Solid State Detectors

Lecture for Summer Students at DESY

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August 17, 2007

Content

Interaction of Particles with Matter

Interaction of Particles with Matter

For charged particles:

- Inelastic collisions with electrons of the atomic shell
  - Soft (Atoms are only excited)
  - Hard: (Atoms become ionized)

    δ-Rays (Energy of knocked-out electrons big enough to ionize further atoms).

→ Bethe-Bloch Formula (see following page)

- Elastic collisions with nuclei
- Cherenkov-Radiation
- Bremsstrahlung
  - Deceleration of charged particles with E>>m over small distance: Electrons
- Nuclear reactions

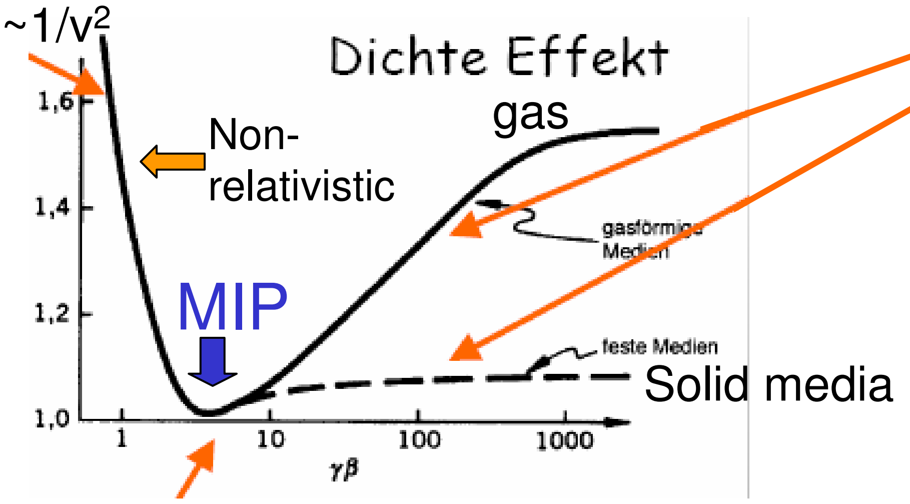
Interaction of Particles with Matter

Ionisation and excitation

$$\frac{-dE}{dx} = \frac{4\pi z^2 e^4 nZ}{m\beta^2 c^2}\left(\ln\left[\frac{2m\beta^2 c^2}{\bar{I}}\gamma^2\right] - \beta^2 - \frac{\delta}{2}\right)$$

Bethe-Bloch Formula

for heavy particles



Relativistic rise ~ln

m:	**rest mass of the electron**
β:	**=v/c rel. velocity of particle.**
γ:	**=$(1-\beta^2)^{-1/2}$ Lorentz-Factor**
ze:	**electric charge of particle**
Z:	**atomic number of medium**
n:	**number of atoms per unit vol.**
	=$\rho A_0/A$; A_0: Avogadro-number A: atomic mass, ρ: spec. density of medium
δ:	**density parameter**
$\bar{I}$:	**mean ionization potential**

Interaction of Particles with Matter

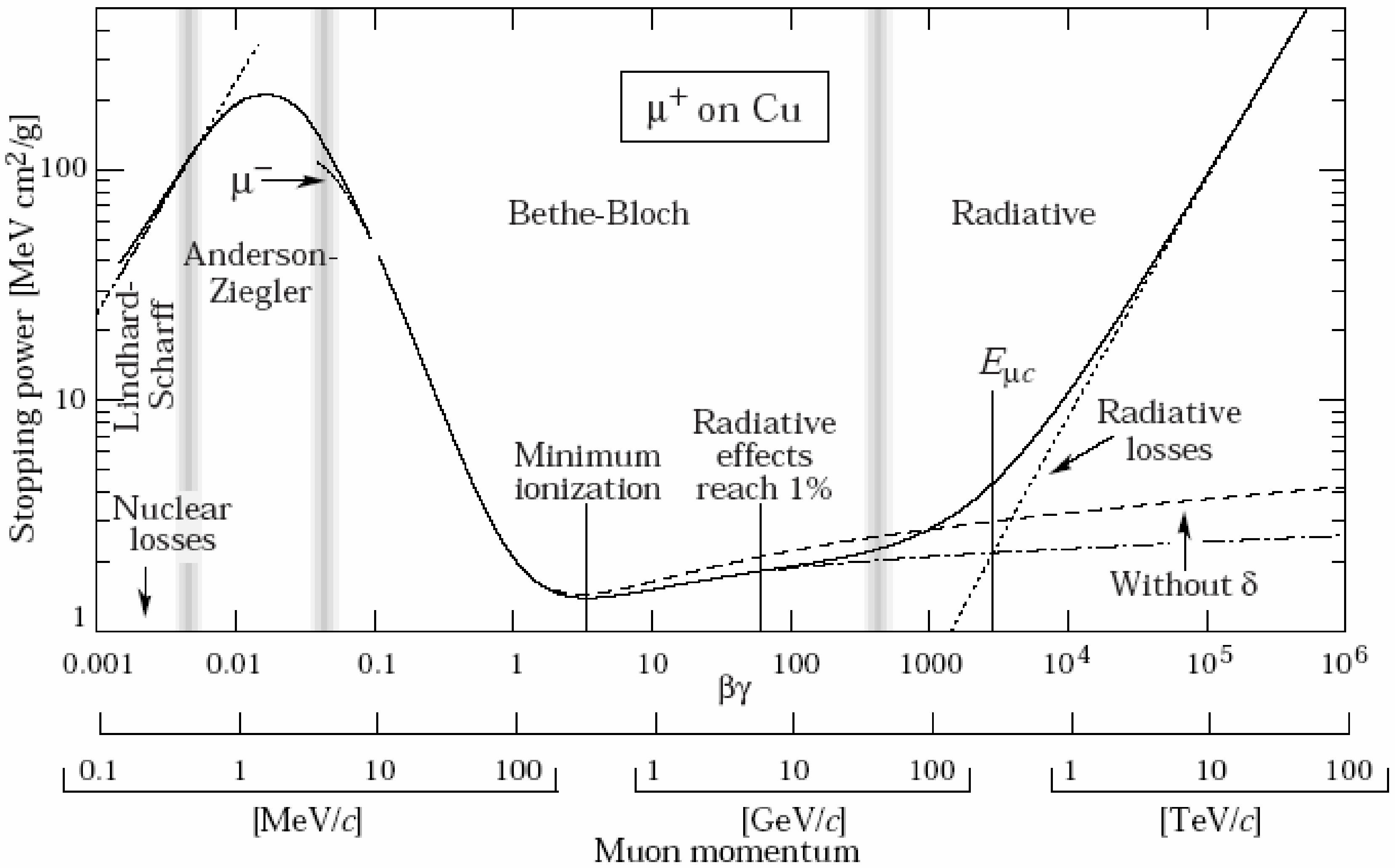
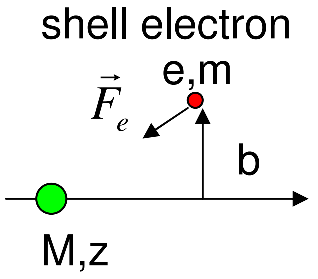


Fig. 27.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum

Bethe-Bloch Formula: “Derivation”



Bohr: Simplified classical derivation of energy loss (stopping power) formula.

Consider inelastic collisions with shell electrons

Momentum transferred to electron:

with impact parameter b

$$\Delta\vec{p} = \int \vec{F}_e\, dt = e\int E_T\, dt = \frac{e}{v}\int E_T\, dx = \frac{2ze^2}{b\cdot v}$$

$$\text{with Gauss: } 4\pi z e = \int \vec{E}\, d\vec{\alpha} = 2\pi b \int E_T\, dx$$

→energy transferred $\Delta E(b) = \frac{\Delta p^2}{2m} = \frac{2z^2e^4}{mv^2b^2}$ (xx)

→For N_e (electron density) energy transferred for impact parameter interval b, b+db

$$-dE = \Delta E(b) N_e \cdot 2\pi b \cdot db \cdot dx$$

$$\rightarrow \frac{dE}{dx} = \left[\frac{4\pi z^2 e^4}{mv^2} N_e\right] \int_{b_{\min}}^{b_{\max}} \frac{db}{b} = \left[\frac{4\pi z^2 e^4}{mv^2} N_e\right] \ln\left(\frac{b_{\max}}{b_{\min}}\right)$$

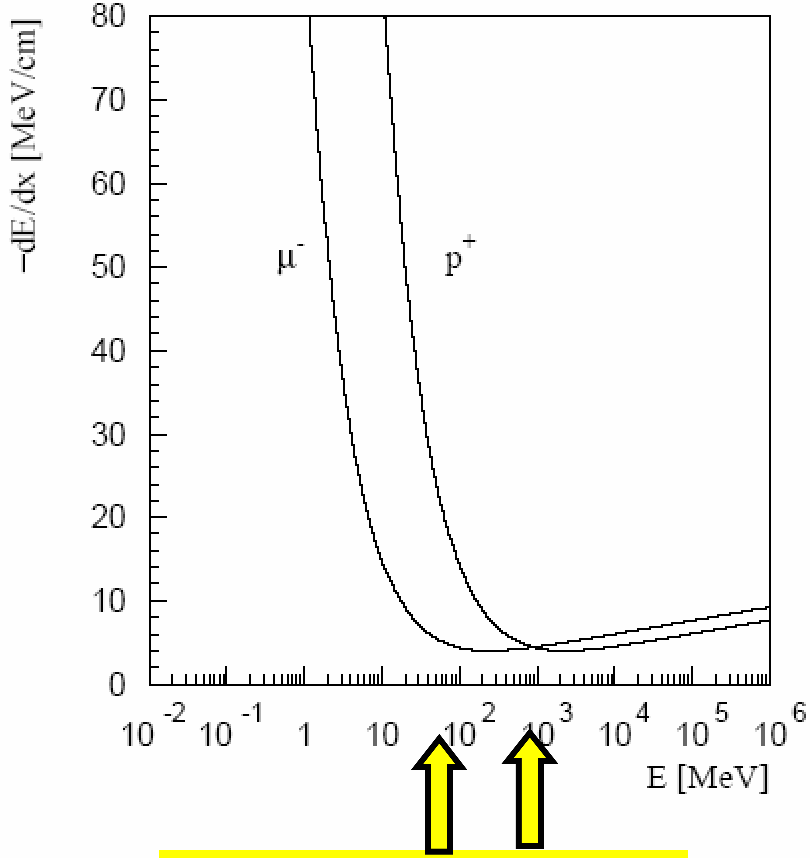
$$\text{max mom. transfer } \Delta p = 2m_e v, \text{ min energy transfer I (binding E)}$$

$$\rightarrow b_{\min} = \frac{ze^2}{m_e \mathrm{v}^2} \qquad b_{\max} = \frac{ze^2}{\mathrm{v}}\sqrt{\frac{2}{m_e I}} \qquad \text{(using (xx))}$$

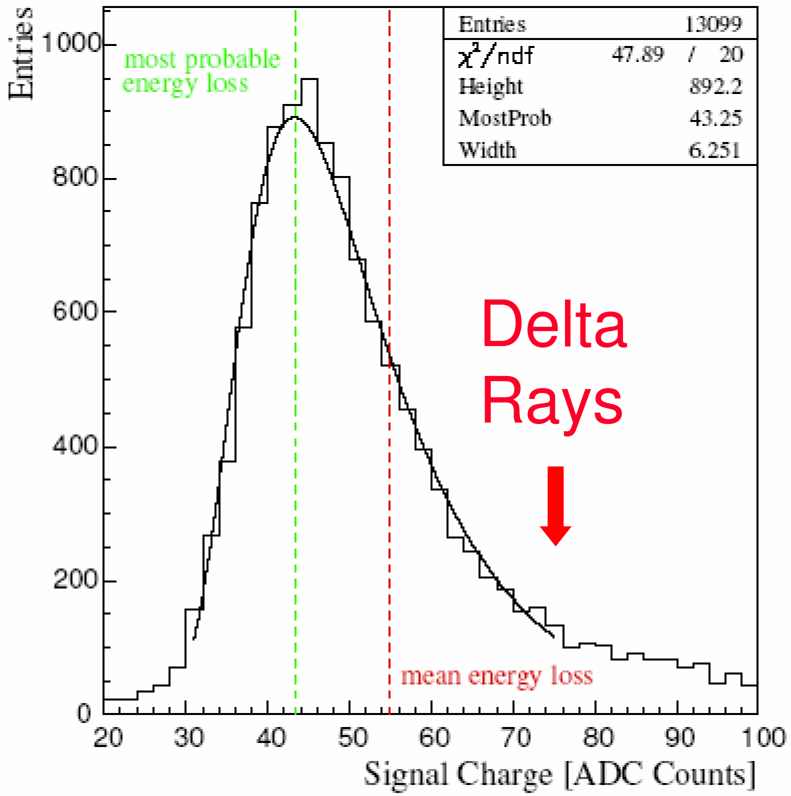
$$\rightarrow \frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} N_e \ln\left(\frac{2m_e v^2}{I}\right)$$

Contains essential features of Bethe Bloch, which has been derived using Quantum Mechanics

Energy Loss in Silicon



Minimal ionizing



1 Mip = on average 32500 e-hole pairs in 300 µm silicon

Bethe-Bloch Formula (see before)

Landau distribution

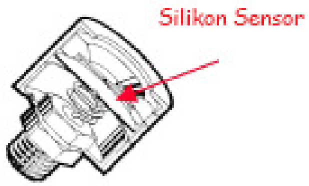
Solid State Detectors: Motivation and Introduction

Solid State Detectors: Motivation

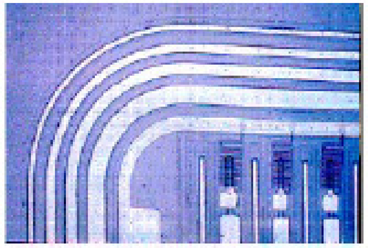
Semiconductors have been used in particle identification for many years.

- ~1950: Discovery that pn-Junctions can be used to detect particles.
  →Semiconductor detectors used for energy measurements (Germaniu
- Since~ 25 years: Semiconductor detectors for precise position measurements.
  - Of special Interest: Discovery of short lived b-and c-mesons, τ-leptons
  - life times $(0.3\text{-}2)\times10^{-12}$ s→$c\tau$=100-600µm
  - precise position measurements possible through fine segmentation (10-100µm)

  →multiplicities can be kept small (goal:<1%)



- Technological advancements in production technology:
  - developments for micro electronics (lithographic chip processing)
- Electrons and holes move almost freely in silicon:
  →Fast Readout possible (O(20 ns)): LHC: 25 ns “bunch spacing”

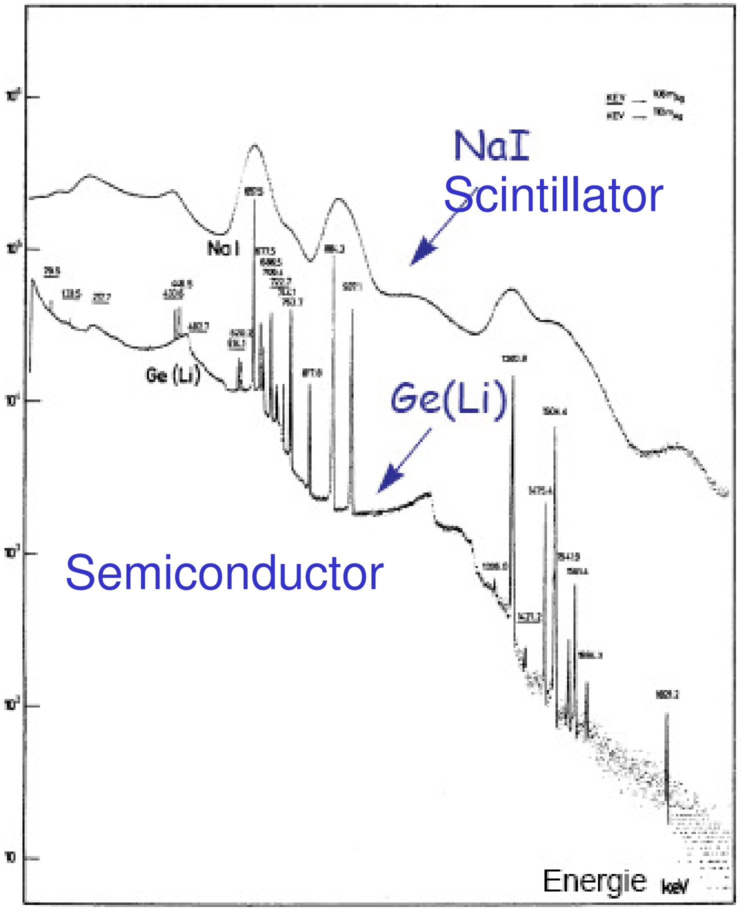


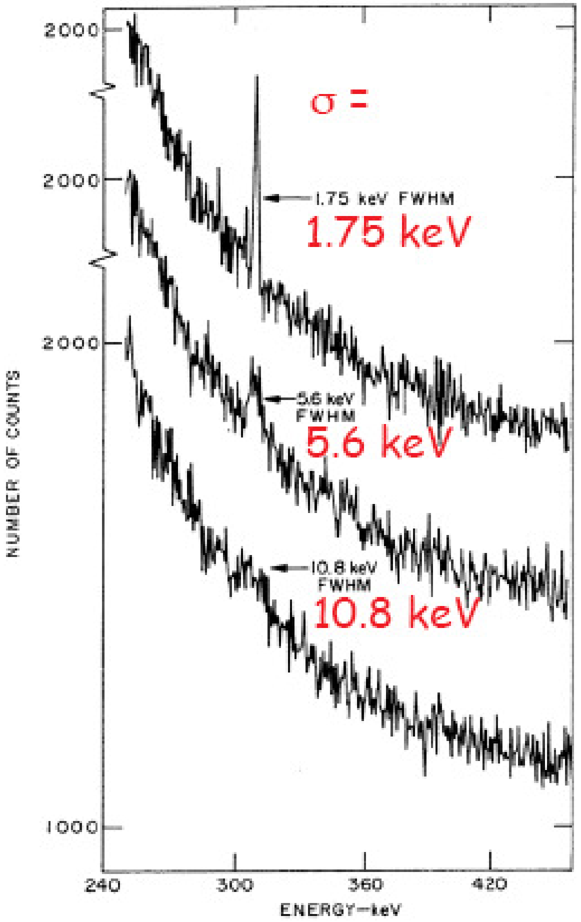
- Generation of 10x more charge carriers compared to typical gases (for the same energy loss)
- Radiation hardness

Motivation II

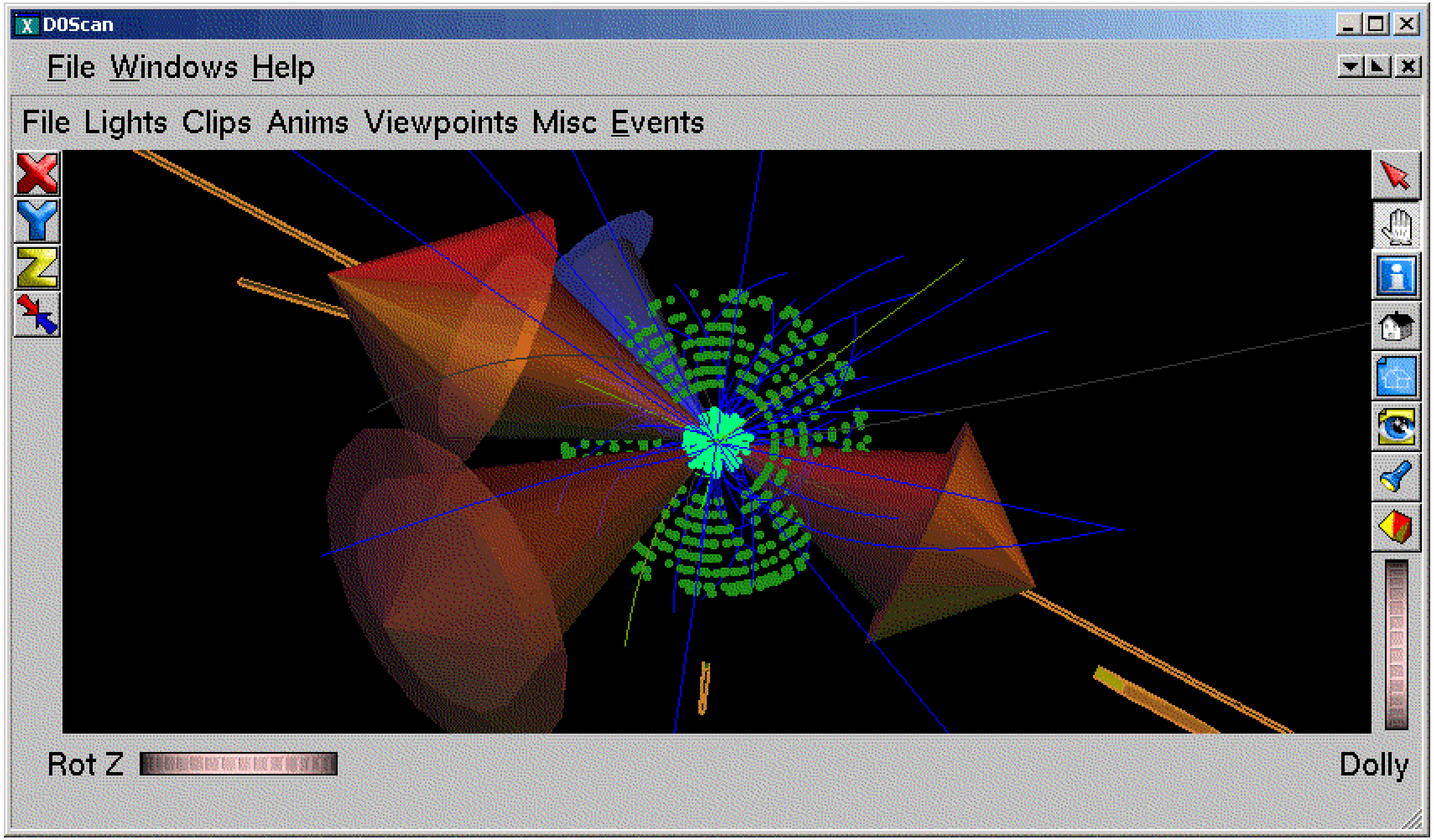
With good resolution structures become visible,

better signal/noise

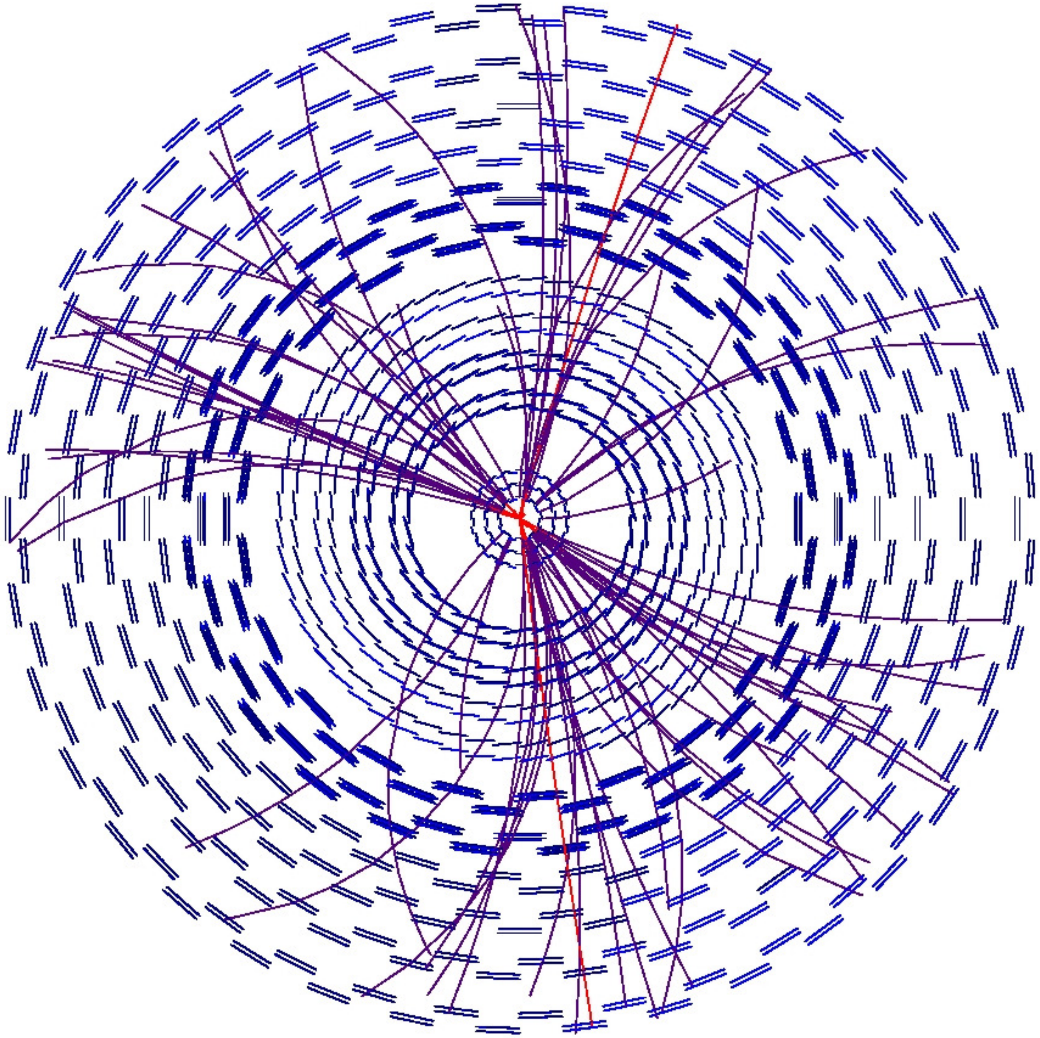




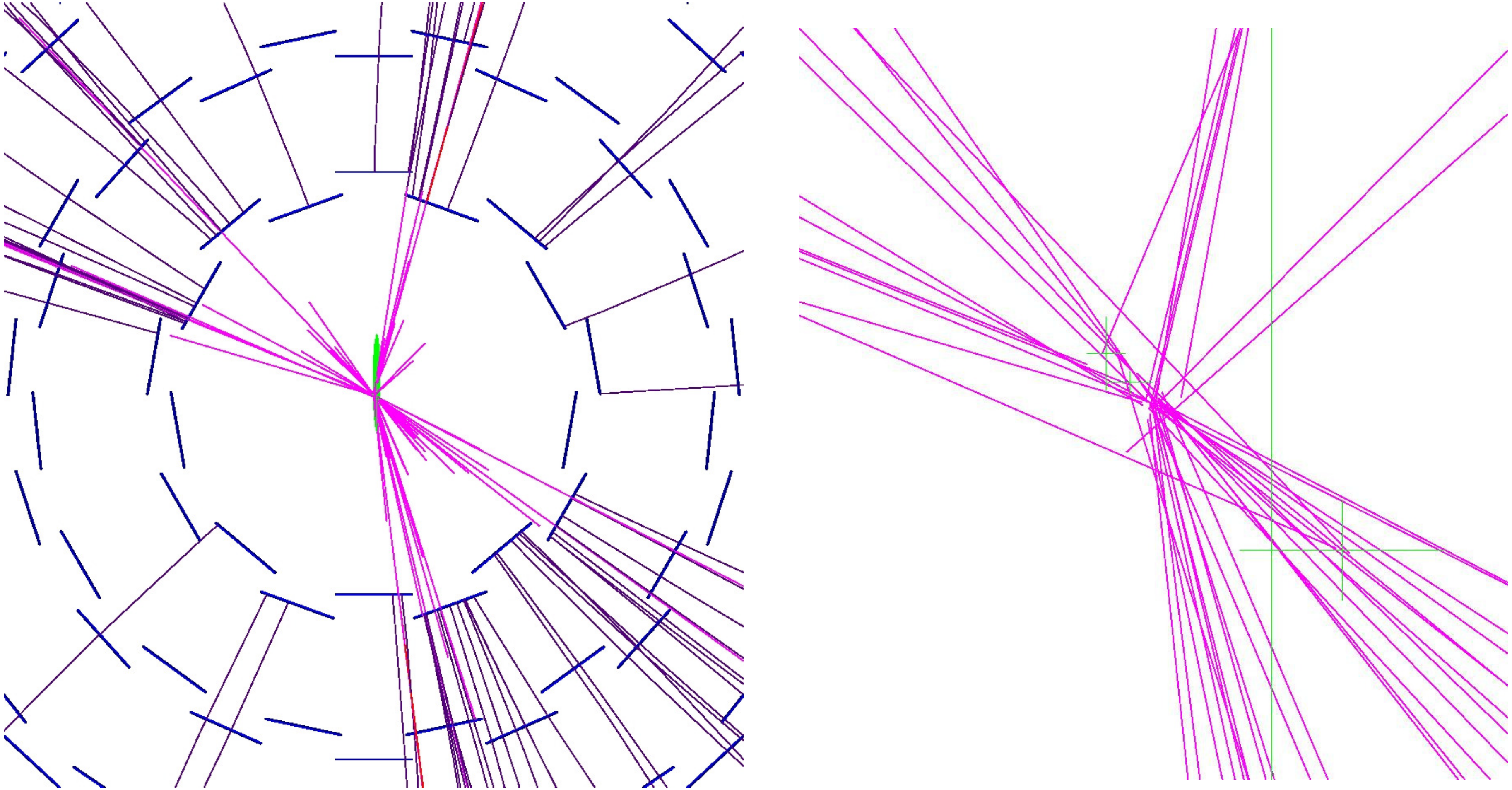
Example: D0 Event



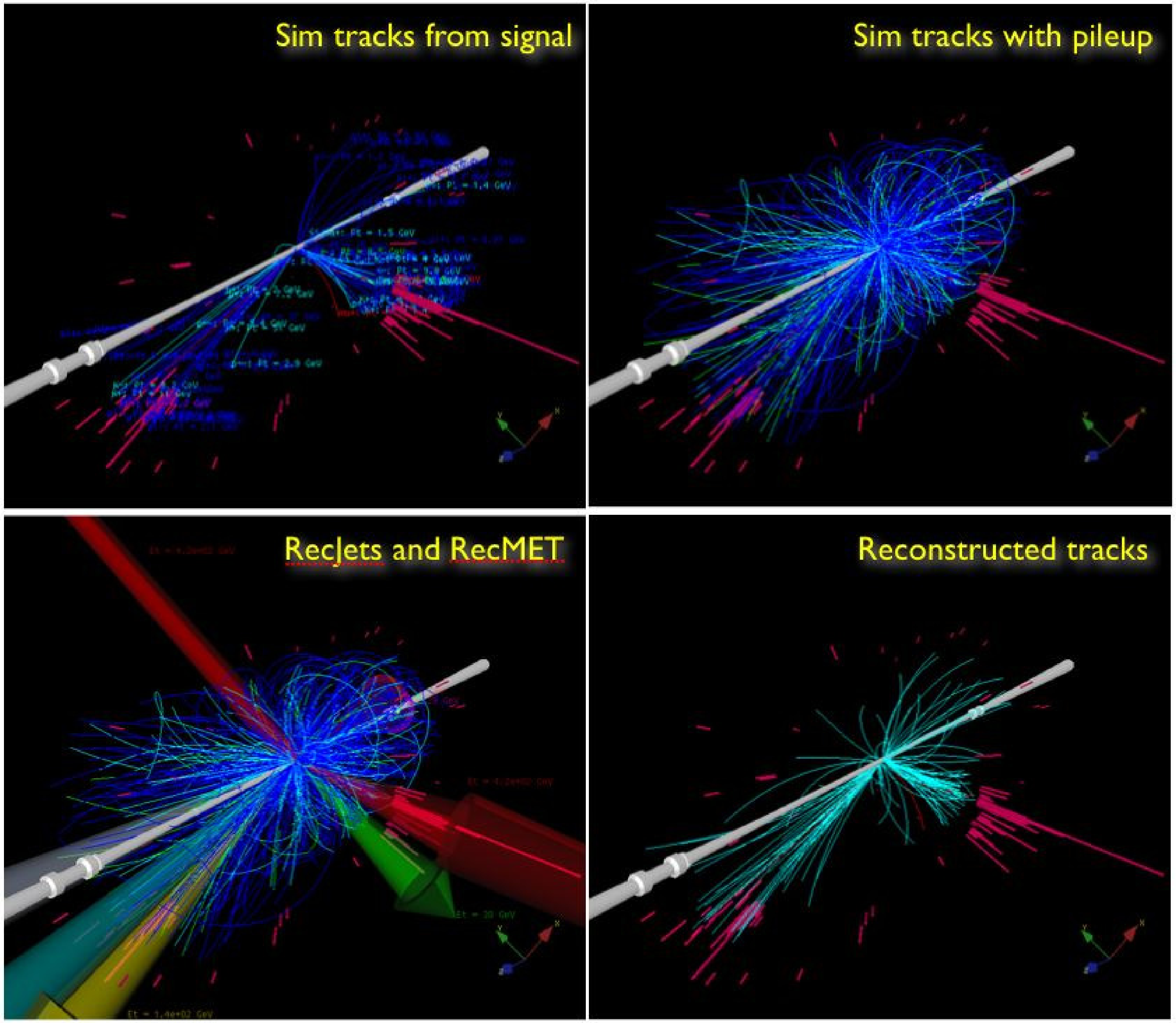
Example: CMS Event (simulated): ttH→bb



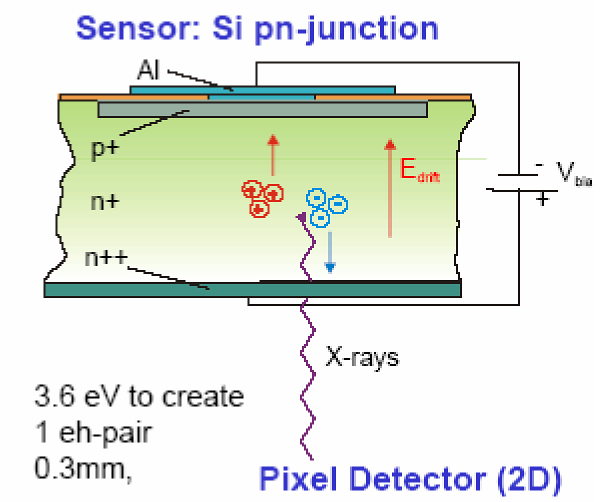
Example: CMS Event (simulated): ttH→bb zoomed in

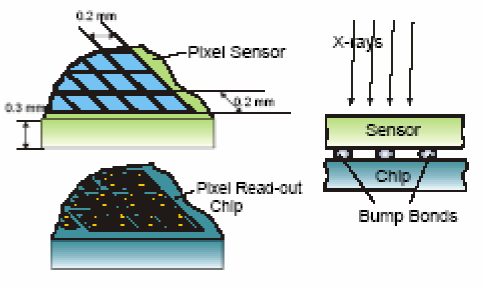


Example: CMS Event (simulated): Supersymmetry, high luminosity

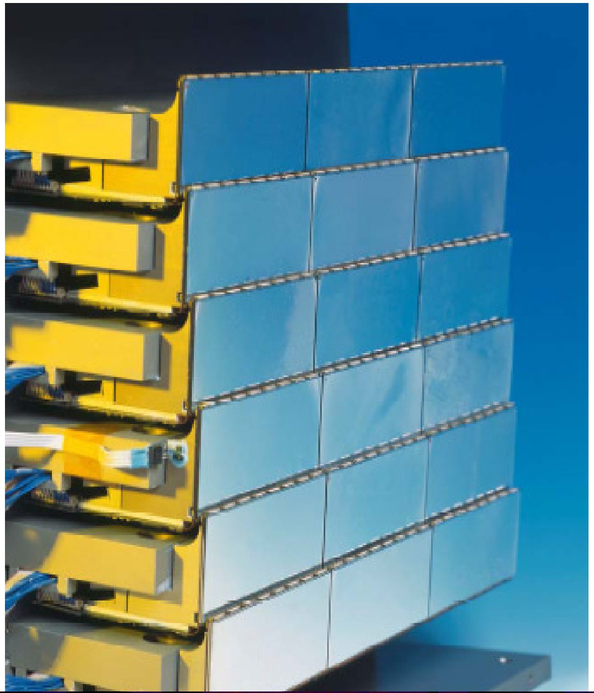


Example: Hybrid Pixel Detector
Pilatus (PSI-CH) forX-ray crystallography

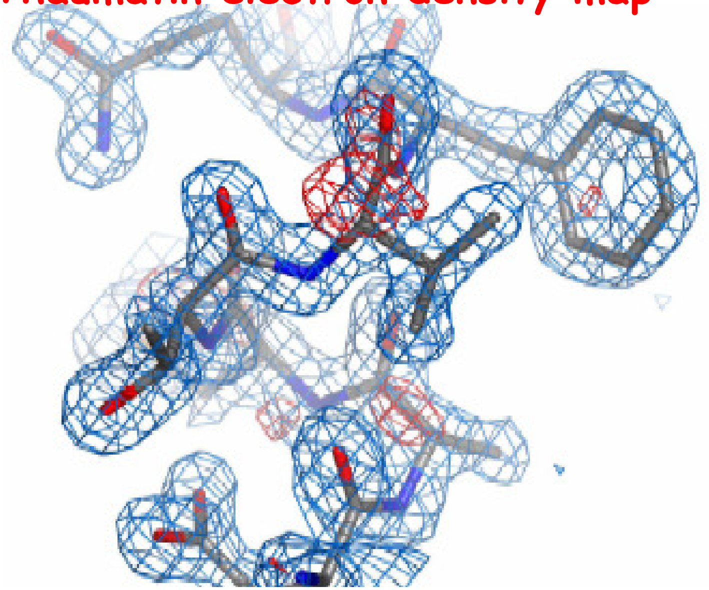


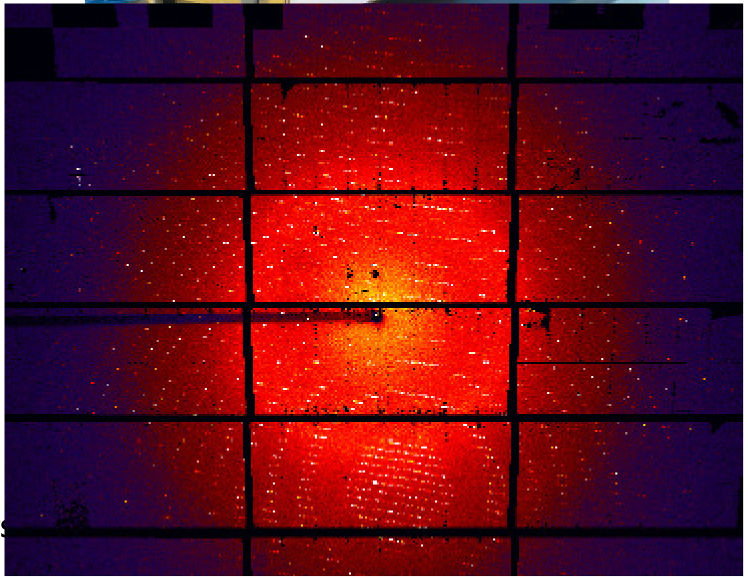


10^6 pixels of ~0.2×0.2 mm^2



Thaumatin electron density map





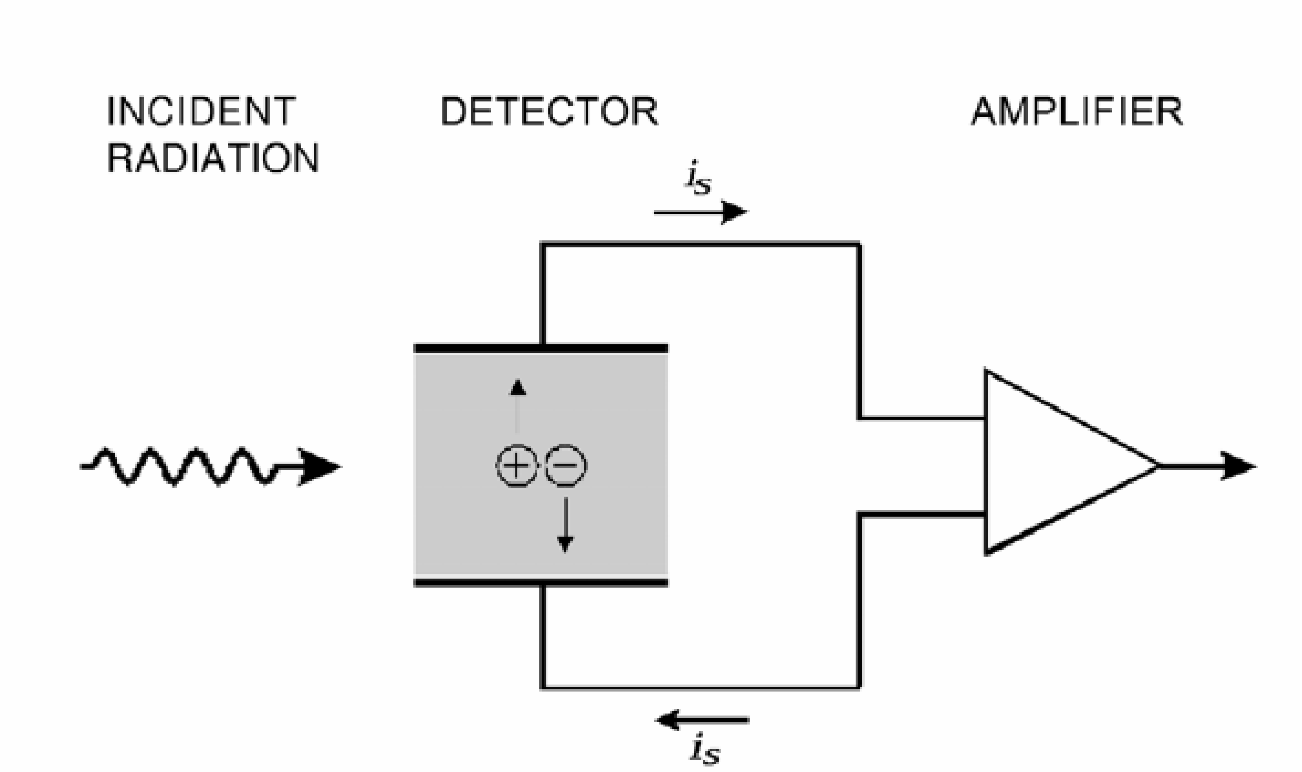
C.Brönnimann et al., J.Synchr.Rad. 13(2006)120

Solid State Detectors: General Remarks

Generally, Two kids of solid state detectors can be distinguished:

- Photo resistors: Resistance changes with irradiation
- Photo diode: Depleted semiconductor layer with typically large electric field used as active zone

→ionization chamber



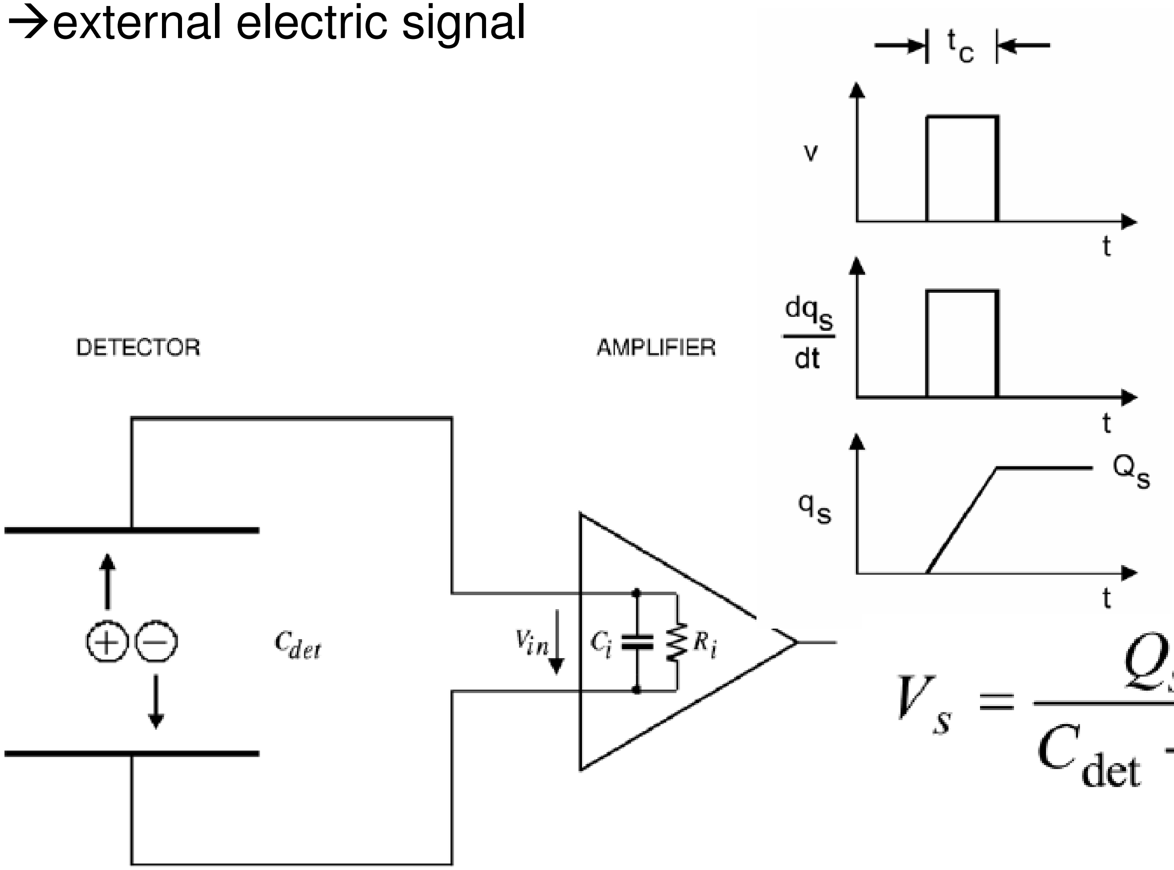
Working Principles

Detection volume with electric field

Charge carrier pairs generated via ionization

Charges drift in the electric field

→external electric signal



Velocity of charge carriers, v

Rate of induced charges on electrode

Signal charge, often Q~E

$$V_s = \frac{Q_s}{C_{\text{det}} + C_i}$$

Peak voltage ~E

if $R_i \, (C_{det} + C_i) \gg t_c$

Materials and their properties

Properties of materials for particle detection: Wish List

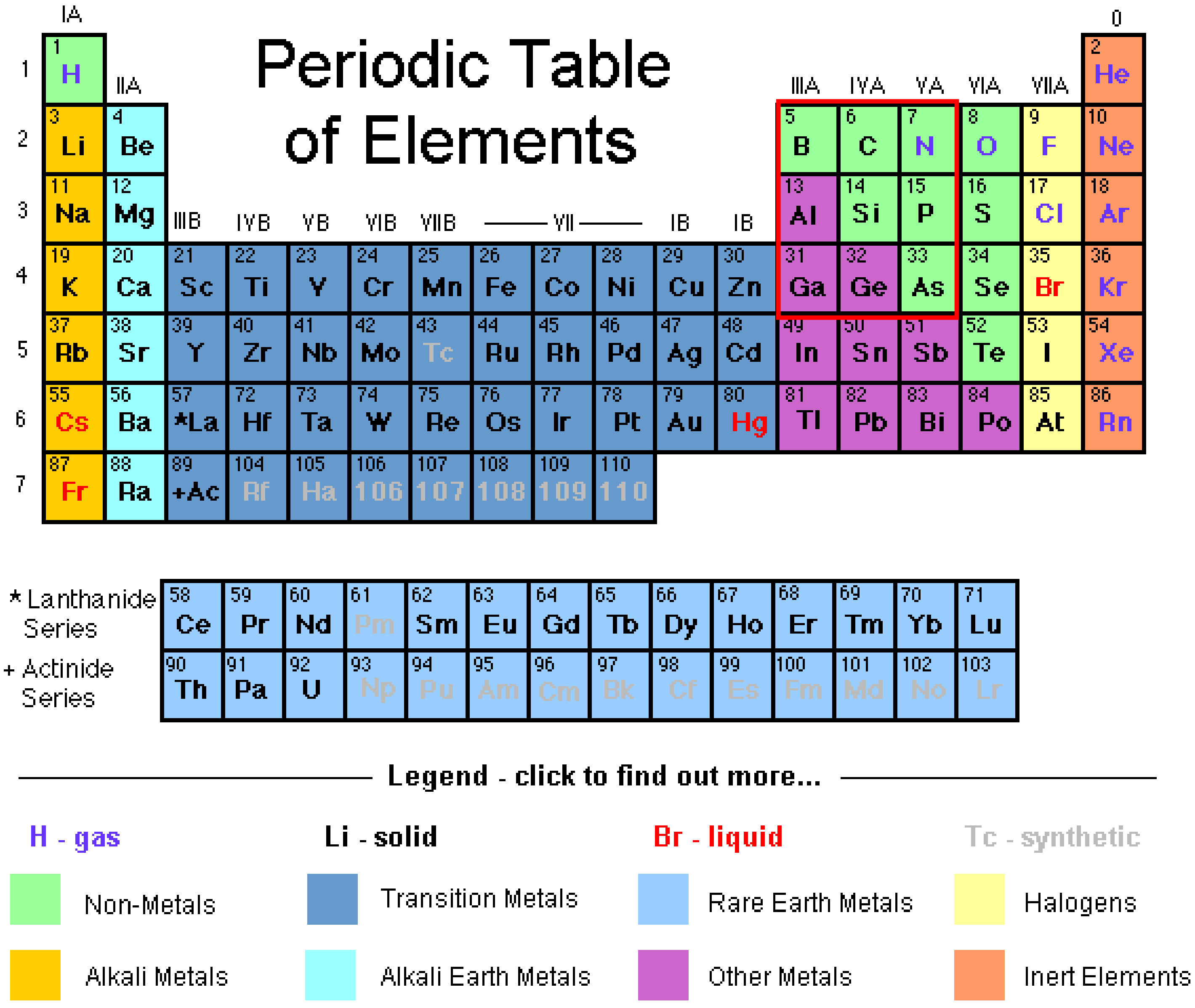
For Ionization chambers, in principle any material could be used that allows for charge collection at a pair of electrodes.

	Gas	liquid	solid
Density	low	moderate	high
Z	low	moderate	moderate
Ionization energy ε_i	moderate	moderate	small
Signal velocity	moderate	moderate	fast

Ideal properties:

Low ionization energy	→Larger charge yield dq/dE
	→better energy resolution
	$\Delta E/E \sim N^{-1/2} \sim (E/\varepsilon_i)^{-1/2} \sim \varepsilon_i^{1/2}$
High electric field	→fast response
in detection volume	better charge collection efficiency

Semiconductors in Periodic Table



Periodic Table of Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Legend - click to find out more...

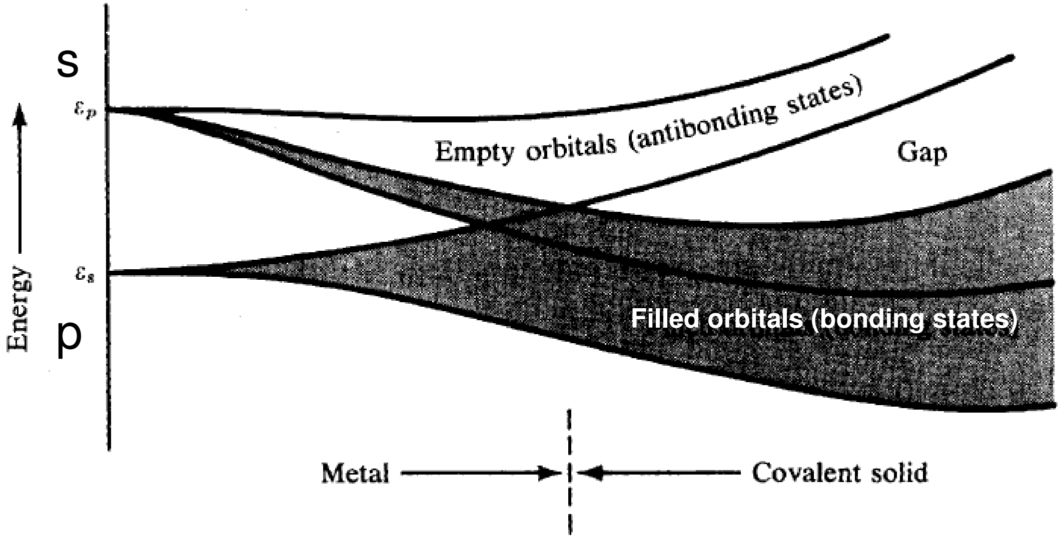
H - gas	Li - solid	Br - liquid	Tc - synthetic
🟩 Non-Metals	🟦 Transition Metals	🟦 Rare Earth Metals	🟨 Halogens
🟧 Alkali Metals	🟦 Alkali Earth Metals	🟪 Other Metals	🟧 Inert Elements

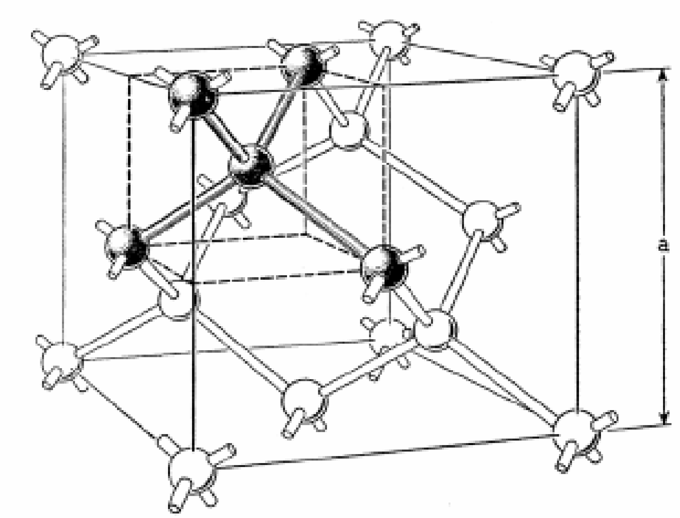
Energy bands and electronic structure

Semiconductors: Principle

When atoms are joined to form a crystal lattice, the discrete energy levels are distorted and form continuous energy bands.

All atoms contribute.



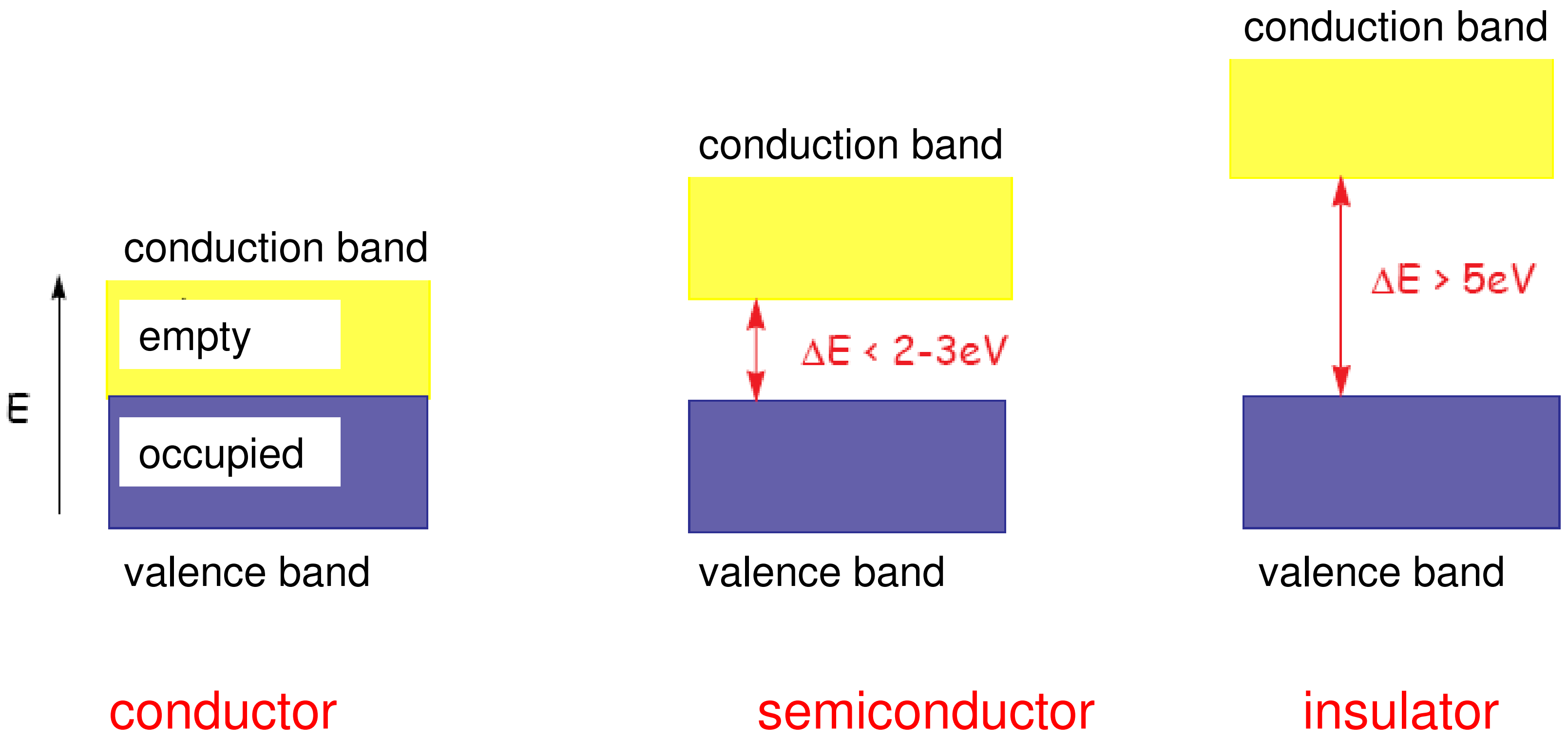


Crystal structure of Si, Ge, diamond

Bound stated generate filled energy bands.

Anti-bound states generate empty bands.

Classification of Conductivity



The probability that an electron occupies a certain energy level is given by the Fermi-Dirac-Distribution:

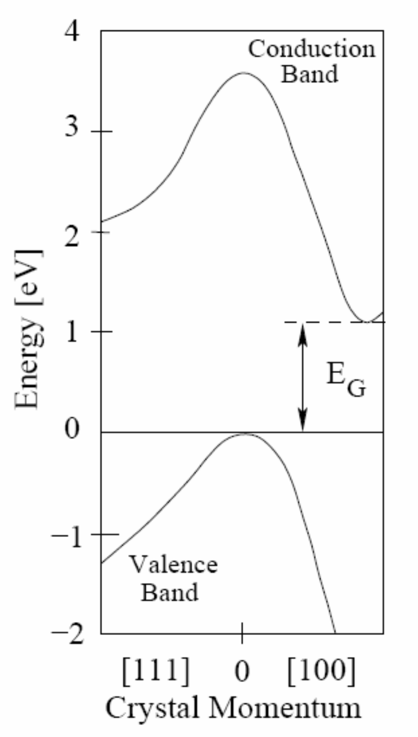
$$f_e(E)=\frac{1}{e^{(E-E_F)/kT}+1}$$

and for holes

$$f_h(E)=1-f_e(E)=\frac{1}{e^{(E_F-E)/kT}+1}$$

For intrinsic semiconductors (e and h concentration equal): $E_F=E_{gap}/2$

Silicon: Properties



•indirect band gap $\delta E = 1.12$ eV
compare to $kT = 0.026$ eV at room temp. → dark current under control

•energy per electron-hole pair: 3.6 eV (rest in phonons, compared to ~30eV for noble gases)

- high Density compared to gases: $\rho = 2.33 \text{g/cm}^3$

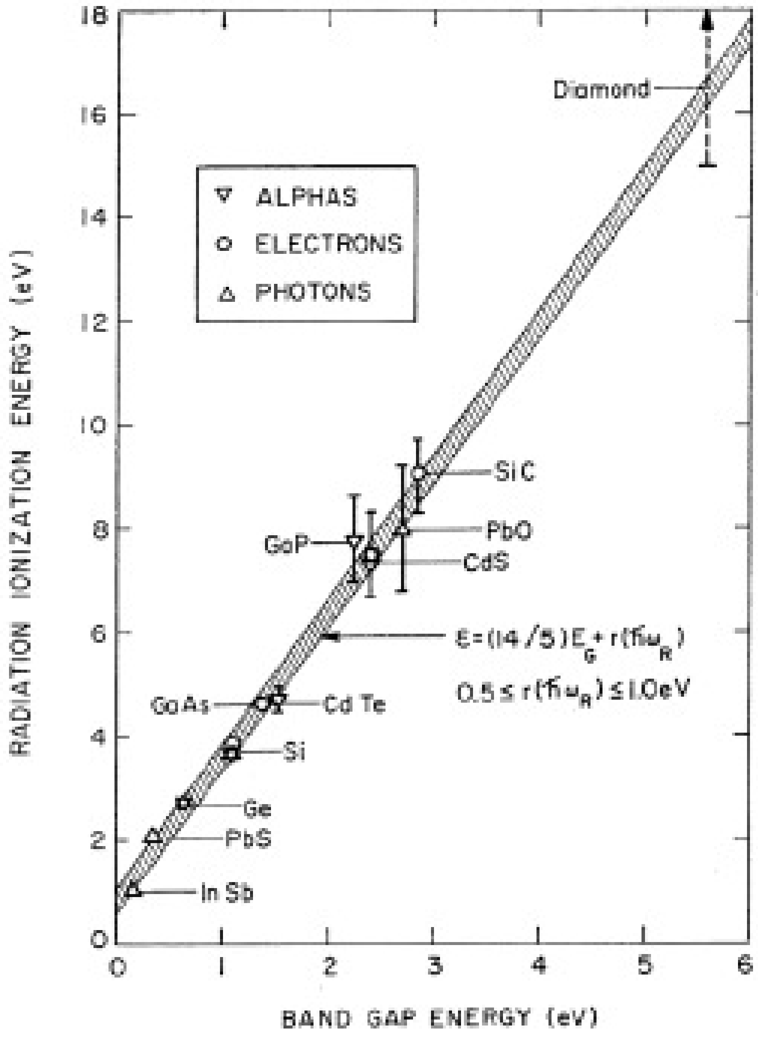
•with $dE/dx|_{min} = 1.664$ MeV/g cm^2:

$N = 1.664 \text{ MeV/g cm}^2 \times 2.33 \text{g/cm}^3 / 3.6 \text{eV}$
→~32000 electron-hole pairs in 300µm (MIP)

- good mechanical stability → possible to produce mechanically stable layers of this thickness

- large charge carrier mobility
→ fast charge collection $\delta t \sim 10$ns

Semiconductors: General Properties

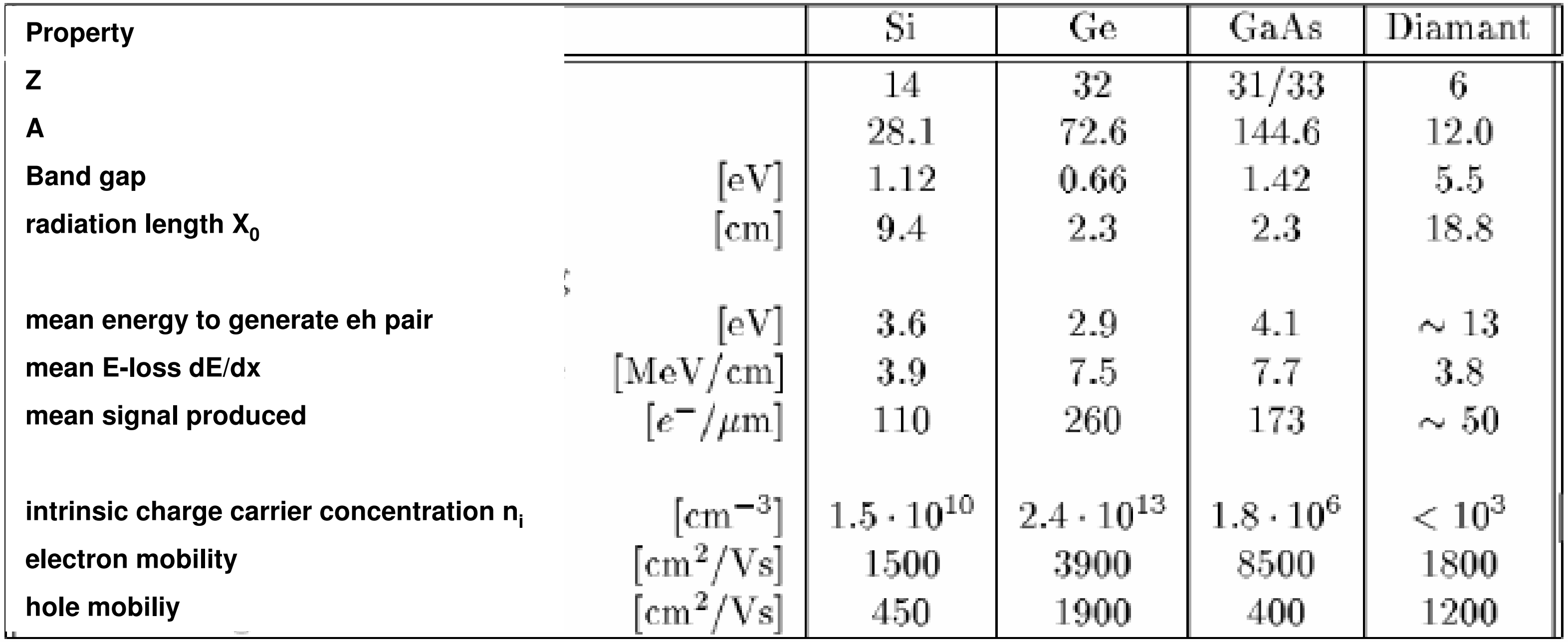


Ratio e_{ffi}/E_{Gap} independant of

- material
- type of radiation

Reason: Fraction of energy going into phonons (momentum transfer) is approximately the same for all semiconductors.

Semiconductors Compared



Property		Si	Ge	GaAs	Diamant
Z		14	32	31/33	6
A		28.1	72.6	144.6	12.0
Band gap	[eV]	1.12	0.66	1.42	5.5
radiation length X_0	[cm]	9.4	2.3	2.3	18.8
mean energy to generate eh pair	[eV]	3.6	2.9	4.1	~ 13
mean E-loss dE/dx	[MeV/cm]	3.9	7.5	7.7	3.8
mean signal produced	$[e^-/\mu m]$	110	260	173	~ 50
intrinsic charge carrier concentration n_i	$[cm^{-3}]$	$1.5 \cdot 10^{10}$	$2.4 \cdot 10^{13}$	$1.8 \cdot 10^{6}$	$< 10^{3}$
electron mobility	$[cm^2/Vs]$	1500	3900	8500	1800
hole mobiliy	$[cm^2/Vs]$	450	1900	400	1200

Si

- currently best compromise for strip detectors

Ge

- small band→high amount of charge produced →good for energy measurements
- high intrinsic charge carrier concentration →has to be cooled (liquid N_2)

GaAs

- good ratio generated charge/ noise
- but: charge collection efficiency strongly dependent on purity and composition
- radiation hard

Diamond

- radiation hard, but still quite expensive
- charge collection length ~ 80µm

Signal Formation in Silicon

- Conduction band really empty only at T=0
- Distribution according Fermi-Dirac Statistics
- Number of electrons in conduction band at room temp.:

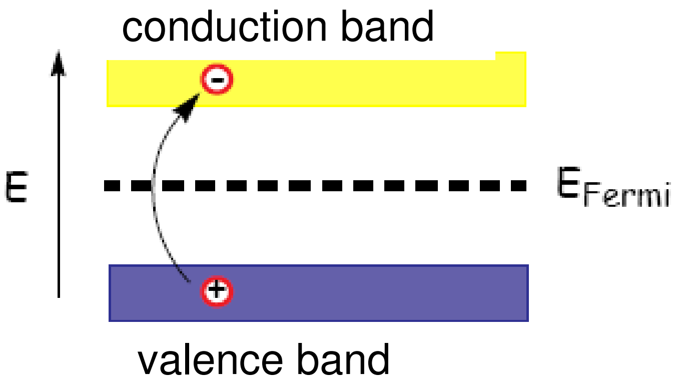
$$n_i = \sqrt{n_V n_C} \cdot \exp\left(-\frac{E_{Gap}}{2kT}\right) = 1.5\times10^{10}\ \mathrm{cm}^{-3}$$

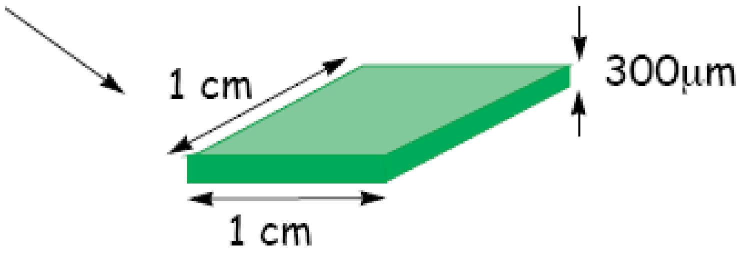
→Ratio of electrons in conduction band 10^{-12} (Silicon ~$5\text{x}10^{22}$ Atoms/cm^3)

- A volume of 1cm x 1cm x 300µm contains ~$4.5\text{x}10^8$ free charge carriers compared to only $2.3\text{x}10^4$ electron-hole pairs for a MIP.

→To detect this signal, the number of free charge carriers has to be reduced drastically. Possibilities are:

  - cooling
  - pn-junction in reverse bias

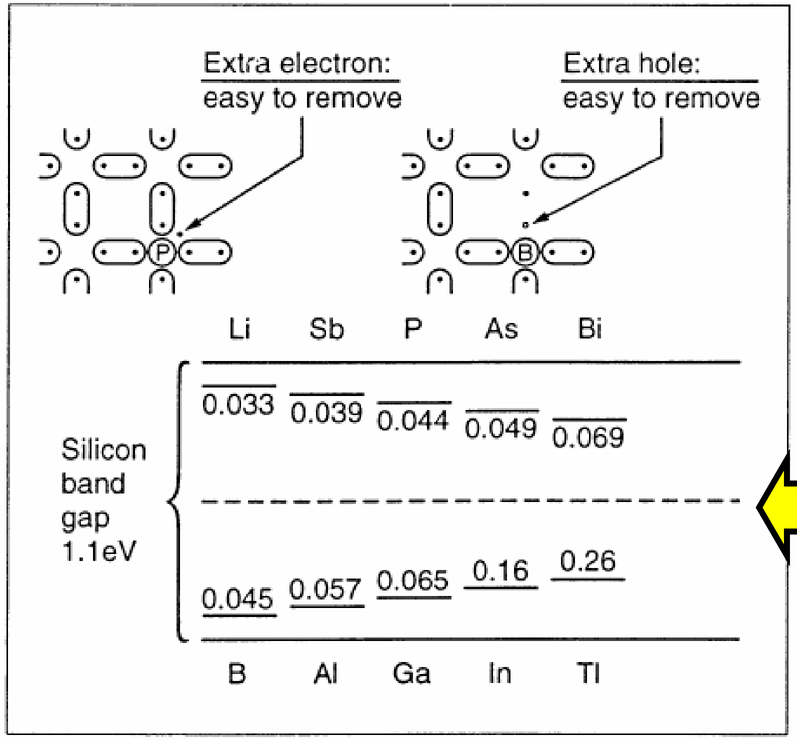




Interlude: Doping

- **Pure silicon has a very high resistance at room temp. (235 kOhm cm)**

- **Doping: A few silicon atoms can be replaced by atoms of an element of the 3rd main group (i.e. Boron) →p type, or of the 5th main group (i.e. Phosphor) →n type.**

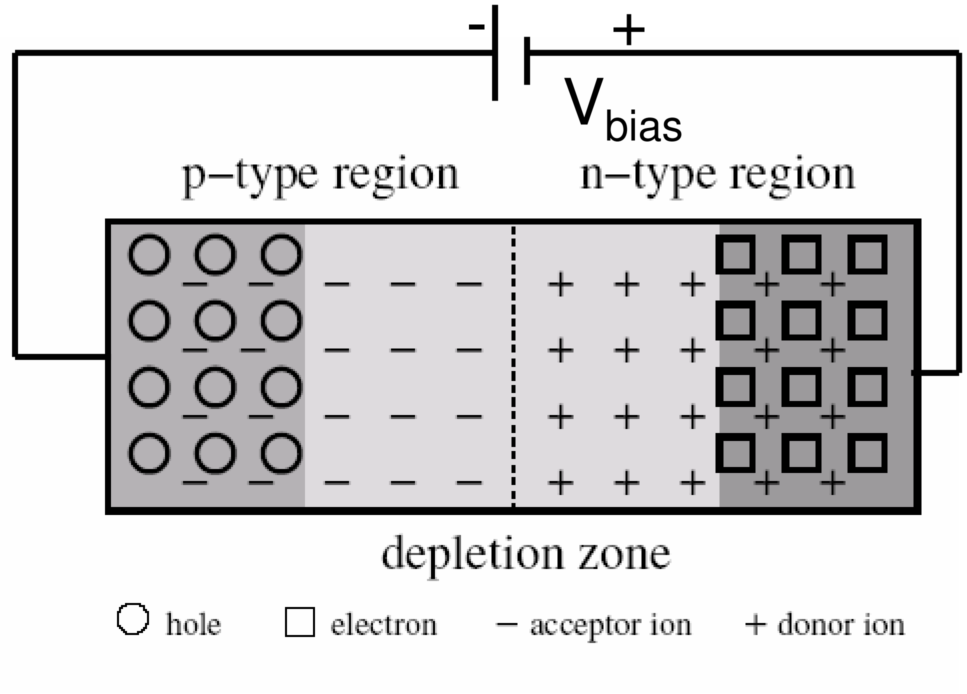


Typical doping concentration 10^{-11} !

Important: Charge carriers only weakly bound.

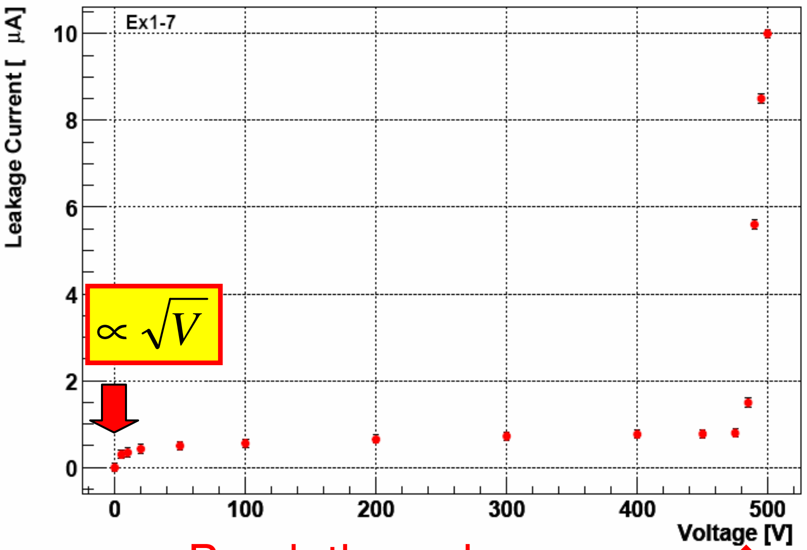
The pn junction

The pn junction



electrons drift towards p-side, holes towards n-side → buildup of a potential.

Leakage current: Thermal generation of e h pairs → temperature dependant



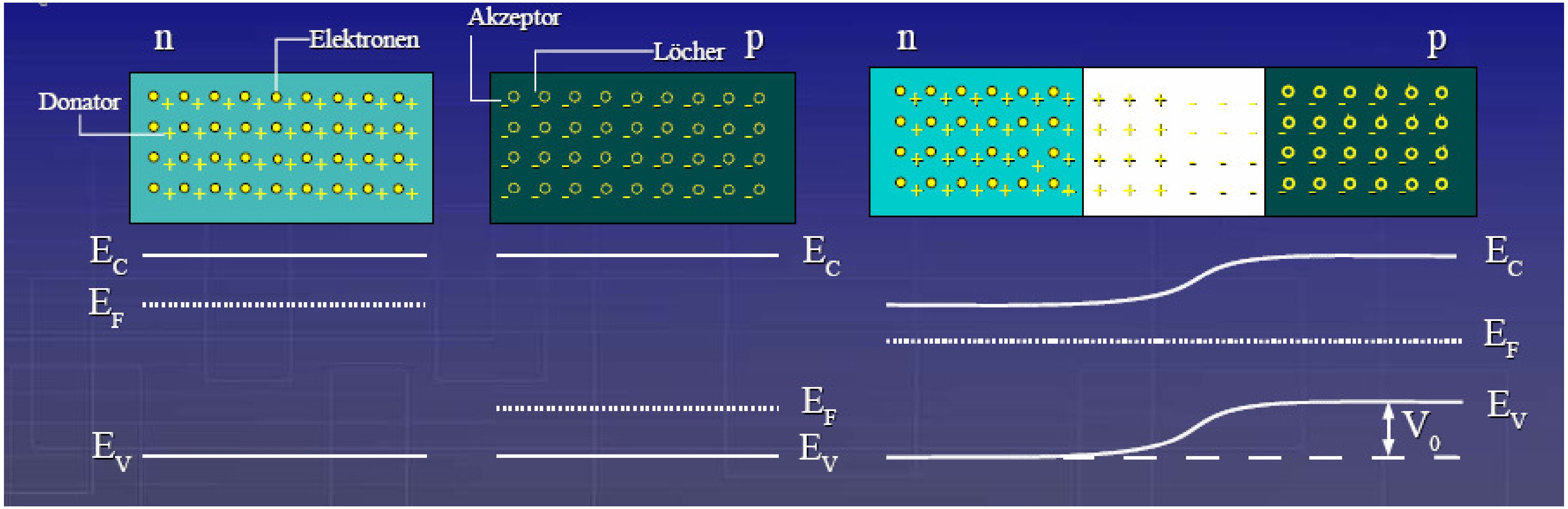
Break through:

Detector behaves like a conductor (charge avalange)

External voltage in the same direction as generated potential (Diode in reverse bias) → Increase of depletion region (Layer depleted of free charge carriers)

→Outstandingly useful for the detection of ionizing radiation.

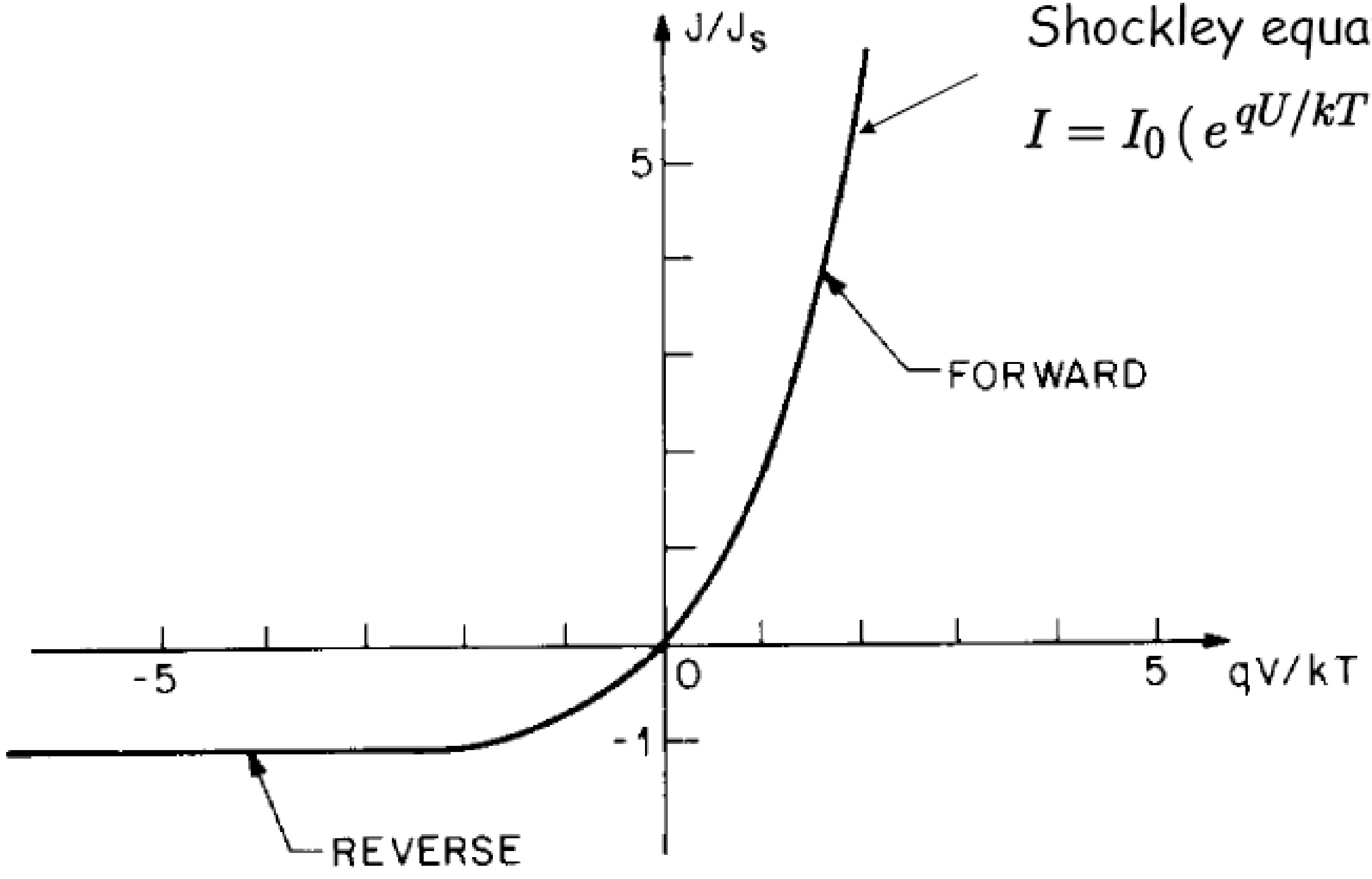
The pn Junction in the Band Model



Note: Fermi-Level in doped semiconductors not in the center of the forbidden zone anymore!

pn-junction: Fermi-levels adjust →the conduction band and valence band distort to compensate →V_0

Diode: Current Against Voltage

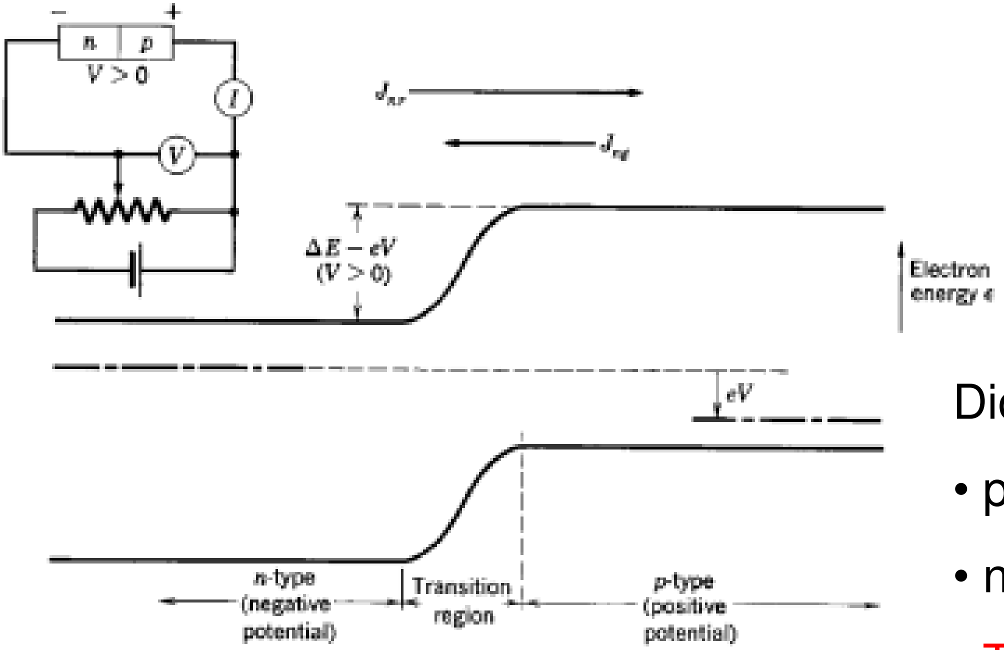


Shockley equation

$$I = I_0\,(e^{qU/kT} - 1)$$

from Sze, Physics of Semiconductor Devices

pn-Junction in Forward Bias



Diode in Forward Bias

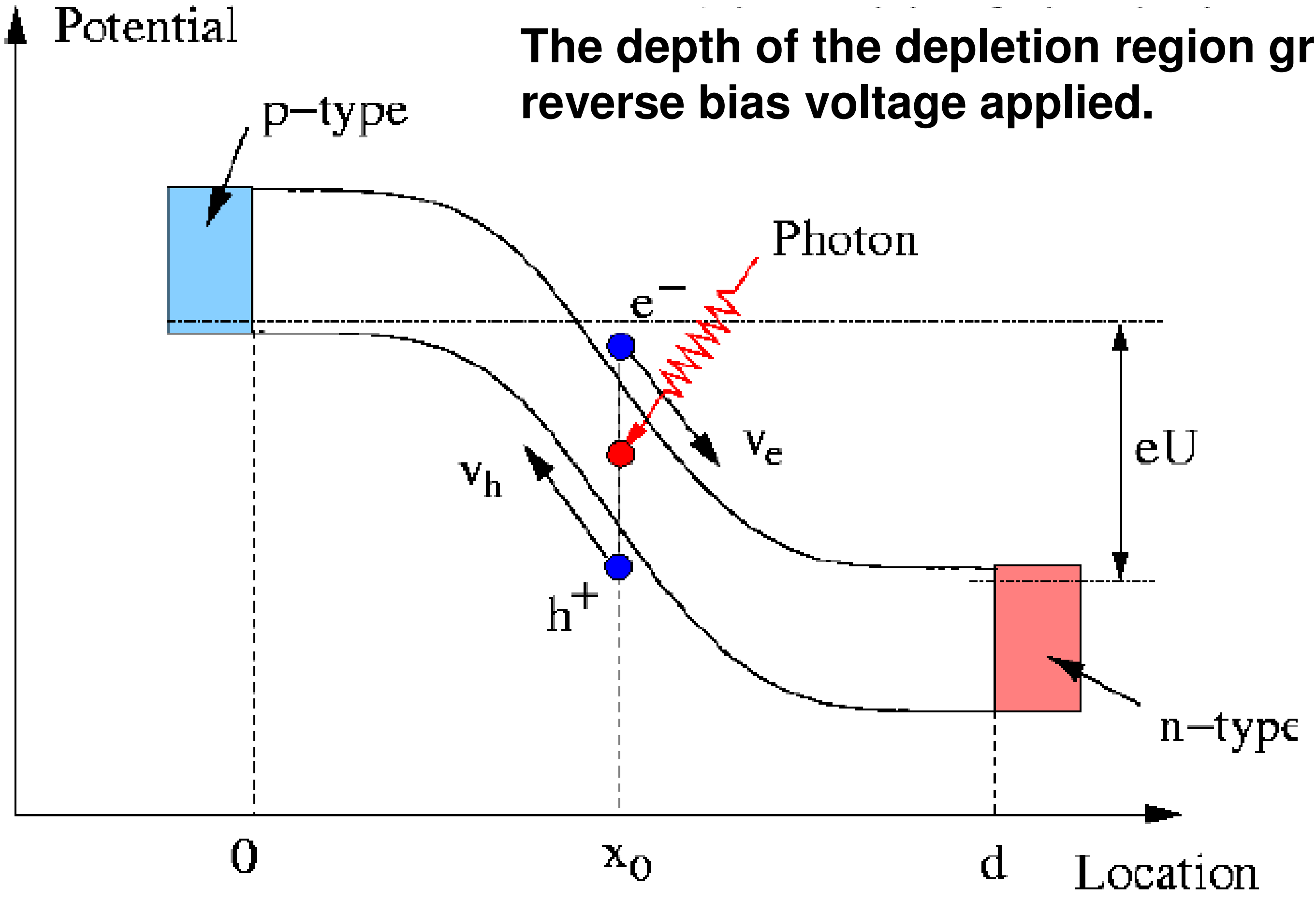
- positive potential at p-region
- negative potential an n-region
- The external voltage reduces the potential barrier.

→electrons from the n-region can cross the barrier.

pn Junction in Reverse Bias

- The external voltage increases the potential barrier
- **The depletion zone can be used as detector, since it contains an electric field.**

The depth of the depletion region grows with the reverse bias voltage applied.

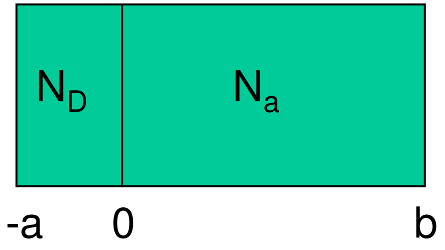


The pn-Junction: Depth of the Depletion layer

Poisson-Equation for the potential U(x) (1-dimensional for simplicity):

$$\frac{d^2U(x)}{dx^2} = \frac{-\rho(x)}{\varepsilon\varepsilon_0}$$

with $E_x = -dU/dx \rightarrow \frac{dEx(x)}{dx} = \frac{\rho(x)}{\varepsilon\varepsilon_0}$



$$\rho(x) = \begin{cases} eN_D & f\ddot{u}r\ -a < x \le 0 \\ -eN_A & f\ddot{u}r\ 0 < x \le b \end{cases}$$

Asymmetric double layer with **N_D, N_A** density of donor- and acceptor impurities.

Assumption: $N_D >> N_A$ and a<b
Boundary conditions for electric field:

$$E_x(-a) = 0 = E_x(b)$$

1. Integration of Poisson equation with above boundary conditions ➡

$$dU/dx = \begin{cases} -\frac{eN_D}{\varepsilon\varepsilon_0}(x+a) & f\ddot{u}r\ -a < x \le 0 \\ +\frac{eN_A}{\varepsilon\varepsilon_0}(x+b) & f\ddot{u}r\ 0 < x \le b \end{cases}$$

Depth of the Depletion Layer II

Boundary condition for the potential:

$$U(-a) = 0 \quad und \quad U(b) = -U_0$$ ←applied voltage

2. Integration:

$$U(x) = \begin{cases} -\dfrac{eN_D}{2\varepsilon\varepsilon_0}(x+a)^2 & für\ -a < x \leq 0 \\ +\dfrac{eN_A}{2\varepsilon\varepsilon_0}(x-b)^2 - U_0 & für\ 0 < x \leq b \end{cases}$$

Use $N_D a = N_A b$ and continuity at x=0:

$$b(a+b) = \frac{2\varepsilon\varepsilon_0 U_0}{eN_A}$$

For the strongly asymmetric case ($N_D >> N_A$) b>>a (b: thickness of p-doped layer)

→d=a+b~b →

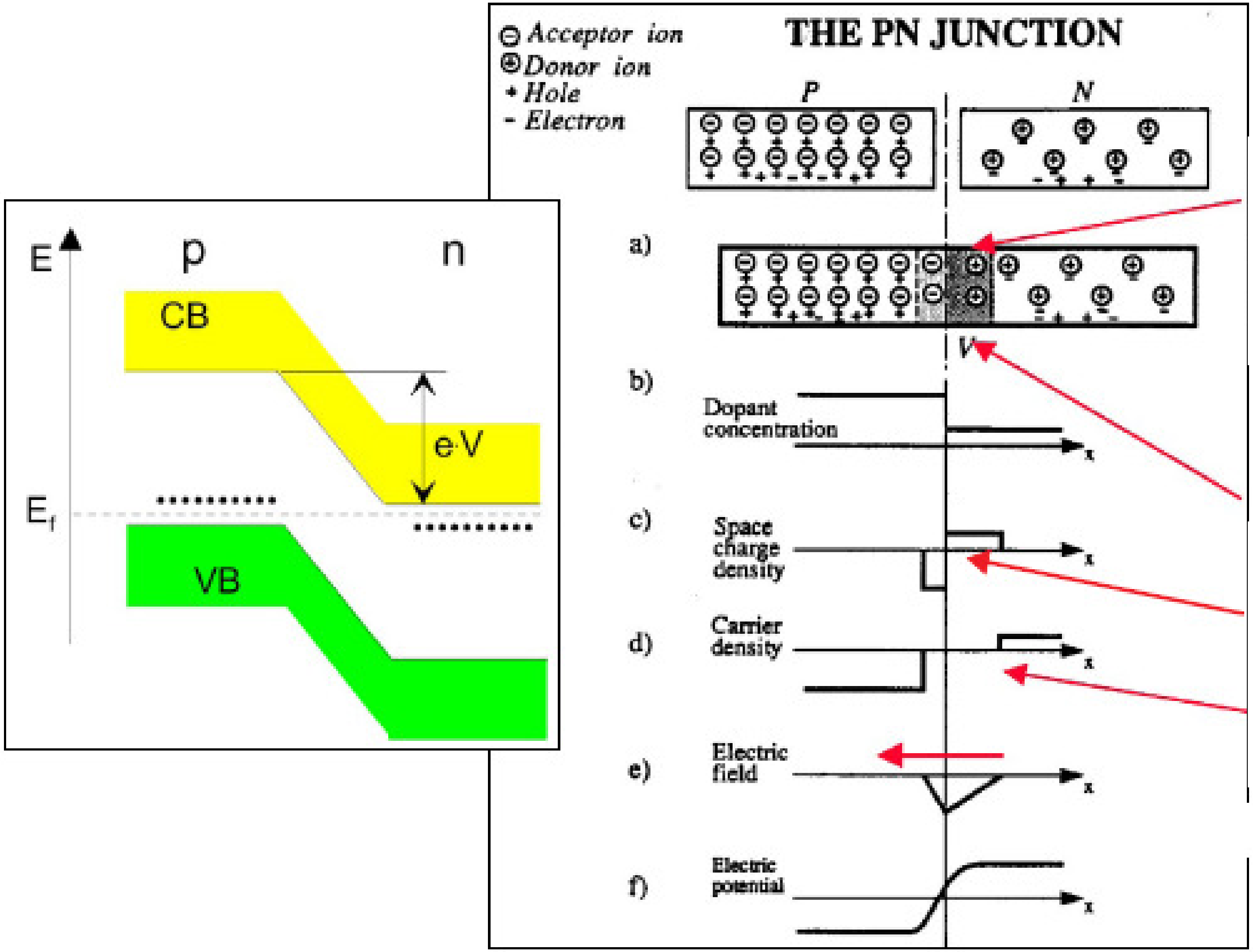
$$d = \sqrt{\frac{2\varepsilon\varepsilon_0 U_0}{eN_A}}$$

The pn-Junction: electric Field

The highest field strength is then at x=0:

$$E_x(0) = \sqrt{\frac{2eN_A U_0}{\varepsilon_0 \varepsilon}} = \frac{2U_0}{d}$$

Der pn junction: Overview



Diffusion of e in p zone

Diffusion of holes in n zone

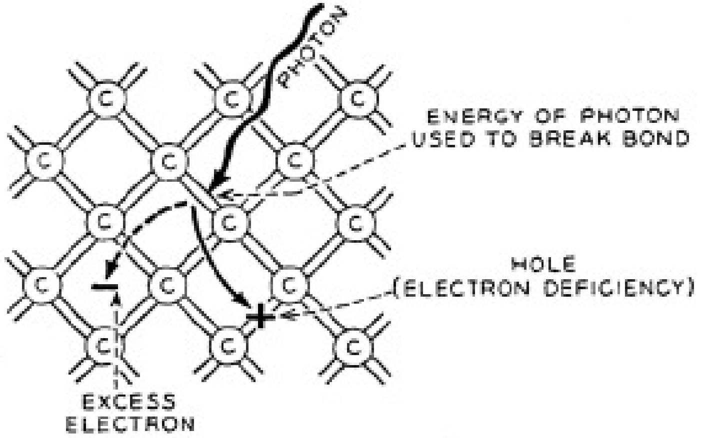
Depletion zone

Asymmetry due to different levels of doping

No free charge carriers

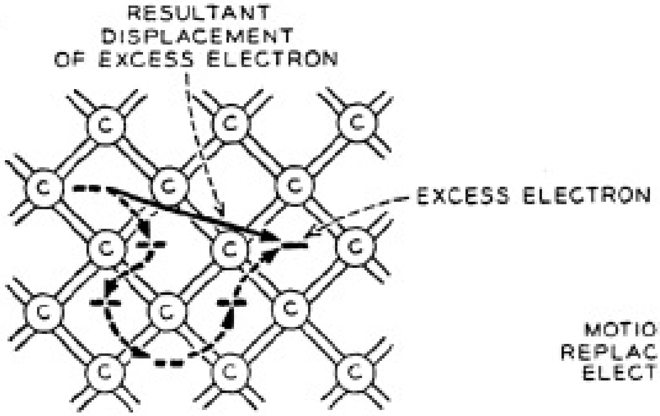
Charge collection : Diffusion and Drift

Motion of charge carriers

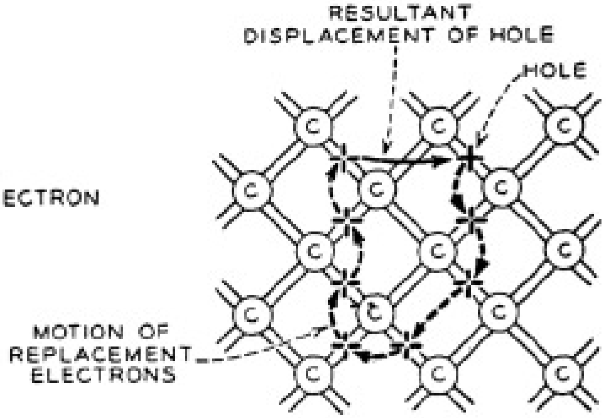


(a) PRODUCTION OF A HOLE-ELECTRON PAIR BY A PHOTON

Motion of holes via successive replacement by electrons →slower!



(C) RANDOM MOTION OF AN EXCESS ELECTRON



(d) RANDOM MOTION OF A HOLE

Drift velocity in Silicon

$$v_N = -\frac{q\tau_C}{m_N} E = -\mu_N E$$

$$v_p = \frac{q\tau_C}{m_p} E = \mu_p E$$

with $\tau_C \approx 10^{-12s}$ being the average time between collisions with irregularities in the crystal lattice due to thermal vibrations, impurities and defects.

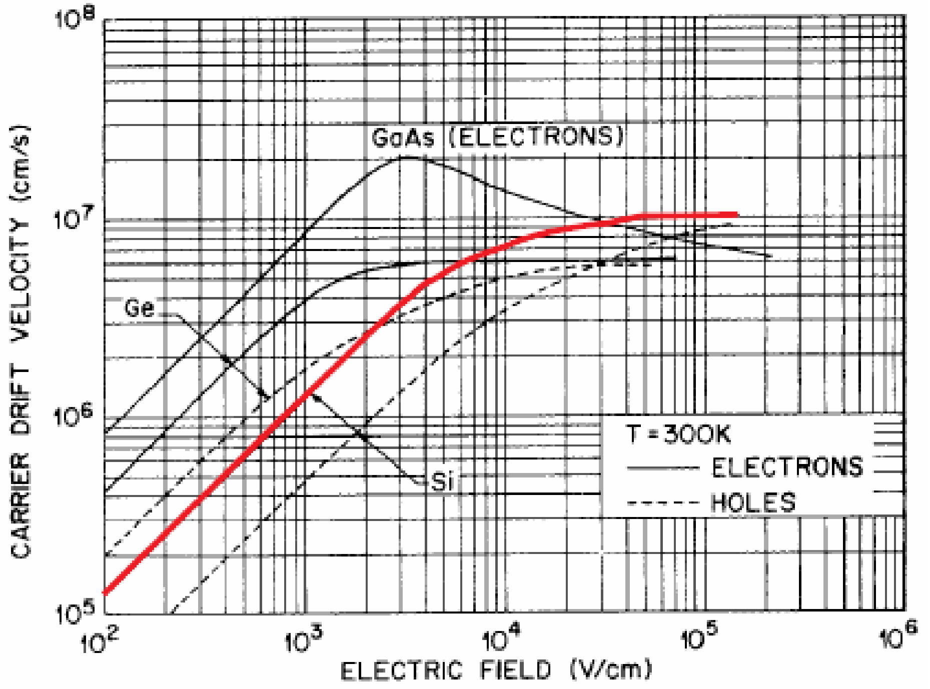
m_N,m_p effective mass of the electrons, holes: Inverse of the 2. derivative of the energy with respect to the momentum at the minimum of the conduction band (e), and the maximum of the valence band (p), respectively.

Only valid for sufficiently small field strength.

- →mobility μ=1450 cm^2/Vs for electrons and 450 cm^2/Vs for holes.
- For larger field strengths: Saturation of drift velocities.
- Typical fields in Si with V_{bias}=100V, d=300 µm:

$$E = 100\,V/300\mu m = 3.3x10^3 V/cm$$

$$Sammelzeit \quad t = \frac{d}{v_{Drift}} \approx 3 - 15ns$$



Diffusion

The diffusion equation is:

$F_n = -D\nabla n$ where F_n is the flux of the electrons, D the diffusion constant and ∇n the gradient of the charge carrier concentration. Similar for holes.

When combining drift and diffusion, the current density becomes:

$$J_n = q\mu_n nE + qD_n\nabla n$$

$$J_p = q\mu_p nE - qD_n\nabla p$$

Where mobility and diffusion constant depend on each other via the Einstein equation:

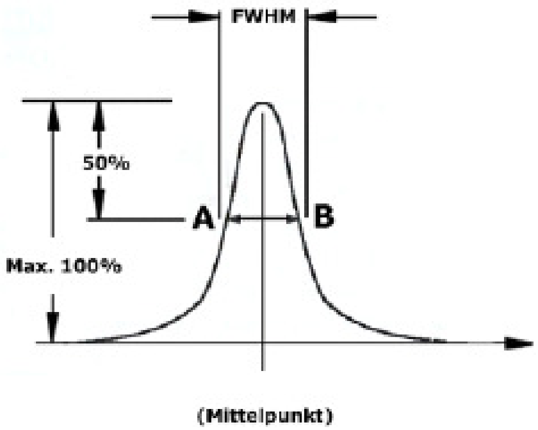
$$D_n = \tfrac{kT}{q}\mu_n$$

$$D_p = \tfrac{kT}{q}\mu_p$$

Energy Resolution

Energy Resolution: The Fano factor

Energy resolution expressed in “full width at half maximum”



Band gap 1.1 eV in Si, however, 3.6 eV necessary for creation of eh pair→ Majority of energy into phonons.

Poisson Statistics: $\sigma^2 = \overline{N}$

$$FWHM \quad \Delta N = 2.35\sigma$$

Average number of charge carriers $\overline{N} = \frac{E}{w}$

→Energy resolution $R = 2.35\frac{\sqrt{\overline{N}}}{\overline{N}} = 2.35\sqrt{\frac{w}{E}}$

Poisson Statistics only partially valid. Correction for standard deviation:

$\sigma^2 = F\,\overline{N}$ F: Fano Faktor, F<1, empirical values for Si, Ge 0.12

$$R = 2.35\sqrt{\frac{Fw}{E}}$$

The Fano factor: Derivation

Energy used for ionization and excitation (phonons)

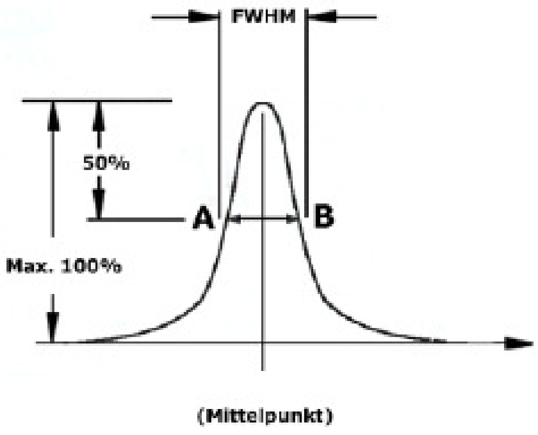
$$E_0 = E_{ion} N_{ion} + E_x N_x$$

Assumption: Gauss Statistics

$$\sigma_x = \sqrt{N_x} \qquad \sigma_{ion} = \sqrt{N_{ion}}$$

Fluctuations have to balance each other:

$$E_x \Delta N_x + E_{ion} \Delta N_{ion} = 0$$



Averaged over many events, the following has to be true:

$$E_{ion}\sigma_{ion} = E_x \sigma_x \Rightarrow \sigma_i = \frac{E_x}{E_{ion}}\sqrt{N_x} \Rightarrow$$

$$E_0 = E_{ion} N_{ion} + E_x N_x \Rightarrow N_x = \frac{E_0 - E_{ion} N_{ion}}{E_x} \Rightarrow \sigma_i = \frac{E_x}{E_{ion}}\sqrt{\frac{E_0}{E_x} - \frac{E_{ion}}{E_x} N_{ion}}$$

$$N_{ion} = N_Q = \frac{E_0}{E_i}$$ where E_i is the average energy to produce a pair of charge carriers (I.e. 3.6 eV in Si)

Derivation II

→ The variance in the ionization process is

$$\sigma_{ion} = \frac{E_x}{E_{ion}} \sqrt{\frac{E_0}{E_x} - \frac{E_{ion}}{E_x} \frac{E_0}{E_i}}$$

For silicon:

$$E_x = 0.037eV, \quad E_{ion} = E_g = 1.1eV,$$
$$E_i = 3.6eV \to F = 0.08$$
$$(measured: \approx 0.1)$$

Which can be written as:

$$\sigma_{ion} = \sqrt{\frac{E_0}{E_i}} \cdot \underbrace{\sqrt{\frac{E_x}{E_{ion}}\left(\frac{E_i}{E_{ion}} - 1\right)}}_{\uparrow \text{Fano Factor F}}$$

Since $N_Q = \frac{E_0}{E_i}$

and σ_{ion} proportional to the variance of the signal charge Q:

$$\sigma_Q = \sqrt{F N_Q}$$

Limitations of Silicon Detectors: Radiation Damage

Radiation Damage

Impact of Radiation on Silicon:

- **Silicon Atoms can be displaced from their lattice position**
  - **point defects (EM Radiation)**
  - **damage clusters (Nuclear Reactions)**

Important in this context:

- **NIEL: Non Ionizing Energy Loss**
- **Bulk Effects: Lattice damage:**
Generation of vacancies and interstitial atoms
- **Surface effects: Generation of charge traps (Oxides)**

Filling of energy levels in the band gap
→Direct excitation now possible
→Higher leakage current
→More noise
→"Charge trapping", causing lower charge collection efficiency
Can also contribute to space charge.
→Higher bias voltage necessary.

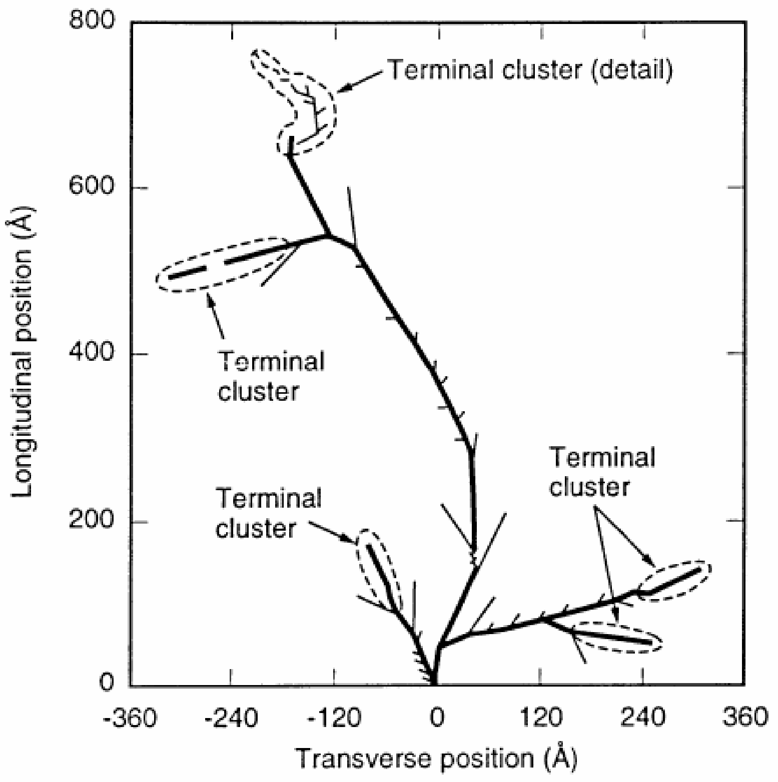
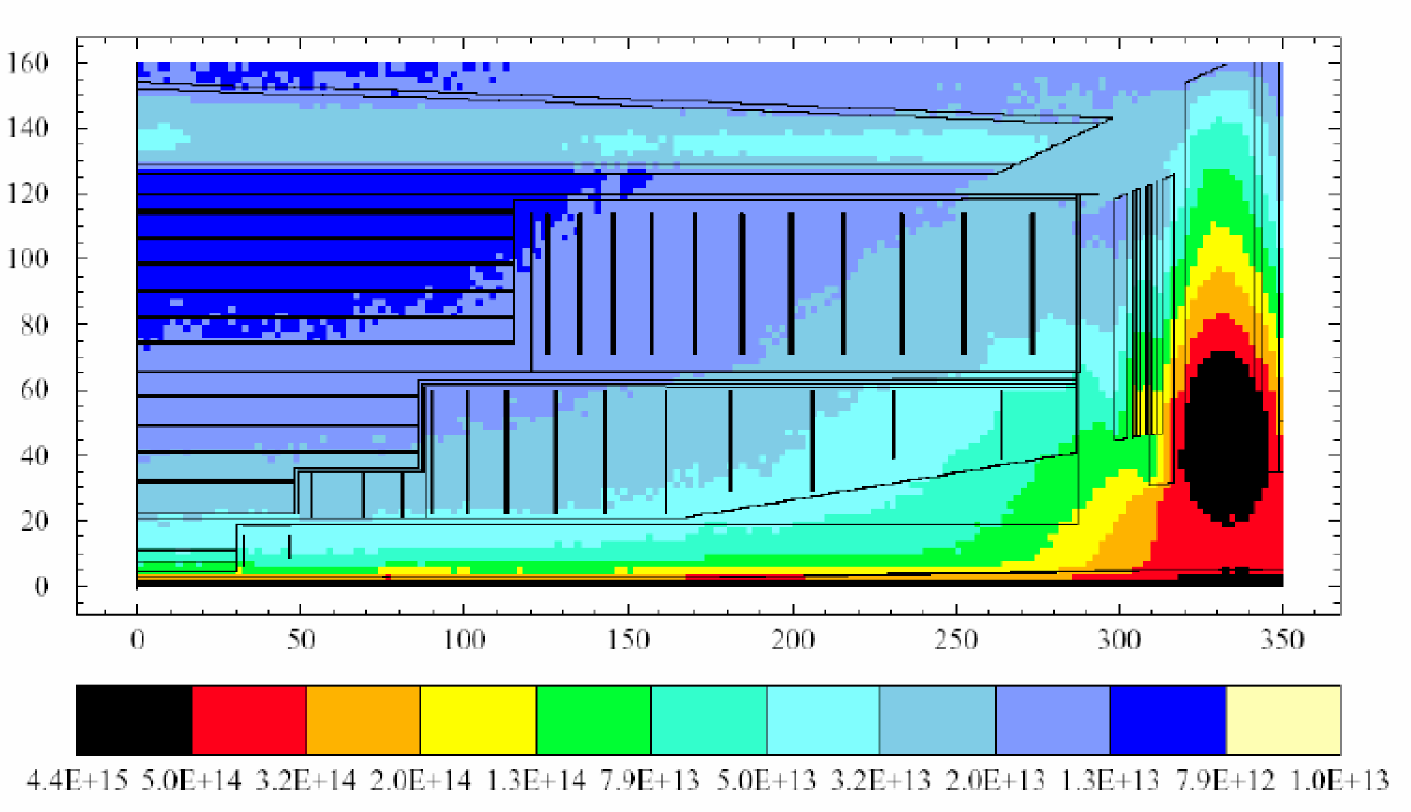


Fig. 55 Development of cluster damage due to a primary knock-on silicon atom of 50 keV, within the bulk material.

Radiation Exposure at CMS

Neutronenfluss (>100 keV) nach 5×10^5 pb^{-1} (10 Jahre LHC)



CMS

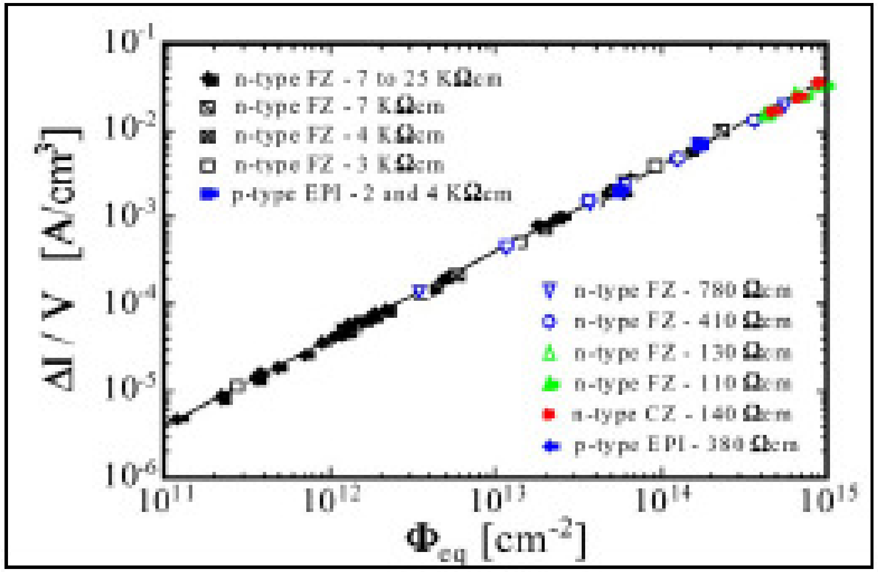
Unit: Neutrons per cm²

Tschernobyl ~ 0,5 Gray
natürlich ~ 2,5 mGray

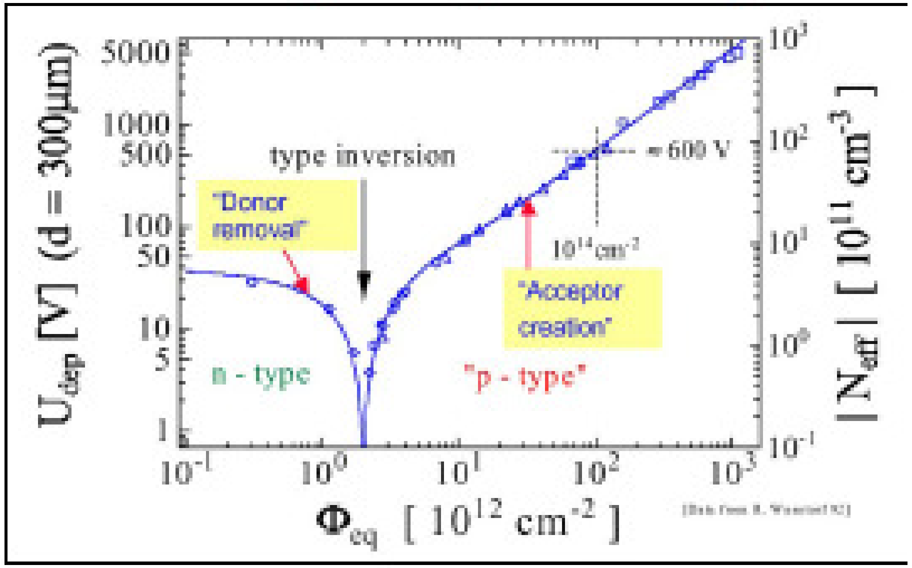
Q=1

Consequences of Radiation Damage

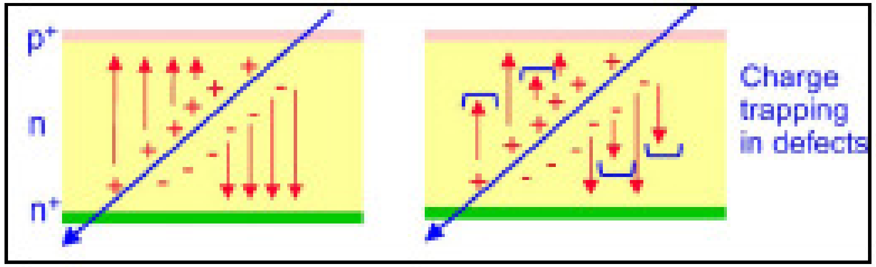
Increase in leakage current



Change in depletion voltage



Abnahme der Ladungssammlungseffizienz

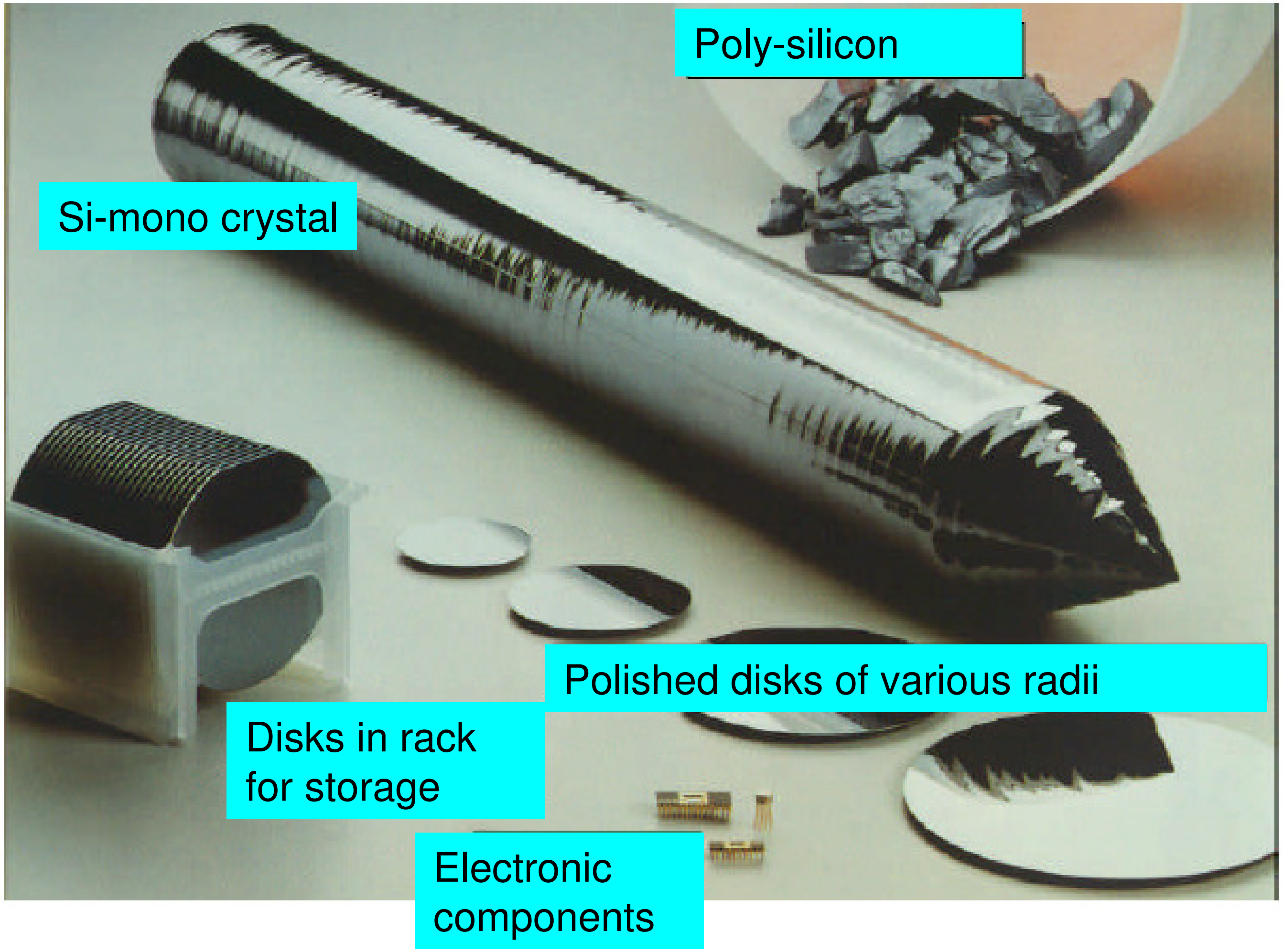


Counter measures

- Geometrical: develop sensors that can withstand higher depletion voltages
- Environment: sensor cooling (~-10 C)
    - Slowing down of “reverse annealing”
    - lower leakage currents

Silicon Detectors: Design and Larger Systems

Production of Silicon-Monocrystals



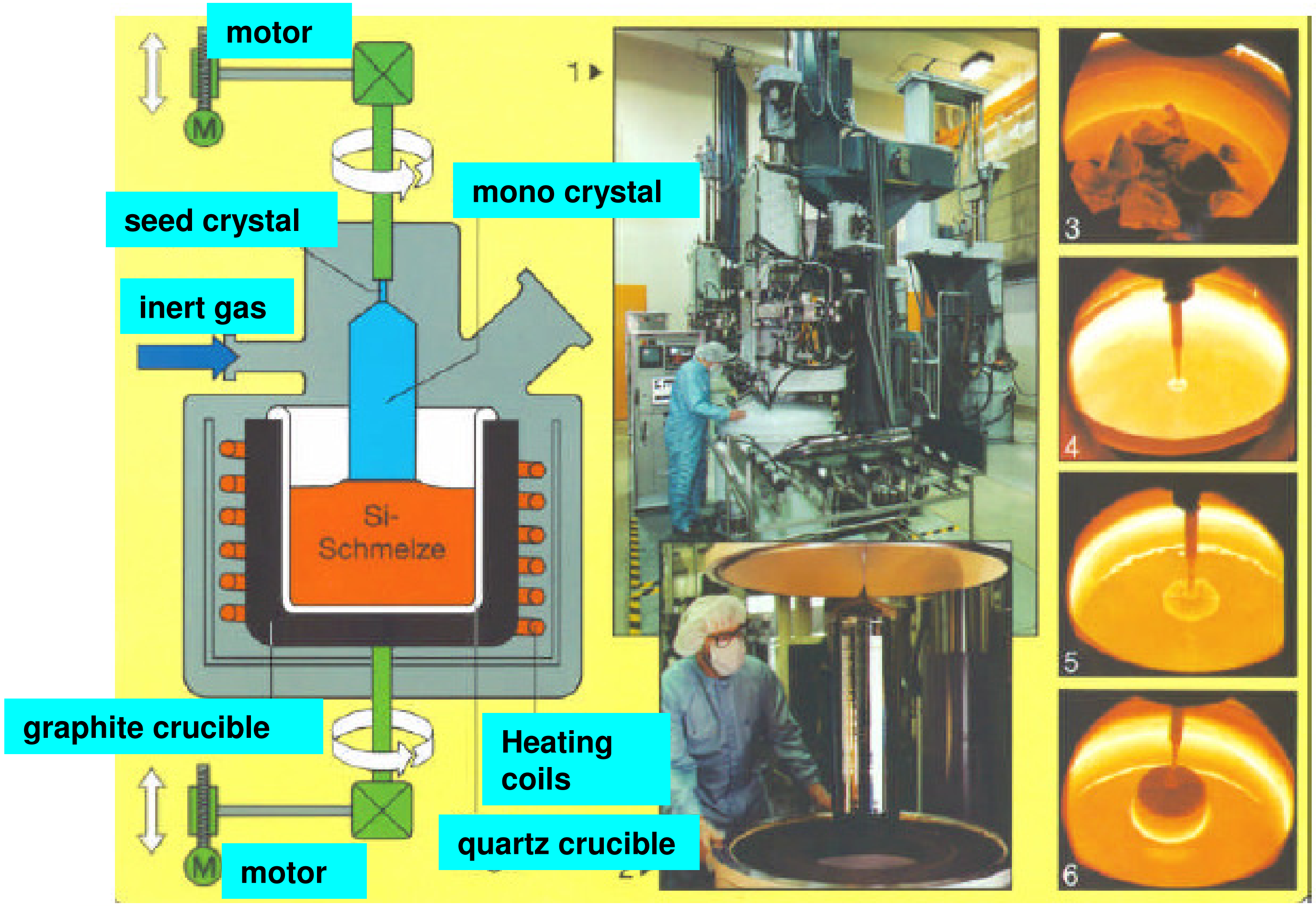
General procedure:

- Production of highly pure poly-silicon from silica sand
- Pulling of a mono-crystalline Si-rod
- Making of Silicon discs from the crystal

Production of Si-Monocrystals I

Three different methods. Most important standard method:

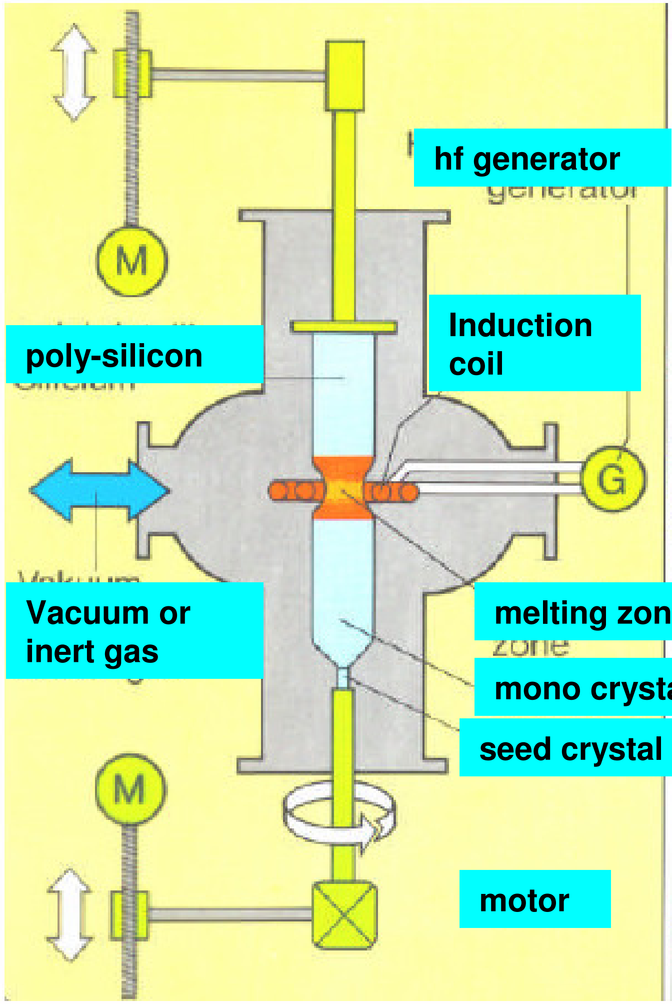
Czochralski process

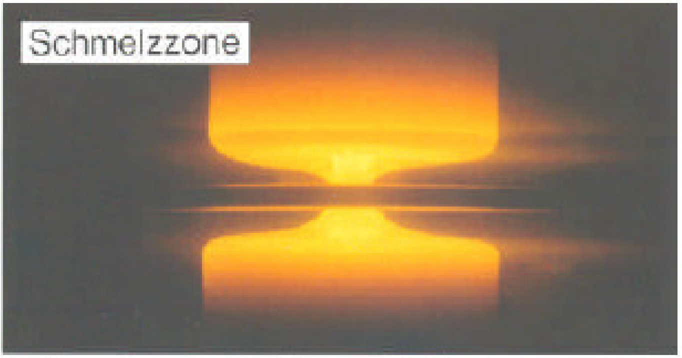


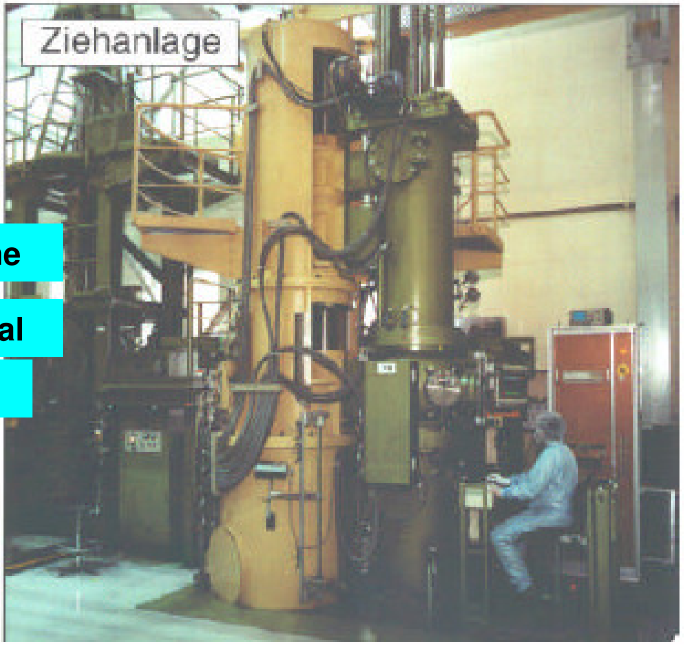
- Growing of a Si-monocrystal from molten Silicon (2-250 mm/h)
- Orientation determined by seed crystal
- Doping applied directly.

Production of Si-Monocrystals II

Float-zone process: crucible-free method: Inductive melting of a poly-silicon rod





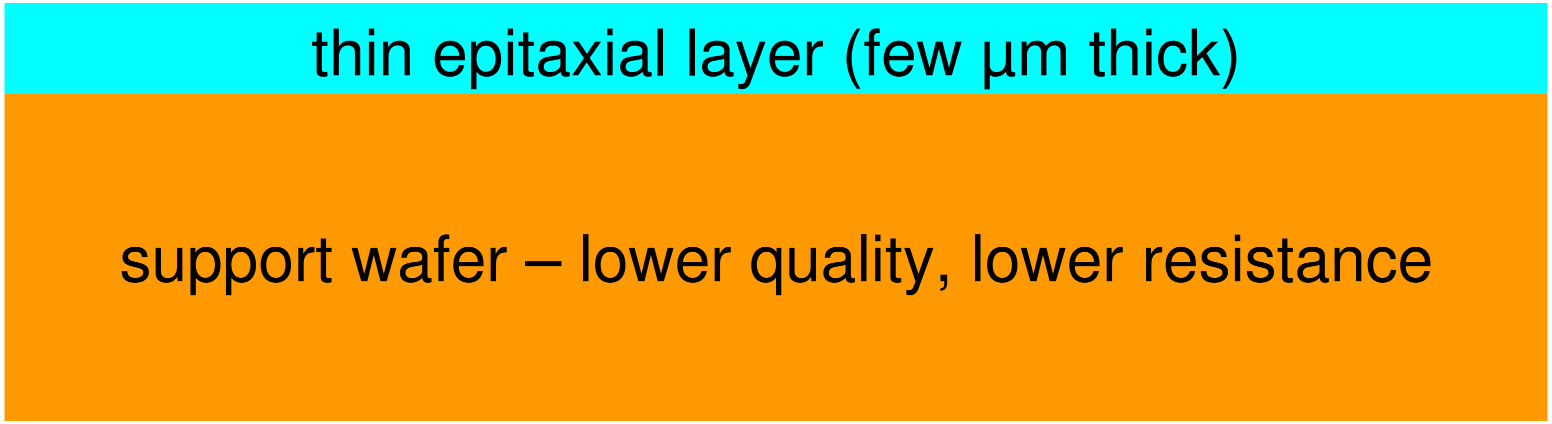


- For the production of highly-pure silicon
- Orientation determined by seed crystal

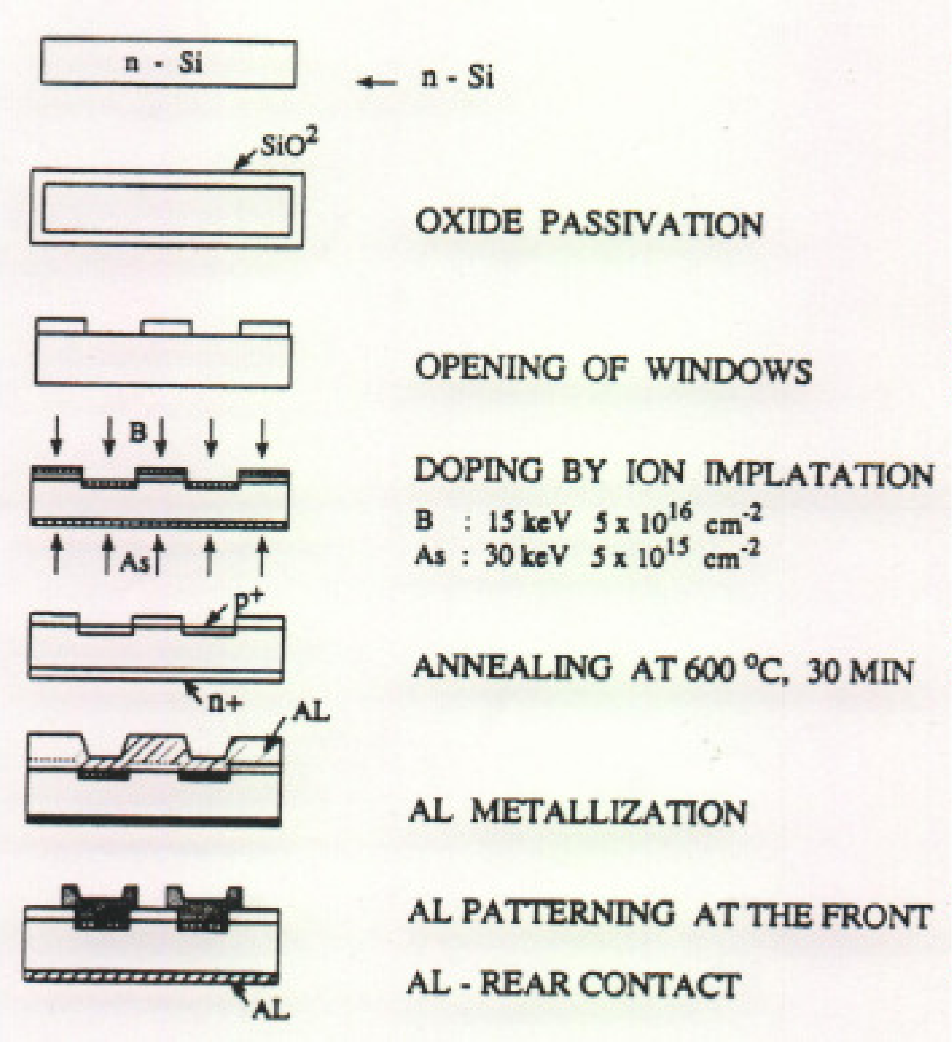
Production of Si-Monocrystals III

Epitaxy:

- Precipitation of atomic Silicon layers from a gaseous phase at high temperatures (950-1150 C)
- Possible to Produce extremely pure layers on lower quality silicon substrate
- Epitaxial layer assumes crystal structure of the substrate



Production Process: Sensors



Cleaning and polishing of the wafer

Oxidation at 1000 C→ passivation

Application of photo sensitive polymer, heating, UV light through mask

Creation of pn junction by implantation/ diffusion

Heating: implanted ions incorporated into lattice

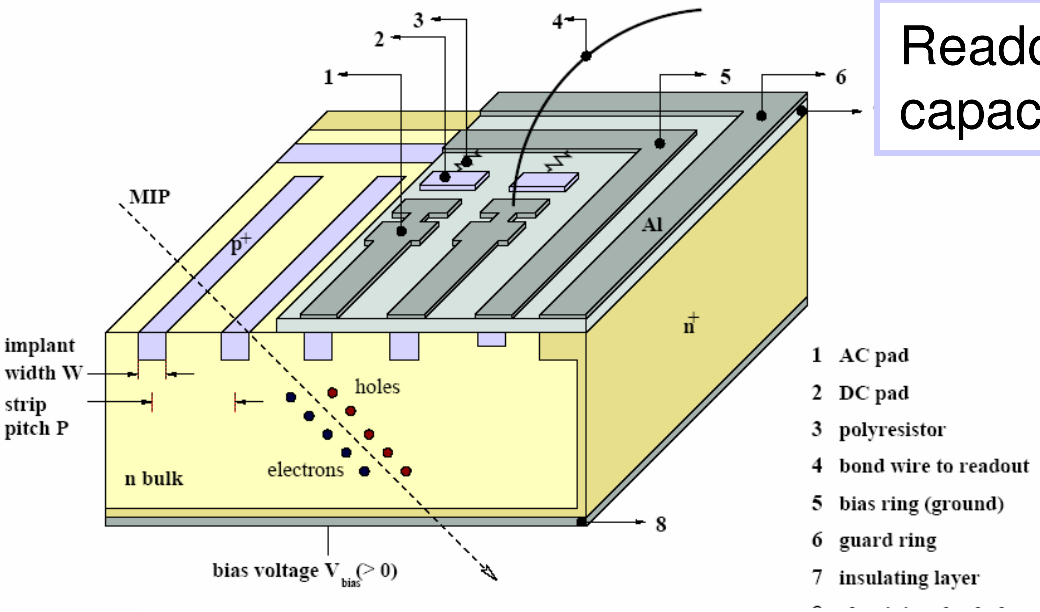
Aluminization of surfaces

Photolithographic processing of metal strips for contacts

Strip Detectors

Segmentation by implanting of strips with opposite doping.

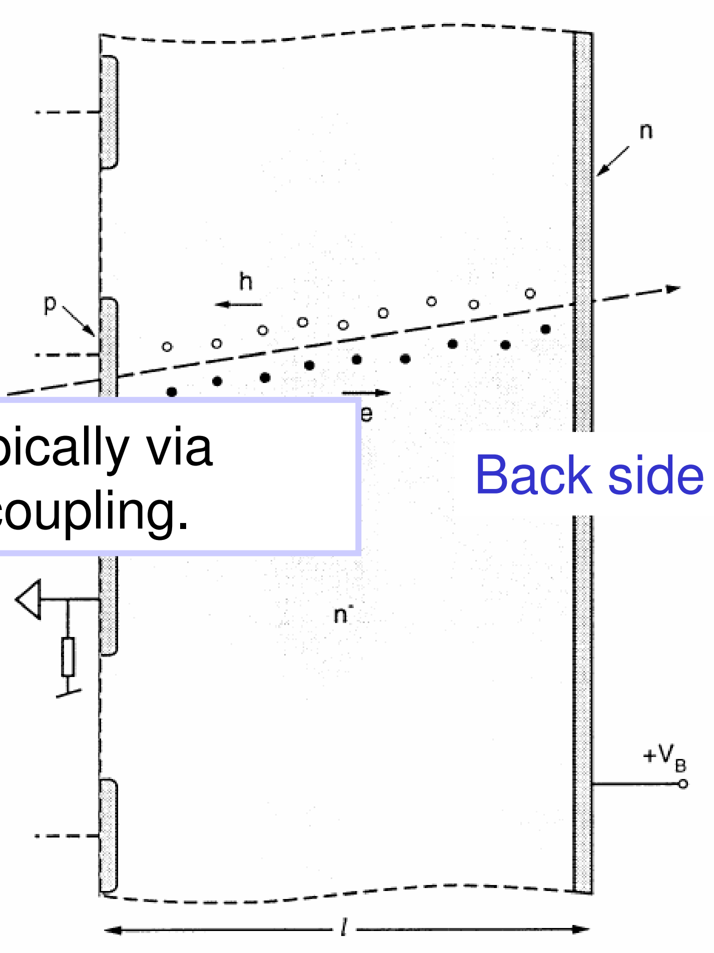
Voltage needs to be high enough to completely deplete the high resistivity silicon. CMS: ~100 V



Schematic view of CMS Si-Sensor.

Figure 2.8: Schematic structure of a CMS silicon microstrip sensor.

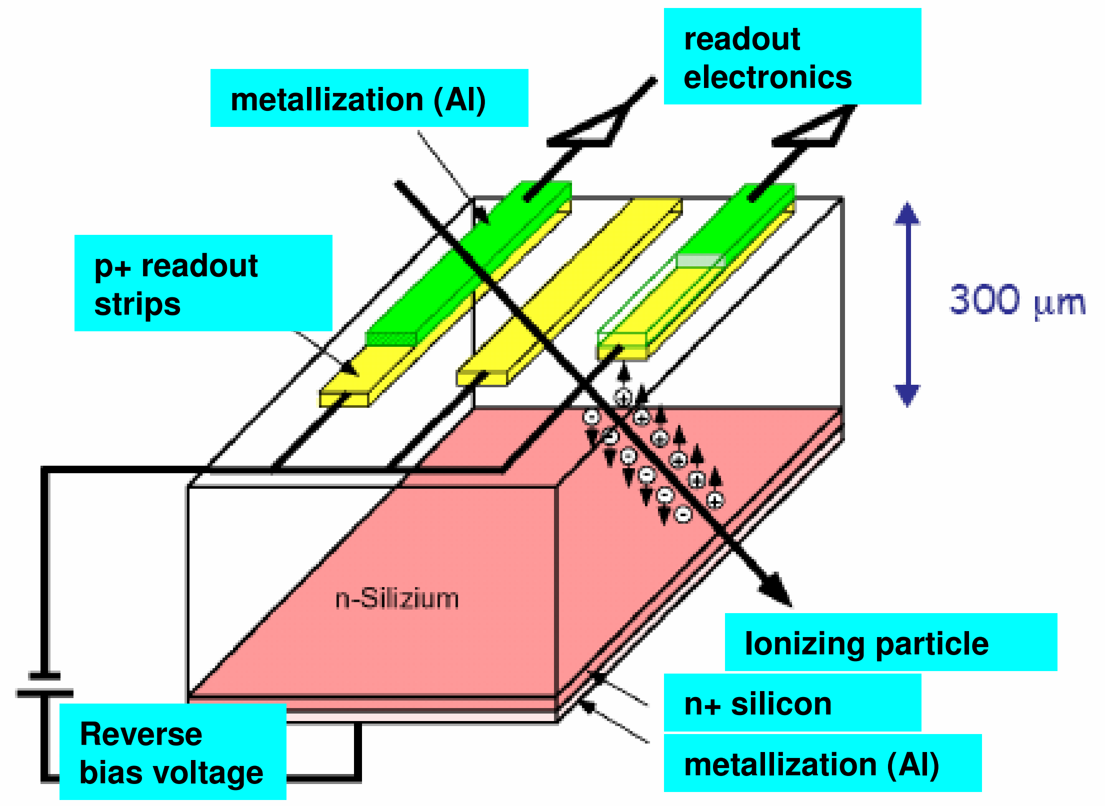
Readout typically via capacitive coupling.



Back side

n-Type silicon easier to produce.

Single Sided Strip Readout



readout electronics

metallization (Al)

p+ readout strips

300 μm

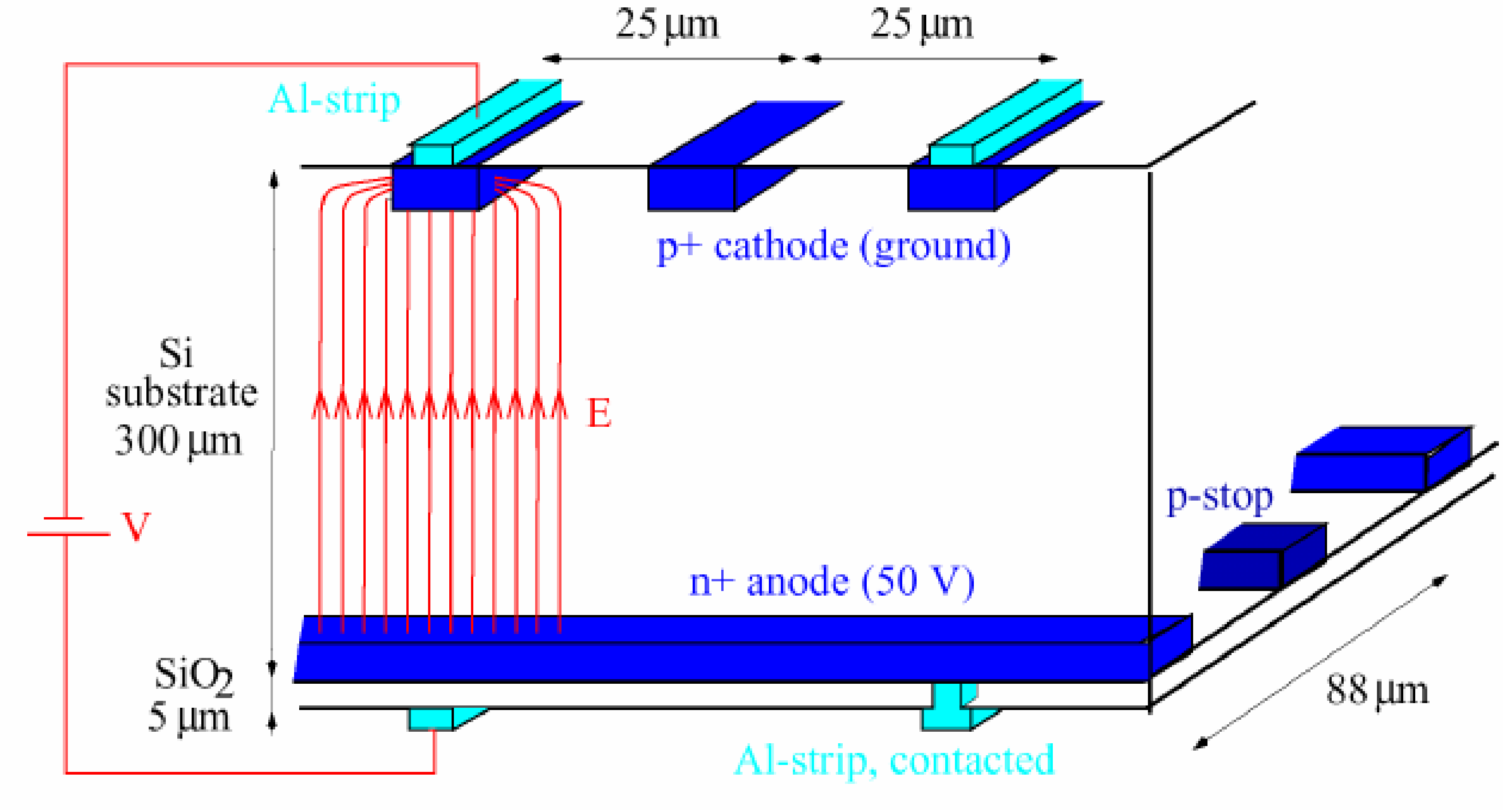
Ionizing particle

n+ silicon

metallization (Al)

Reverse bias voltage

Double Sided Strip Readout



Making use of the drift electrons:

2nd coordinate without additional material.

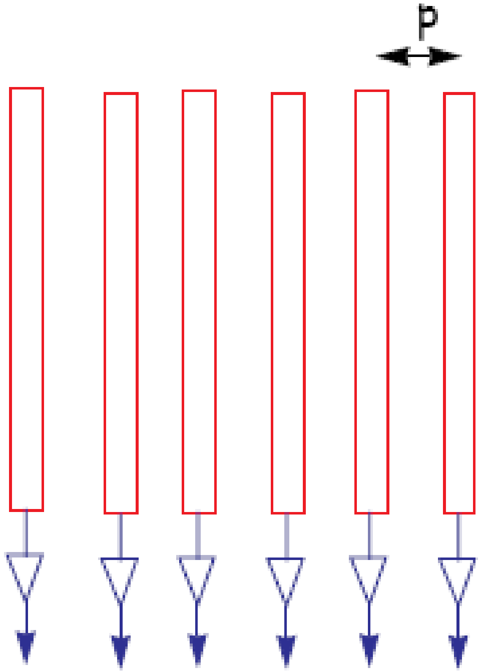
Strip Detectors: Resolution

Digital readout:

Resolution given by

$$\sigma_x = \frac{p}{\sqrt{12}}:$$

$$\text{Resolution} = \overline{x-\bar{x}} = \sqrt{\frac{\int_{-p/2}^{p/2}(x-\bar{x})^2\,dx}{p}} = \sqrt{\frac{1}{3}\frac{p^3/4}{p}} = \frac{p}{\sqrt{12}}$$



Analog readout:

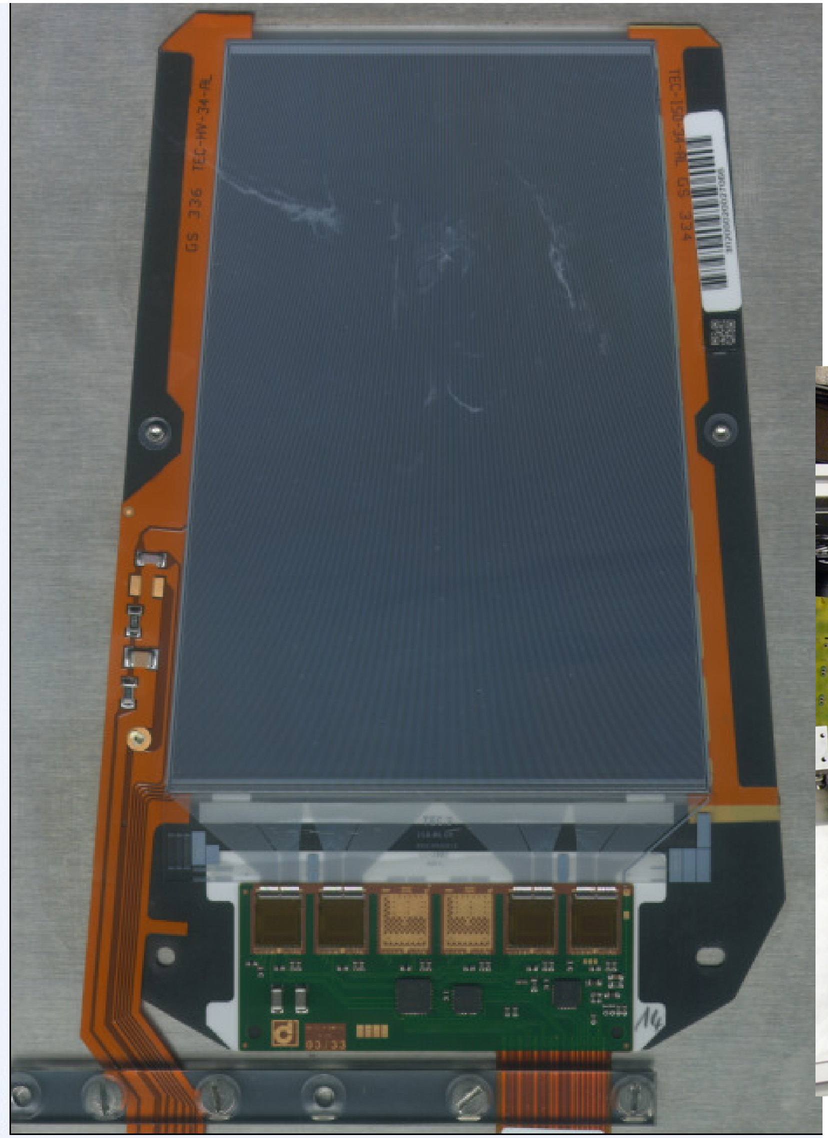
Improved resolution σ<<p possible using center-of-gravity of charge distribution

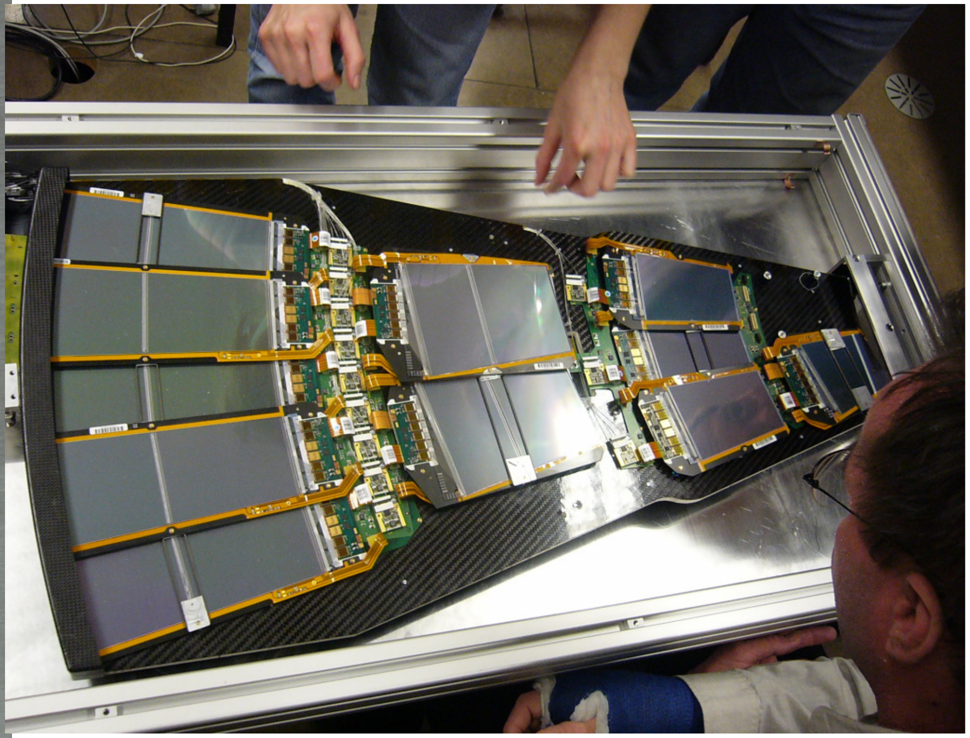
Resolution limited by transverse diffusion of charge carriers

Typical values for Silicon: σ~5-10 µm

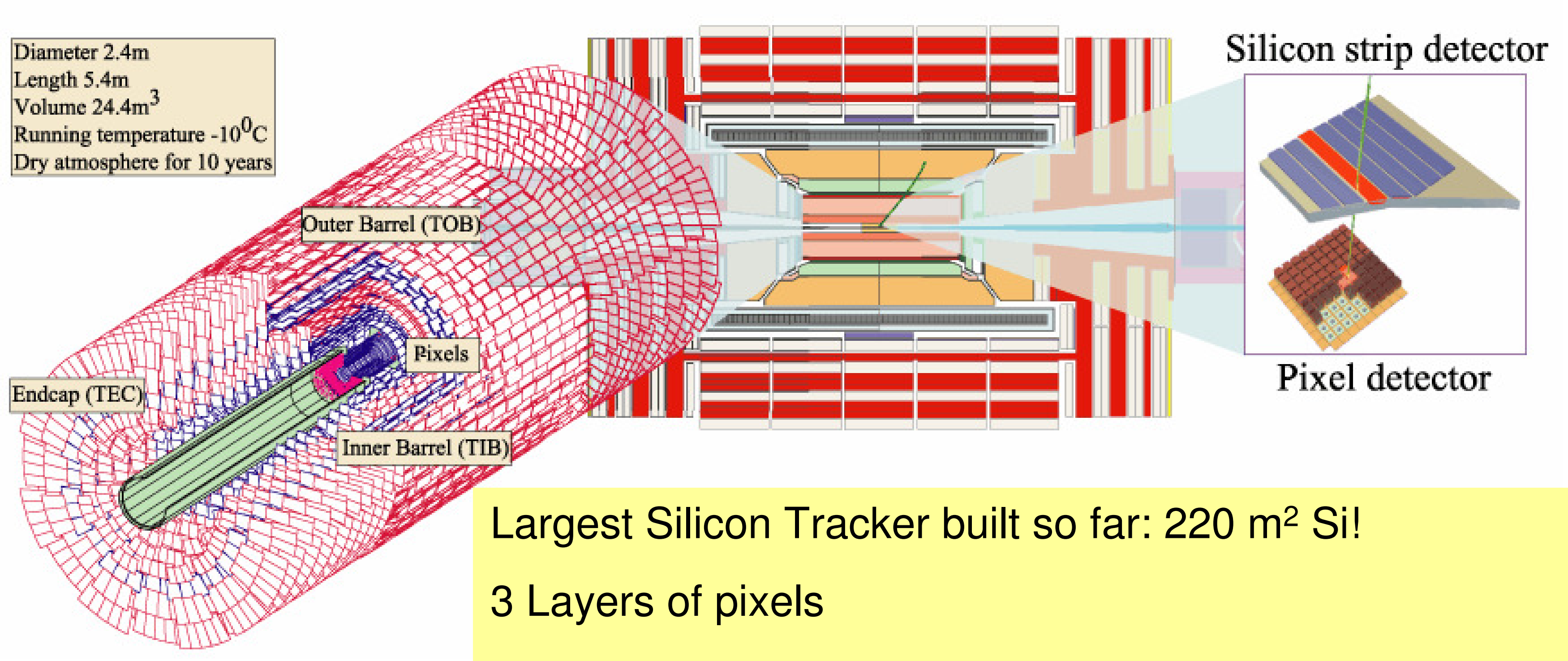
Typical pitch p=25-150 µm

Examples: Detectors (CMS)





Example: The CMS Silicon Tracker



Largest Silicon Tracker built so far: 220 m² Si!

3 Layers of pixels

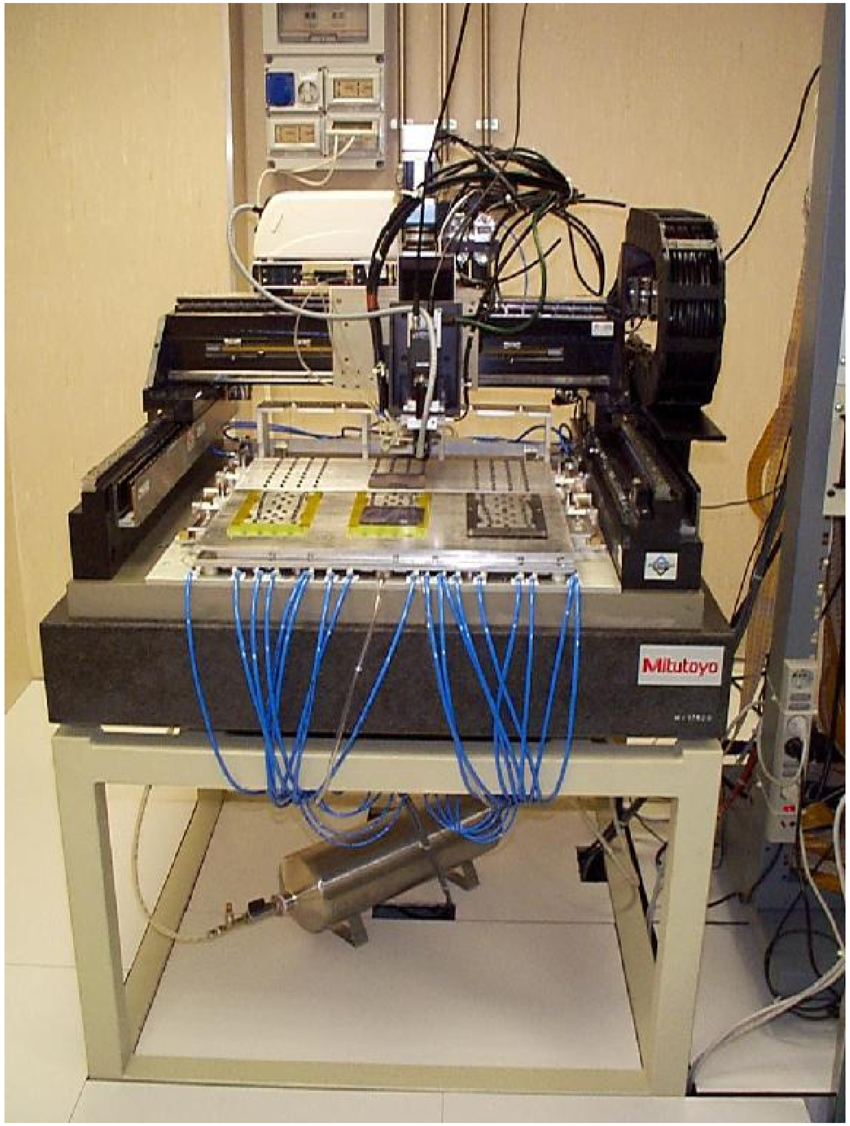
10 layers of strip sensors (barrel)

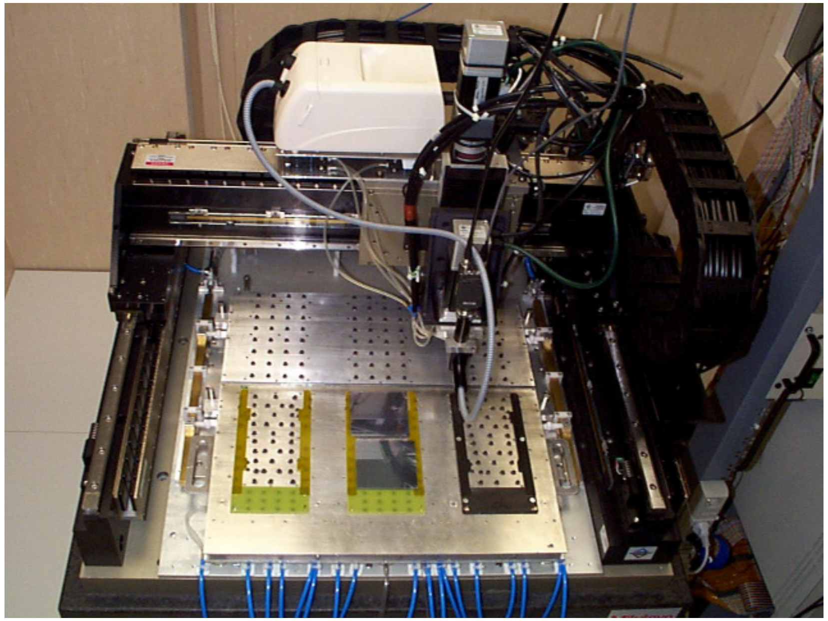
9 endcap wheels

25k strip sensors, 75k readout chips, almost 10M readout channels →industrial production necessary.

silicon-only solution

CMS Module Production

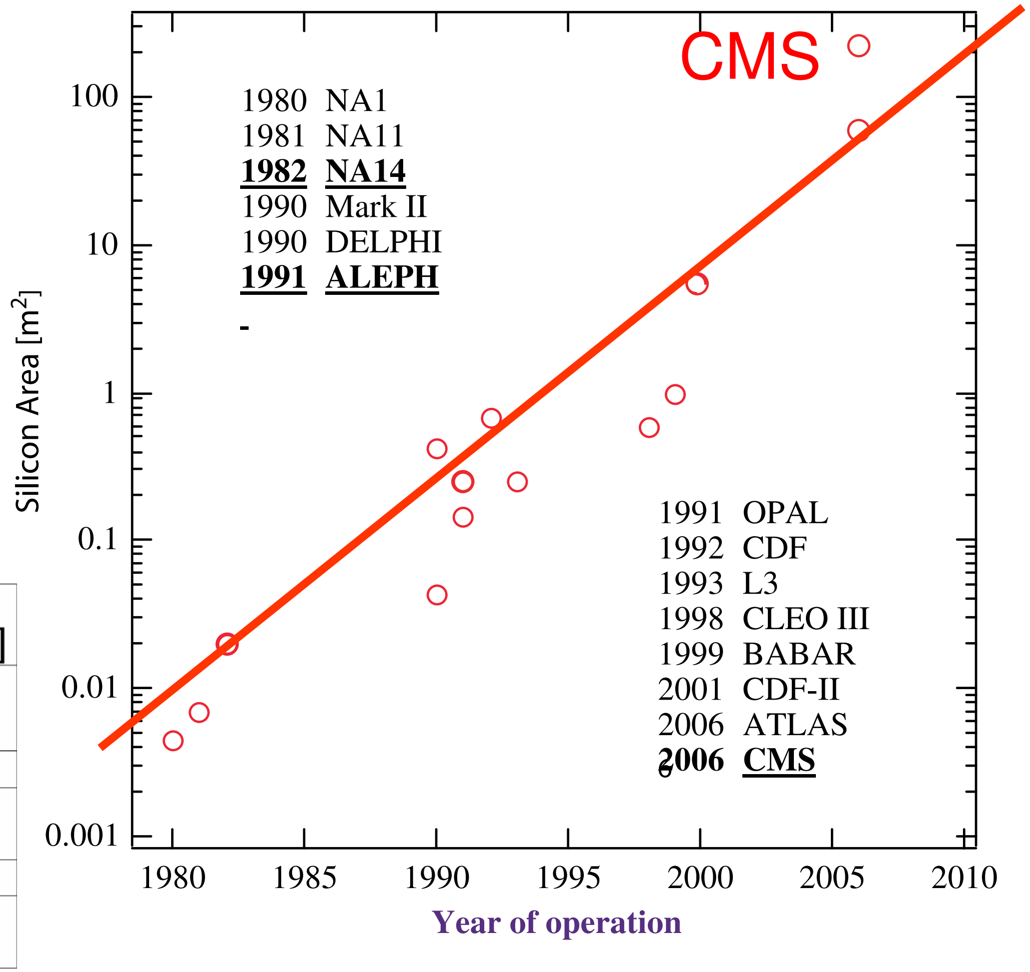




Si modules are precisely glued using a robot (gantry). Tolerances few µm!

History of Silicon Detectors

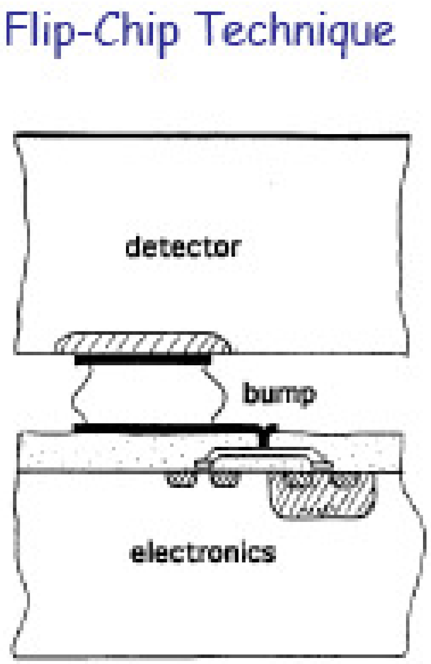
experiment	nb. of detectors	nb. of channels	silicon area [m^2]
CMS	15.95 k	10×10^6	223
ATLAS	16.0/2 k	6.15×10^6	60
AMS 2	2.3 k	196 k	6.5
DO 2		793 k	4.7
CDF SVX II	720	405 k	1.9
Babar		140 k	0.95
Aleph	144	95 k	0.49
L3	96	86 k	0.23

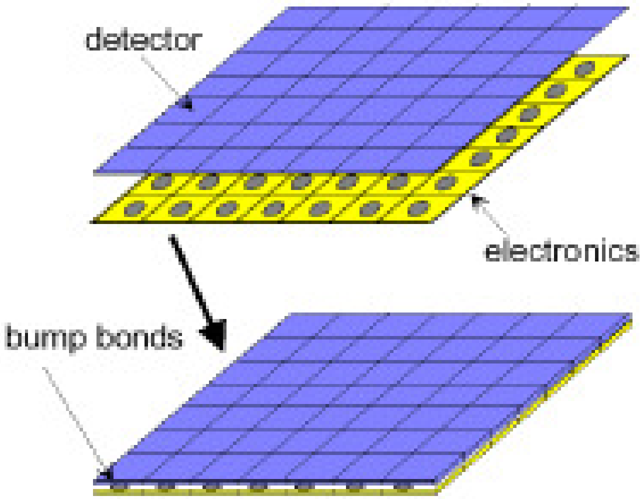


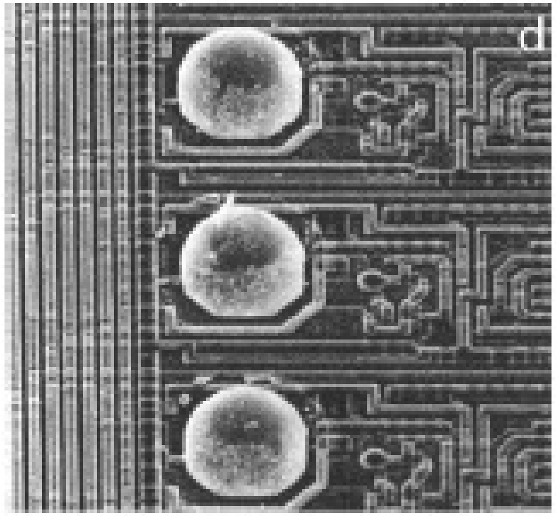
Special Detectors: CMS Silicon Pixel Detector

- Segmentation in both directions →Matrix
- Readout electronics with identical geometry
- Contacts using “bump bonding” technique
- Using soft material (indium, gold)
- Complex readout architecture
- real 2D hits

→use in LHC experiments



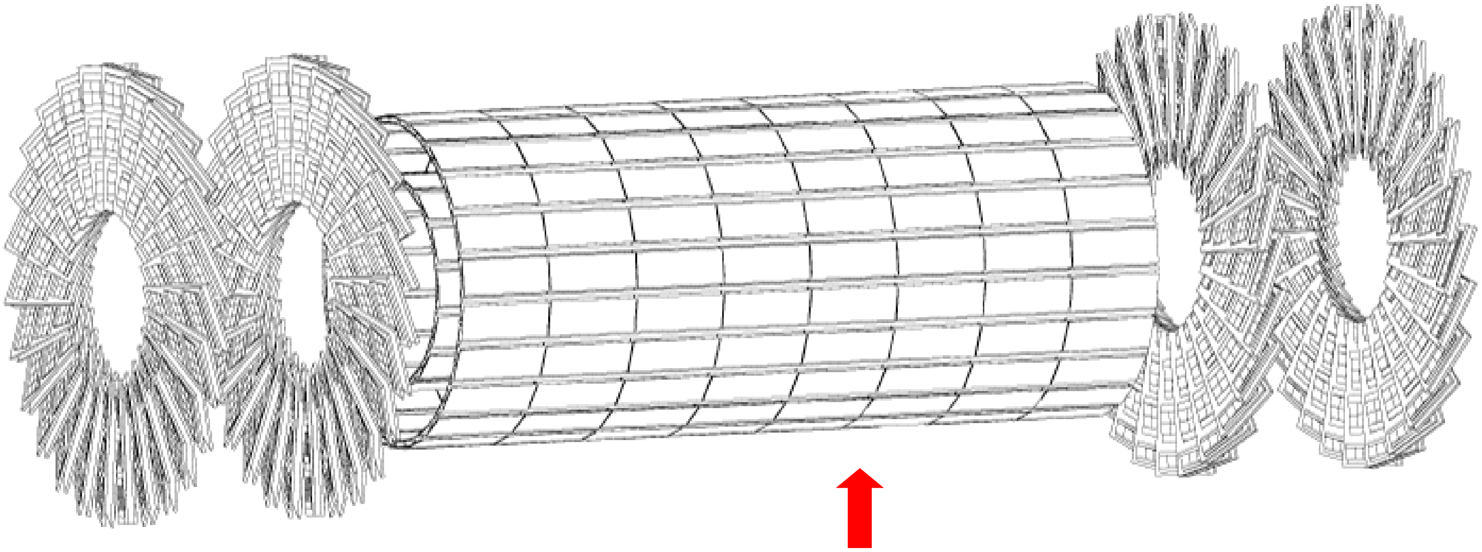




The CMS Pixel Detector II

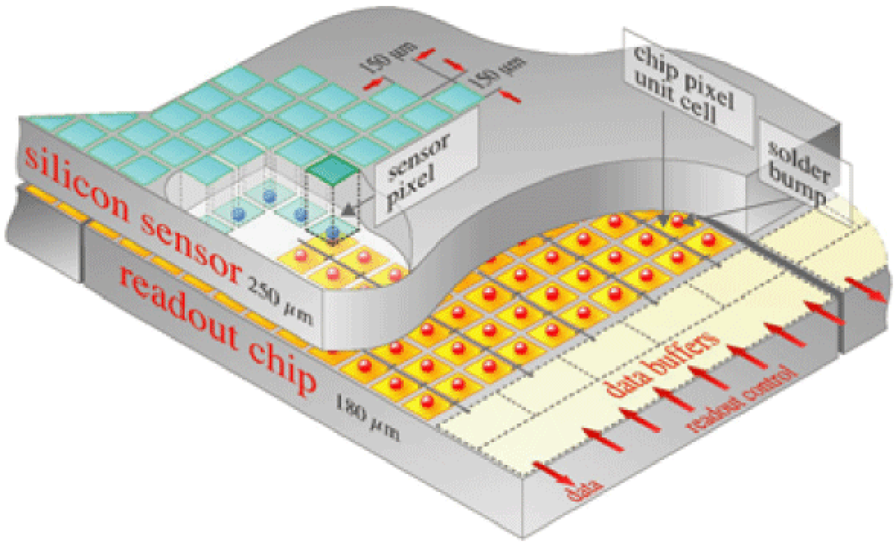
- The inner layers feature:
  - high multiplicity
  - good spatial resolution needed (vertex finding)

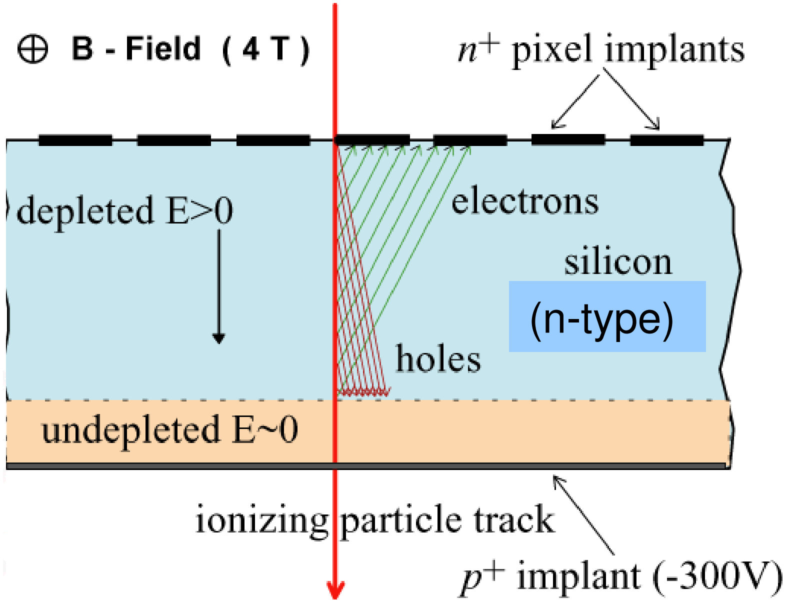
→Pixel good.



3 layers

The CMS-Pixel Detector III





Pixels 150x150 µm

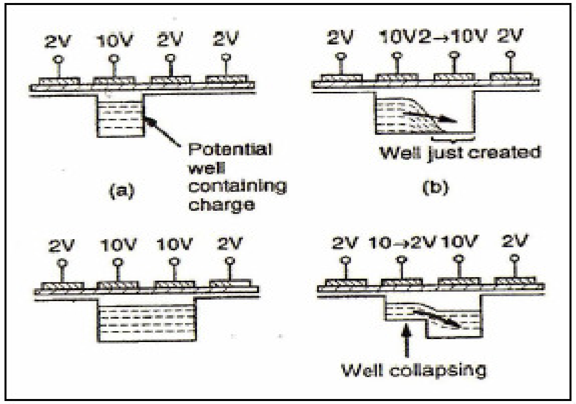
Each pixel is bump-bonded to a readout pixel

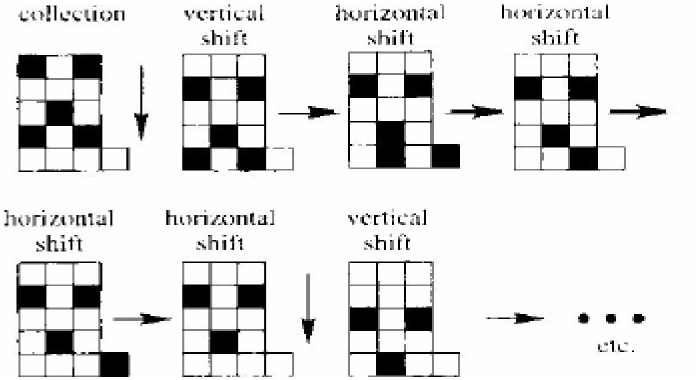
Making use of the large Lorentz-angle for electrons (barrel). Lorentz-angle: drift angle for charge carriers in magnetic field.

→Charge spreads over several pixel.

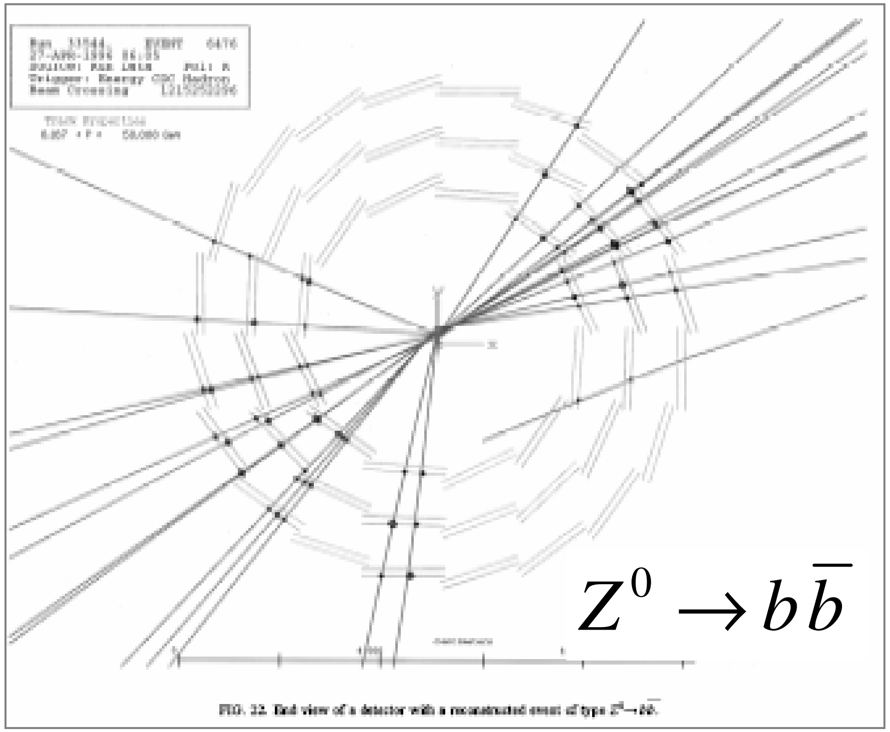
→Spatial resolution 10, 15 µm in ϕ, z

Charged Coupled Devices





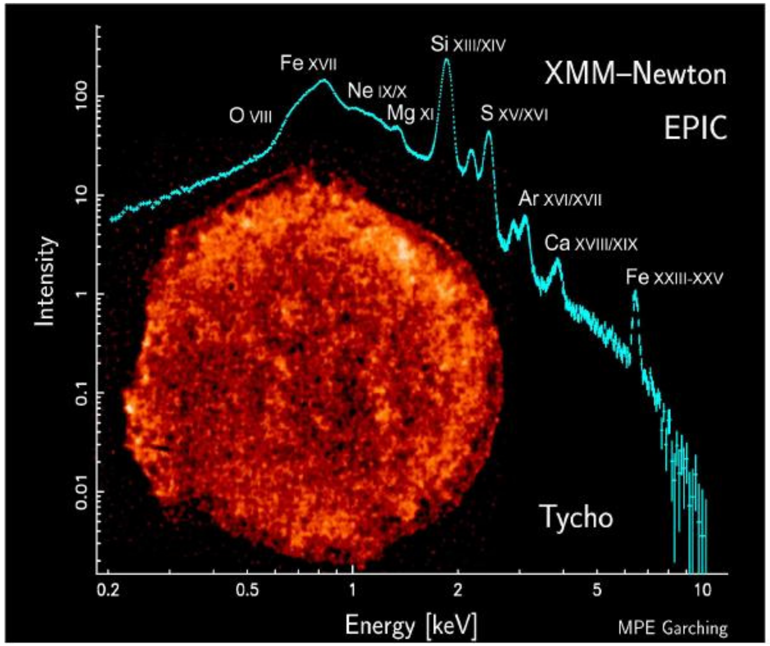
CCD principle of operation
-“analog shift register“
- many (106) pixels – small no. read channels
- excellent noise performance (few e), but small charge
- small pixel size (e.g. 22x22 mm2)
- slow (many ms) readout time
- sensitive during read-out
- radiation sensitive
→ used at SLC → best vertex detector so far with 3x108 pixels !!!



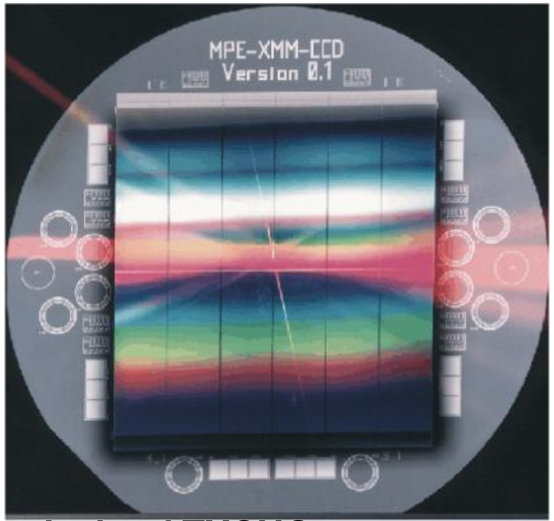
Charged Coupled Devices: Examples

XMM-Newton satellite

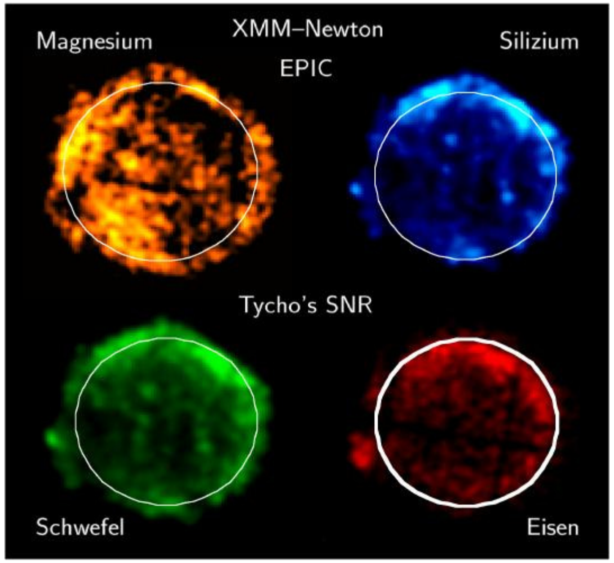
<u>Fully depleted CCD</u> (based on drift chamber principle) – astronomy XXM-Newton



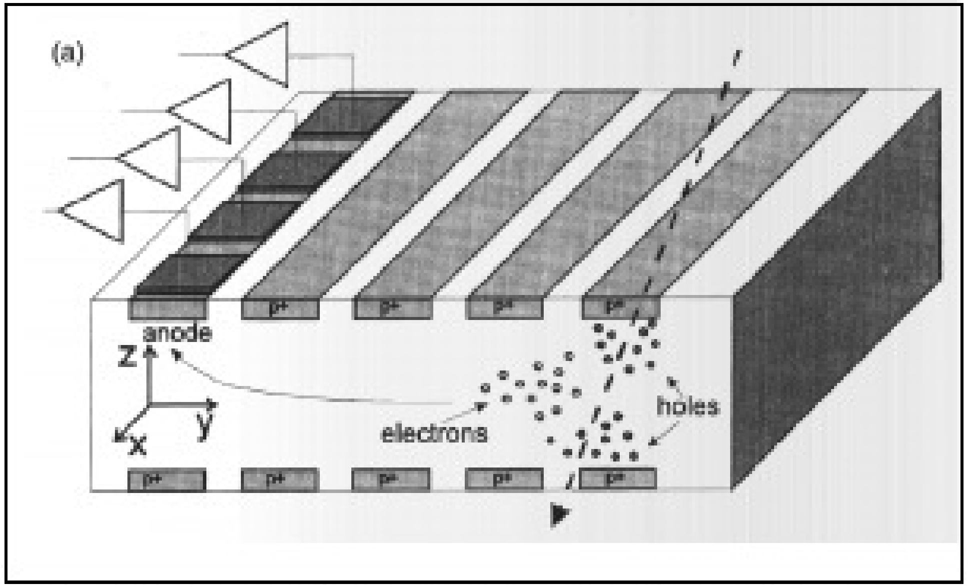
L. Strüder, IEEE-Nucl. Sci. Symposium (Rome 2004)

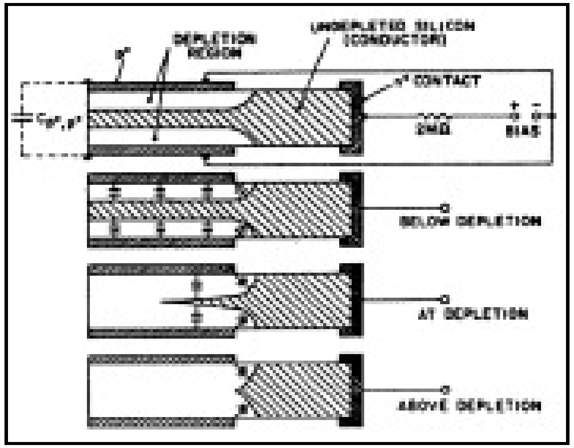


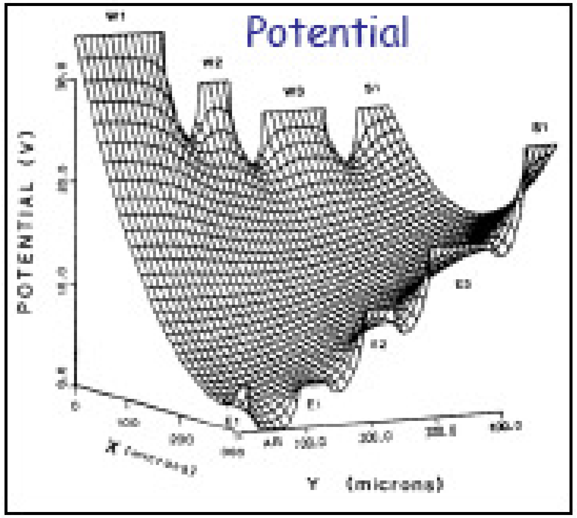
elemental analysis of TYCHO supernova remnant:



Si Drift Chambers







- Principle: anode position + drift time give 2 coordinates
- Capacitance relatively small (noise)
- Resolution ~10µm for 5-10 cm drift length
- dE/dx (STAR heavy ion)
- Drift velocity has to be well known

→Need to reduce trapping

- Problems with radiation damage

Monolytic Pixel Detectors

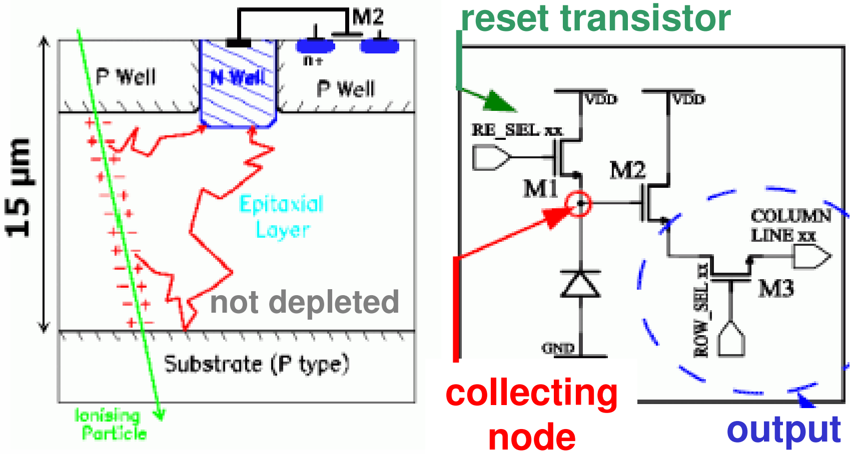
Idea: radiation detector + amplifying + logic circuitry **on single Si-wafer**

- **dream!** 1st realisation already in 1992
- difficult : Det. Si != electronics Si
- strong push from ILC → **minimum thickness, size of pixels and power !**
- so far no large scale application in research (yet)

CMOS Active Pixels

(used in commercial CMOS cameras)

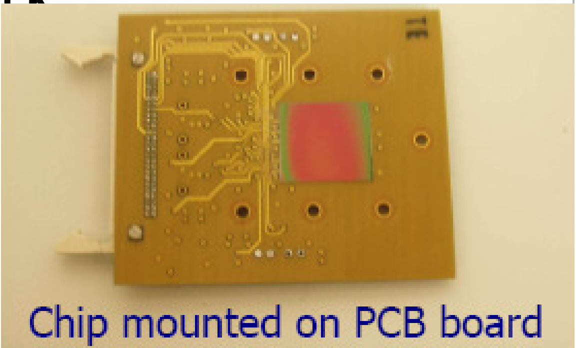
Principle:

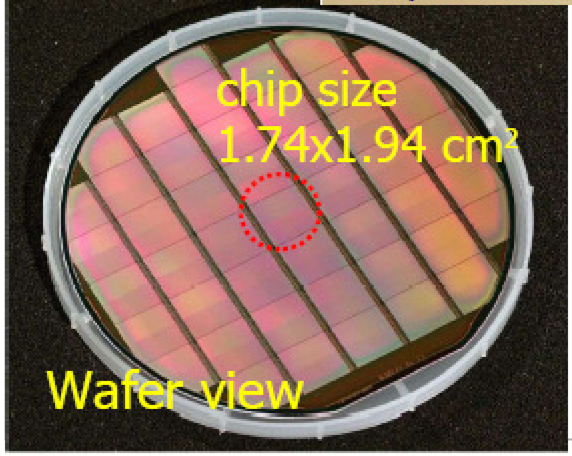


- technology in development – with many interesting results already achieved

example: MIMOSA (built by IReS-Strasbourg; tests at DESY + UNIHH)

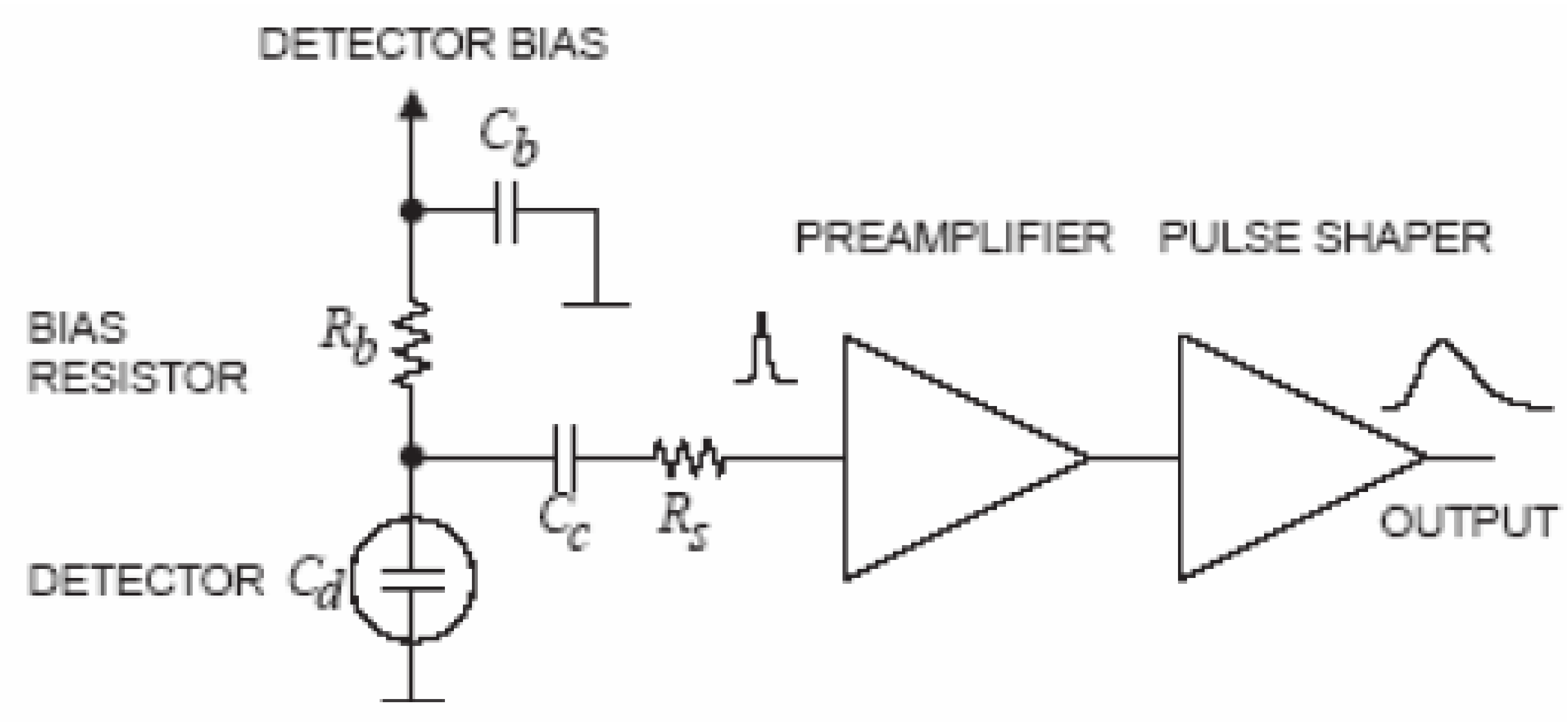
3.5 cm^2 produced by AMS (0.6mm)
14 mm epi-layer, (17mm)^2 pixels
4 matrices of 512^2 pixels
10 MHz read-out (→ 50ms)
120 mm thick


Chip mounted on PCB board



Readout Electronics

Readout Electronics



C_d + R_d detector model

C_C block capacitance

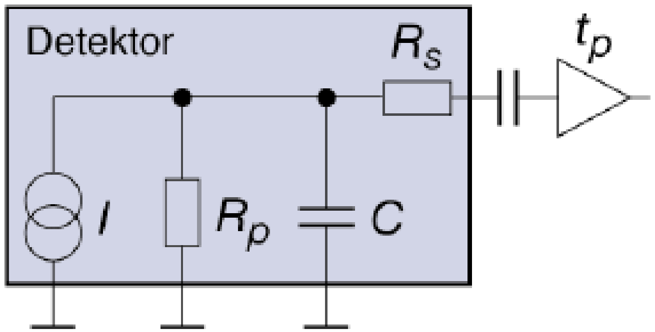
R_b bias resistor

R_S total input resistance

Readout Electronics: Noise

Most important noise contributions:

1. Detector capacity (ENC_C)
2. Detector dark current (ENC_I)
3. Detector parallel resistor (ENC_{Rp})
4. Serial readout resistance (ENC_{Rs})



Noise components independent → Quadratic sum

$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

Readout Electronics: Noise

ENC_C: Often dominating. The load capacity for the charge sensitive amplifier caused by the detector capacitance. $ENC_C = a + bC$ where a and b are determined by the amplifier design. Typical values for 1µs integration time are a=160e and b=12 e/pF
→Want detectors with small capacity (fine segmentation helps)

ENC_I: Noise Component caused by dark current

$$\boxed{ENC_I = \frac{e}{2}\sqrt{\frac{I t_p}{e}}}$$

→Want small dark current and short integration time

ENC_{Rp}: Noise caused by parallel bias resistor

$$\boxed{ENC_{Rp} = \frac{e}{e}\sqrt{\frac{kTt_p}{2R_p}}}$$

→Want large R

ENC_{Rs}: Noise caused by readout resistor

→Want small resistor and large integration time.

$$\boxed{ENC_{Rs} \approx 0.395\, C\sqrt{\frac{R_s}{t_p}}}$$

Tracks
Momentum Measurement

Momentum Measurement of Particles

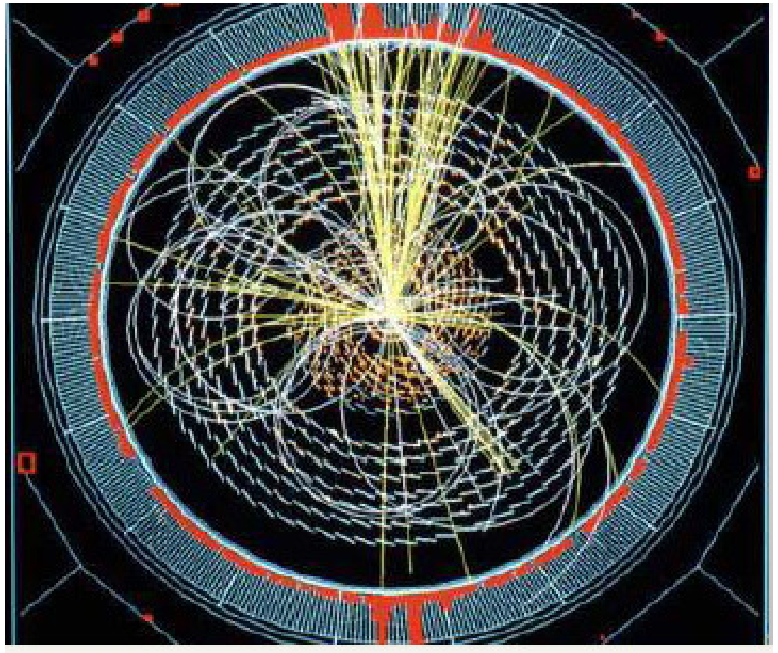
Deflection of particles in magnetic field:

$r = p/0.3\,B$ (r[m], B[T],p[GeV])

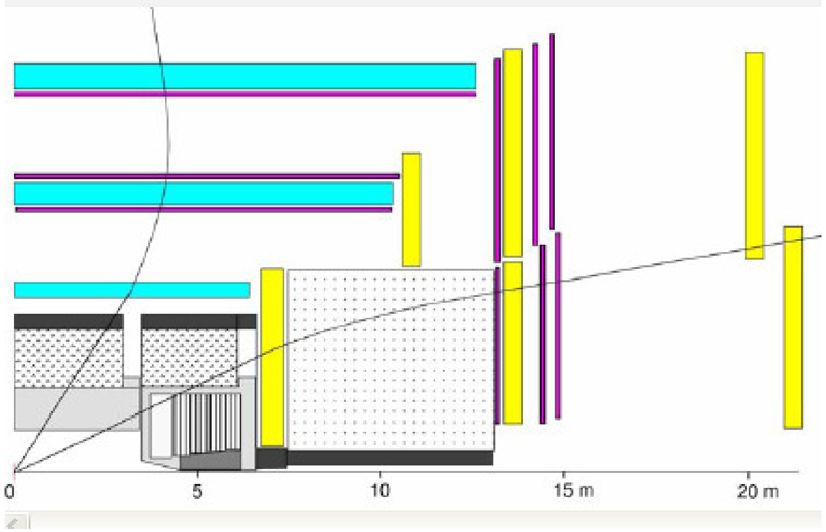
Measurement of r →measurement of p

Side effect: low energy particles never reach the outer layers of the tracker or the calorimeter

Deflection in solenoid field



Deflection in torroid field

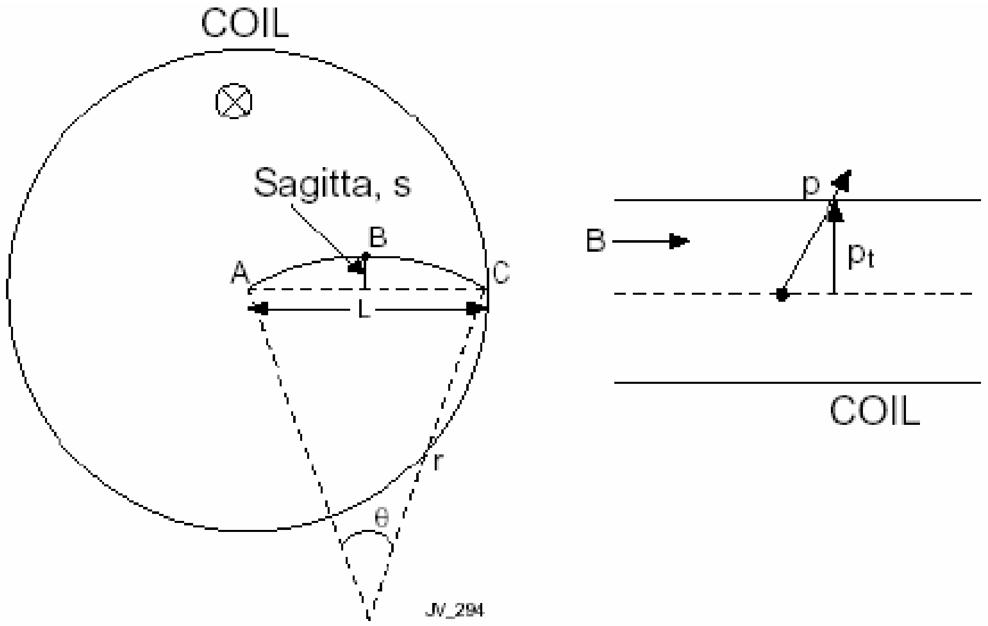


Momentum Measurement II

$$\frac{dp_t}{p_t} = \frac{\sigma_x p_t}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

Measurement error small if:

- B large
- many measurement points
- L large (large tracking volume)



CMS: 17 layers, 4T B field, resolution 100μm/$(12)^{1/2}$, L=1.1 m

→ $\frac{dp_t}{p_t} =$ 1.2% at 100 GeV and 12% at 1 TeV

Including multiple scattering: 1.5% / 15%

Track Fitting

General: Two steps

- pattern recognition
- track fit

Multiple scattering!

Chi sq Fit (global method)

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{\xi_i - \xi(i,a)}{\sigma_i} \right)^2$$

ξ_i Is the ith measured coordinate

$\xi(i,a)$ is the expected ith coordinate with helix parameter vector a

Minimization of χ^2 → a.
Solution via matrix inversion. If σ_i independent of each other, t~n
Including multiple scattering: σ_i depend on each other, additional (non-diagonal) matrix, taking multiple scattering into account → t ~n^3.

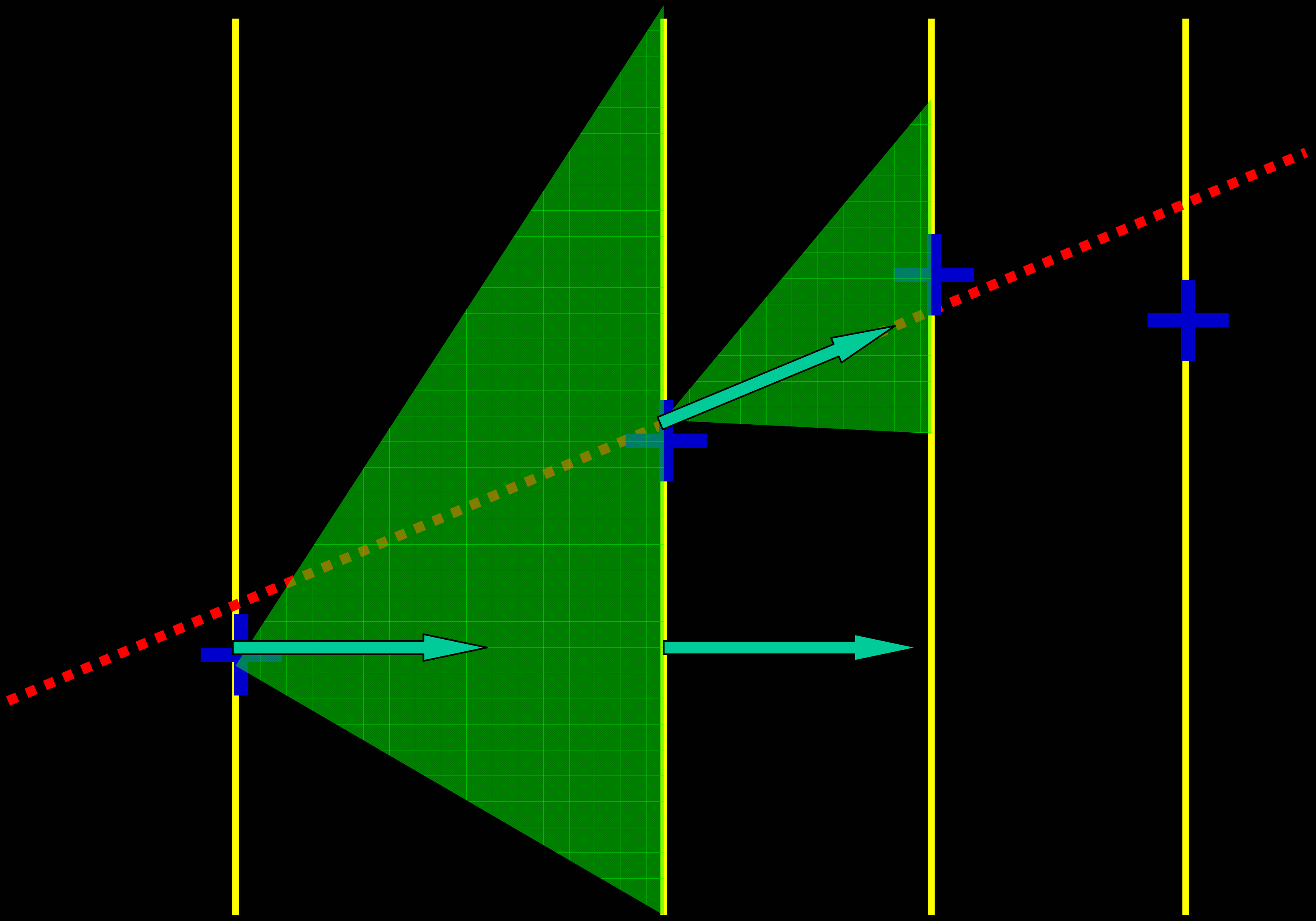
See f.e. book by Rainer Mankel

Track Fitting II: Kalman Filter

Kalman Filter:

- local, iterative method
- from outside inwards
- initial assumption for track parameter + error (covariance matrix)
- propagation of track to next layer
- calculation of new track parameters using hits + errors and track + errors (including multiple scattering)
- propagation to next layer, etc.

- t~n
- combined pattern recognition and track fit
- can be used same algorithm to reconstruct tracks in several sub-detectors (i.e. tracking chambers, muon system)
- can be nicely implemented in object oriented software



Summary

- Solid state detectors play a central role in modern high energy and photon physics

- Used in tracking detectors for position and momentum measurements of charged particles and for reconstruction of vertices (specially pixel detectors)

- By far the most important semiconductor: Silicon, indirect band gap 1.1 eV, however: 3.6 eV necessary to form eh pair

- Advantages Si: large yield in generated charge carriers, fine segmentation, radiation tolerant, mechanically stable, …

- Working principle (general) diode in reverse bias (pn junction)

- Important: S/N has to be good. Noise consists of many components, which are generally statistically independent, and therefore have to be added in quadrature. Each component is integrated over the frequency range of the amplifier.

- Radiation damage influences the material properties of the Si:
vacancies and interstitial atoms →new energy levels in the band gap
→ direct excitation possible →Increase in leakage current
trapping → reduction in charge collection efficiency

- Most track finding and fitting algorithms minimize χ^2 of tracks, Kalman filter commonly used