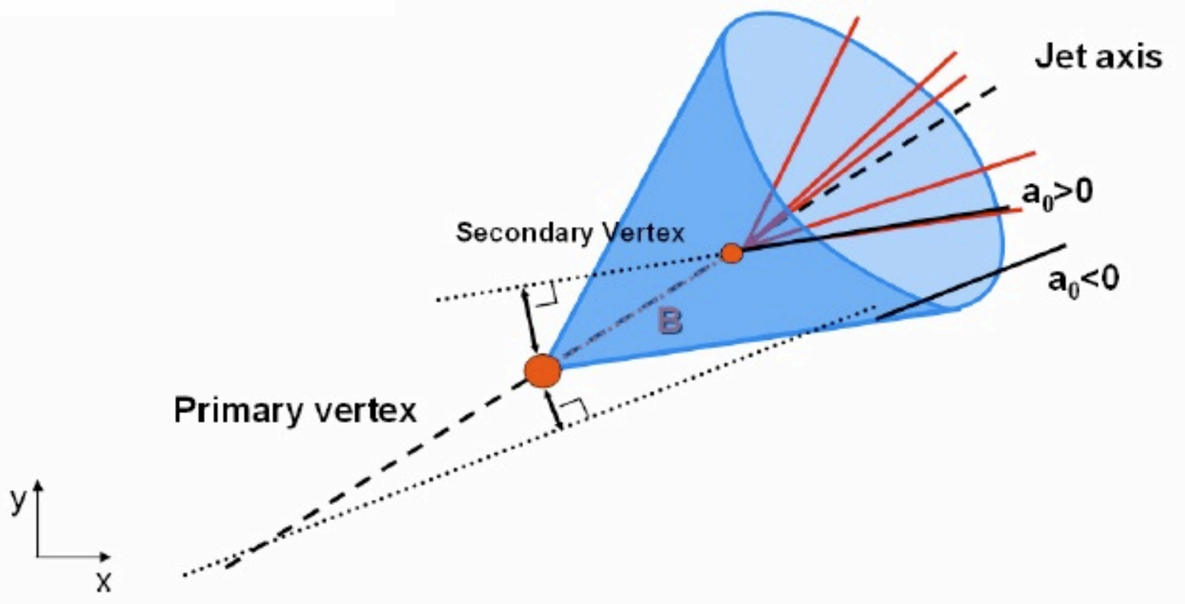
- Aber: Auf einer Seite befindet sich dann die Elektronik auf hohem Potential (durch Bias-Spannung über dem Detektor)

Silizium-Streifendetektoren

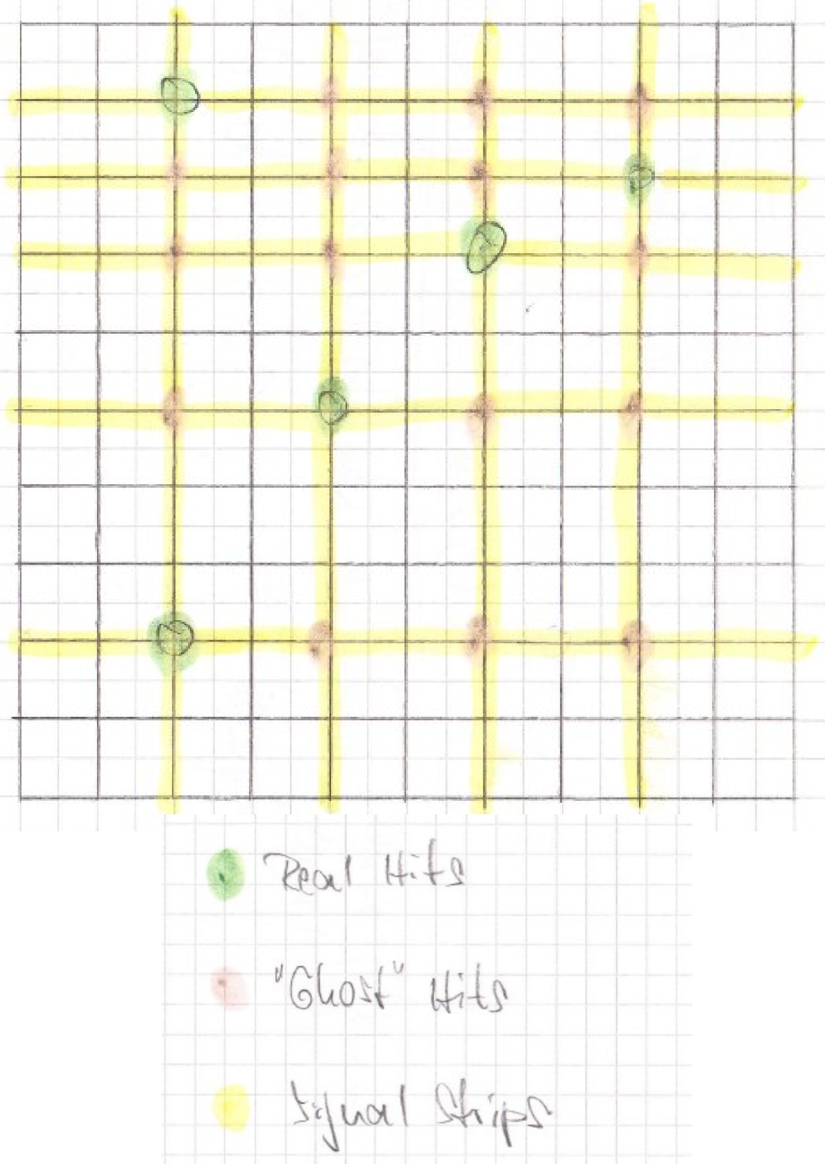


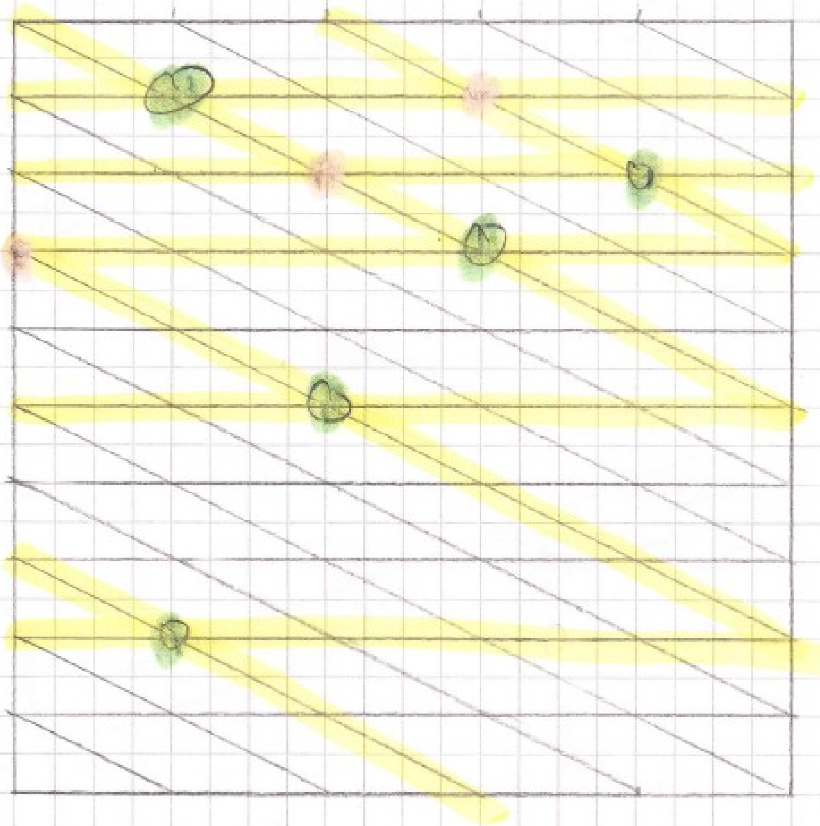
- Bei hoher Teilchendichte gibt es Ambiguitäten bei der Streifenauslese: Spurrekonstruktion bricht zusammen

- Ortsauflösung ist nur in einer Koordinate gut, meist nicht ausreichend, um sekundäre Zerfalls-Vertices zu rekonstruieren



Senkrechte- und Stereostreifen





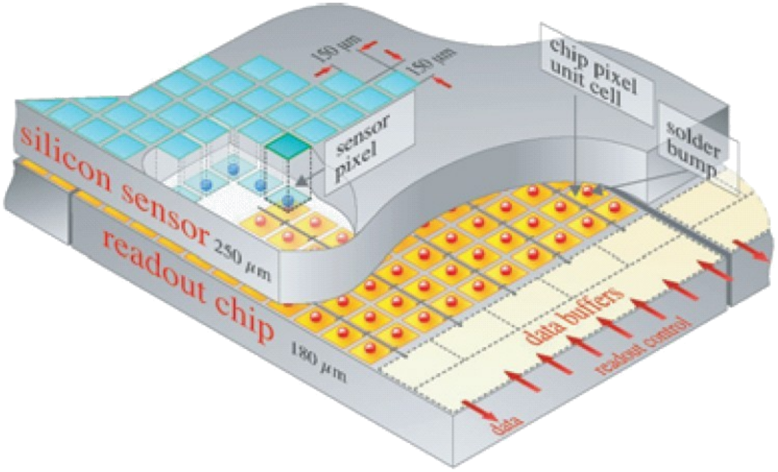
Stero angle < 90° strongly reduces number of ghost hits (in practice: few degrees)

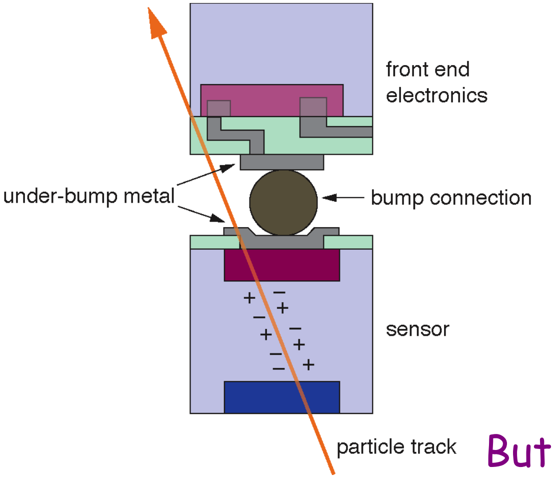
Hybride Pixeldetektoren

- Different pixel detector types

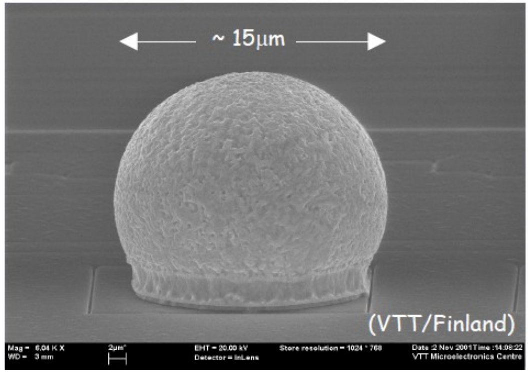
- Hybrid Active Pixel Sensors (HAPS)
  - Detector and readout ASIC are sandwiched together ($N_{readout} = N_{pixel}$)
  - Limitation from readout:
    Pixel size > 120 x 120 µm (2004)
  - Used widely in collider experiments
    - ATLAS: 100M pixels (50x400 μm^2)
    - CMS: 23M pixels (150x150 μm^2)

HAPS design principle



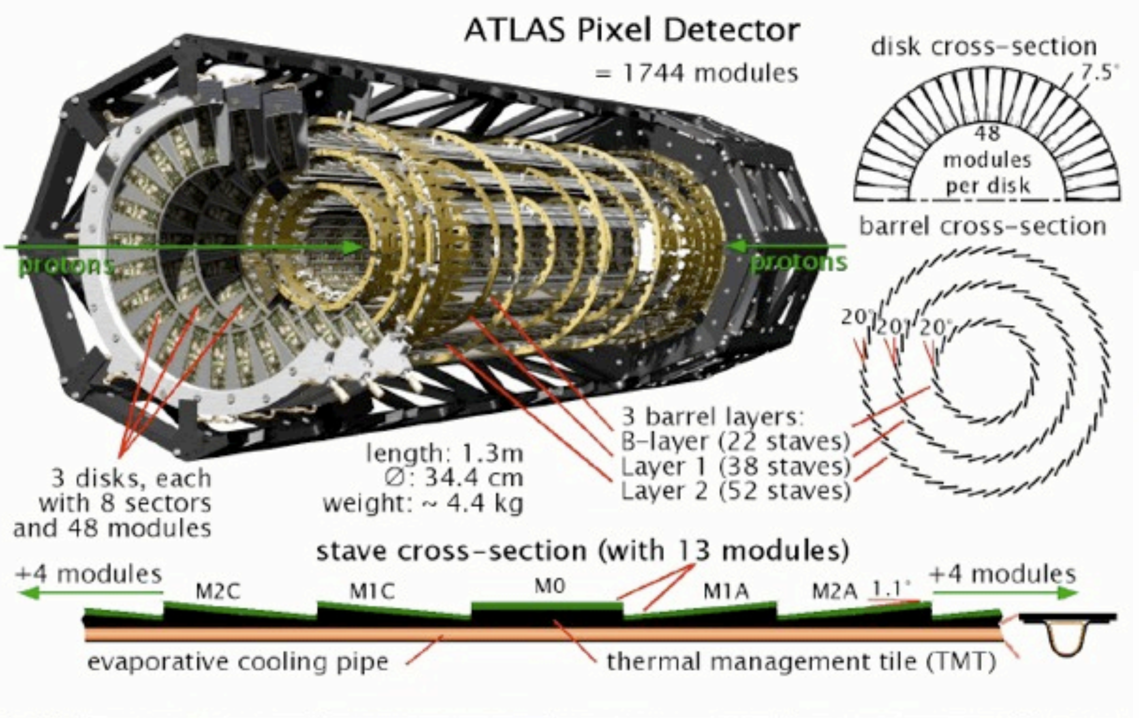


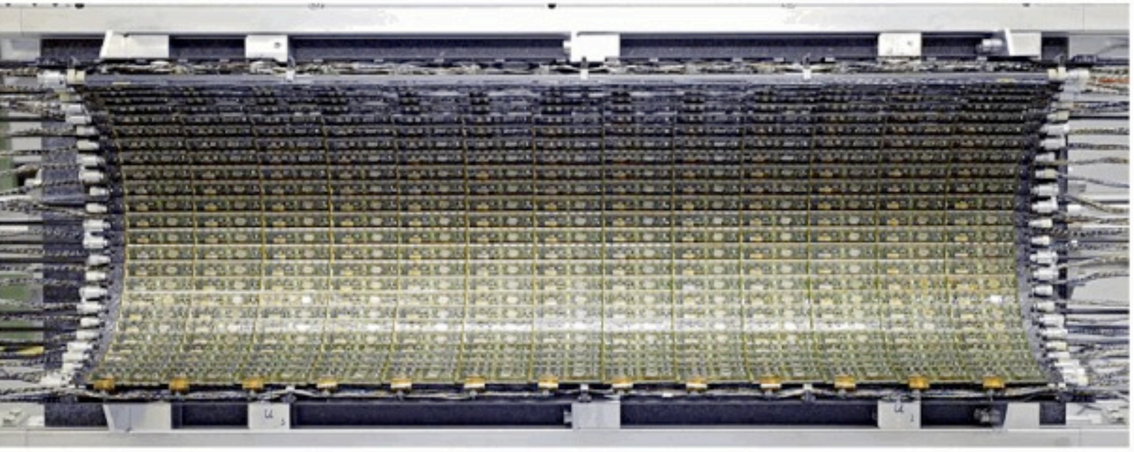
flip-Chip detector:
readout chip
'bump bonded'
to Si detector

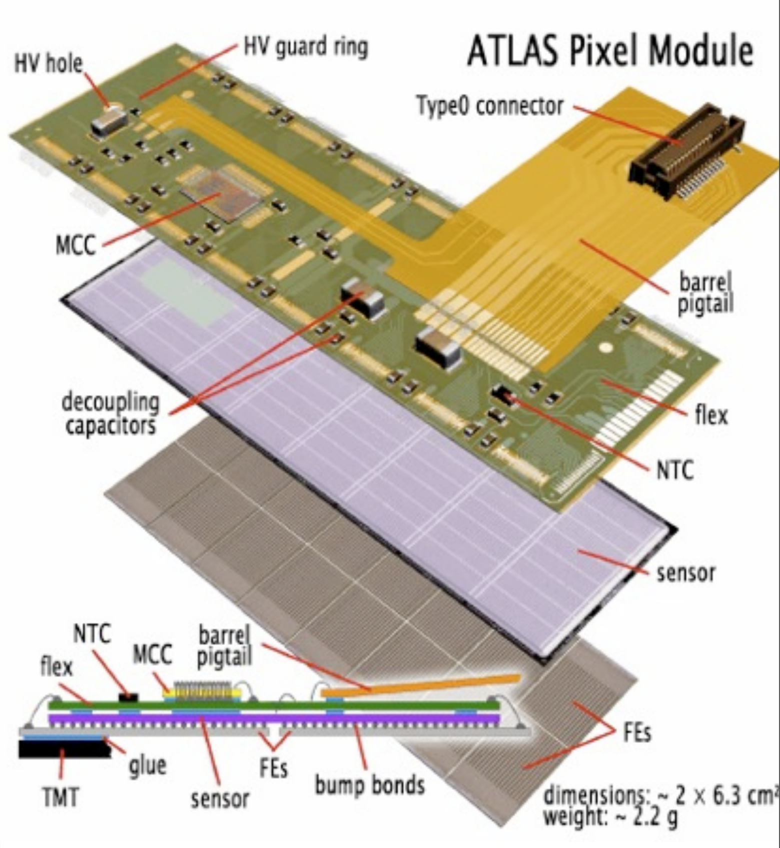


But: Large number of channels!
→ Large number of electrical connections and large power consumption

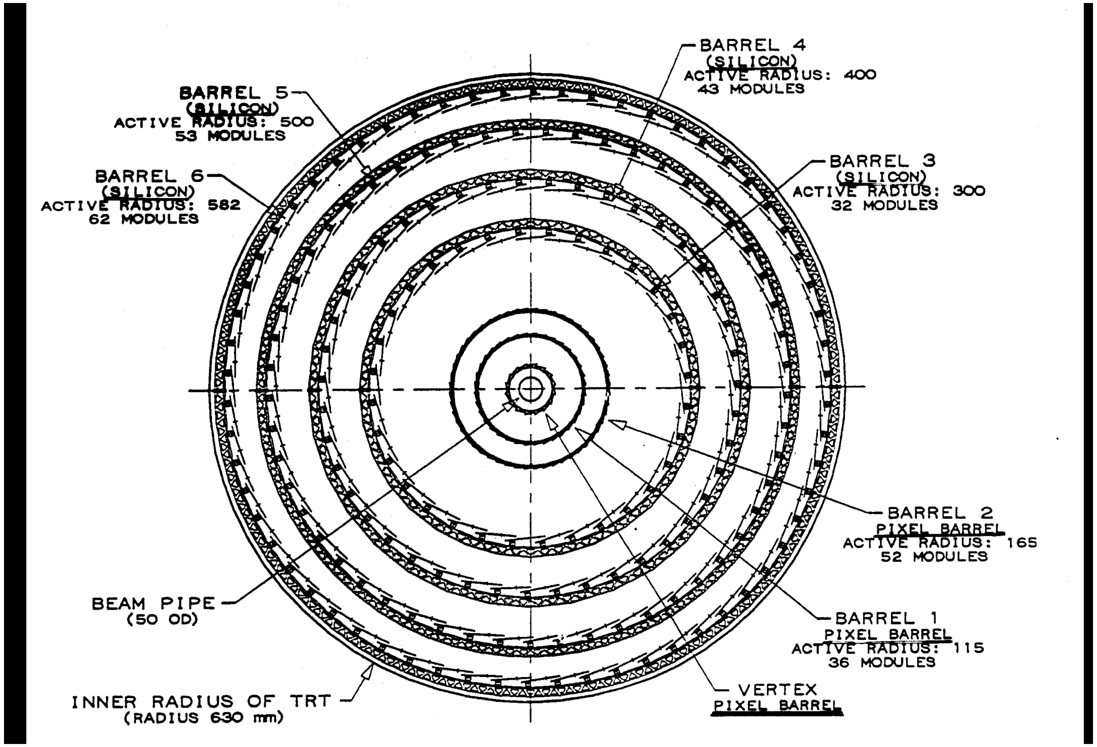
Siliziumdetektoren in ATLAS







Siliziumdetektoren in ATLAS



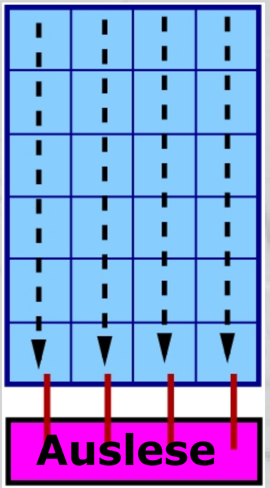
System	Position	Area (m^2)	Resolution σ (μm)	Channels (10^6)	η coverage
Pixels	(1 low-lum. barrel layer)	(0.2)	($R\phi = 14$, $z = 87$)	(12)	(± 2.5)
	2 barrel layers	1.4	$R\phi = 14$, $z = 87$	140	± 2.5
	4 forward disks on each side	0.8	$R = 87$		
Silicon strips	(1 low-lum. barrel layer)	(0.2)	($R\phi = 10$, $z = 20$)	(0.03)	(± 2.1)
	4 barrel layers	41	$R\phi = 15$, $z = 770$	2.9	± 1.4
TRT	Axial barrel straws		170 (per straw)	0.1	± 2.5
	Radial forward straws			0.32	
	36 straws per track				

Ausleseprinzip von CCDs und neuen Technologien

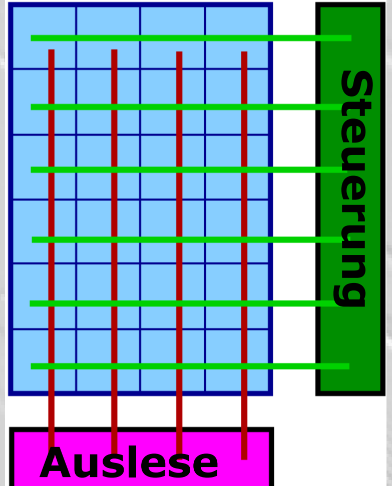
Etablierte Technologieoption: CCDs

Exzellente Erfahrung von SLD (300 Millionen Kanäle)

F&E: Effizienz und Stabilität des Ladungstransports
Auslesegeschwindigkeit, dünne Sensoren,
mechanische Stabilität, Strahlenhärte



„Neue" Technologien: MAPS (Monolithtic Activ Pixel Sensors) und DEPFET (Depleted Field Effect Transistor)



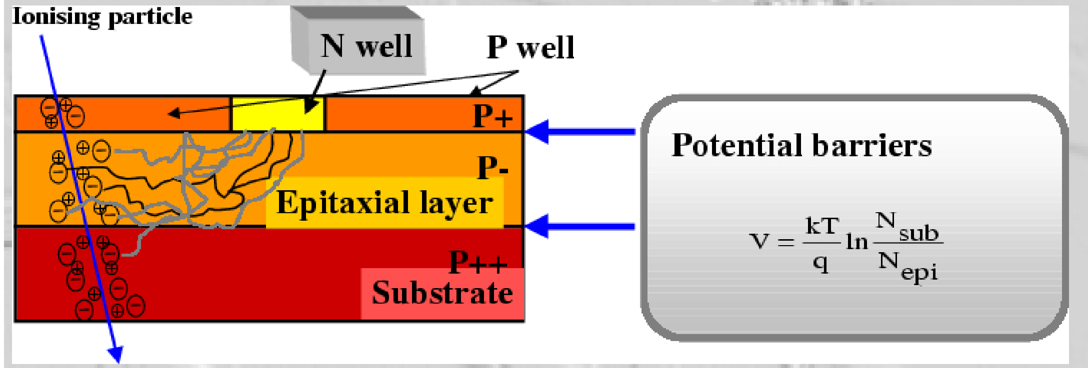
jeder Pixel selektiv ansteuerbar

nur jeweils eine Zeile aktiv
⇨ geringerer Leistungsverbrauch

erste Signalverarbeitung im Pixel
⇨ geringeres Rauschen

Ladungssammlung von CCDs und neuen Technologien

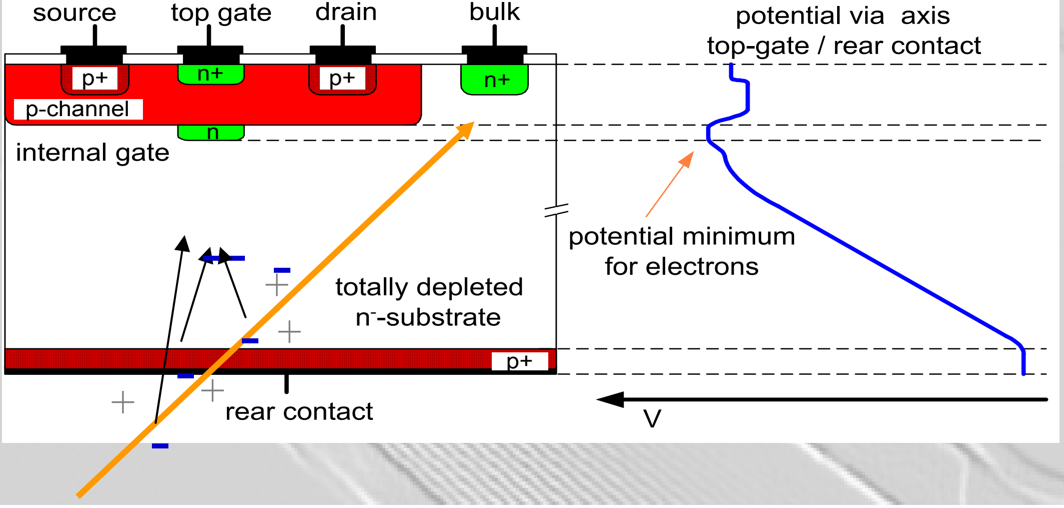
Monolithtic Activ Pixel Sensors



Standard CMOS-Technologie

Ladung aus „Epitaxial Layer" diffundiert thermisch zum „N well"

Depleted Field Effect Transistor



Ladung wird in der Potentialmulde (internes „Gate") gesammelt

⇨Modulierung des Transistorstroms