Principles of Semiconductor Detectors

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Organization and purpose of the lecture

- Simple (and hopefully not too superficial) introduction to semiconductor detectors
- Emphasis will be given to understanding basic concepts – details will be mostly left out
- The exmphasis will be on silicon, but should nevertheless stay general as much as possible for other semiconductors
- Many of small, but at real work important details will be left out – those not important for general understaning – talk not intended for experts
- I am biased to applications of semiconductor detectors in high energy physics – fast charge particle detection… so the talk will be more general on particle detection
- SiPMs are not going to be discussed …

Outline

- **Semiconductor as detector material**
  - Detection of different types of radiation (charged particles, γ n)
  - Material properties of semiconductors
  - Electric properties of semiconductors
- **Semiconductor detector**
  - How to make a detector
  - P-N junction
  - Electrical properties of P-N junction
- **Signal formation**
  - Ramo's theorem and its implications
  - Effects of segmentation
  - Examples of induced currents and measured spectra in silicon detectors
- **Performance of segmented detectors**
  - Noise, its sources, and SNR
  - Position resolution
  - Energy resolution
  - Timing resolution
- **Various silicon detector structures**
  - Processing steps
  - Planar (Strips, Pixel,Drift)
  - 3D detectors,
  - CCD, DEPFET, MAPS, HVCMOS
- **Other semiconductor materials**
  - Diamond
  - SiC
  - HgI_2
  - Cd(Ze)Te
- **Radiation damage in semiconductor detectors**
  - Consequences of irradiations
  - Manifestation of macroscopic damage
  - Review of effects
  - Damage in other semiconductors (diamond,SiC)
- **References**

Semiconductor as detector material

Semiconductor detector = solid state ionization cell/chamber

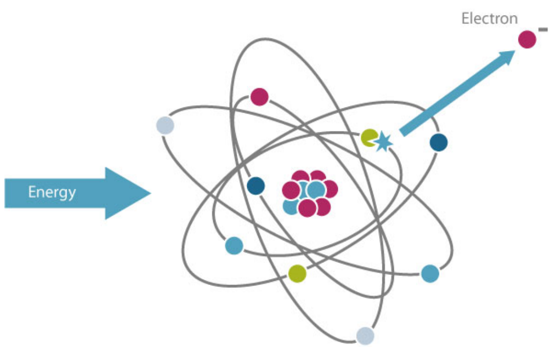
Main advantages:

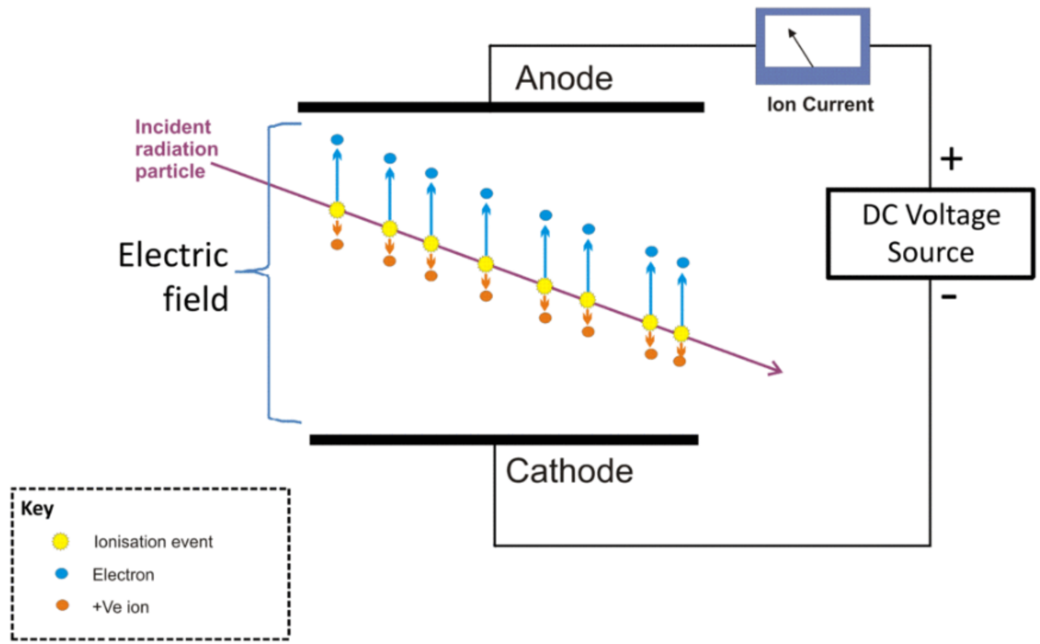
- Much lower ionization energy (eV instead of tens eV) and much larger density – more charge i.e. "signal"
- Faster (smaller distances, larger speed of moving carriers)
- Better resultion (energy and position)
- ...

A major disadvantage:

- Gas can be replaced, while crystals get damaged by radiation
- Multiplication… not easy

ion – electron creation in gas atom





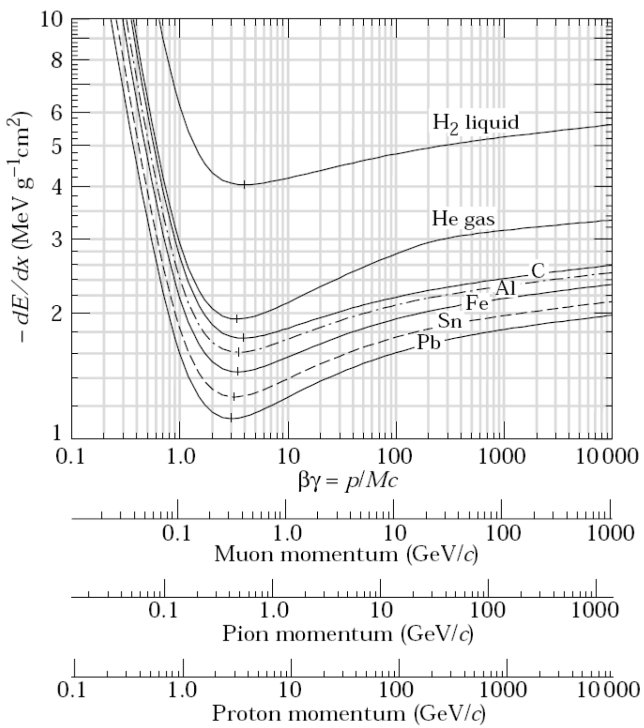
The mechanism of detection in semiconductor material will be described in more details in the following slides.

Types of radiation and choice of material

The choice of material depends a lot on application.

To ionize semiconductor material the particles have to be charged

- Charged particles (e,p,$\pi^{\pm}$,$K^{\pm}$,μ, α particles, ions)
- **Photons and neutrons** – have to react in the crystal to produce ionizing particles, which are then detected



Silicon: ~380 keV/mm
Diamond: ~460 keV/mm

Bethe Bloch formula (calculate **average/mean** amount of energy lost due to ionization per unit of distance in the media)

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

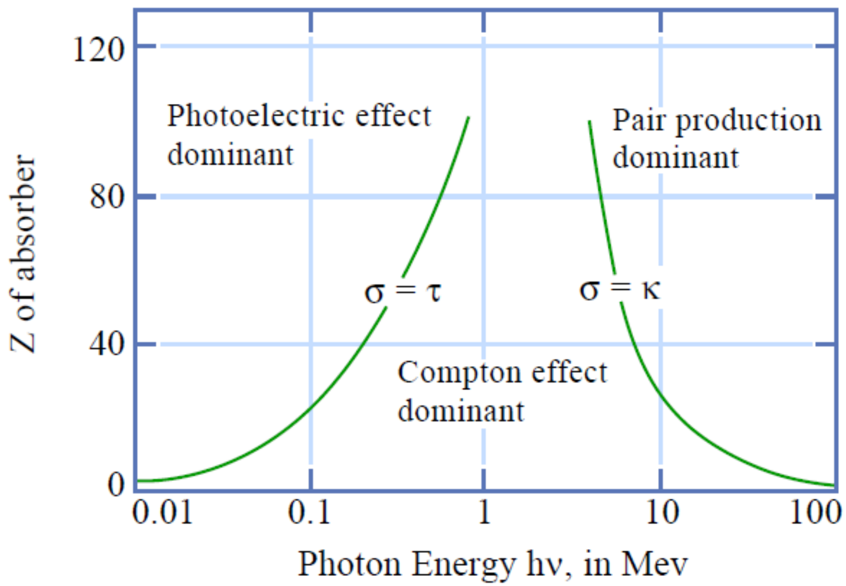
$$n = \frac{N_A \cdot Z \cdot \rho}{A \cdot M_u}$$

n - density of electrons in material

Larger losses for:
- ➢ low $\beta = v/c << 1$
- ➢ high z (i.e. α particles)
- ➢ denser material

For each material at β=0.96 there is a minimum – minimum ionizing particle
- ➢ Small ionization energy *I*

Interaction of photons with matter



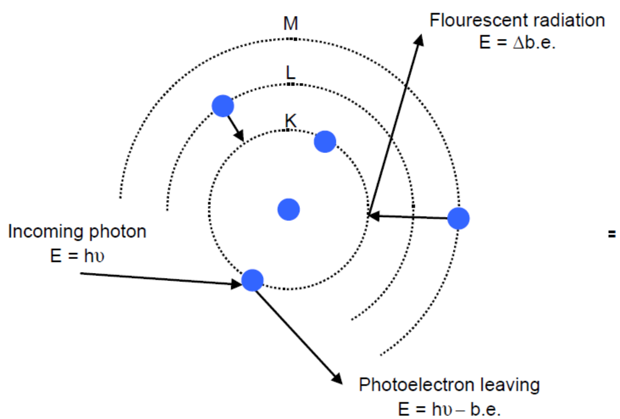
Photon flux in material exponentially decreases with μ

- Photoelectric effect: produces a an electron, varies as ~ Z^4/E^3
- Compton effect: produces an electron and scattered photon, varies as ~ Z
- Pair production: produces an electron and a positron, varies as ~Z^2 (threshold 2 m_ec^2)

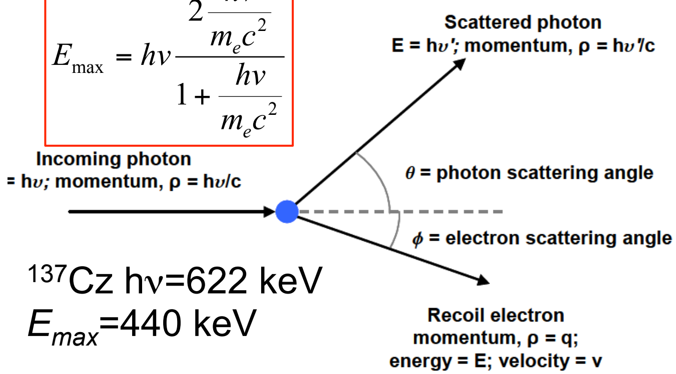
The interaction probability μ:

$\mu=\kappa+\sigma+\tau$

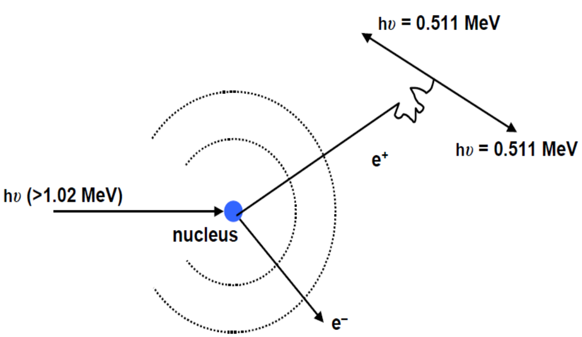
τ is the photoelectric effect interaction probability
σ is the Compton scattering interaction probability
κ is the pair production interaction probability



$$E_{\max} = h\nu \frac{2\frac{h\nu}{m_e c^2}}{1+\frac{h\nu}{m_e c^2}}$$



^{137}Cz hν=622 keV
E_{max}=440 keV



Interaction of neutrons with matter

- **Principle of neutron detection (only react with nucleus of the atom):**
  - **Conversion** of incident neutron into secondary charged particles
  - **Direct detection** of recoiled charged particle

Relative probabilities of different interaction changes rapidly with E_n

Cross section are sizable only at very low energy (slow and thermal n)

- **slow neutrons** (E_n < 0.5 eV):

  neutron-induced reactions creating secondary radiation with sufficient energy e.g. radiative capture (n,γ) or (n,α), (n,p), (n, fission)

- **fast neutrons:**
  - elastic scattering probability becomes greater: large energy transfer in one collision

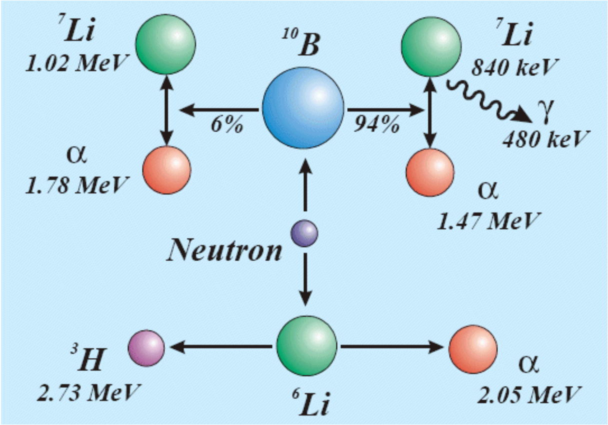
  neutron loses energy and is moderated/slowed to lower energy

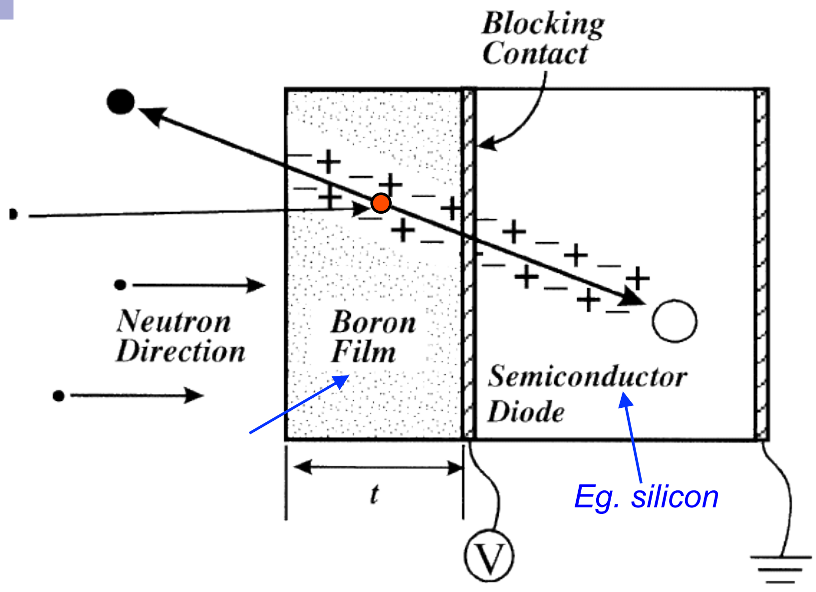
  Best moderator is hydrogen - it can get all n-energy in a single collision

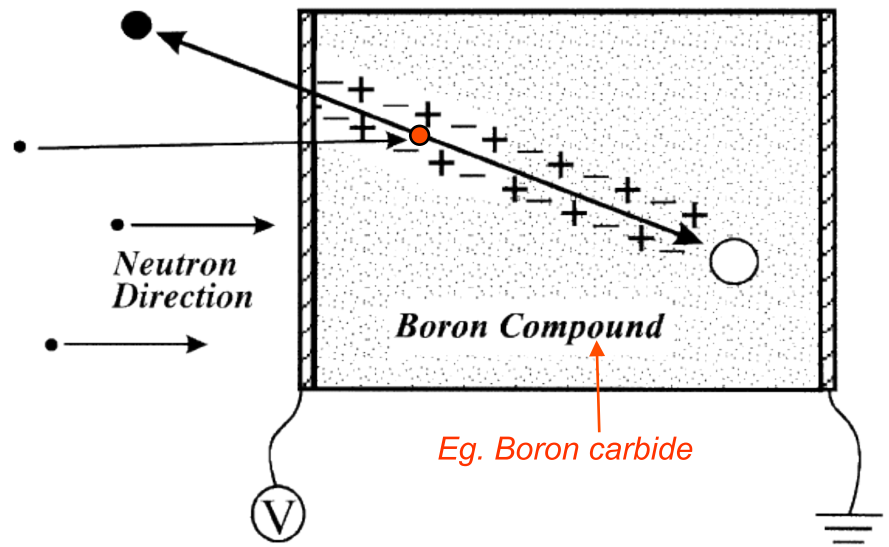
  - Inelastic at high energies (break up of target nuclei)

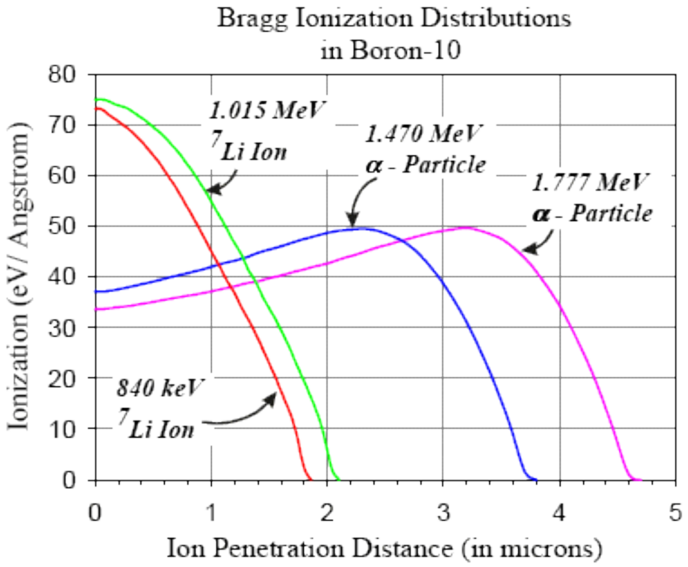
Slow neutrons – converter is incorporated with semiconductor detector e.g. ^{6}Li or ^{10}B .

Fast neutrons : hydrogen rich converter – direct moderator followed by converter









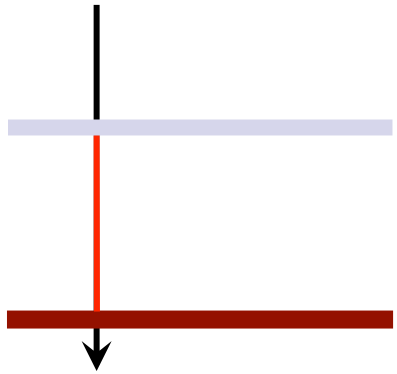
Boron coated silicon detectors have an intrinsic efficiency limit of ~4%:

- ✗ Only the 'final' 5 μm thickness of the boron layer is active
- ✗ Thicker boron layer does not increase efficiency due to limited range of alpha particle and lithium ion:
- ✓ However a 'solid' boron-based semiconductor detector will have an efficiency only limited by the thickness of the device…

A moderator can be used in front of the converter to slow down faster neutrons.

Charge generation in a detector

ionizing particle track

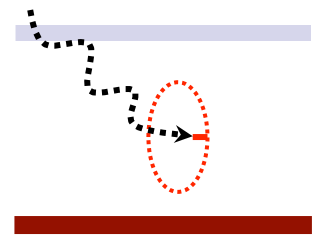


•deposition of e-h pairs along the track

•average 32000 e-h in 300 μm of Si for m.i.p.

•Energy loss is distributed (shown later)

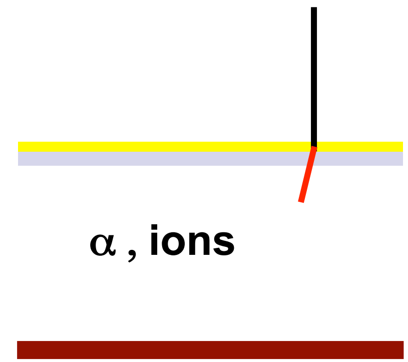
single γ generation (E_γ<1 MeV) (photo effect, Compton, pair production)



•deposition of e-h pairs at the point of conversion

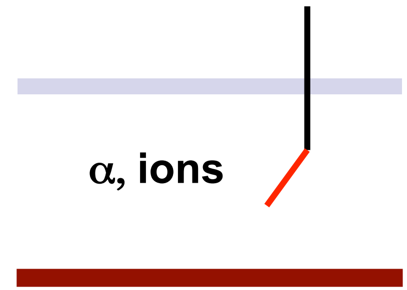
•efficiency depends on thickness

neutrons



•deposition of e-h pairs near (few μm away) absorber – limited efficiency, but detector can be thin.

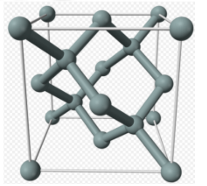
1.77 MeV α gives <= 490000 e-h in Si



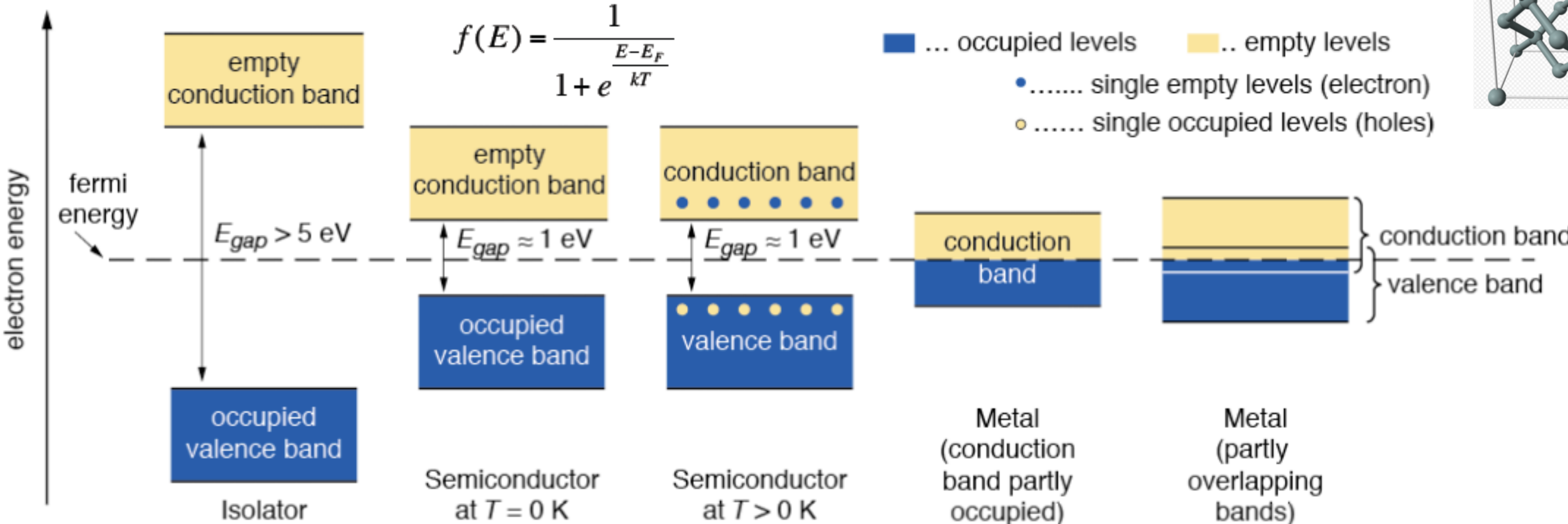
•deposition of e-h pairs in the detector – efficiency depends on thickness

We want to measure charge – but how it is created, how much energy is required, how it is collected … ?

Energy bands in crystaline materials



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



In pure silicon the intrinsic carrier concentration is **$1.45 \cdot 10^{10}$ cm^{-3}** (300 K)
With approximately 10^{22} Atoms/cm^3 about 1 in 10^{12} silicon atoms is ionised.

$$n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

Ionizing energy loss (dE/dx) manifests in the same mechanism – excitation of the holes from valence to conduction band.
Only a fraction of energy is used for ionization other goes to lattice heating (phonons) – for silicon 3.62 eV are needed for a single e-h pair on average (E_g=1.12 eV)

Charge movement

Excited charges must move in order to be detected.

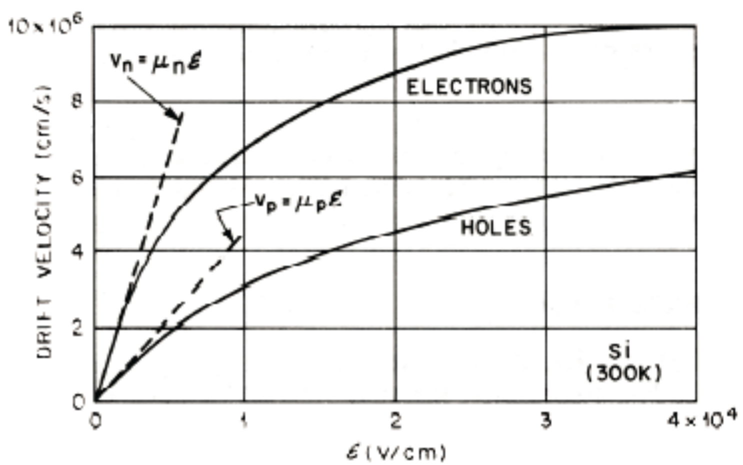
Drift velocity

For electrons: $\vec{v}_n = -\mu_n \cdot \vec{E}$ and for holes: $\vec{v}_p = \mu_p \cdot \vec{E}$

Mobility

For electrons: $\mu_n = \frac{e\,\tau_n}{m_n}$ and for holes: $\mu_p = \frac{e\,\tau_p}{m_p}$

μ_n(Si, 300 K) ≈ 1450 cm²/Vs μ_p(Si, 300 K) ≈ 450 cm²/Vs



e ... electron charge

E ... external electric field

m_n, m_p ... effective mass of e⁻ and holes

τ_n, τ_p ... mean free time between collisions for e⁻ and holes

$$\rho = \frac{1}{e_0\left[\mu_e n_e + \mu_h n_h\right]} = 230\ \mathrm{k\Omega cm\ at\ 300K}$$

Source: S.M. Sze, *Semiconductor Devices*, J. Wiley & Sons, 1985

A more detailed table for other semiconductors follows.

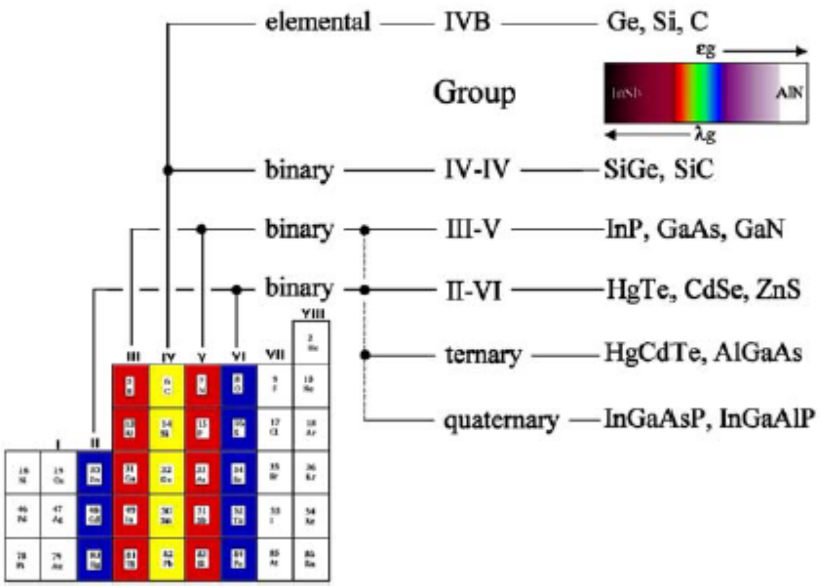
Comparison of different semiconductors

Apart from elemental semiconductors, there are binary, ternary compounds – mainly used for γ,x-ray detection due to high Z

Silicon is by far most studied, understood, manufactured and used.

$$I_0 \approx (2-3)\cdot E_g$$

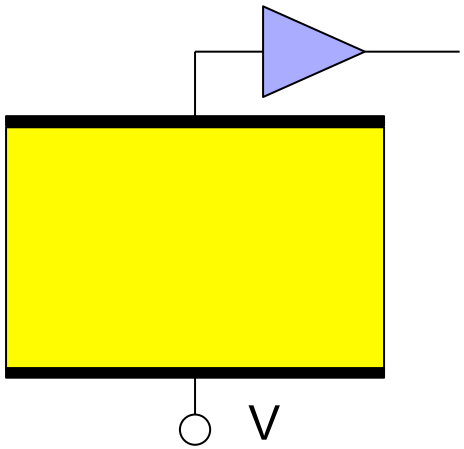
Other faction of the energy lost goes to phonons!



Property	Diamond	Si	a-Si(H)	4H–SiC	6H–SiC	GaN	GaAs	Cd(Zn)Te	TlBr	HgI_2
Z	6	14	14	14/6	14/6	31/7	31/33	48/52	81/35	80/53
E_g (eV)	5.5	1.12	1.7	3.3	3.03	3.39	1.4	1.4–1.6	2.7	2.1
μ_e (cm^2/Vs)	1800–2200	1450	1–10	800–1000	370	1000	⩽8500	1000	40	100
μ_h (cm^2/Vs)	1200–1600	450	0.01–0.005	50–115	50	30	⩽400		12	4
Saturated electron drift velocity (cm/s)	2.7×10^7	1.0×10^7		2.0×10^7	2.0×10^7		1.2×10^7			
e–h pair creation (eV)	13	3.6	4–4.8	7.8		8.9	4.3	4.4–4.7	5.9	4.2
eV/μm for MIPs	36	81		51						
Displacement (eV)	43	13–20		21.8		Ga–20 N–10	10			
Density (g/cm^3)	3.5	2.3	2.3	3.2		6.2	5.3	5.9–6.0	7.5	6.4
ε_R	5.5			9.7	10		≈0.4			8.8
Breakdown voltage, (MV/cm)	10	0.5		4[a]	2.4					

Semiconductor detector

How to make a detector?



Semiconductor is sandwiched between two electrodes with either Ohmic or Schottky contact with semiconductor (how to deposit appropriate metal electrodes is a very delicate and often patented process)

- SIGNAL : Charged particles generated inside or traversing the detector create e-h pairs which are separated by the electric field – move/drift to the electrodes.
- SNR : If you want to be able to clearly see the signal it should be sufficiently larger than the noise. A good detector should have a large SNR
- However this leads to two contradictory requirements:

✘ Large signal

➔ particles should produce many electron-holes ➔ low ionization energy ➔ small band gap!

✘ Low noise

➔ very few intrinsic charge carriers ➔ large band gap!

Semiconductors as detector material?

A simple calculation for silicon with , mean ionization energy I_0 **= 3.62 eV**
with mean energy loss ***dE/dx = 3.87 MeV/cm***

A detector with a thickness of *d = 300 µm and an area of A = 1 cm² at 300 K:*

Signal charge: $$\frac{dE/dx \cdot d}{I_0} = \frac{3.87\cdot 10^6\,\mathrm{eV/cm}\cdot 0.03\,\mathrm{cm}}{3.62\,\mathrm{eV}} \approx 3.2\cdot 10^4\ \mathrm{e^-h^+}\text{–pairs}$$

Intrinsic carrier charge: $$n_i\,d\,A = 1.45\cdot 10^{10}\,\mathrm{cm^{-3}}\cdot 0.03\,\mathrm{cm}\cdot 1\,\mathrm{cm^2} \approx 4.35\cdot 10^8\ \mathrm{e^-h^+}\text{–pairs}$$

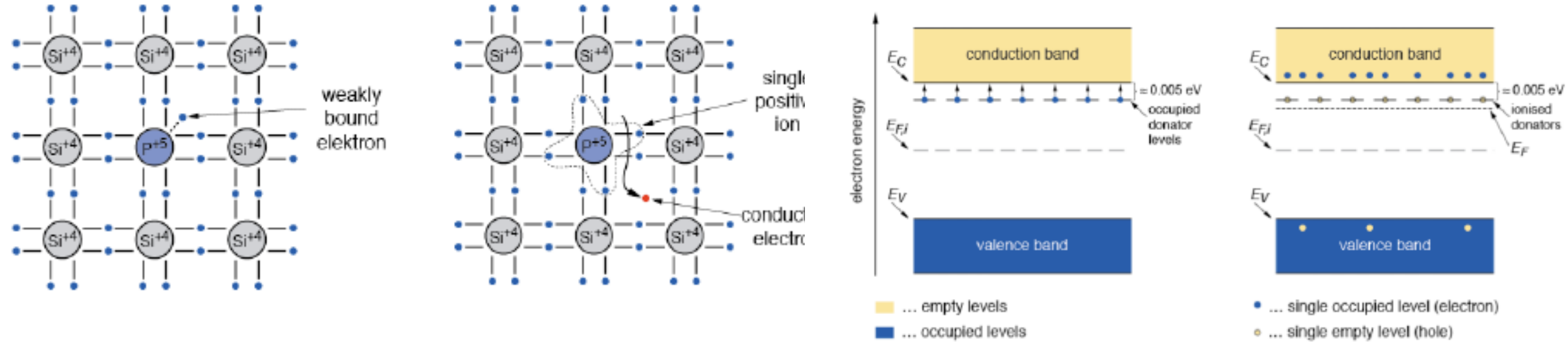
Number of thermal created e^-–h^+-pairs is four orders of magnitude larger than signal!

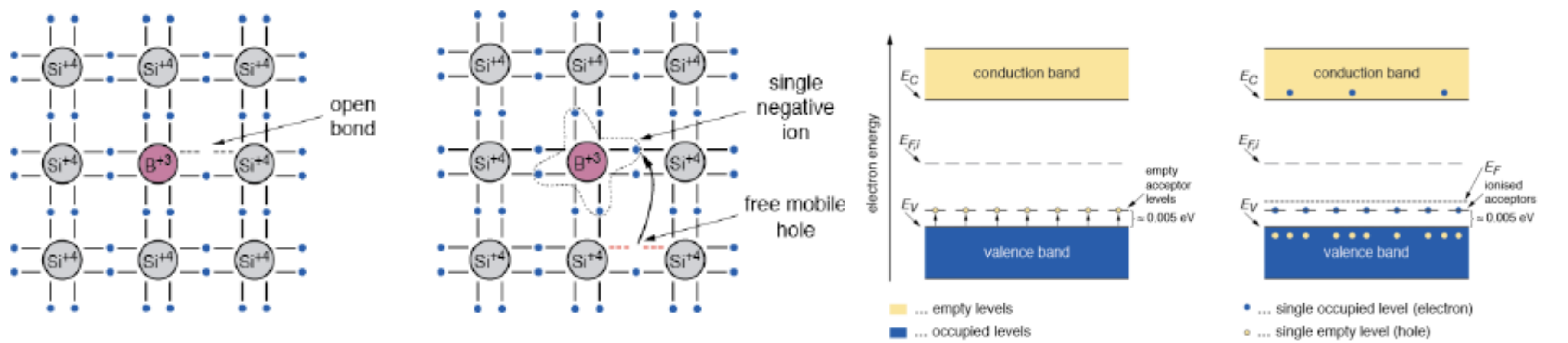
How to reduce it?

- For silicon and other materials with small band gap one has to reduce intrinsic carriers by
  - cooling – $n_i \propto \exp(-\frac{E_g}{2k_BT})$
  - **forming a reversed biased P-N junction !**
- For wide band gap semiconductors (diamond, CdZnTe, HgI_2) resistivity can be large enough so that they can be operated with ohmic (or Shottky) contacts

Extrinsic semiconductors: n and p doping

n doping with an element 5 atom (e.g. **P, As, Sb**). The 5th valence electrons is weakly bound. The doping atom is called **donor.** The released conduction electron leaves a positively charged ion: the effective space charge **N_{eff} is positive**.

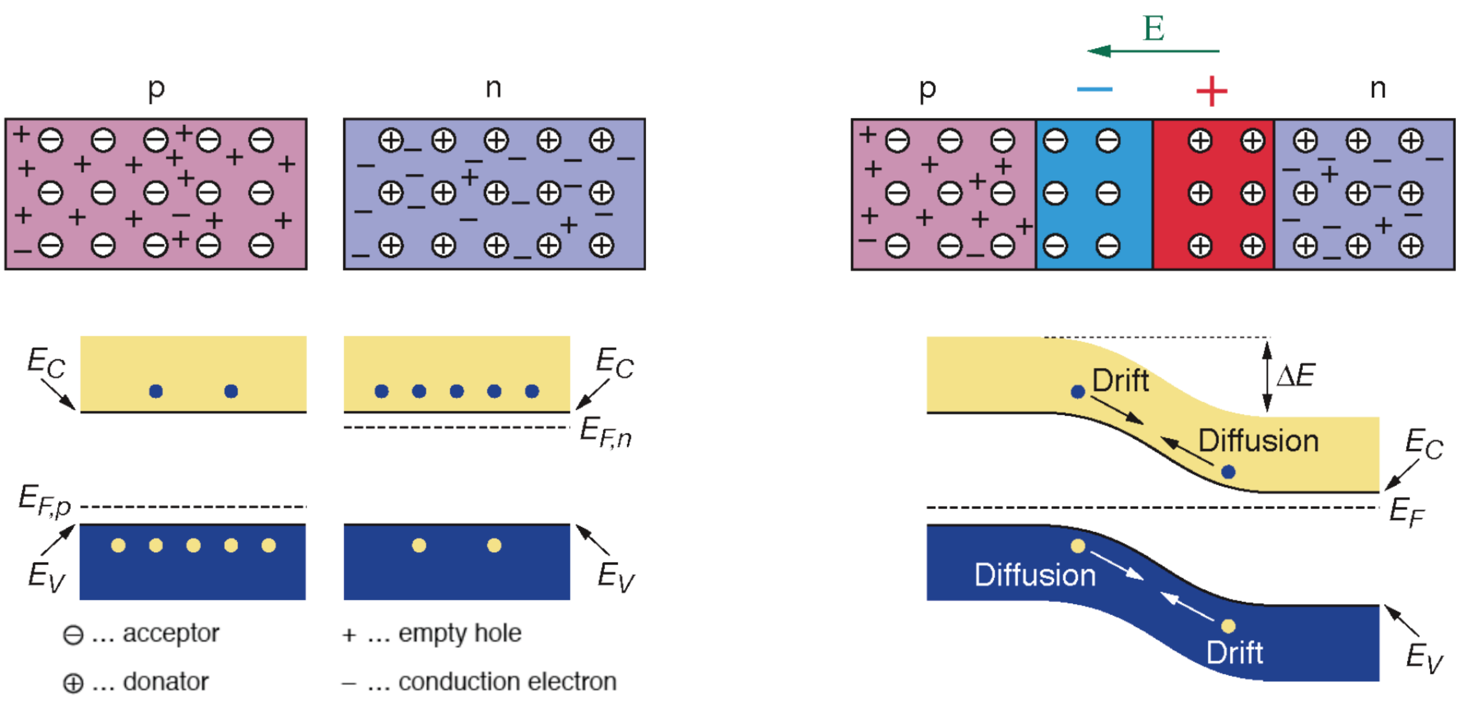




p doping with an element 3 atom (e.g. **B, Al, Ga, In**). One valence bond remains open. This open bond attracts electrons from the neighbour atoms. The doping atom is called **acceptor.** The acceptor atom in the lattice is negatively charged ion: **N_{eff} is negative**.

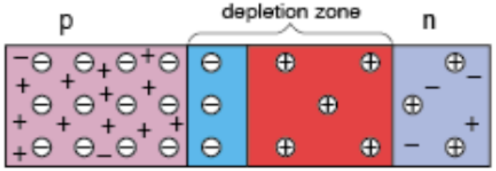
Creating a p-n junction

At the interface of an n-type and p-type semiconductor the difference in the Fermi levels cause diffusion of surplus carries to the other material until thermal equilibrium is reached. At this point the Fermi level is equal. The remaining ions create a space charge and an electric field stopping further diffusion. The stable space charge region is free of charge carries and is called the depletion zone.

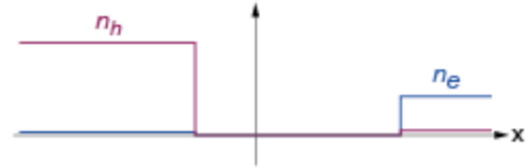


Electric field in p-n junction

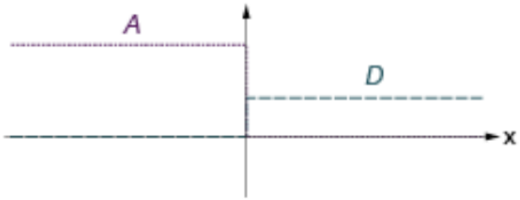
pn junction scheme



concentration of free charge carriers



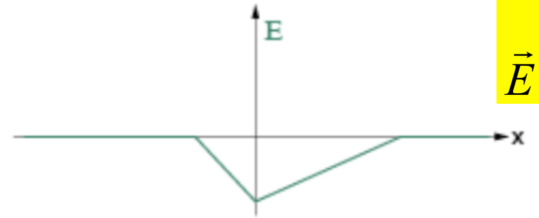
acceptor and donator concentration



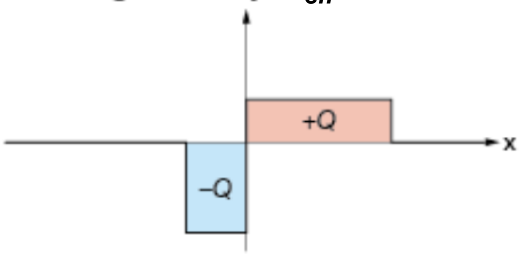
Electric field follows from Gauss law:

$$\Delta U = \frac{-e_0 N_{eff}}{\varepsilon \varepsilon_0}$$

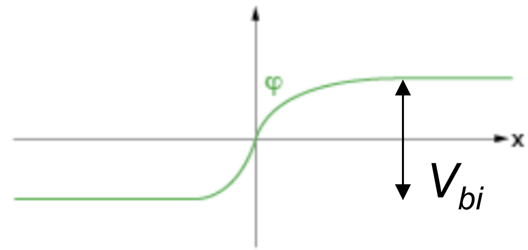
$$\vec{E} = -\nabla U$$



space charge density N_{eff}



electric potential



⊖ ... acceptor + ... empty hole

⊕ ... donator − ... conduction electron

V_{bi}= potential difference between open contacts

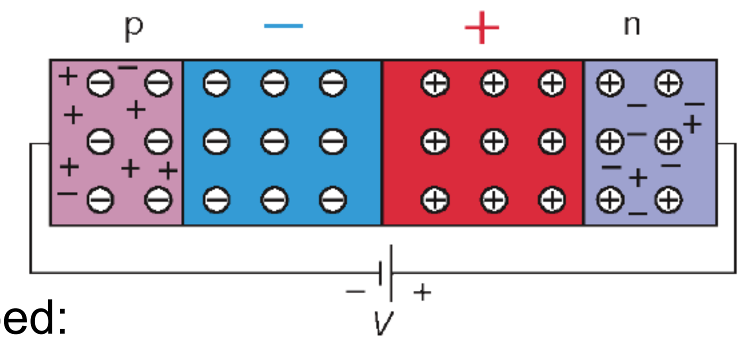
Usually one side is far more doped than the other

$N_A >> N_D$

Electric field in p-n junction

Applying an external voltage V with the cathode to p and the anode to n e- and holes are pulled out of the depletion zone. The depletion zone becomes larger.

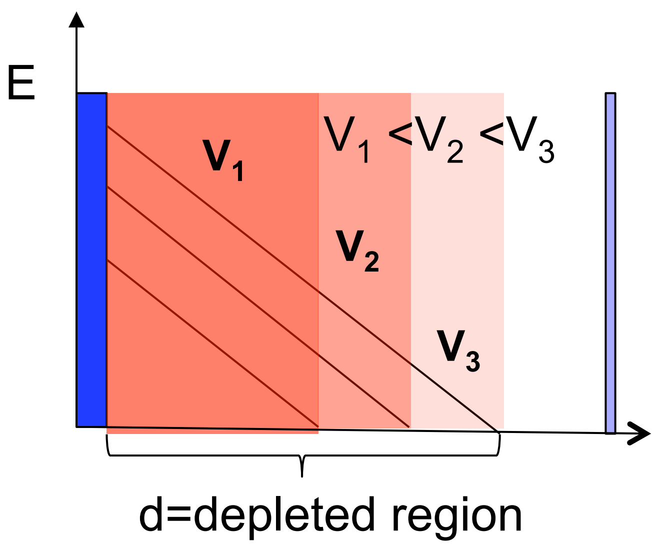
p-n junction with reverse bias



One of the junction side is usually more heavily doped:
$N_A=10^{15}$ cm^{-3} , $W_p=0.2$ μm
$N_D=10^{12}$ cm^{-3} , d~$W_d=23$ μm

$$\Delta U=-e_0 N_{eff}/\varepsilon\varepsilon_0$$

$$d=\sqrt{2\varepsilon\varepsilon_0/e_0 N_{eff}\,(V+V_{bi})}$$

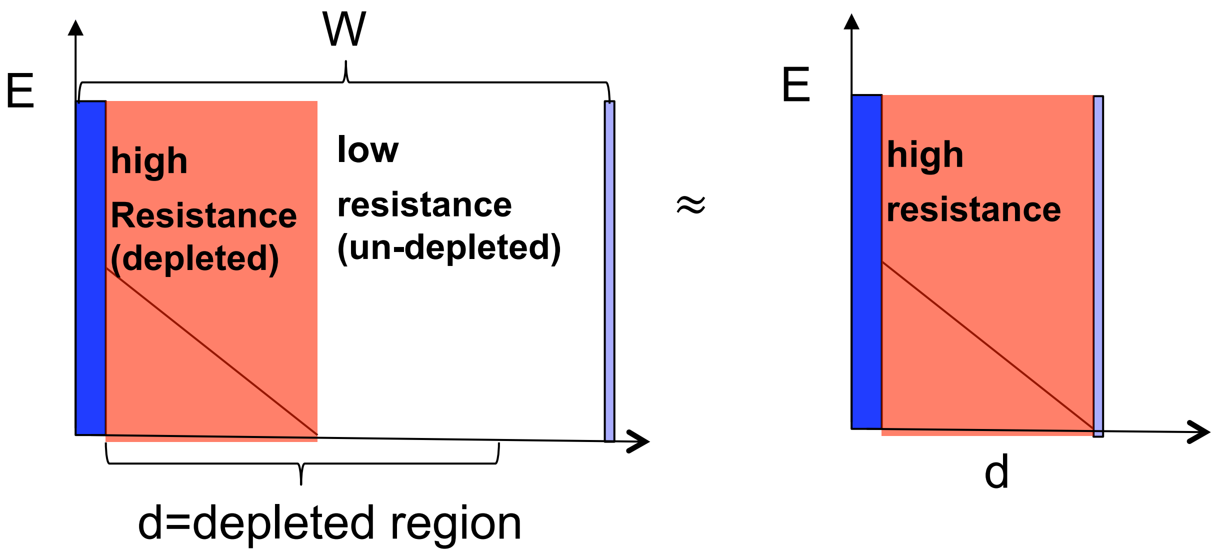


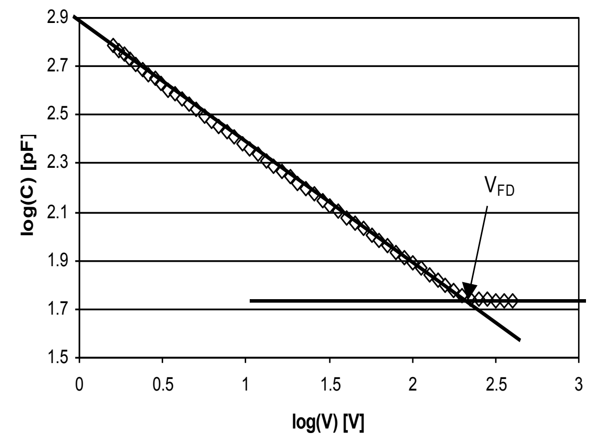
At V_{FD} the electric field is present in all of the detector

At V_{BD} the electric field becomes so strong that the detector breaks down (high field - impact ionization – many carriers – breakdown)

Electrical properties - capacitance

$C=\varepsilon_0 \varepsilon S/d$ At $V \geqq V_{FD}$ $C_{geom}=\varepsilon_0 \varepsilon S/W$ → d from *C(V)*





For non-junction materials the capacitance is always geometric – not dependent on voltage.

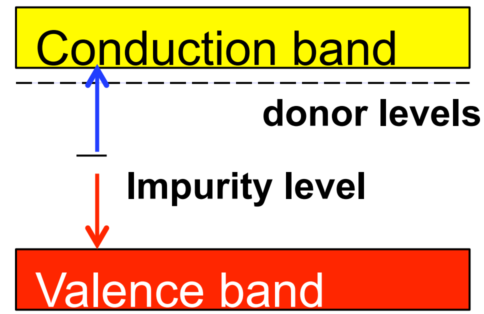
Capacitance of the electrode plays a mayor role in electronics noise.

Leakage current/dark current

It is present in any semiconductor and comes from:

1) **generation at impurities**
2) **diffusion from un-depleted bulk**

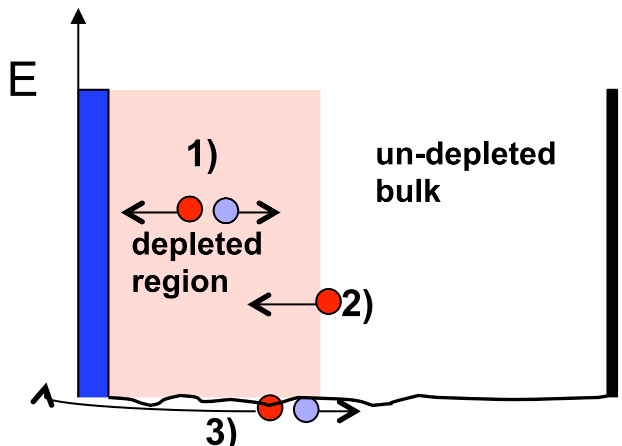
3) **edge and surface effects**

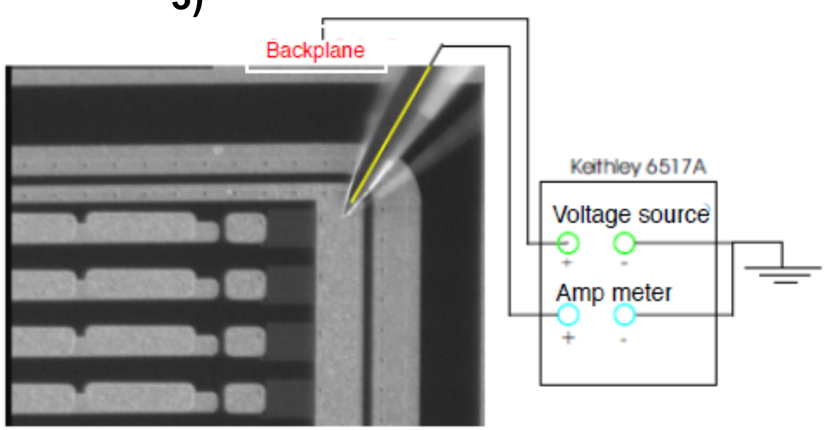


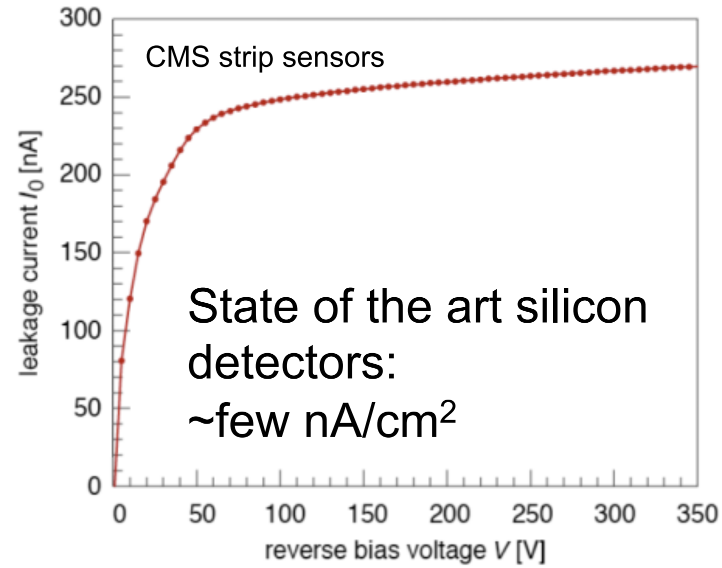
$$I = \frac{e_0 n_i}{2\tau_m} V_{det}$$

V_{det} =active volume

τ_m = carrier-lifetime (long for good material)

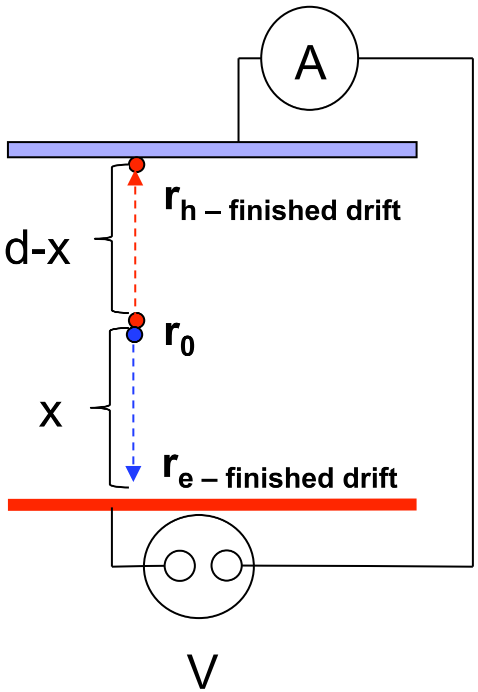






Signal formation

Signal formation – pad detector



First look at the simple pad detector with electrodes connected to low impedance.

Whenever generated charge moves in the detector it induces current in the electrodes according to Ramo's theorem (Proc. I.R.E. 27 (1939) 584., E. Gatti et al., NIM 193 (1982) 651.) (electrons and holes don't need to reach electrodes)

For a simple pad detector:

$$I=qv/d$$

$$Q=\int_0^t I\,dt' = \int_0^t v\,dt' = q\,x - x_0/d$$

$$Q_{e-h}=Q_e+Q_h=-e_0\,(0-x_0)/d+e_0\,(d-x_0)/d=e_0$$

If the drift is completed the amount of induced charge is equal to half of the generated charge (e-h = double charges)! The other half is induced at the other electrode.

Incomplete drift (trapping , short measurement time) by either carrier type results in reduced induced charge and the dependence of the signal on starting point of the drift.

Signal formation – segmented detectors

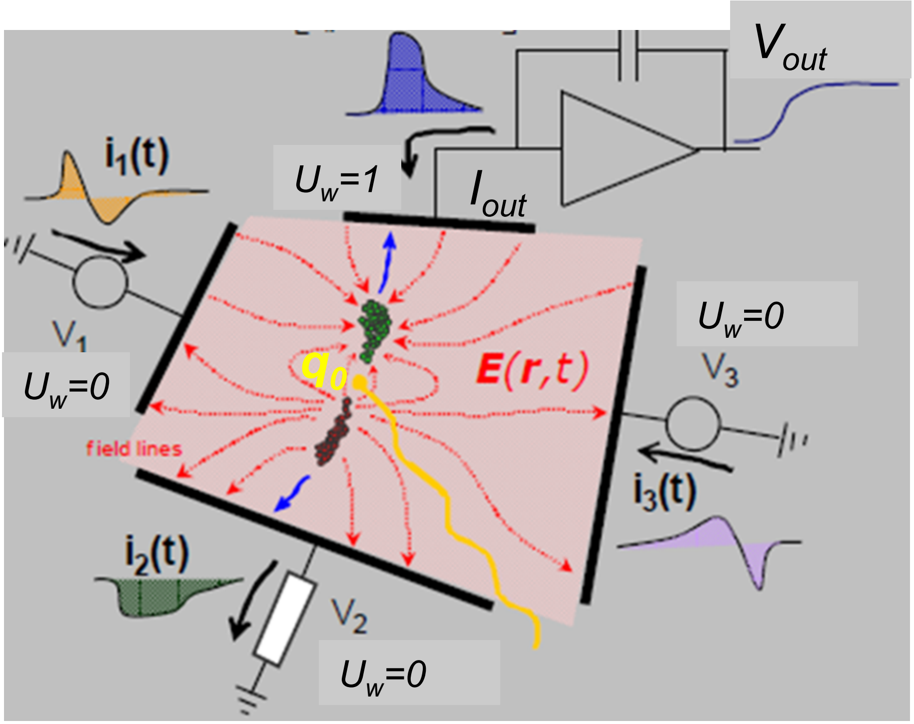
Induction of current is done through the concept of the weighting/ramo field:

Note bipolar pulses on neighbouring electrodes.

1D – pad detector: $I = q\frac{v}{d} \quad , E_w = \frac{1}{d}$

2D, 3D - detector: $I = q\,\vec{v}\cdot\vec{E}_w$

$$\Delta U_W = 0 \quad , \quad \vec{E}_w = -\nabla U_W$$



$$Q = \int_{t=0}^{t} I dt = e_0 \int_{t=0}^{t} \vec{v}\vec{E}_w dt = e_0 \int_{\vec{r}_0}^{\vec{r}(t)} \vec{E}_w d\vec{r}$$

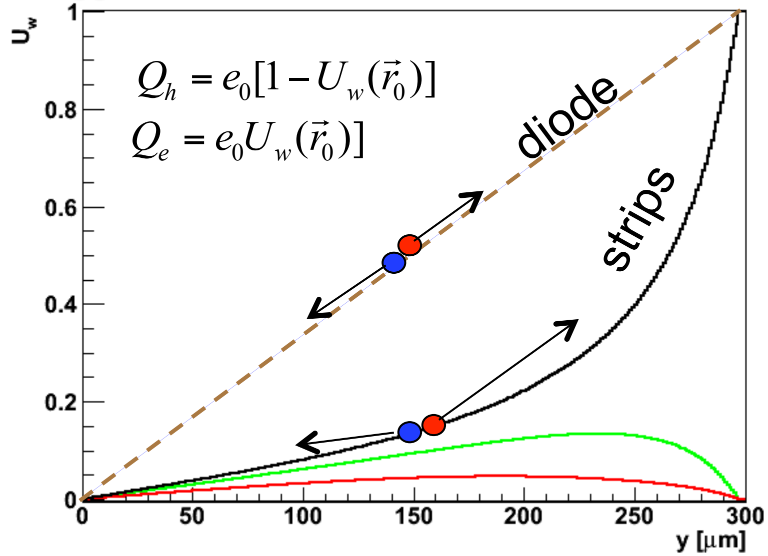
$$Q_{e,h} = e_0[U_w(\vec{r}) - U_w(\vec{r}_0)]$$

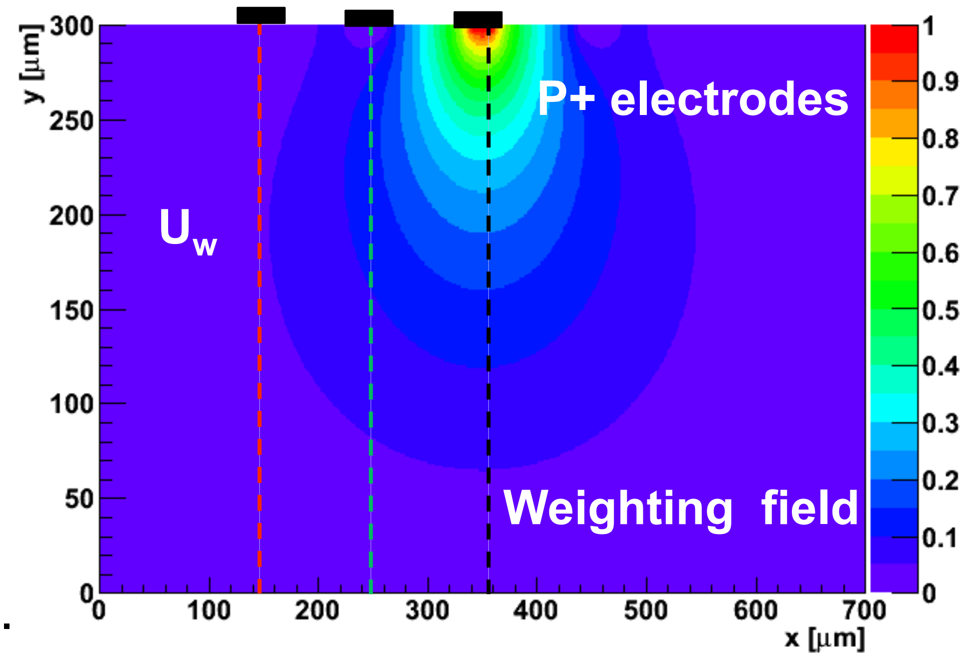
$$Q_{e-h} = Q_e + Q_h$$

$$Q_{particle} = \sum_{all\ pairs} Q_e^{\ i} + Q_h^{\ i}$$

The charge induced when a carrier moves a certain distance is given by a difference in weighting potential at two points.

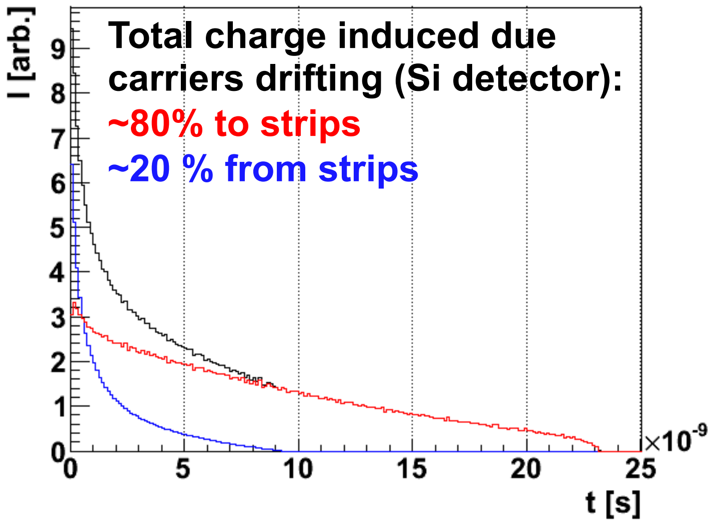
U_w in strip detector and diode

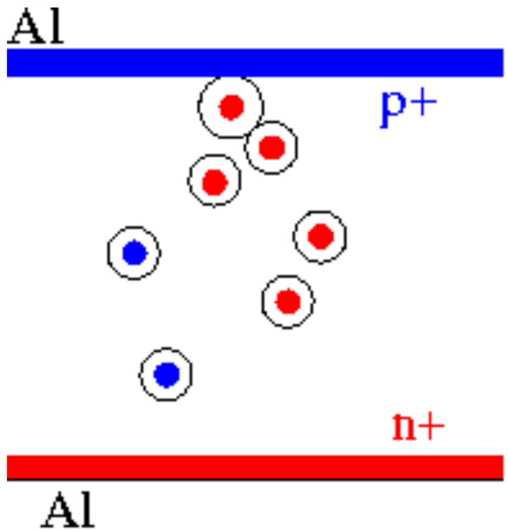




The dashed lines denote the U_w along the line.

- If e-h pair is generated in the middle of the detector carrier drifting to the electrode induces more charge
- **In segmented detectors most of the charge is induced by movement of carriers close to the electrodes!**
- If e-h is generated under neighbors the total net charge is Q=0 but the current is not.





$$I = q \cdot \exp\left(\frac{-t}{\tau_{eff}}\right) \mu \vec{E} \cdot \vec{E}_w$$

If traps are homogenously distributed τ_{eff} = const. otherwise $\tau_{eff} = \tau_{eff}(\vec{r})$

Often the drift is not completed: Two reasons:

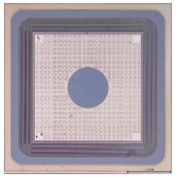
- Trapping of the drifting charge
  - Charges trapped at defects introduced during the growth (energy levels in the band gap) - not in silicon detectors though
  - Charges trapped at the defects introduced by irradiation (will be explained later)
- Integration time of the current is smaller than the drift time (ballistic deficit)

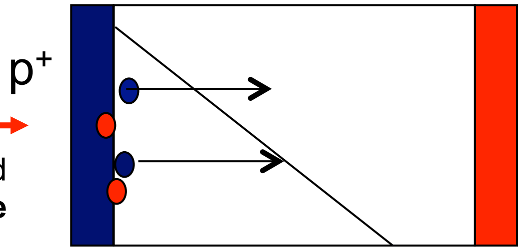
Mean Free Path - can be directly related to induced charge

$$\lambda_{e,h} = \tau_{eff,e,h} \, \mu_{e,h} \cdot E$$

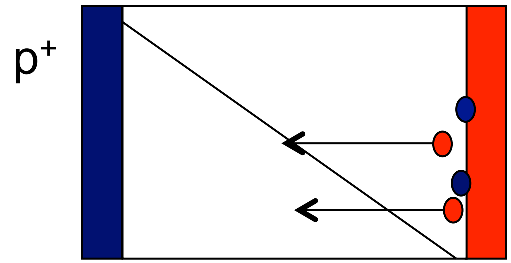
often taken a figure of merit

Example of measured induced currents



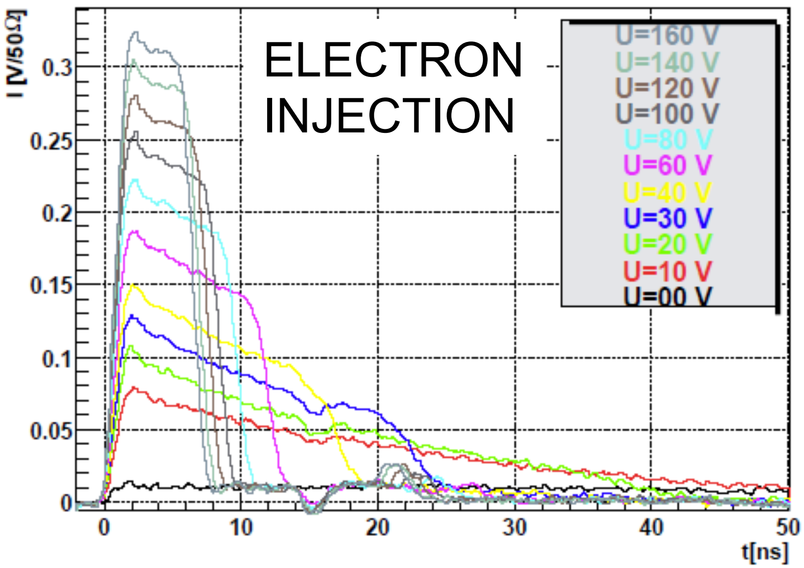


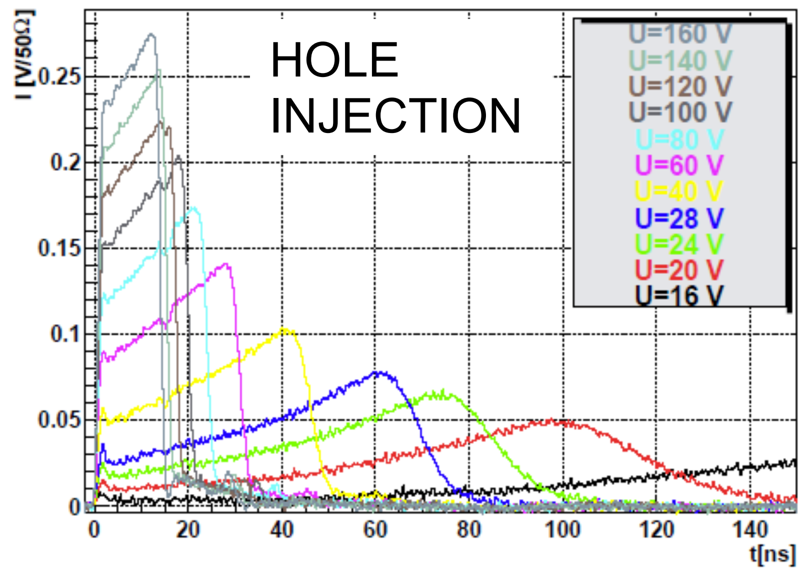
Illumination by a red **660 nm laser pulse or α particle**



Illumination by a red **660 nm laser pulse**

or α particle



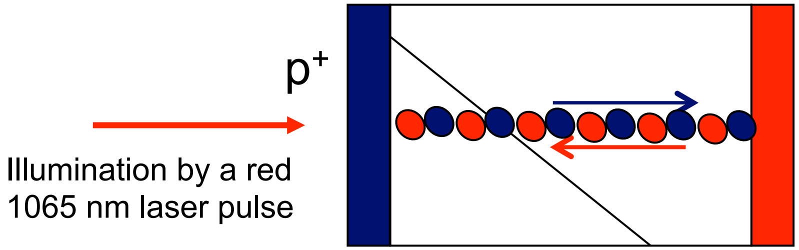


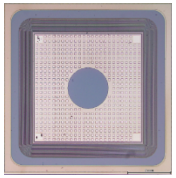
p-n pad detector (15 kΩcm, n type, 300 μm thick)

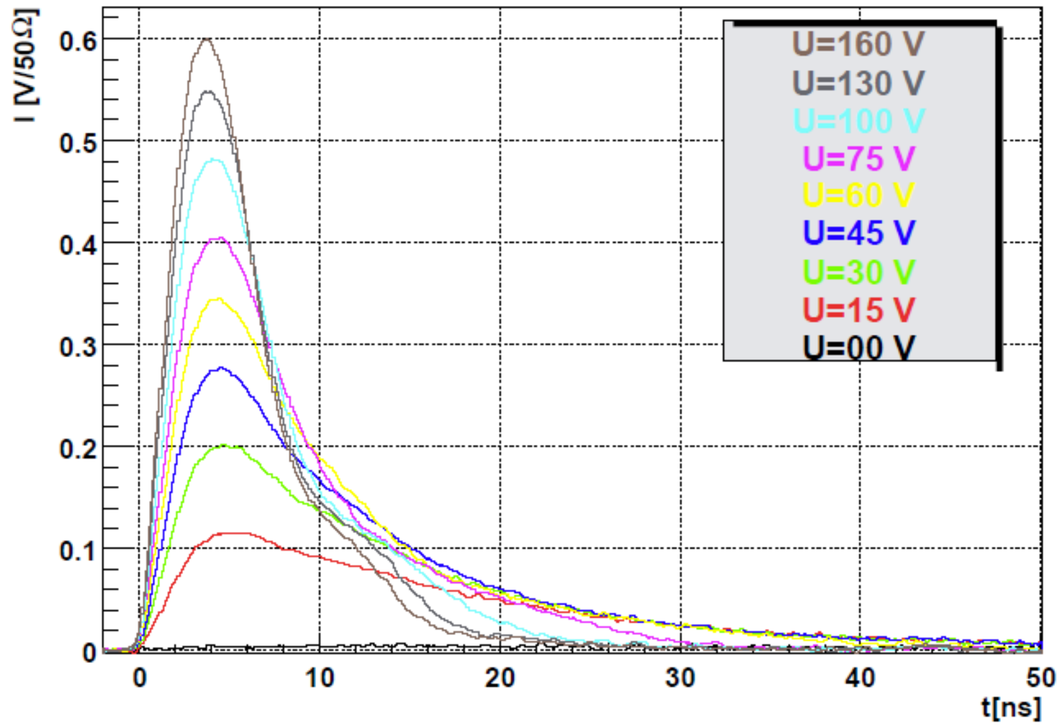
Remember – the shape of *I* gives you the shape of *electric field !*

The same induced current shapes are measured by few MeV α particles!

Example of measured induced currents

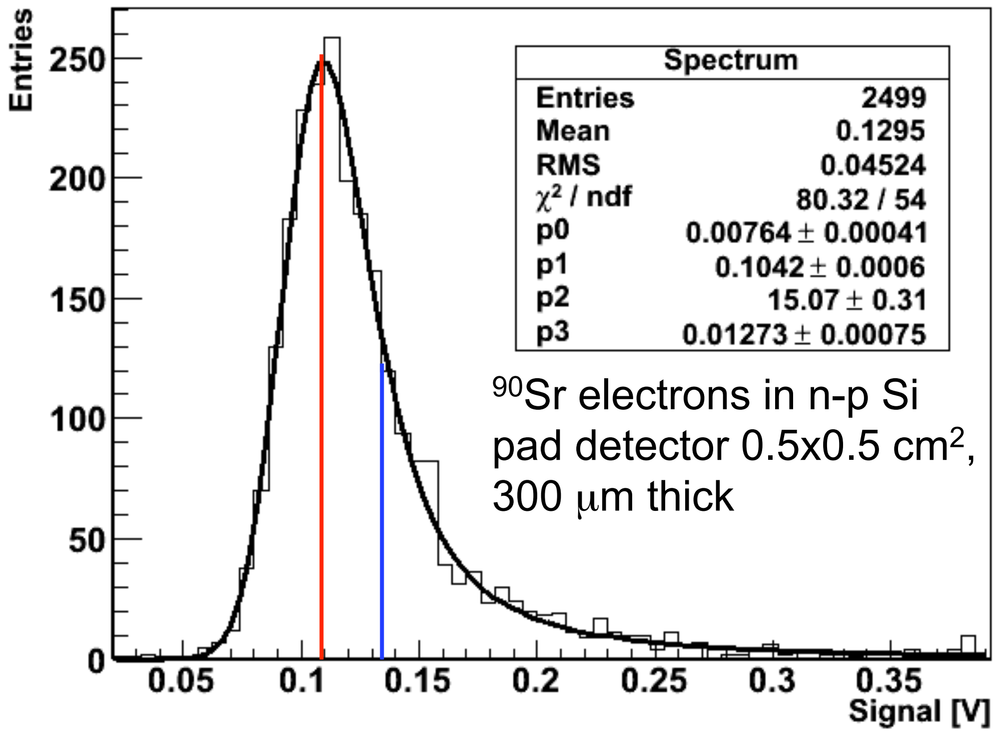


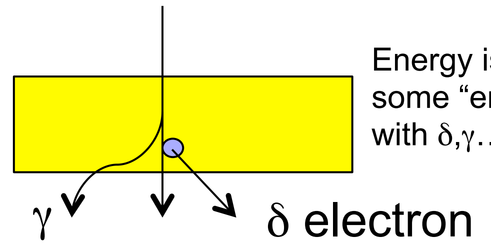




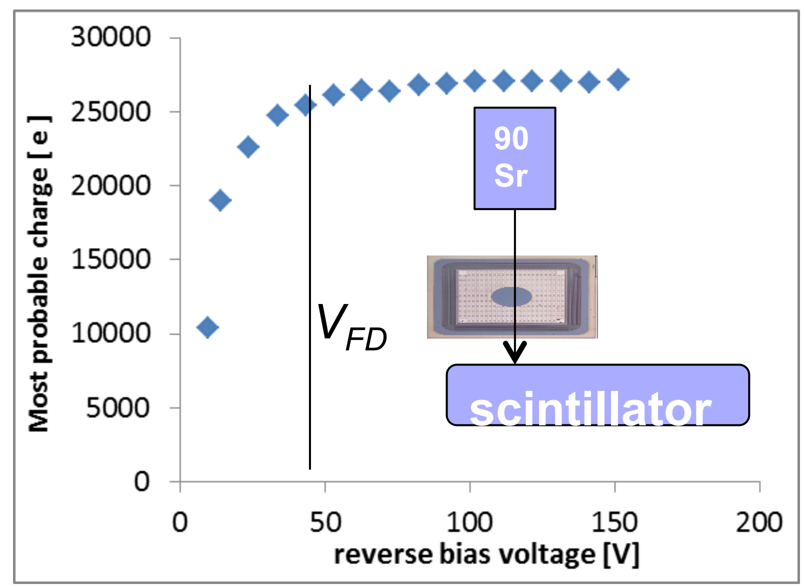
Example : mip particles in Si

Bethe-Bloch – gives only mean energy loss; energy loss distribution – Landau/Vavilov:
Be careful : energy loss is not equal to energy deposited in the material for thin layers!



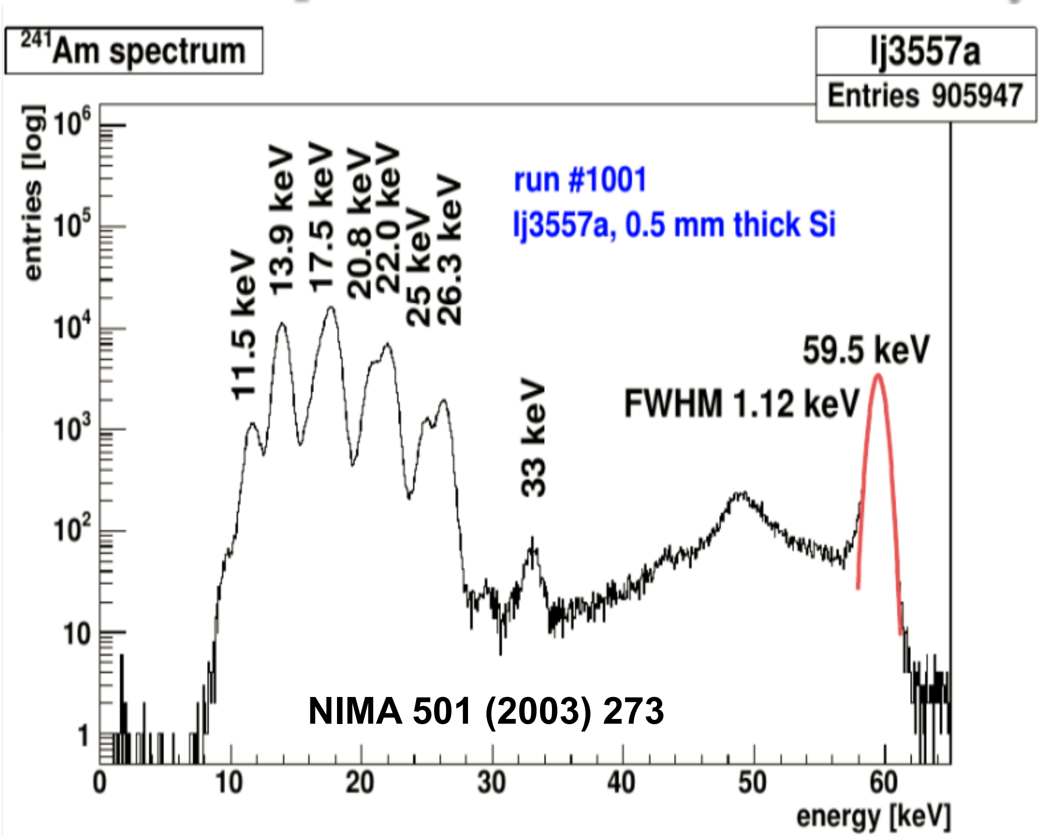


Energy is lost in the Si, but some "energy escaped with δ,γ…



- Mip signal: 72 e/μm, 22600 300μm:
- Medium/mean signal 300 μm: 32400 (~30% higher).

Example : measured γ in silicon

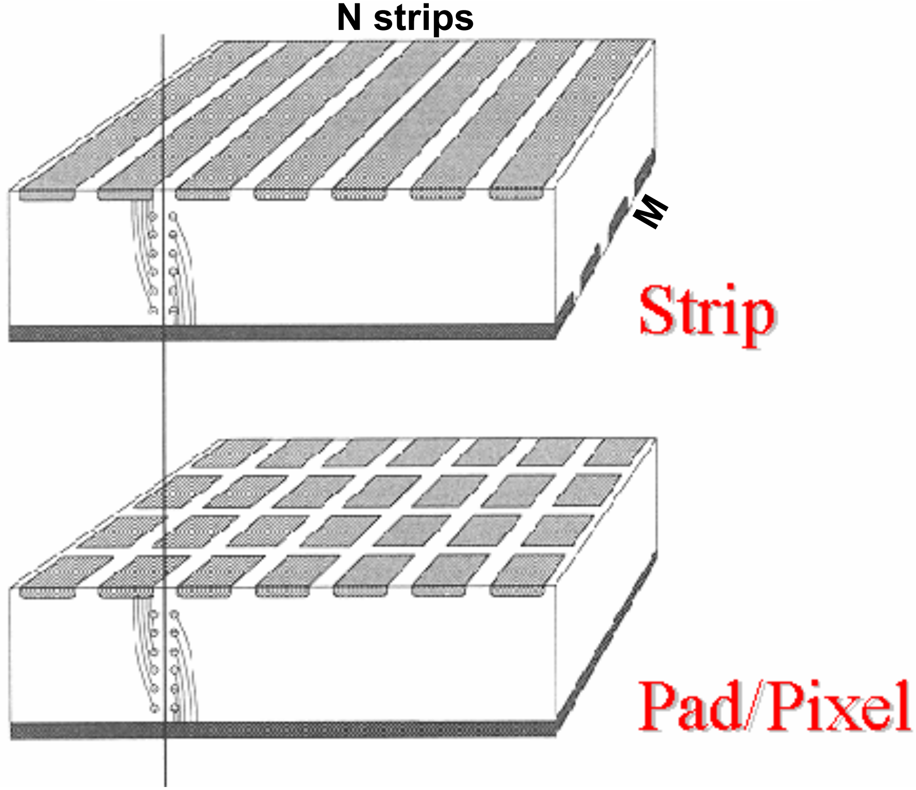


Reconstruction of ^{241}Am spectrum in 0.5 mm thick silicon (macro pixel detectors)

Electrons from photon interactions deposit energy in silicon.

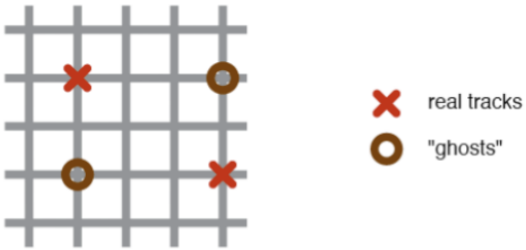
Properties of segmented detectors

2 strip detectors or a double sided detector should be used for position determination



Two main ways of segmenting the detector:
1D = strips (shapes can be more innovative)
2D = pixels

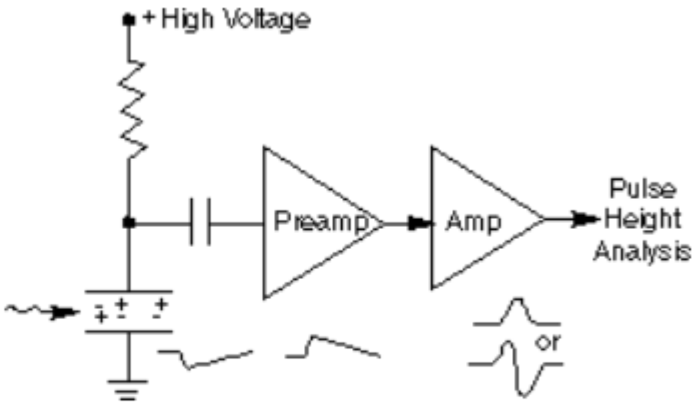
- Strips are not suitable for high rate applications (ambiguous determination for several simultaneous hits)

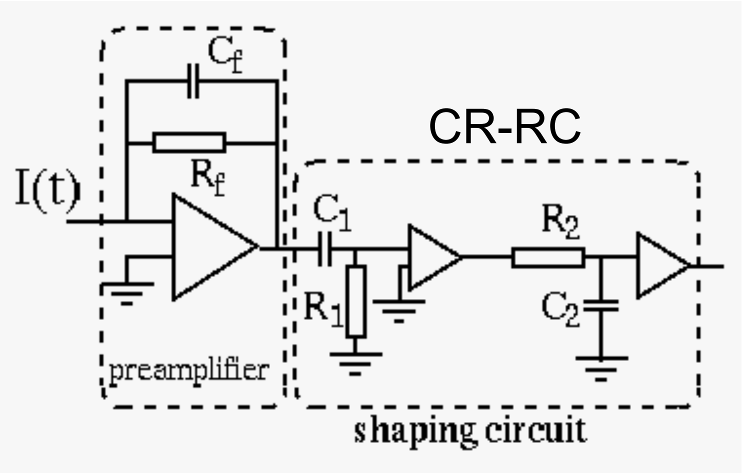


- Number of channels (power consumption, required services…):
  - **Strips : M+N**
  - **Pixels : M·N**

Noise of the detectors

- Semiconductor detectors used for single particle detection are mostly read with charge-sensitive amplifiers followed by pulse shaping circuits to optimize the noise performance



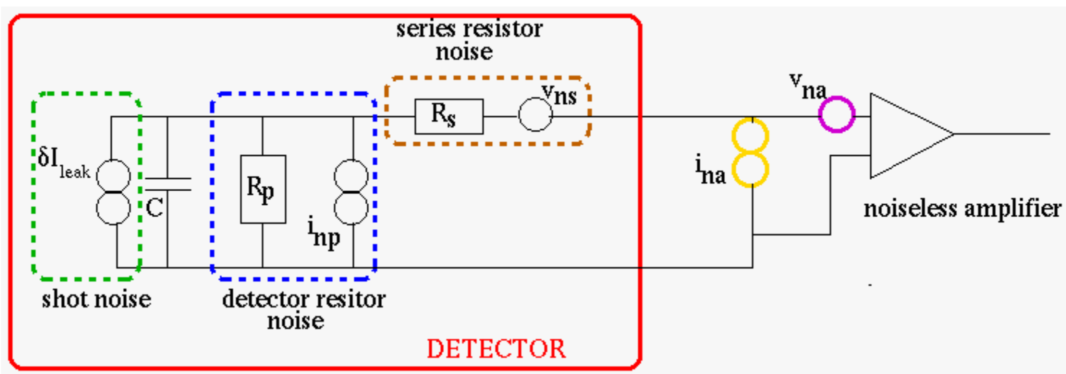


- The most important parameter is Signal-To-Noise ratio (SNR)
- **The noise** in a silicon detector system depends on various parameters: geometry of the detector, the biasing scheme, the readout electronics, etc. Noise is typically given as "equivalent noise charge" ENC. This is the noise at the output of the amplifier given in elementary charges at the input

  ENC=S for S/N=1

Noise of the detectors

- Regarding the origin of the noise from the detector we talk about voltage (series) and current noise (parallel noise)
  - Current noise (i_n = noise current) - independent on detector capacitance
    - shot noise (fluctuations of the free carriers responsible for leakage current)
    - Noise of the resistance in parallel with the detector (bias resistor)
  - Voltage noise (v_n = noise voltage) – increases with detector capacitance:
    - Series resistance noise - ENC_{Rs}



Amplifirer related noise sources

v_{na}, i_{na} = amplifier input noise (1/f noise + white noise) depend on input stage transistor technology as well as on physical limits

Different contributions are independent so they sum in squares

$$ENC^2 = i_n^{\ 2} \cdot T_s \cdot F_i + C^2 v_n^{\ 2} \cdot \frac{F_v}{T_S}$$

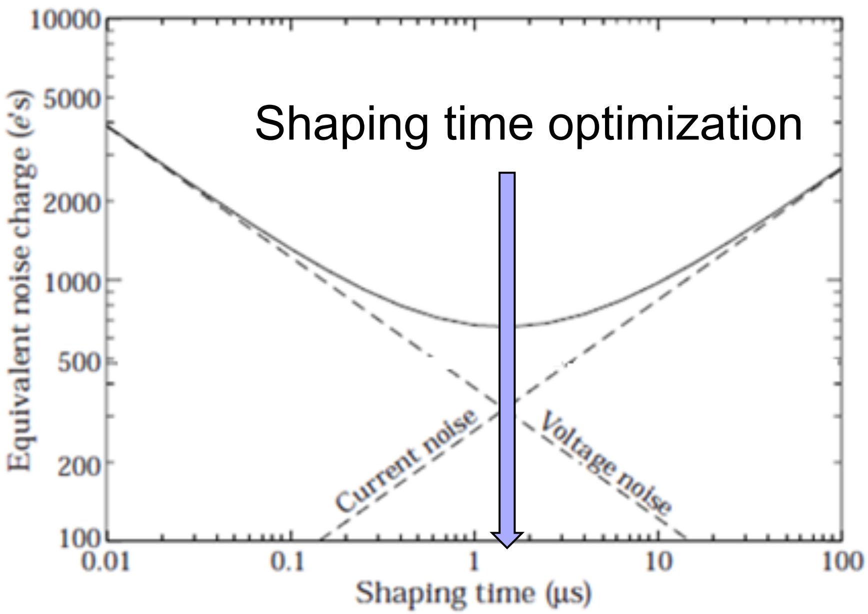
$$ENC^2 = \left(2e_0 I_{leak} + \frac{4k_B T}{R_p} + i_{na}^{\ 2}\right) \cdot T_s \cdot F + \left[4k_B T R_S + v_{na}^{\ 2}\right] C^2 \cdot \frac{F_v}{T_S}$$

- ***T_S*** ~ integration/shaping time
- ***Fi , Fv*** "Shape Factors" that are determined

by the shape of the pulse (bandwidth)

- **C** total capacitance at input ($C=C_A+C_D$)

ENC has a minimum (depends on different contributions)



So ideally to achieve smallest possible noise :

- Low capacitance
- Low leakage current
- High Rp
- Low resistivity of electrodes and routing lines to the electronics
- Good choice of input transistor (technology, T, speed…)
- Optimum shaping:

CR-RC: $F_i = 0.924$ $F_v = 0.924$
CR-(RC)^4: $F_i = 0.45$ $F^v = 1.02$
CR-(RC)^7: $F_i = 0.34$ $F_v = 1.27$

H. Spieler see ref.

❖ Voltage noise is often written as $ENC_s = a + b \cdot C_D$

Here C_A, T_S , $F_{i,v}$ were already taken into account. Parameters of input transistor can be optimized for best *a* and *b* for required application!
Typical values are (amplifier with ~ 1 μs integration time): a ≈ 160 e und b ≈ 12 e/pF.

❖ Current noise is most of the times dominated by shot noise!

semiconductor detectors: ENC~100 e to few 1000 e

Noise spoils efficiency/purity of detection as well as energy, position and time resolution.

Position resolution of segmented detectors

The position resolution is the main parameter of detectors for tracking of imaging systems – superb for semiconductor detectors.

It depends on various factors: device physics and the design of the system.

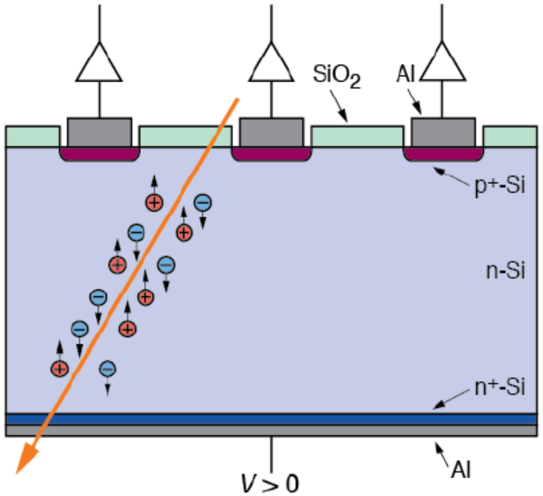
Physics processes:

- Statistical fluctuations of the energy loss : delta rays, depositing large amount of charge locally or escaping the detector
- Diffusion of charge carriers
- Charge trapping

External parameter:

- Binary readout (threshold counter) or read out of analogue signal value
- Distance between strips (strip pitch)
- Signal to noise ratio

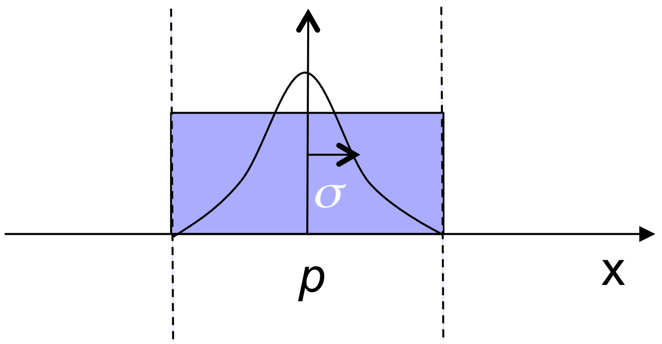
Strip/Pixel charge determines position of the hit



Position resolution of segmented detectors

Binary resolution: detection of hit without any information of the collected charge (worst possible case)

x = strip position
p = strip pitch (distance between strips)



$$\sigma^2 = \frac{1}{p}\int_{-p/2}^{p/2} x^2 dx = \frac{p^2}{12} \Rightarrow \sigma = \frac{p}{\sqrt{12}}$$

Analogue readout – algorithms based on charge measurement

x_i = location of the strip, Q_i=signal at the strip

- centre of gravity of the between strips
- more complex algorithms (eta) taking into account charge collection for various positions

$$x_{hit} = \frac{\sum_{strips} x_i Q_i}{\sum_{strips} Q_i}$$

$$\sigma \propto \frac{p}{S/N}$$

Position resolution : Diffusion

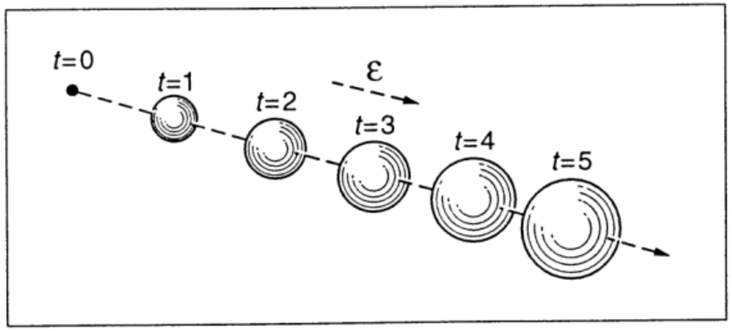
Electrons and holes in the detector move by drift and **diffusion.**

The width (rms) of the charge cloud increases with time *t* as :

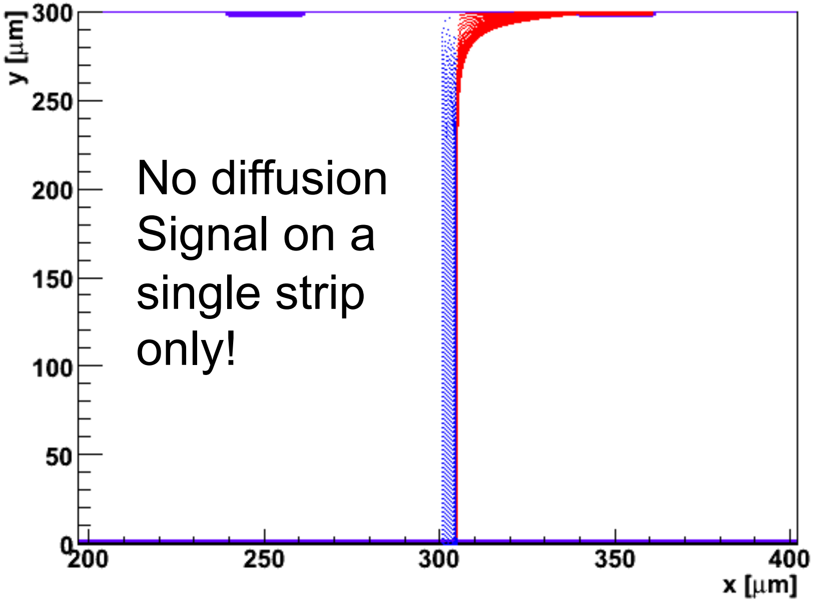
Note: *$D \propto \mu$ and $t \propto 1/\mu$, hence σ_D is equal for e^- and h^+.*

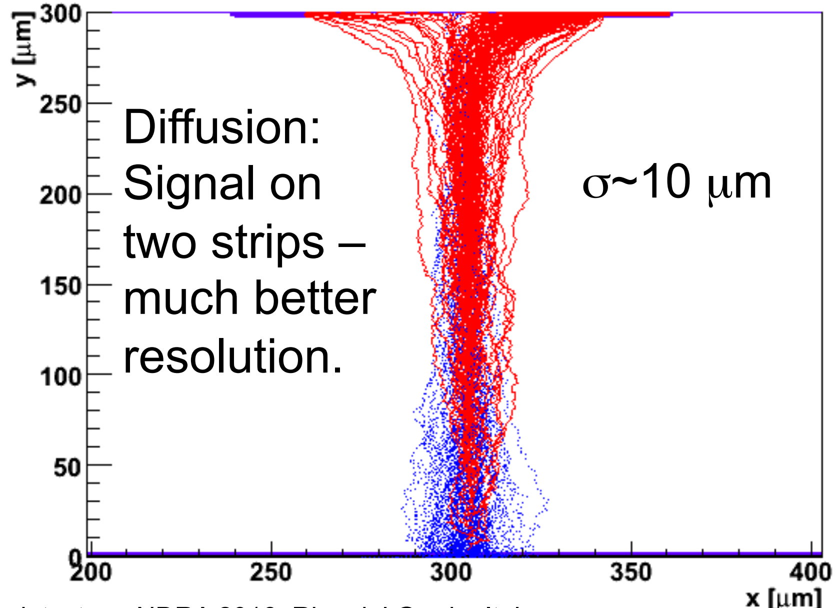
$$\sigma_D = \sqrt{2Dt}$$

$$D = \frac{k_B T}{e_0}\mu$$



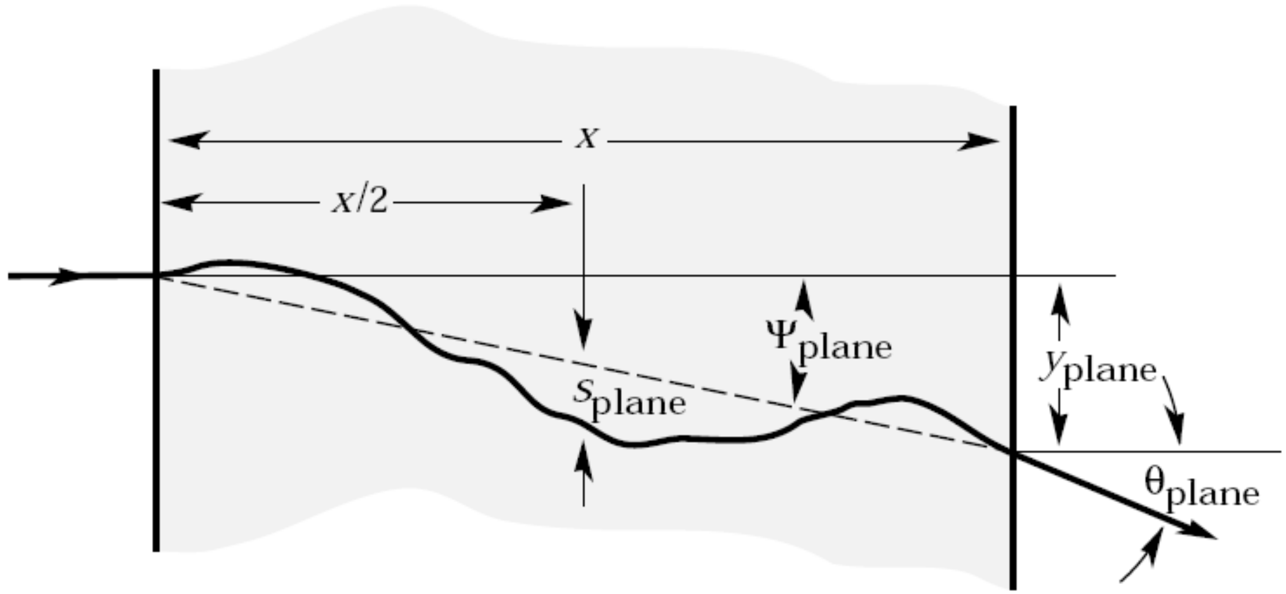
σ_D width of the charge carrier distribution
t **drift time**
D **diffusion coefficient**
k_B Boltzmann constant
T temperature
e_0 electron charge
μ charge carrier mobility





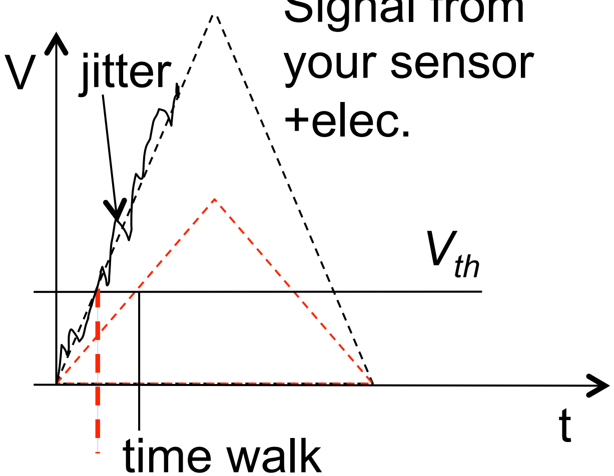
Position resolution : Multiple scattering

Particles don't only loose energy … they also change direction



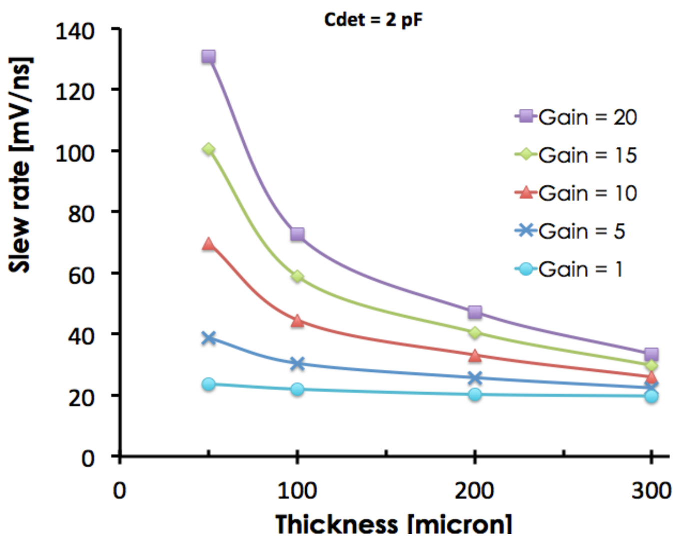
The multiple scattering is more important for light particles – electrons, positrons at smaller energies.

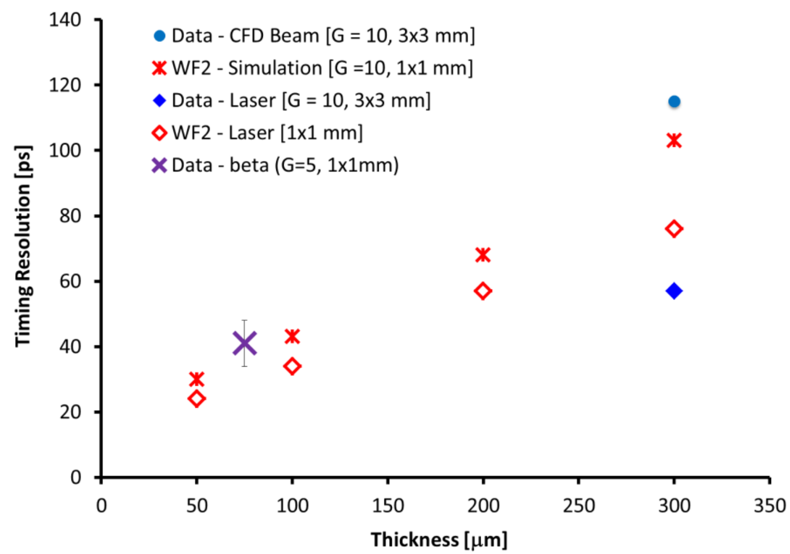
Time resolution



$$\sigma_t^{\,2} = [\frac{V_{th}}{dV/dt}]_{RMS}^{\;2} + [\frac{N}{dV/dt}]_{RMS}^{\;2} + [\frac{TDC_{bin}}{\sqrt{12}}]^2$$

↑ time walk — ↑ noise jitter — ↑ TDC





Energy resolution of detectors

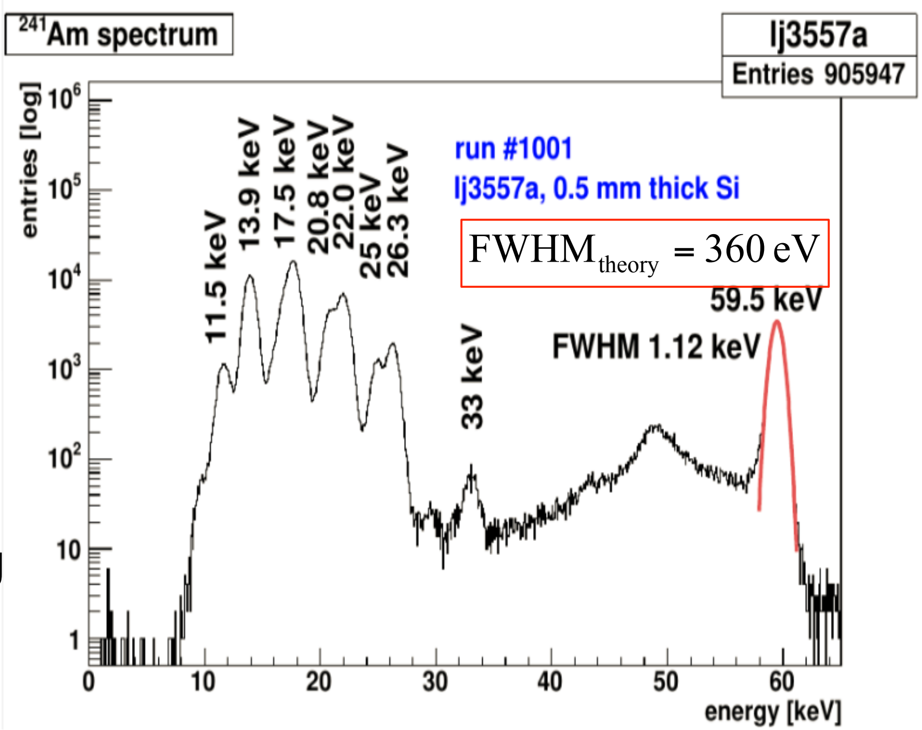
Energy resolution is determined by

Physics processes:

- Statistical fluctuations of the deposited energy
  - Fano factor
  - Delta rays or converted particles leaving detector (γ,n)
  - Other physics processes (e.g. Doppler broadening for Compton)
- Incomplete carrier collection (weighting field plays a crucial role)
  - Charge trapping of carriers
  - Low mobility of carriers
  - Limited integration times

Electronics and readout:

- Noise of the readout
- Charge clustering algorithms related to diffusion of charge carriers



Theoretical limit:

$$\frac{\delta E}{E} = 2.35 \frac{\sqrt{F I_0}}{\sqrt{E}}$$

Fano factors:

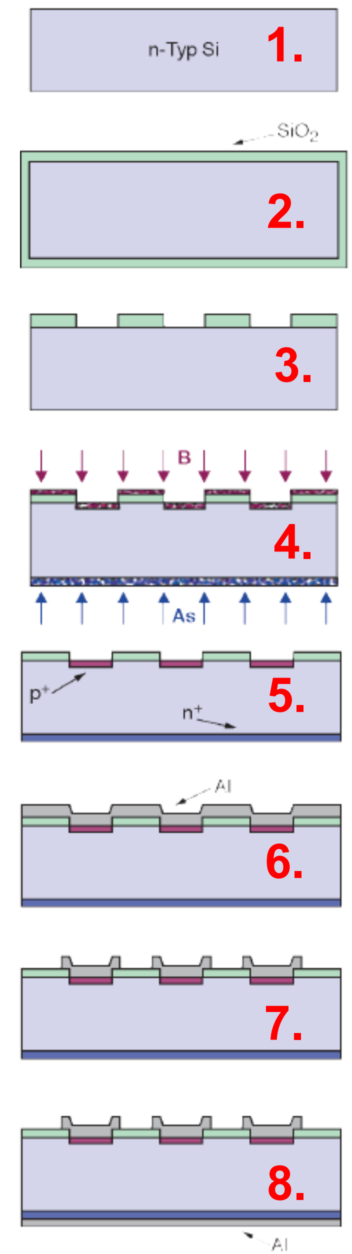
Si = 0.11

CdZnTe= 0.09

Diamond=0.08

Various silicon detector structures

Fabrication of a silicon detector

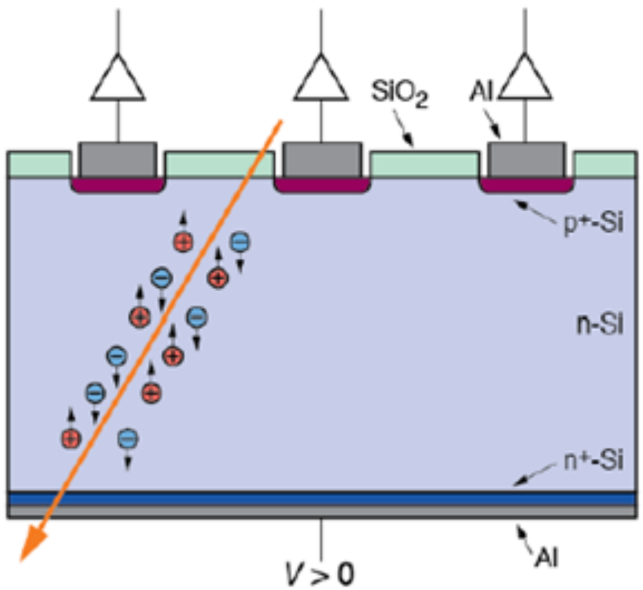


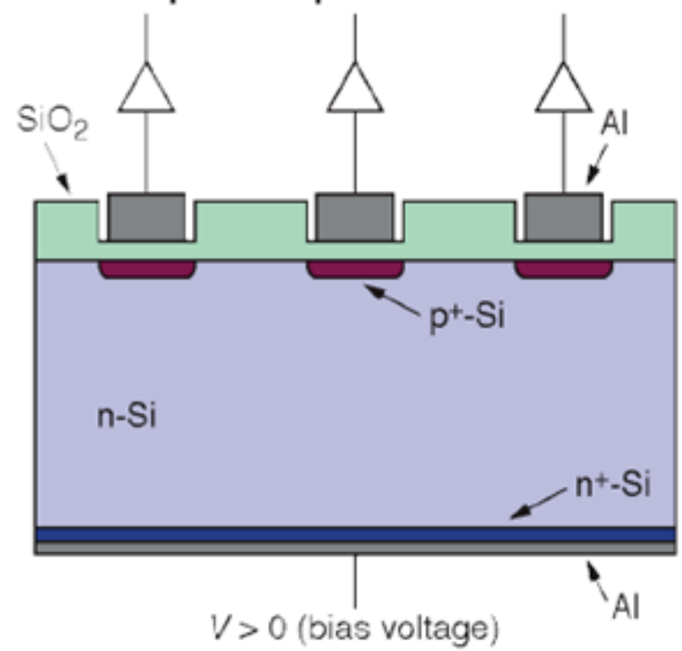
1. Starting Point: single-crystal n(p)-doped wafer ($N_D \approx 1–5 \cdot 10^{12}$ cm^{-3})
2. Surface passivation by SiO_2-layer (approx. 200 nm thick). E.g. growing by (dry) thermal oxidation at 1030 °C.
3. Window opening using **photolithography technique with** etching, e.g. for strips
4. Doping using either
- Thermal diffusion (furnace)
- Ion implantation (p^+-strip: Boron, 15 keV, $N_A \approx 5 \cdot 10^{16}$ cm^{-2}; Ohmic backplane: As, P, 30 keV, $N_D \approx 5 \cdot 10^{15}$ cm^{-2}.

5. After ion implantation: Curing of damage via thermal annealing at approx. 600°C, (activation of dopant atoms by incorporation into silicon lattice)
6. Metallization of front side: sputtering or CVD
7. Removing of excess metal by photolithography: etching of non-covered areas
8. Full-area metallization of backplane with annealing at approx. 450°C for better adherence between metal and silicon
Last step: wafer dicing (cutting)

This example: DC coupled micro-strip detector.

Silicon strip detectors



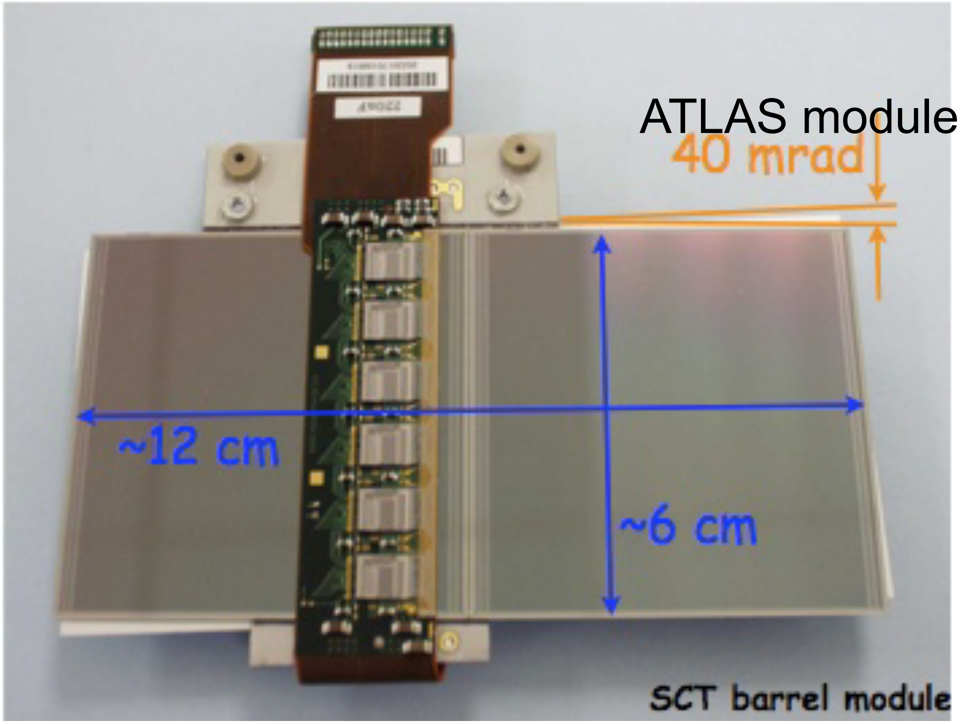


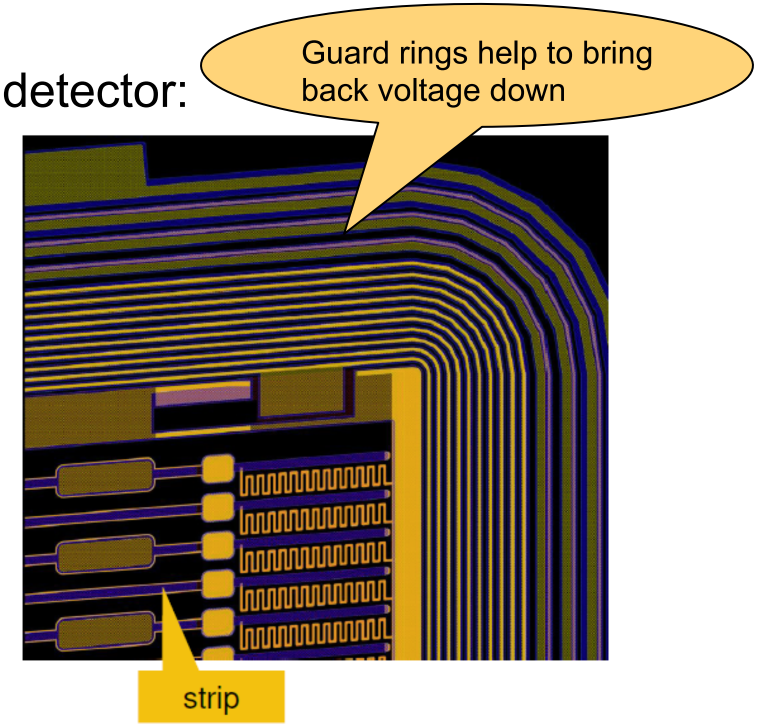
- p-n junction (or n-p junction)
- *Na* ≈ 10^{15} cm-3, *Nd* ≈ 1–5·10^{12} cm^{-3} (vice versa for n-p type detector)
- n-type bulk: ρ > 0.5 kΩcm

  p-type bulk: ρ >2 kΩcm ➔ thickness <1 mm !
- Operating voltage up to 1000 V
- Highly doped layer n^+ (p^+) on backplane to improve ohmic contact!

- Strips AC coupled:
  - Capacitors integrated in the process (SiO_2 and or Si_3/N_4)
  - Electronics doesn't have to sink current
- Implants connected over long and highly resistive poly-silicon resistor (or FET) to ground

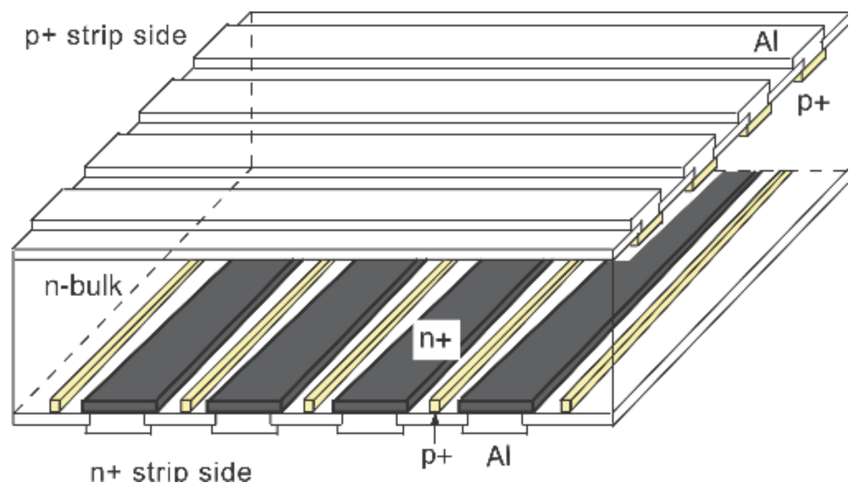
ATLAS module strip detector:



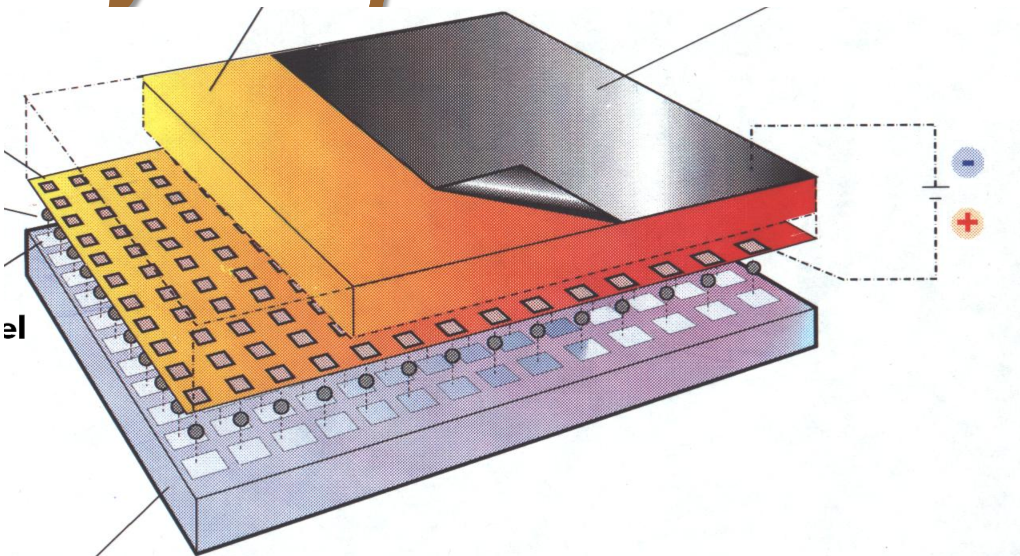


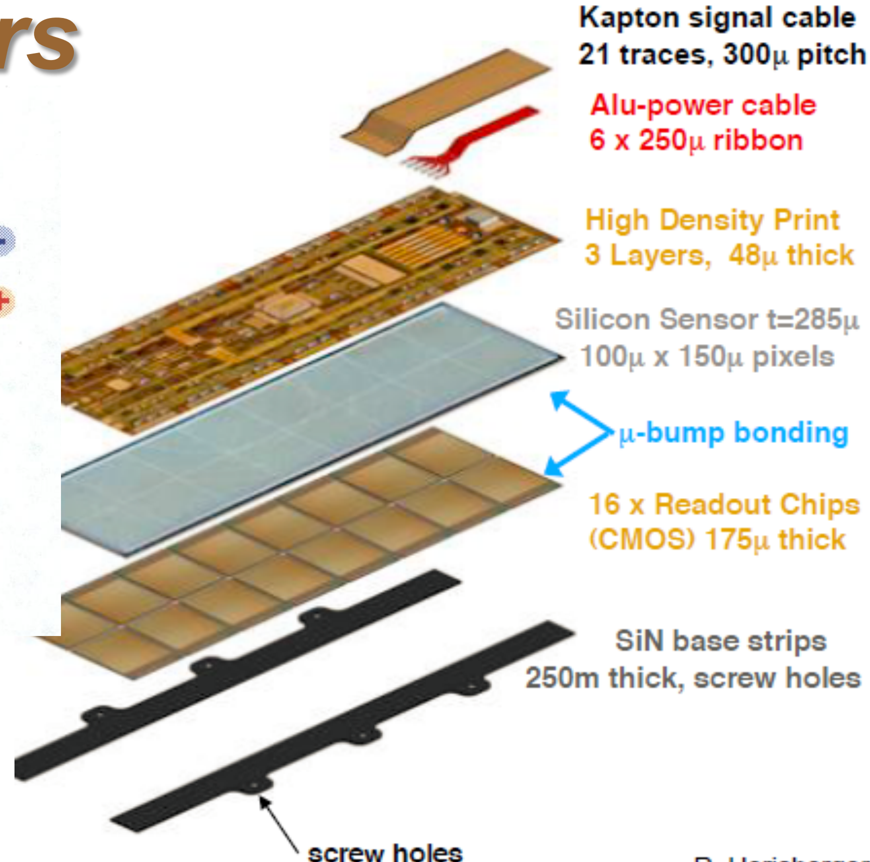
Double sided strip detectors:

- AC coupling is mandatory on one side to separate HV bias from LV input to the amplifiers (usually ohmic side)
- n^+ electrodes need to be isolated p^+ implant
- Double sided processing – high cost

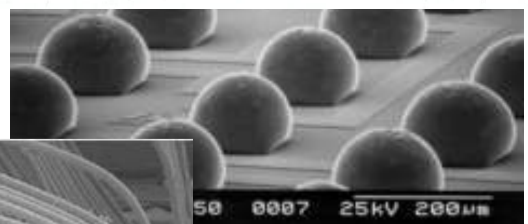


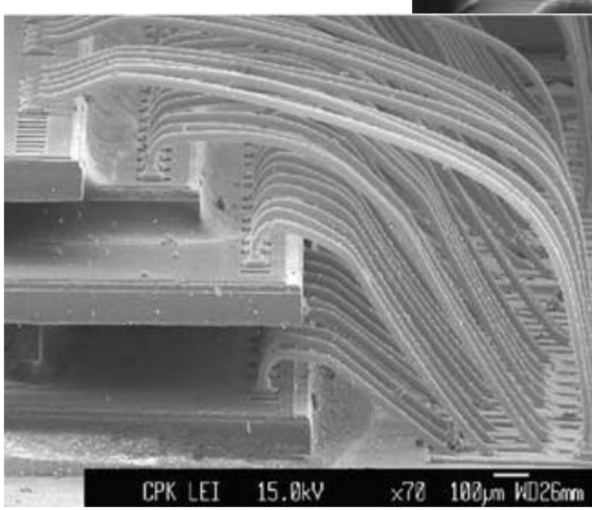
Hybrid pixel detectors

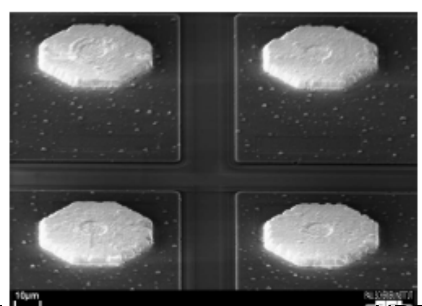


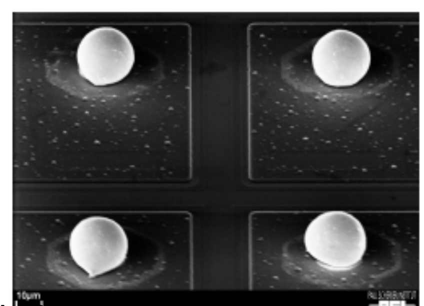


R. Horisberger

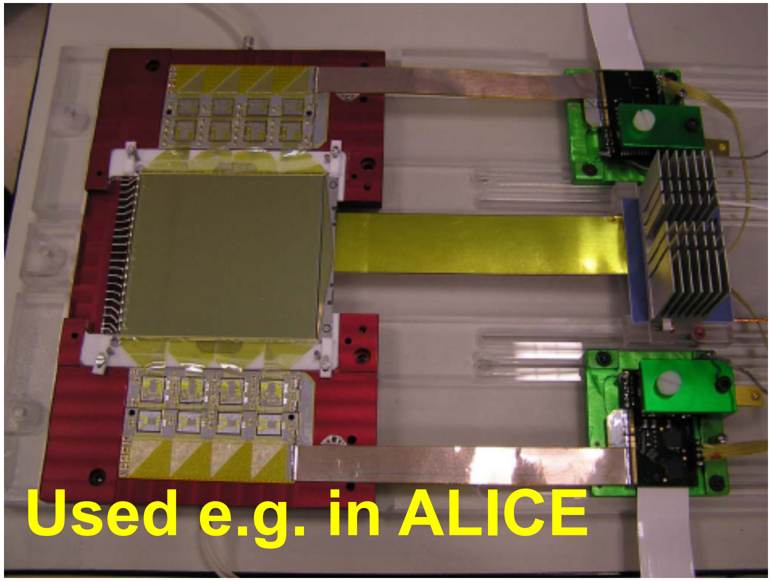








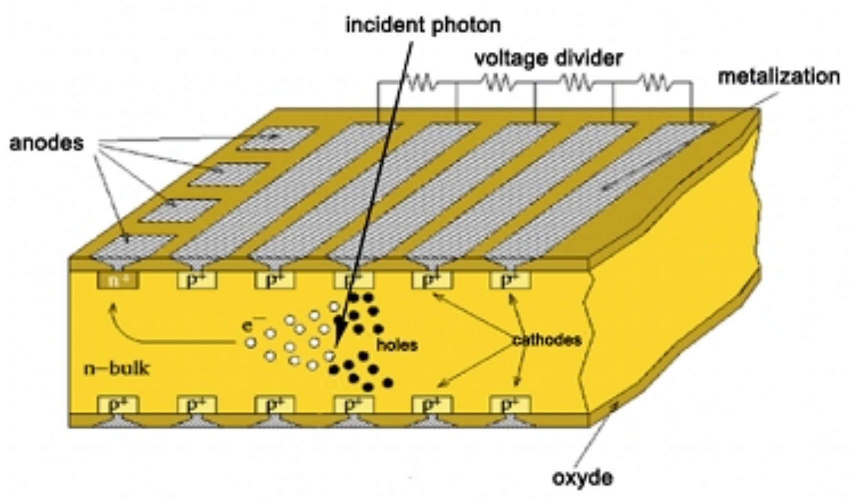
Silicon drift detector

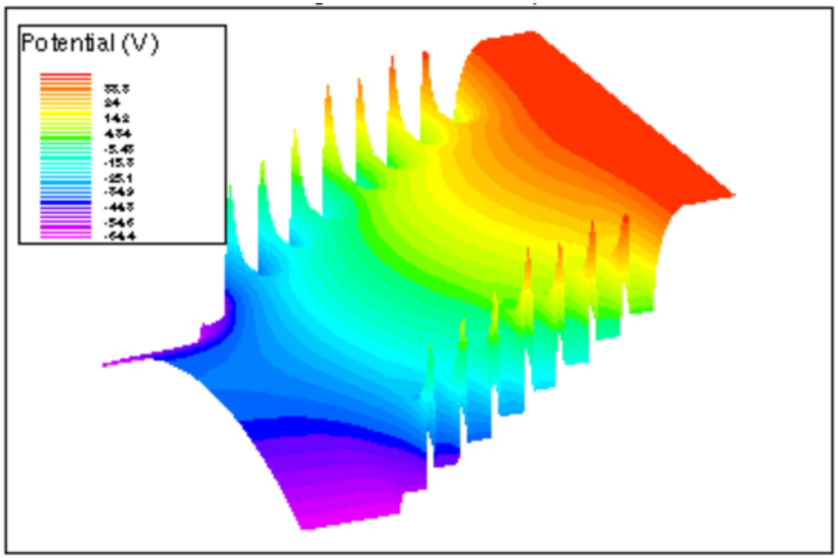


- Very low noise of down to few e : small anode capacitance
- Determination of both coordinates by using also time of arrival with small number of readout channels (anode readout)
- No extra material in the active area!

BUT

- … relatively slow (drift speed ~1 cm/μs)

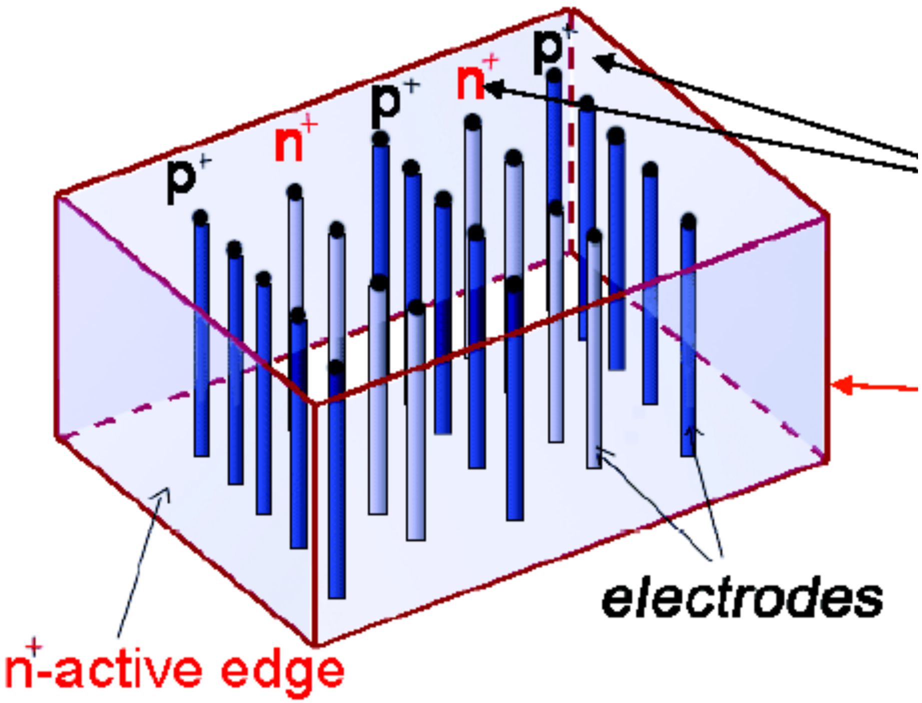




3D detectors

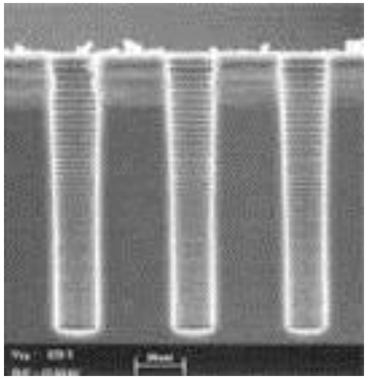
Columns: 10 μm
Pitch: 50 - 100 μm

Combine traditional VLSI processing and MEMS (Micro Electro Mechanical Systems) technology.



Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.

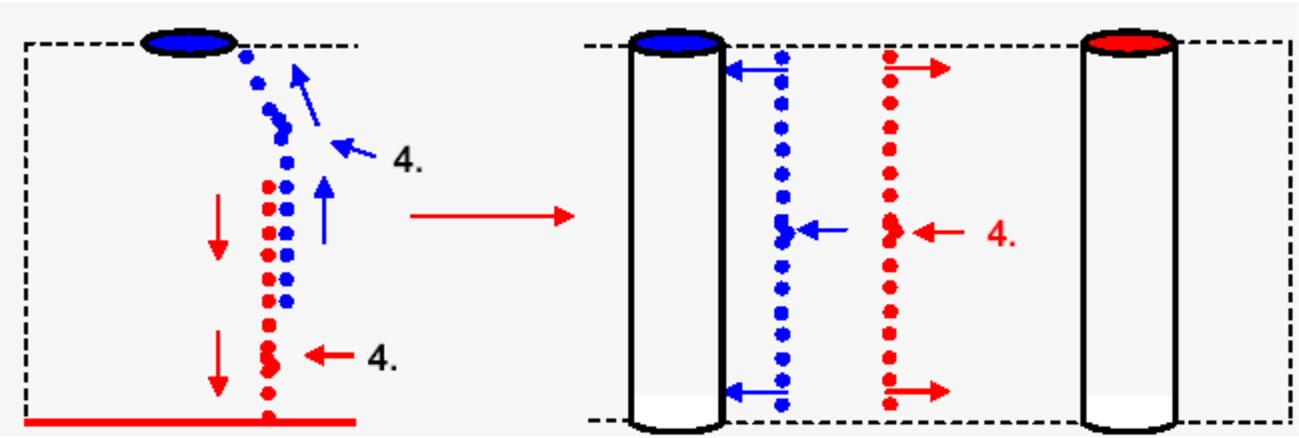
The edge is an electrode. Dead volume at the Edge < 5 microns! Essential for forward physics experiments and material budget



S.I. Parker, C.J. Kenny, J. Segal, Nucl. Instr. and Meth. A395 (1997) 328.

State of the art : first implemented in HEP experiment :
CNM and FBK production for the ATLAS-IBL

3D detectors



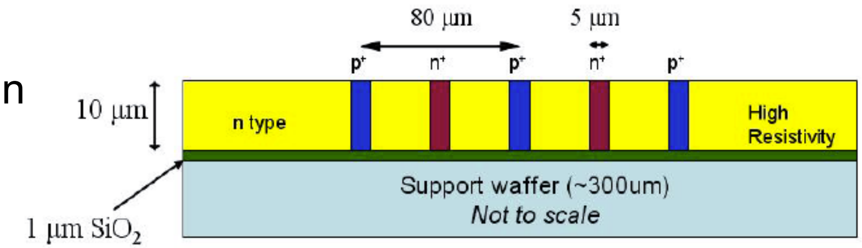
Pros.
•Better charge collection efficiency
•Faster charge collection (depends on inter-column spacing)
•Reduced full depletion voltage and by that the power
•Larger freedom for choosing electrode configuration

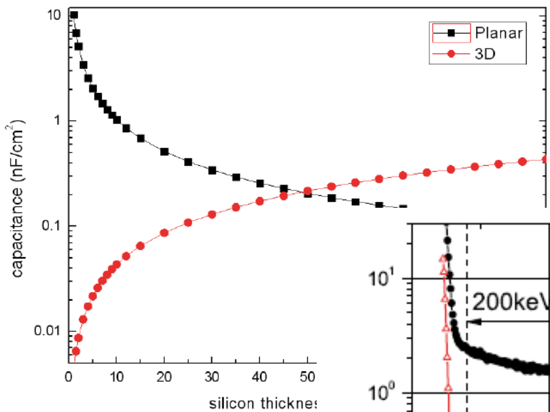
Cons.
•Columns are dead area (aspect ratio ~30:1)
•Spatially non-homogenous CCE (efficiency=function of position)
•Much higher inter electrode capacitance (hence noise), particularly if small spacing is desired, but it decreases with thickness
•Availability on large scale
•Time-scale and cost

3D and thermal neutron detection

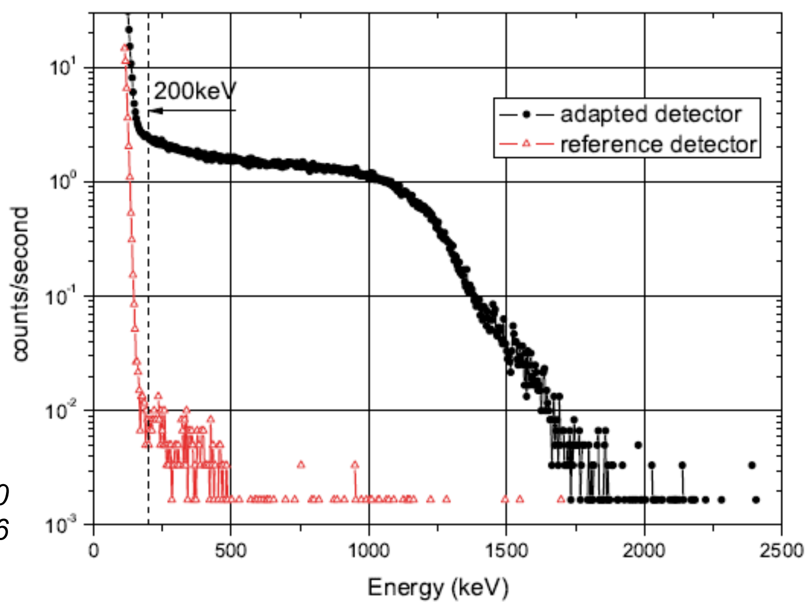
Unlike for planar detectors the capacitance is smaller for thin sensors (remember low capacitance is crucial to achieve good noise performance, hence energy resolution) !
Thin sensors are needed for good detection of α after conversion and high rejection of γ at the same time !

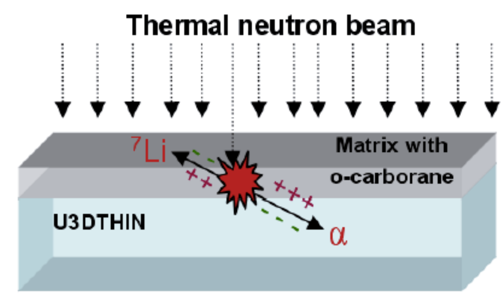
1st run: $C_2B_{10}H_{12}$
2nd run: 3 μm B_4C – full wafer coverage (PVD on whole wafer is possible)

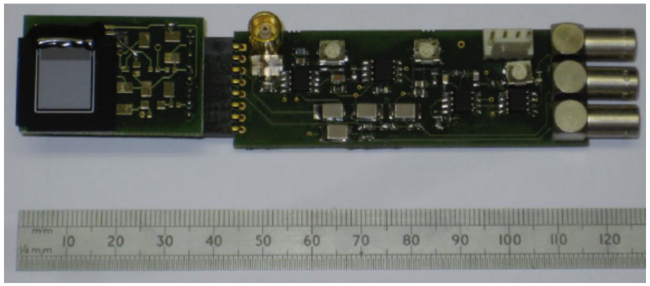




~2% detection efficiency



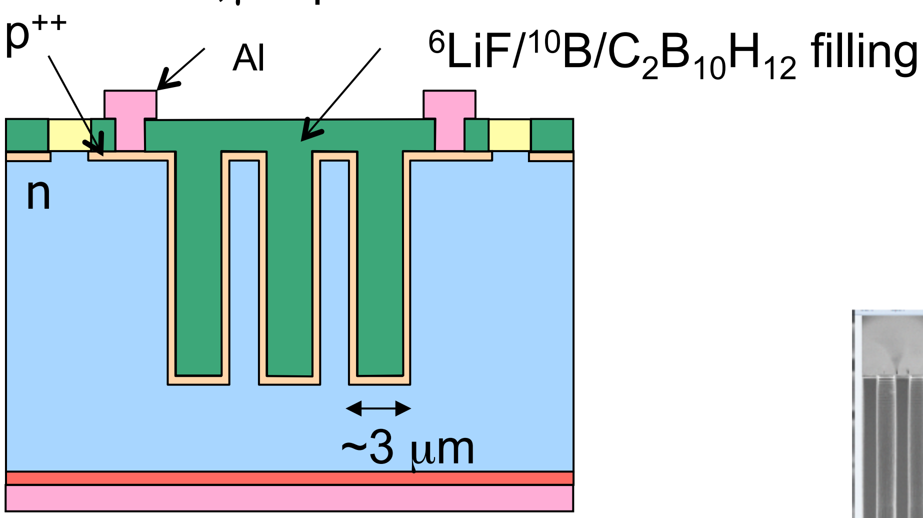


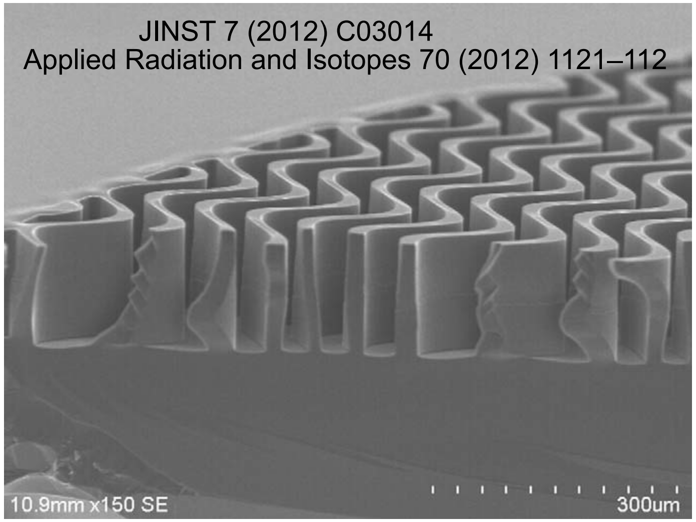


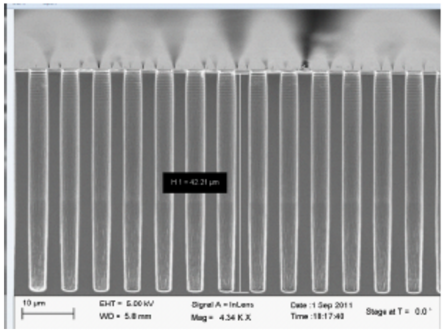
CNM Barcelona
JINST 9 (2014) P04010
JINST 7 (2012) P03006

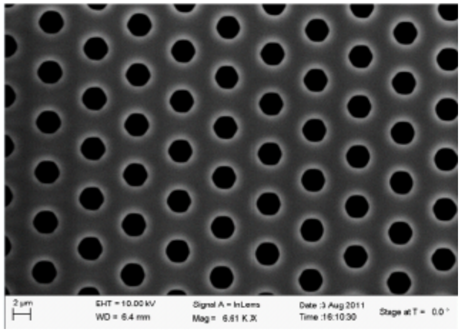
3D trench detectors – perforated neutron detectors

- Normal incidence intrinsic efficiency of ~40%
- **Can be made position sensitive**
- Careful design of the trenches needed to optimize for:
  - Capacitance
  - Electric and weighting field (signal)
  - Conversion efficiency
- Good n,γ separation



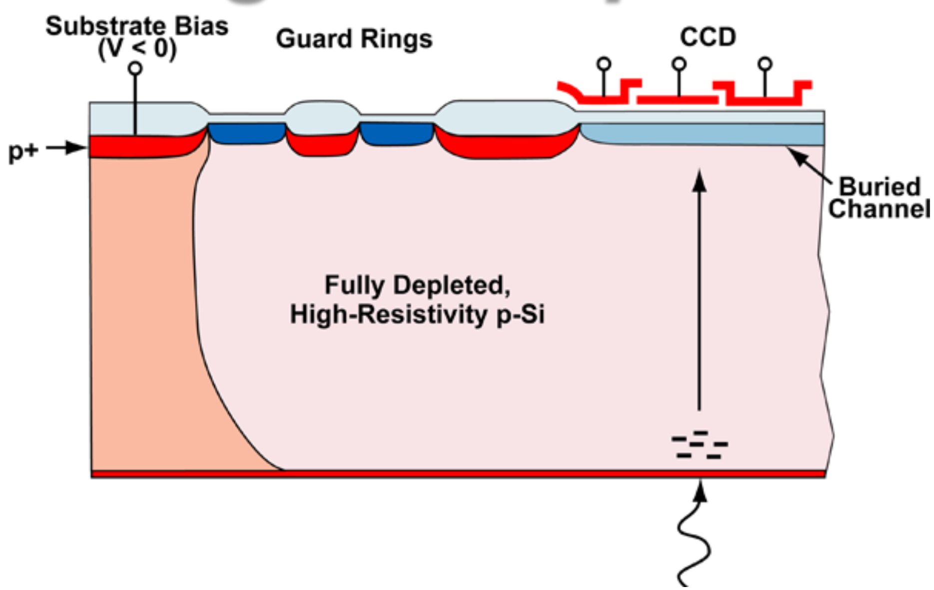






See HYDE FBK-INFN project

Charged Coupled Devices



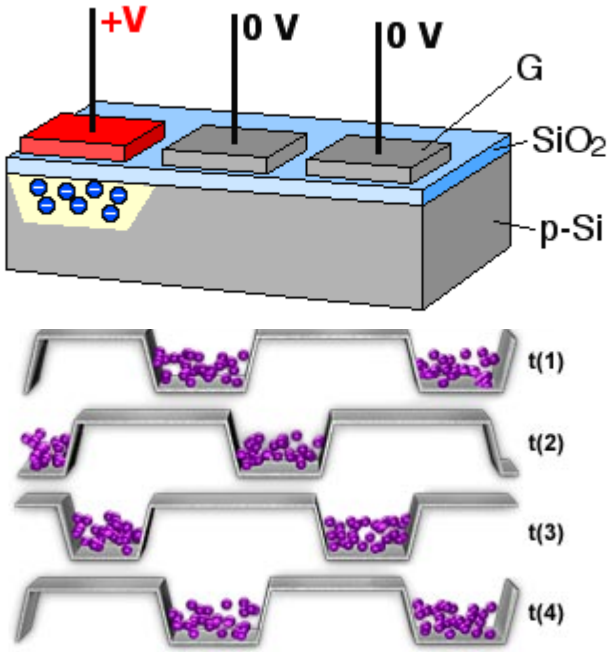
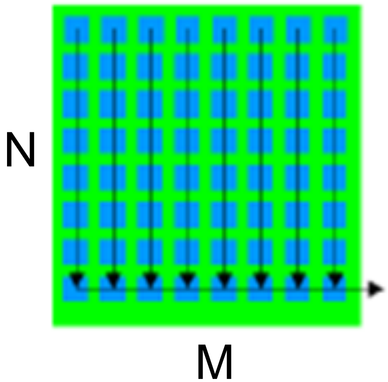


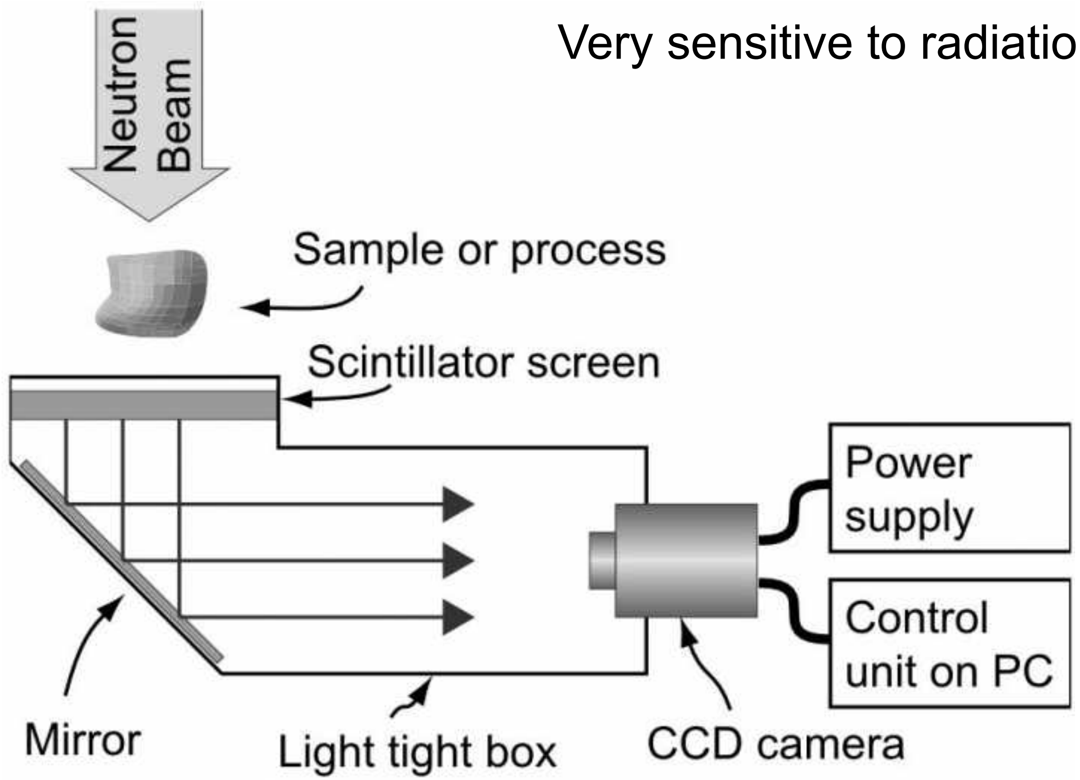
Figure 1

- Depletion depth depends on type:
  - Fully depleted (particle detection)
  - Depleted only few μm underneath the electrode (optical light detection) – fill factor <100%
- Clock pulses used create potential minimum and shift collected charges
- A single signal readout channel (vertical and horizontal shifting), but relatively slow (NxM shifts)
- Very low noise – up to few e



CCD are often implemented to detect light from other neutron converters (scintillators)!

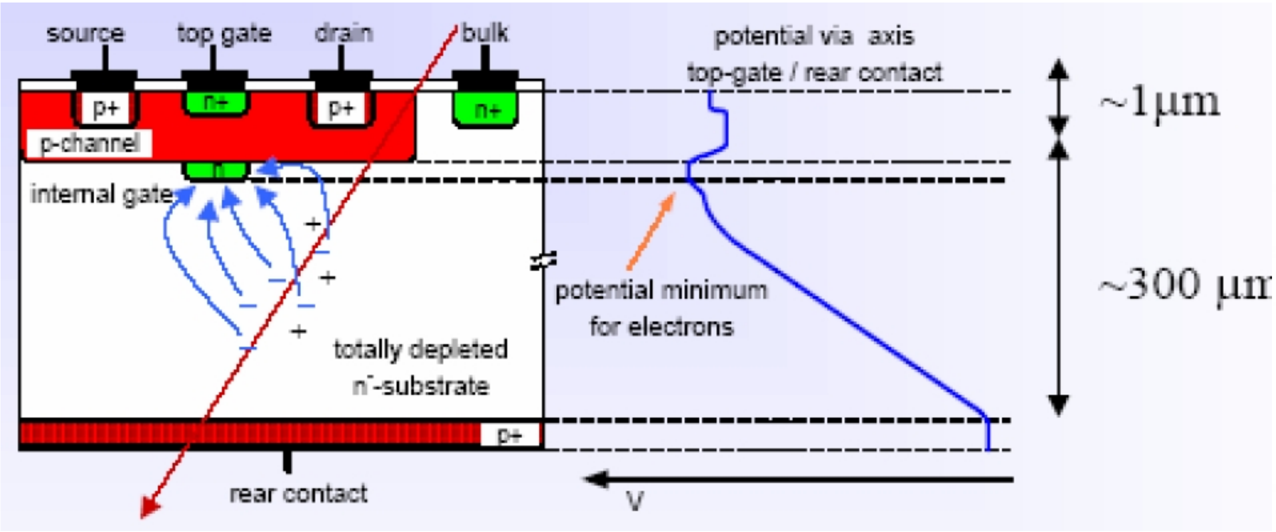
Charged Coupled Devices

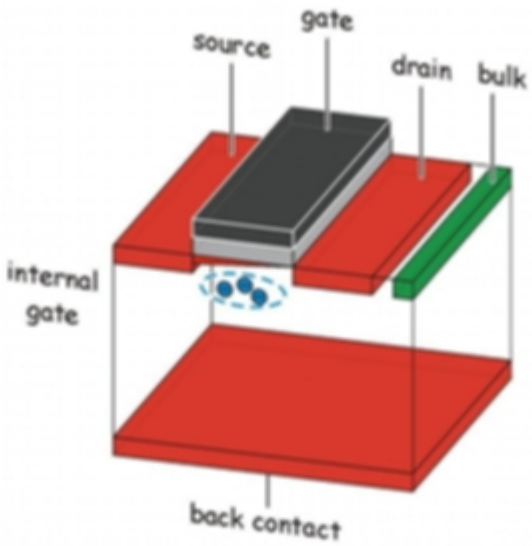


Very sensitive to radiation damage.

CCD are often implemented to detect light from other neutron converters (scintillators)!

DEPFET Pixel Detectors





- detector has internal amplification (FET transistor incorporated)
- Basically a fully depleted p-n detector with charges collected by n electrode modifying the FET channel and its current.
- An active clear is necessary to remove the electrons.

- Very low noise of only up to few e
- Very fast (collection by drift)
- Large signals so excellent S/N
- Pixels of ~50x50 μm^2 possible

Used in astronomy
Particle physics

Monolithic Active Pixels & HVCMOS

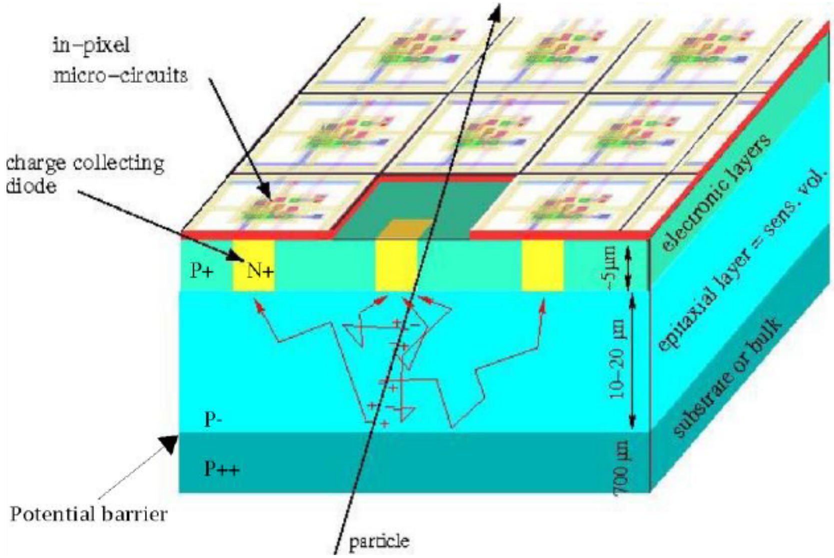
MAPs, **standard CMOS processing**. Active pixel cell with an NMOS transistor. The N-well collects electrons from both ionization and photo-effect.

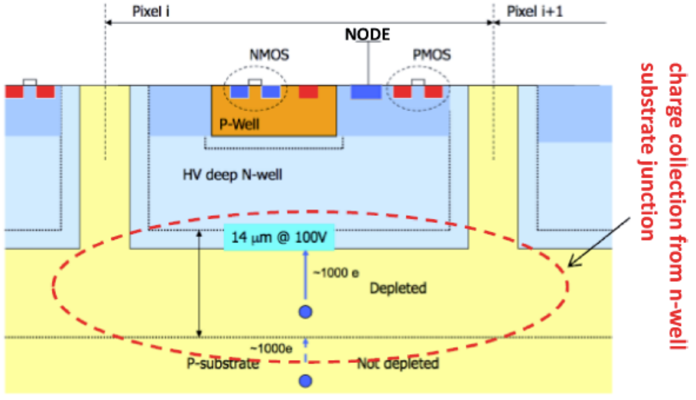
Similar to CMOS imagers for light detection, but with 100% fill factor

- Sensitive layer ~10-20 μm which gives few 100 e for mip
- Very low noise few 10 e (small pixels)
- Integrated electronics

BUT …

- Not radiation hard – collection by diffusion
- Not very fast
- Technology restrictions (epitaxial layer, metal layers)





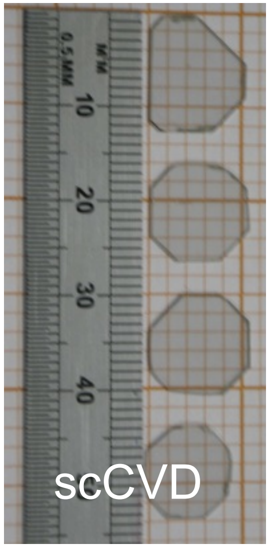
New detector technology – HVCMOS – drift becomes dominant the "buts" above disappear ….

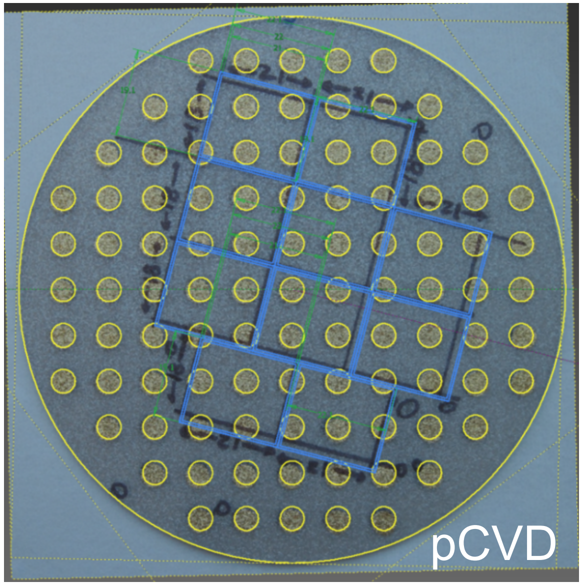
Other semiconductor detectors

(by for not all of them)

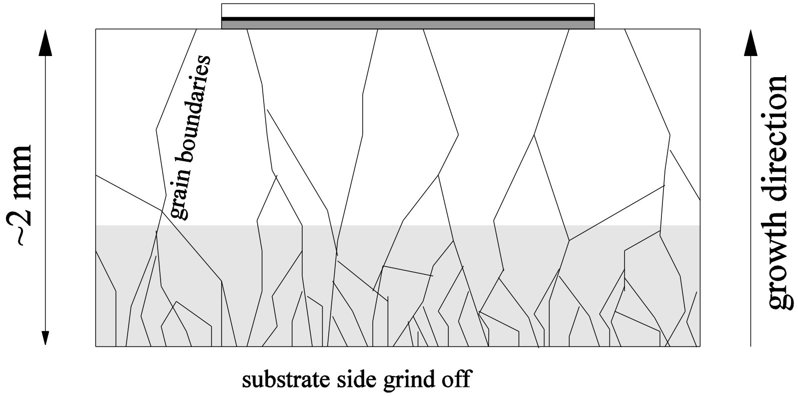
Other semiconductors-CVD diamonds

- Detector grade polycrystalline diamonds are grown with CVD technique
  - **scCVD diamonds 5x5x0.5 mm^3 are state of the art**
  - **Polycrystalline can be very large 8" wafers up to 2 mm thick**
- Ohmic contacts are used – no processing put electrodes on, apply electric field (reusable material!) (very larger resistivity , E_g=5.5 eV)
- Diamond detectors are direct competition to silicon with advantages: faster, lower dielectric constant, best heat conductance, low/non-existing leakage current, but smaller signal (13 eV/e-h pair are required)
- E_g/k_BT = long de-trapping times, polarization effects, takes time to settle





Surface preparation and metallization are non-trivial and crucial for operation



Other semiconductors–CVD diamonds

- pCVD : charge collection is usually parameterized with charge collection distance CCD

$$CCD = \frac{<Q_{col}>}{36\,\frac{e_0}{\mu m}}$$

$$CCD \sim \lambda_e + \lambda_h = (\mu_e \tau_e + \mu_h \tau_h) E$$

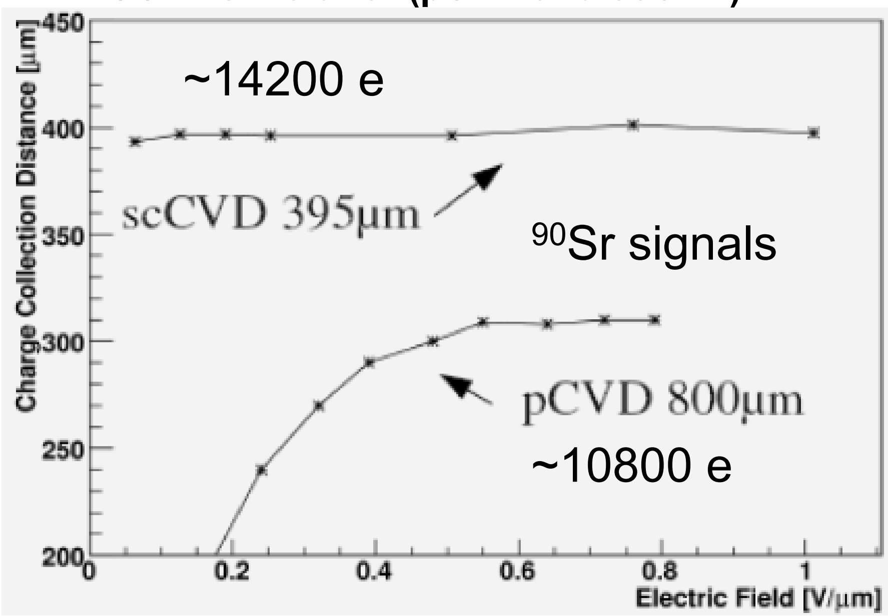
Holds only for *CCD* < thickness

λ = mean free path

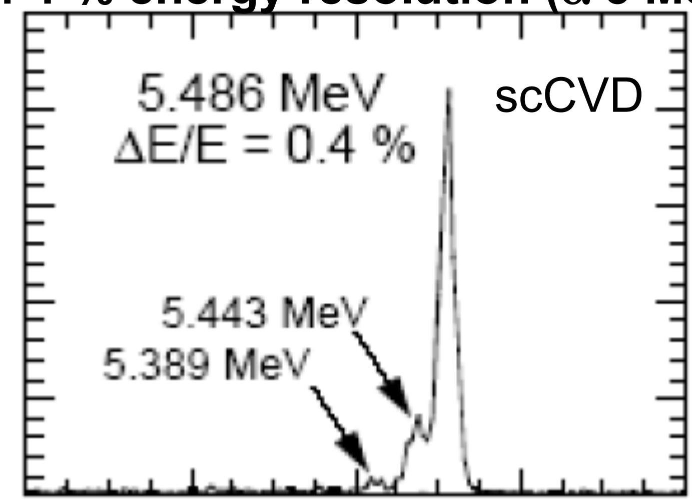
$<Q_{col}>$ = mean collected charge

Main reason for smaller signal : trapping on grain boundaries (pCVD) and in bulk much like in heavily irradiated silicon

***CCD* vs. field for (pCVD and scCVD)**



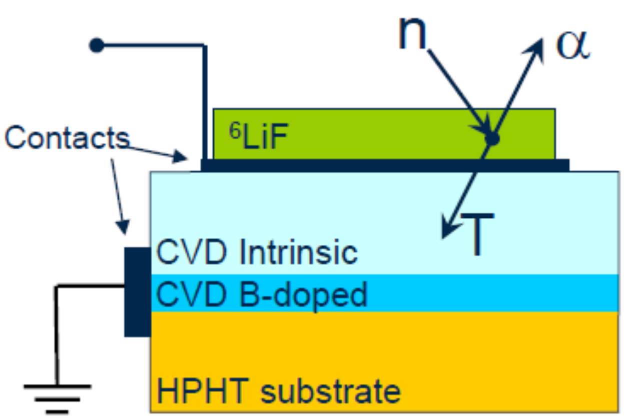
- **100 % charge collection efficiency**
- **100 % counting detection efficiency**
- **0.4-1 % energy resolution (α 5 MeV)**



J.H. Kaneko et al. 2003

Neutron detection with scCVD diamond

Thermal Neutrons

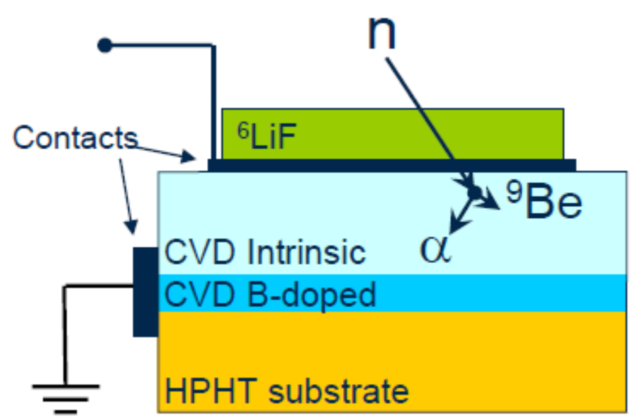


neutrons interact with ^{6}Li in the 95% enriched ^{6}LiF layer:

$n + {}^{6}Li \rightarrow Tritium + \alpha + 4.8$ Mev

T (2.73 MeV) and α (2.06 MeV) are emitted at 180°, so only either the T or the α particle is detected

Fast Neutrons



neutrons directly interact with ^{12}C in the diamond sensing layer:

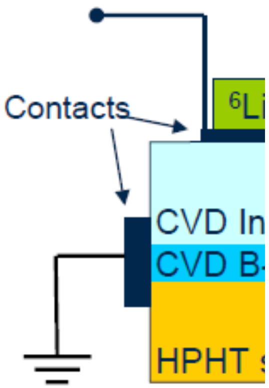
$n + {}^{12}C \rightarrow \alpha + {}^{9}Be - 5.7$ MeV

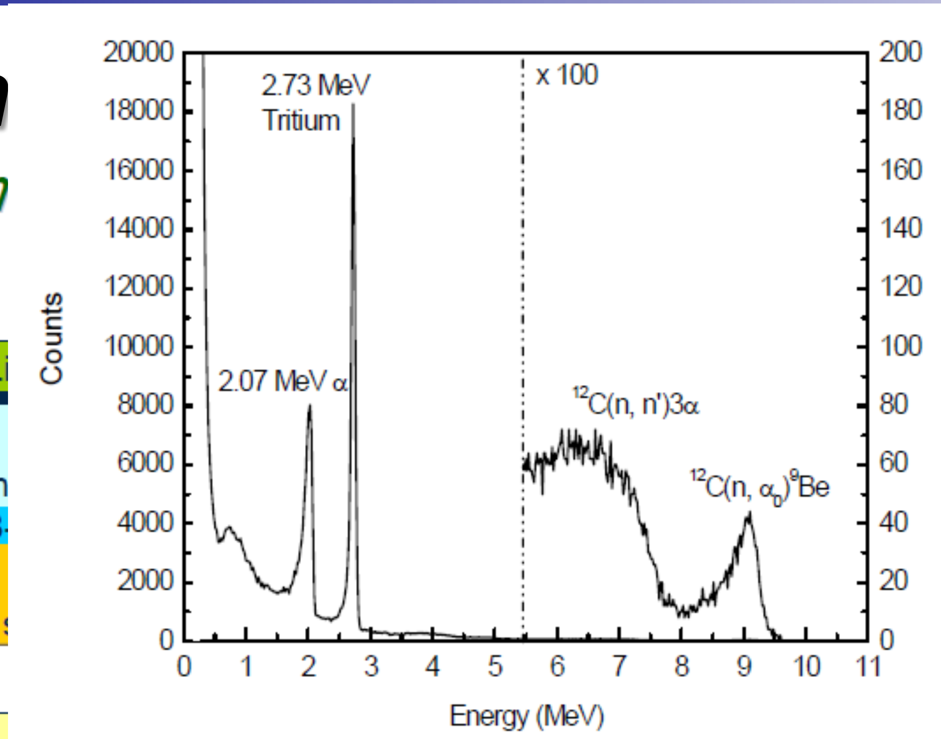
(for 14.1 MeV neutrons) with α and Be having a total energy of 8.4 MeV

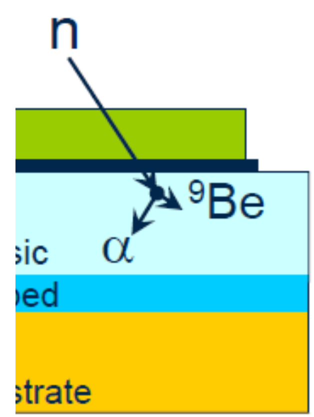
Single crystal CVD diamond neutron detectors in a p-type/intrinsic/metal layered structure - Gianluca Verona-Rinati, Uni Roma Tor Vergata

Neutron … D diamond

Thern … leutrons







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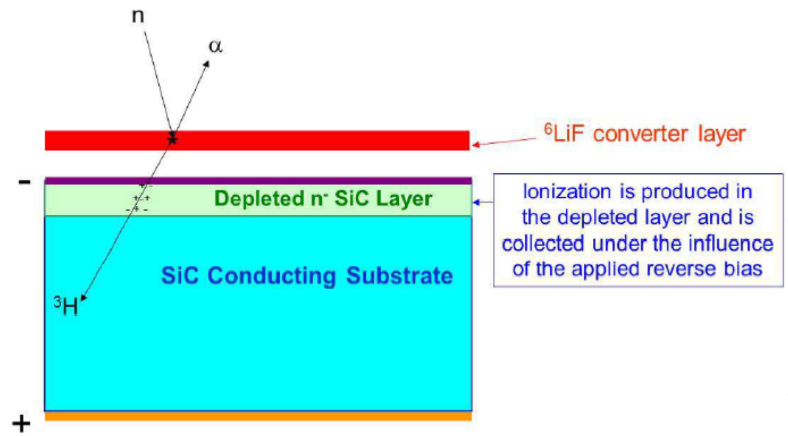
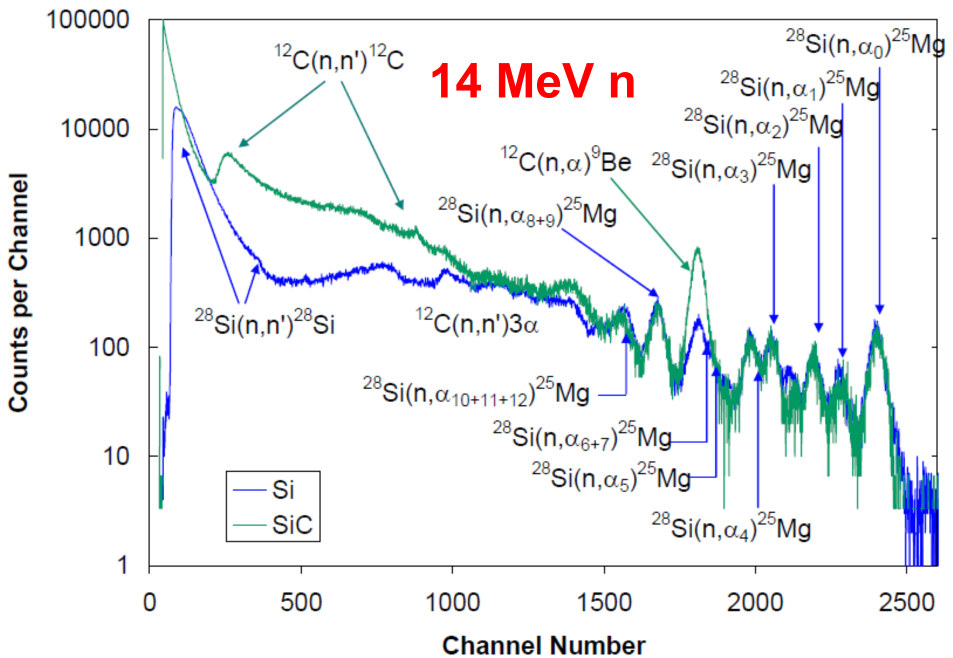
Single crystal CVD diamond neutron detectors in a p-type/intrinsic/metal layered structure - Gianluca Verona-Rinati, Uni Roma Tor Vergata

Other semiconductors – SiC

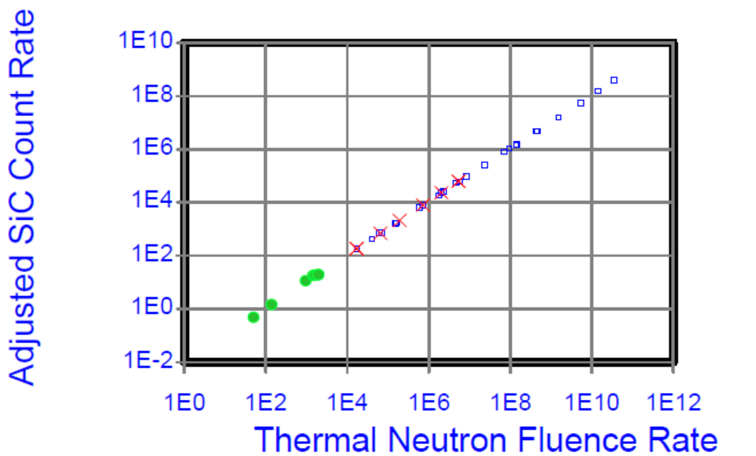
- Usually based on Shottky diode (up to 100 μm thick layers and ~1 cm large diodes), heavily doped
- Advantages over Si:
  - more reaction channels **for fast neutrons**; basically combines silicon and diamond
  - tolerates much higher operation temperatures (300°C) than silicon (E_g=3.3 eV)
  - of interest for heavy ion experiments

F. Franceschini, F. H. Ruddy, Silicon carbide detectors





Detection of thermal neutrons:



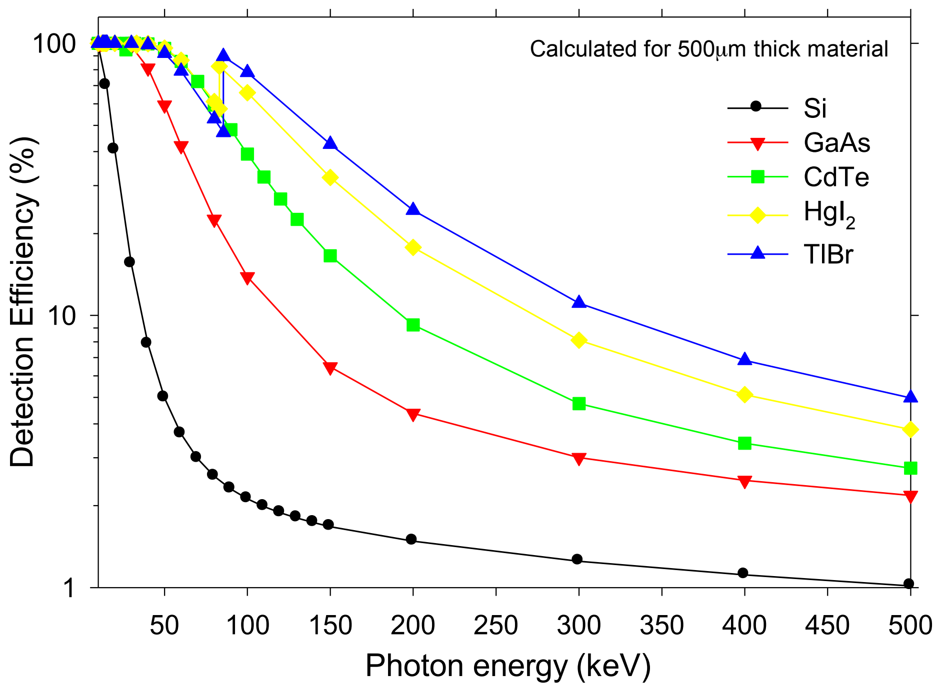
Other semiconductors – γ detection

Commercially available material continues to be predominately CdZnTe (CdTe), GaAs and HgI2

Mostly used for γ detection:

- Nuclear physics
- Space applications
- Medicine

They are used for position resolved spectroscopy/imaging!



They all have band gap larger than silicon so in a perfect crystal less leakage current, but …

- They use ohmic or shottky contacts instead of p-n junction
- They are usually polycrystalline detectors (remember the picture from diamond), but the quality improves and detector grade single crystalline detectors are becoming available
- The trapping of the drifting charge, due to growth defects, degrades the performance (as in diamond)
- Some of them (CdZnTe and HgI2 in particular) suffer from very low hole mobility

HgI2 and CZT – charge collection

Carrier drift length λ defines the induced charge Q, and hence the spectroscopic performance of the detector:

For electrons:
$$CCE = \frac{Q}{Q_0} \approx \frac{\lambda_e}{d}\left(1 - \exp\left(\frac{-d}{\lambda_e}\right)\right)$$

The mobility-lifetime product μτ is often used as a measure of charge transport quality:
$$\lambda_e = \mu\tau E$$

Remember: both e and h have to finish the drift to get full charge induced:

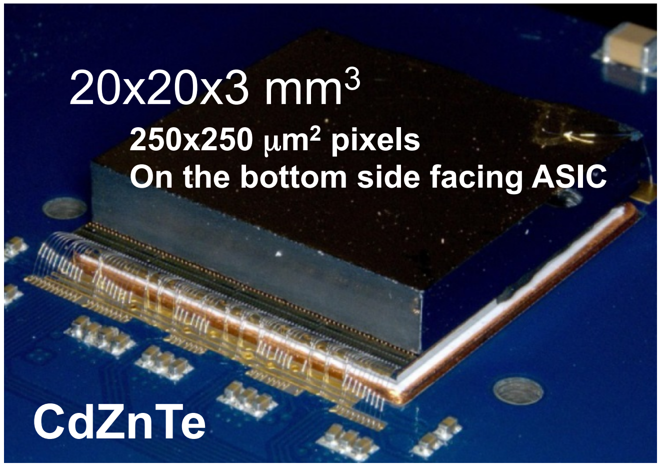
- Holes are too slow to be collected (noise, rate reasons)
- Electrons get trapped (problems with thicker detectors as the carriers diffuse more and find more traps)

A way to overcome these problems is:

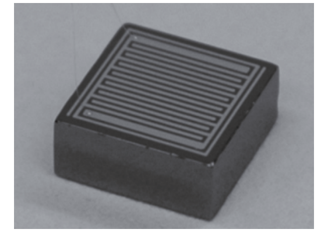
- use weighting field to maximize electron contribution to the total signal
- use high bias voltages

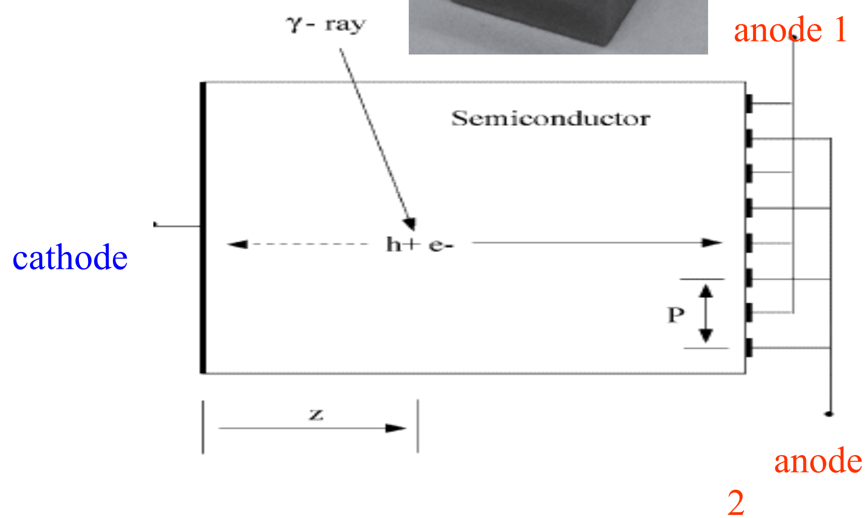
“Small pixel” effect

(interplay between charge sharing/complex reconstruction and weighting field “sharpening”)

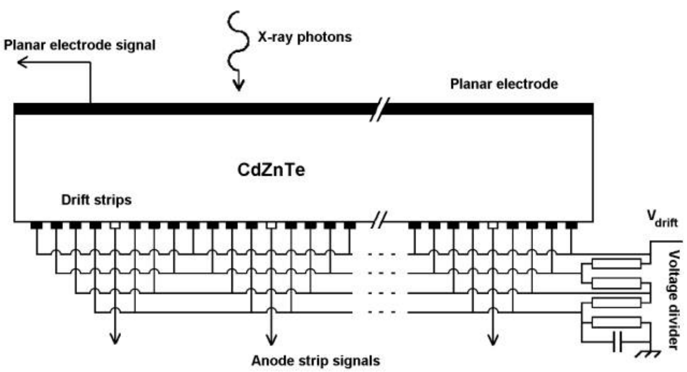


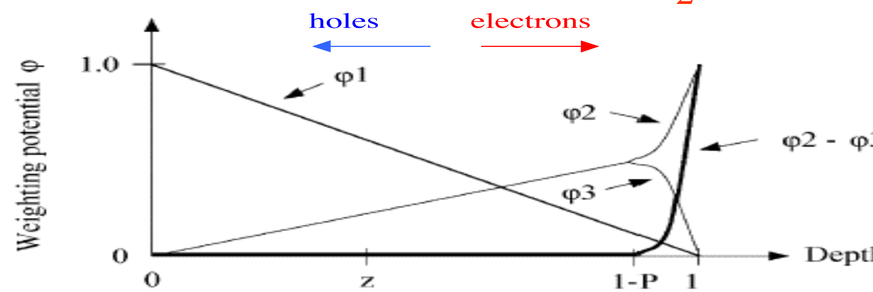
Coplanar grid





“Small strip” effect with field shaping



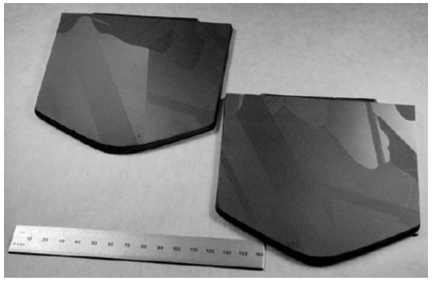


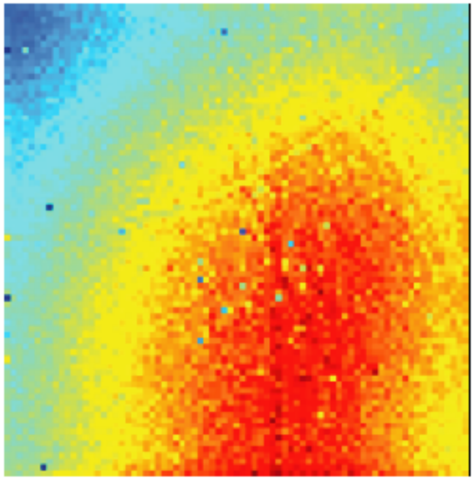
Subtraction of signals diminishes hole contribution!
If cathode also read one can determine the position of the hit inside the detector.

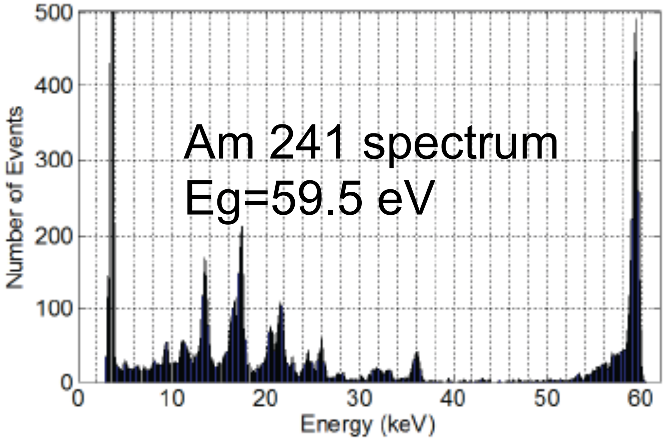
Cd(Zn)Te detectors

- CdTe and CdZnTe cover a suitable range of band gaps: 1.44 eV (CdTe), 1.57 eV (CdZnTe, 10% Zn), 1.64 eV (CdZnTe, 20% Zn)
- Resistivity of CdZnTe is higher than CdTe => lower dark current, higher spectroscopic resolution (also no polarization effects at Shottky contacts)
- Large progress in last years in terms of production of crystals
- 20x20x3 mm^3 single crystals available
- Operations at ~1kV with $\mu\tau$~5x10^{-3} cm^2/V
- Also demonstrated for neutron detection through

  ^{113}Cd (n,γ)^{114}Cd reaction with Eγ lines 558.6 keV and 651.3 keV





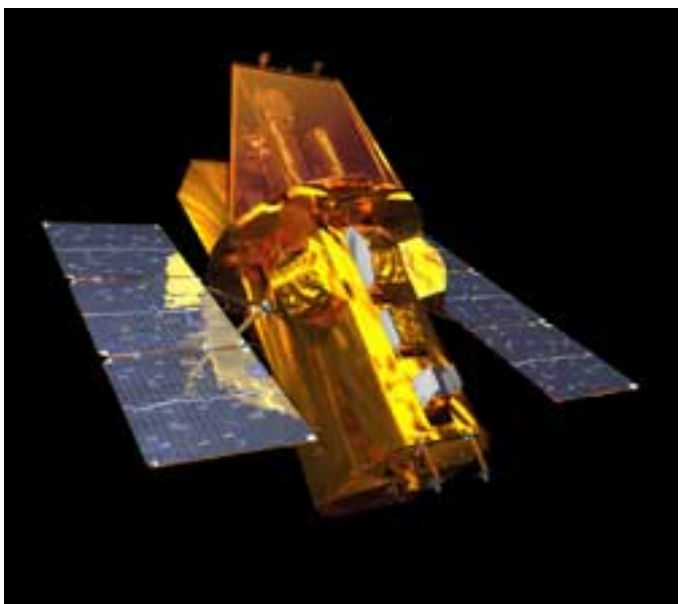


Energy resolution:
59.5keV (241 Am) = ~3%
141keV (99Tc) = ~2%
622keV (137 Cs) = ~1%

Imaging detector used in space

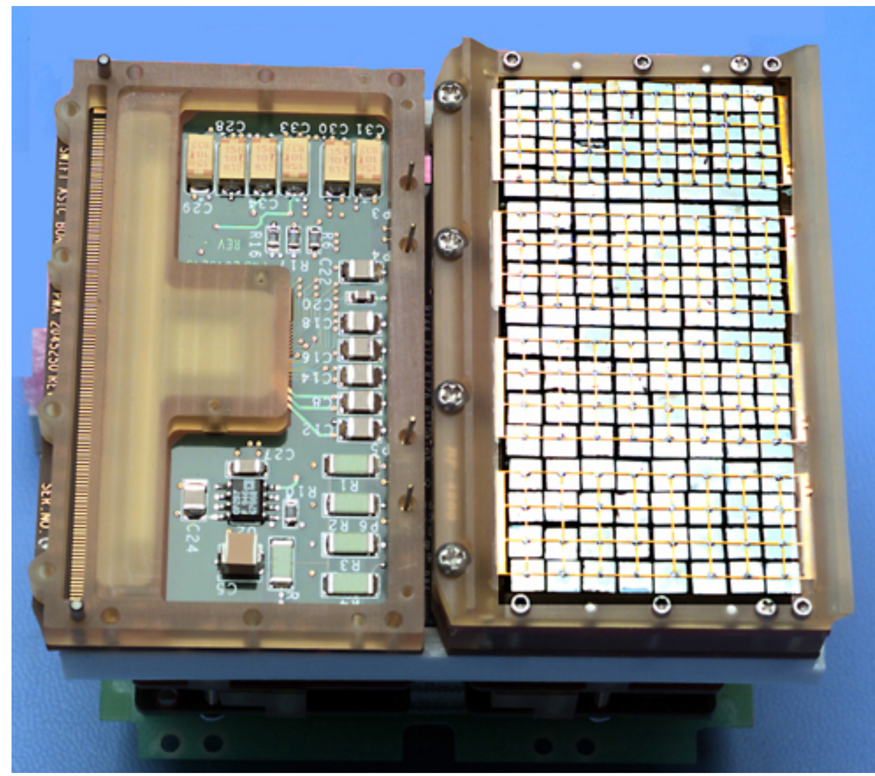
- SWIFT Burst Alert Telescope (BAT) produces a first image within 10 seconds of the event trigger
- large imaging range (15-150 keV) using CZT, with additional response up to 500 keV
- 32768 elements of 4x4x2mm CZT, forming an array detector 1.2 x 0.6 m

SWIFT launched November 2004



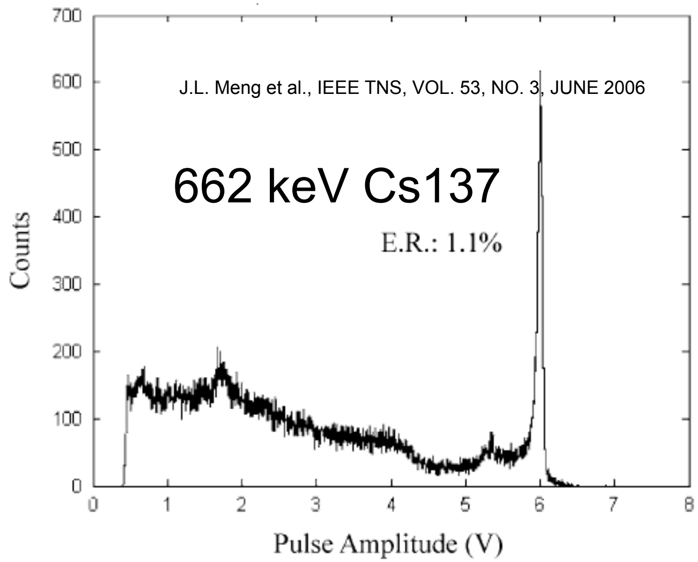
SWIFT CZT detector array:

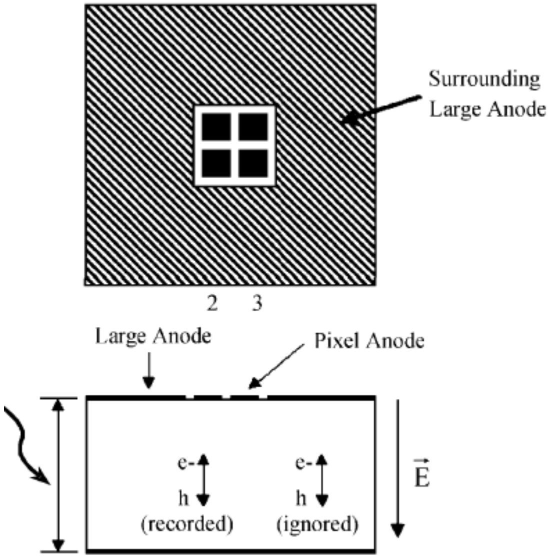
- Contains 32768 elements of 4x4x2mm CZT, forming an array detector 1.2 x 0.6 m
- The coded aperture mask is ~54,000 lead tiles!



HgI_2

- Eg=2.1 eV , I=4.2 eV, μ_e ~90 cm^2/Vs and μ_h ~5 cm^2/Vs for single crystalline
- Operations at fields up to E ~300 V/mm with $\mu\tau$~1×10^{-2} cm^2/V
- Very delicate surface often covered with polymer to prevent evaporative degradation
- Severe polarization effects (E field) – long settling times
- Large resistivity (10^{13} Ωcm) is the main advantage over CZT in addition to larger stopping power at high energies.
- Crystals sizes of ~1-2x1-2x1 cm^3 are available – multi pixel
- Energy resolution: 1-2% at 662 keV





Radiation Damage

- Only the aspects of the damage done by neutrons will be addressed
- Only silicon and two slides of diamond and SiC will be addressed
- Very basic understanding

Types of radiation damage

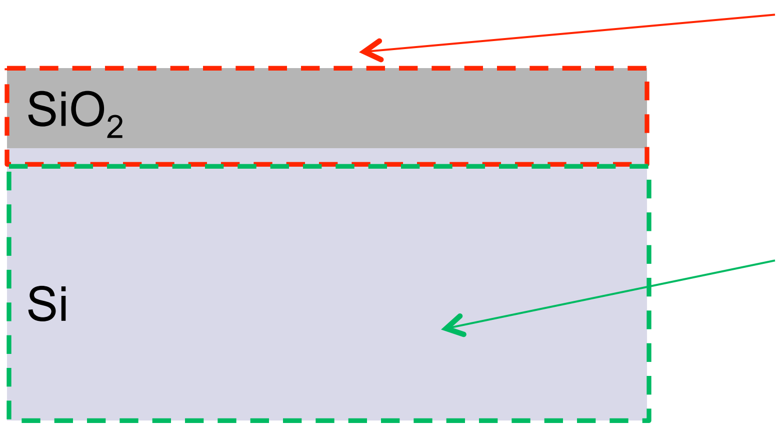
Two types of radiation damage in detector materials:

- **Bulk (Crystal) damage** due to **Non Ionizing Energy Loss (NIEL)**

  \- displacement damage, built up of crystal defects –

- **Surface damage** due to **Ionizing Energy Loss (IEL)**

  \- accumulation of charge in the oxide (SiO_2), traps at Si/SiO_2 interface –



Region affected by ionizing energy loss - surface damage

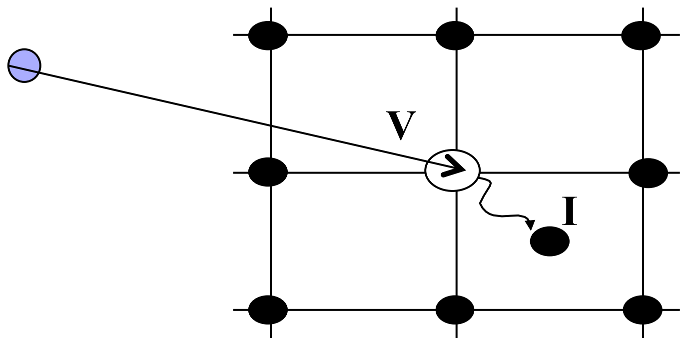
Region affected by non-ionizing energy loss - bulk damage

Generation of bulk damage (I)

Imping particle hits the lattice atom and knocks it out of the lattice site.

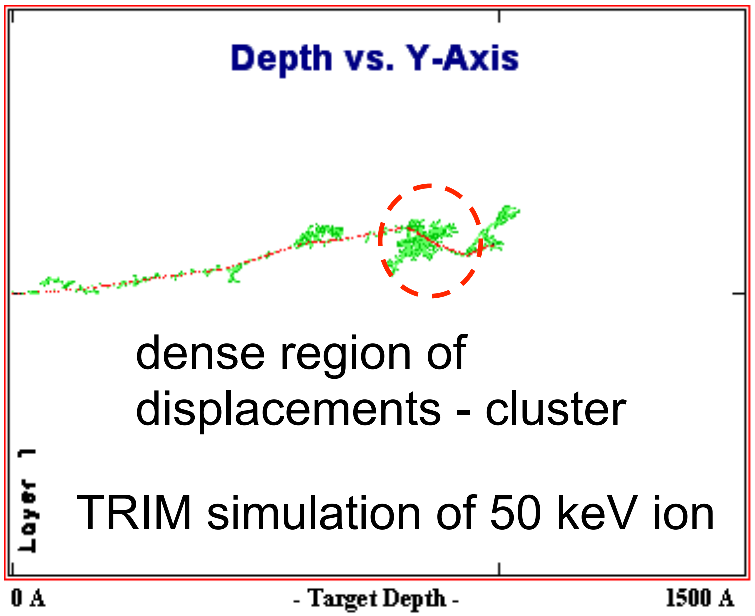
- energy of E_k>25 eV is required for formation of a Frenkel pair (point defects)
- for E_k>5 keV than knocked off atom displaces further lattice atoms (cluster defects)

$E_K > 25$ eV



Frekel pair – (Vacancy-Interstitial pair)

$E_K > 5$ keV



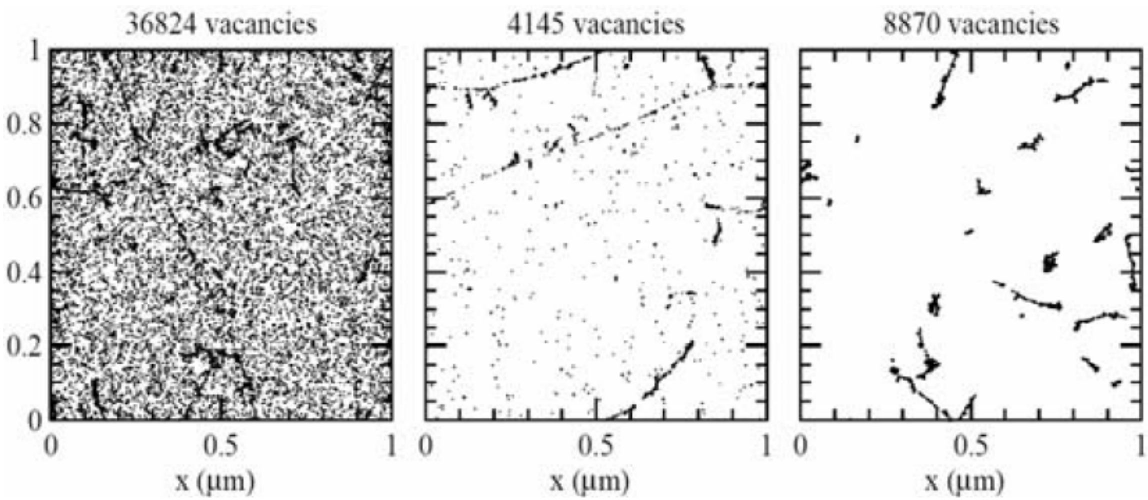
Vacancies and Interstitial migrate in the crystal and react with other V,I or impurities.

Generation of bulk damage (II)

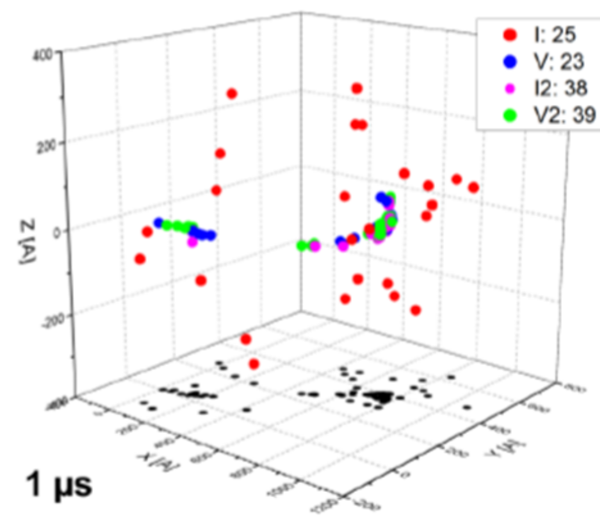
How much clusters/point defects are produced by impinging particle depends on particle type and energy.

- reactor neutrons – more clusters , less point defects
- 24 GeV protons – both in similar share
- 10 MeV protons – more point defects less clusters
- γ with < 8 MeV – only point defects

10 MeV p　　24 GeV p　　1 MeV n



Vacancies and Interstitial migrate in the crystal and react with other V,I or impurities.



Generation of bulk damage (III)

How do we then compare the fluences of different particles?

NIEL hypothesis – the damage effects in silicon depend only on the non-ionizing energy loss regardless of the particle type and energy.

It is wrong (not extremely) for some radiation damage effects, but correct for leakage current. Still serves as a reference point.

Total displacement energy/unit volume

$$\rho_{dis} = \frac{8}{a^3} t_{irr} \int_0^\infty \frac{d\phi}{dE} D(E)\, dE$$

One can normalize different particle fluences to the equivalent fluence of 1 MeV neutrons – equivalent fluence.

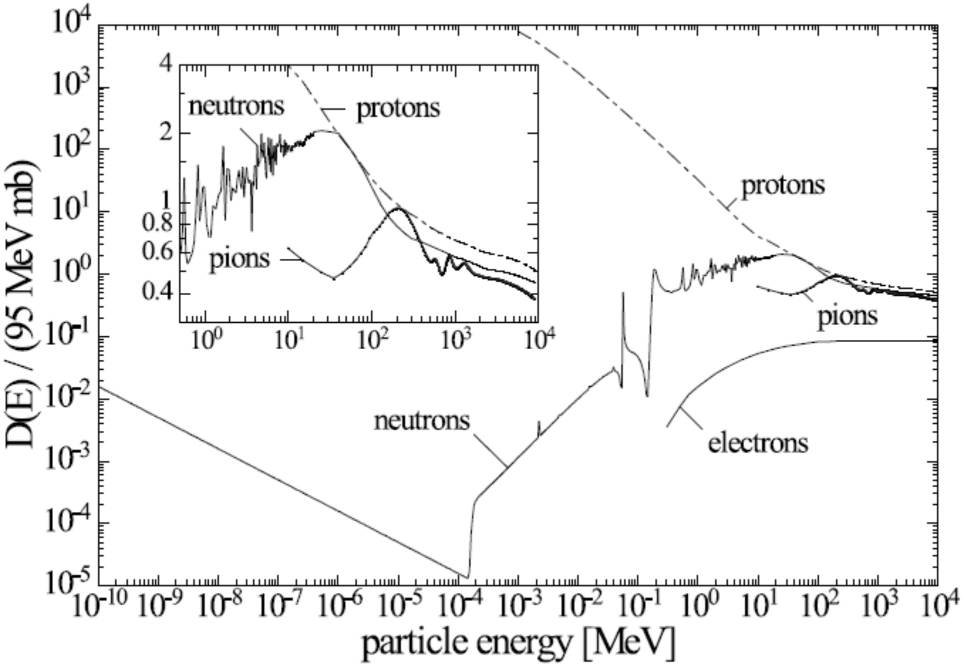
$$\Phi_{eq} = \kappa_x \Phi_x$$

$\kappa_p = 0.62$ (24 GeV protons)

$\kappa_p = 1.85$ (26 MeV protons)

$\kappa_\pi = 1.14$ (300 MeV pions)

$\kappa_n = 0.92$ (reactor neutrons >100 keV)



Effects of bulk damage to detector operation

Lattice defects give rise to energy levels. If they are in the bang gap they are electrically active and lead to:

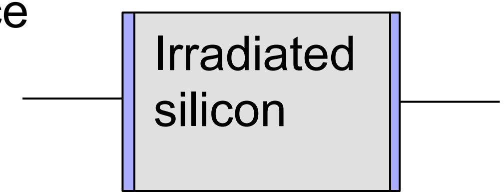
I. Increase of **leakage current** (increase of shot noise, thermal runaway)

II. Change of **effective doping concentration**
(higher depletion voltage, under- depletion)

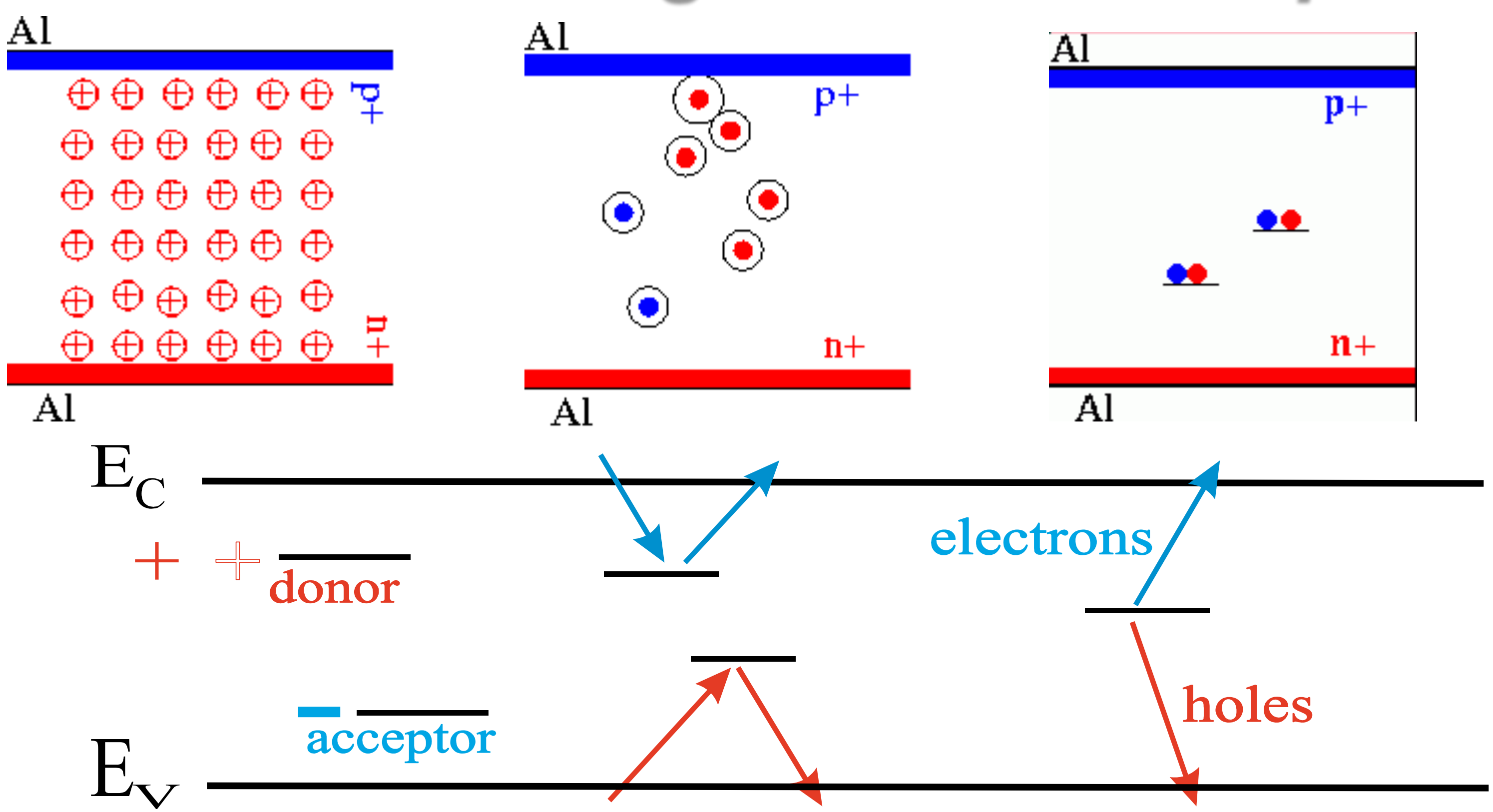
III Increase of **charge carrier trapping** (loss of charge)

IV. Increase of silicon **resistivity**

The resistivity of silicon bulk increases with fluence -deep defects push Fermi level close to mid-gap and the material becomes highly resistive. The upper limit is set by intrinsic silicon.



Effects of bulk damage to detector operation



charged defects

⇒ N_{eff} , V_{dep}

e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)

⇒ CCE

shallow defects do not contribute at room temperature due to fast detrapping

generation

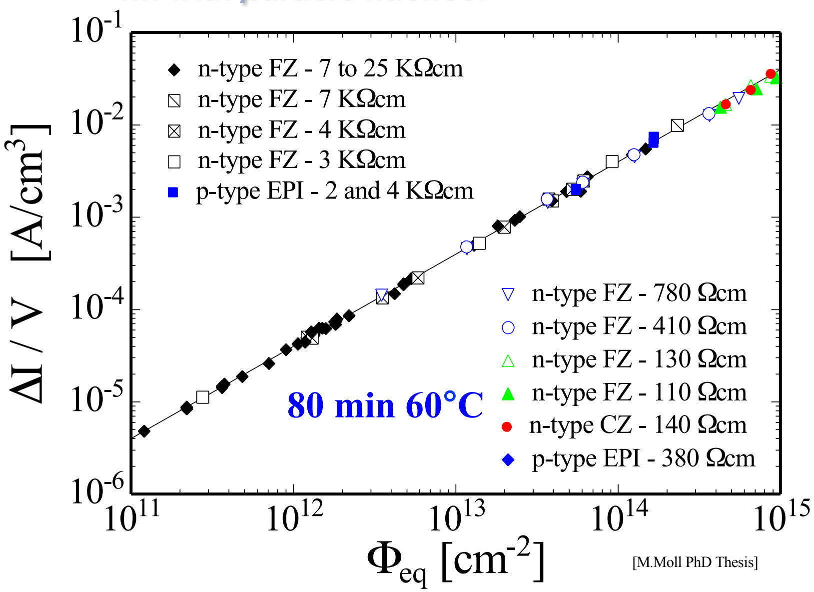
⇒ leakage current, N_{eff}

Levels close to mid-gap most effective

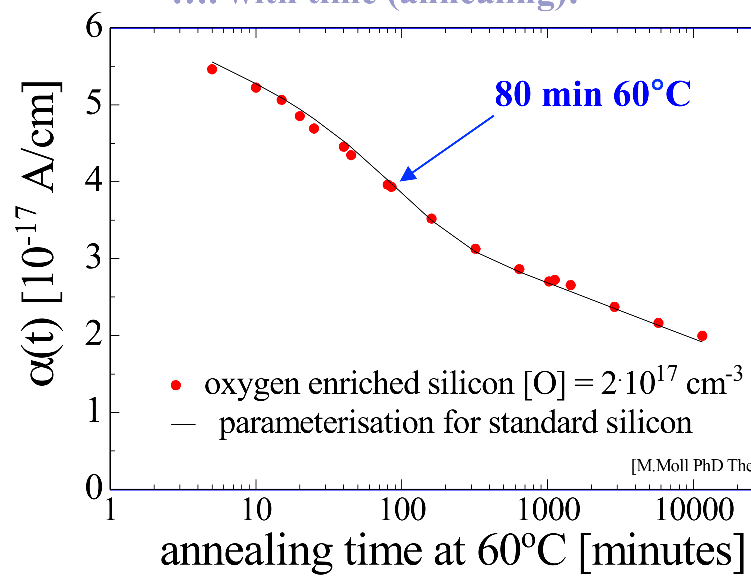
Leakage current

- *Change of Leakage Current (after hadron irradiation) -> increase of noise*

.... with particle fluence:



.... with time (annealing):



- Damage parameter α (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current per unit volume and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement

- Leakage current decreasing in time (depending on temperature)
- Strong temperature dependence

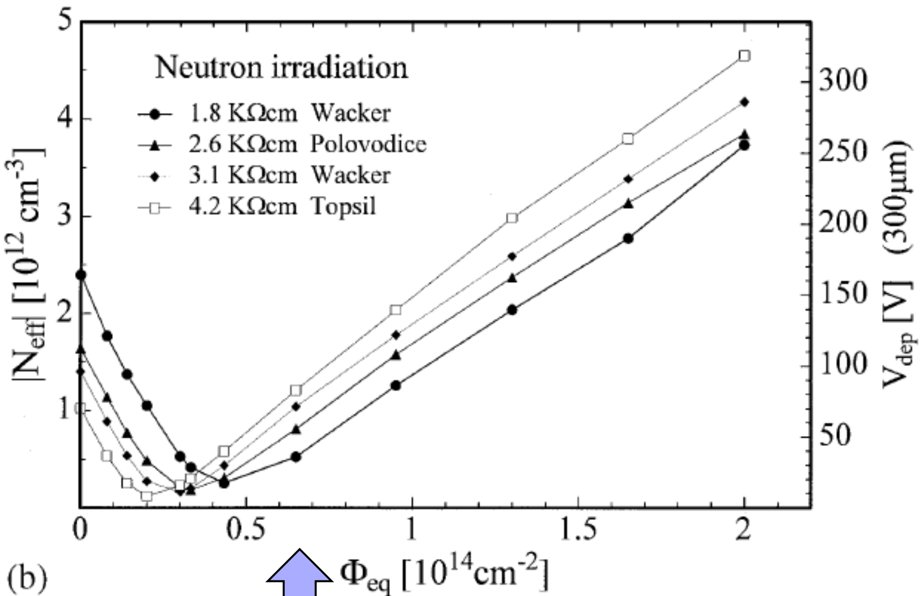
$$I \propto \exp\left(-\frac{E_g}{2k_B T}\right)$$

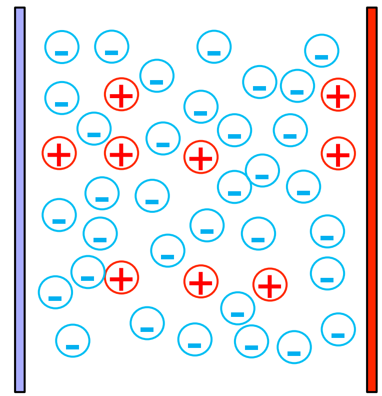
Consequence:

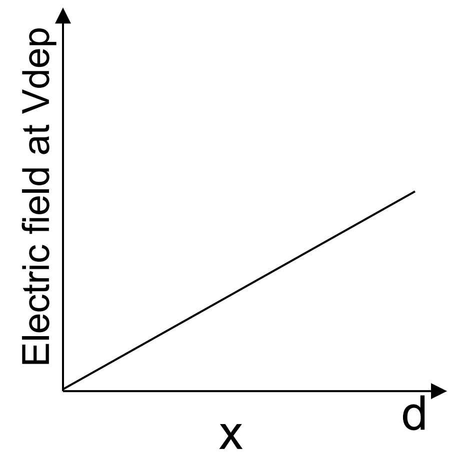
Cool detectors during operation!
Example: $I(-10°C) \sim 1/16\ I(20°C)$

Silicon

Evolution of V_{FD} with neutron fluence …







The increase of V_{FD} i.e. $|N_{eff}|$ is almost linear with fluence.

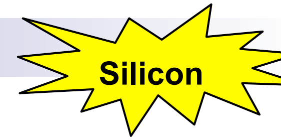
The neutron irradiations show:

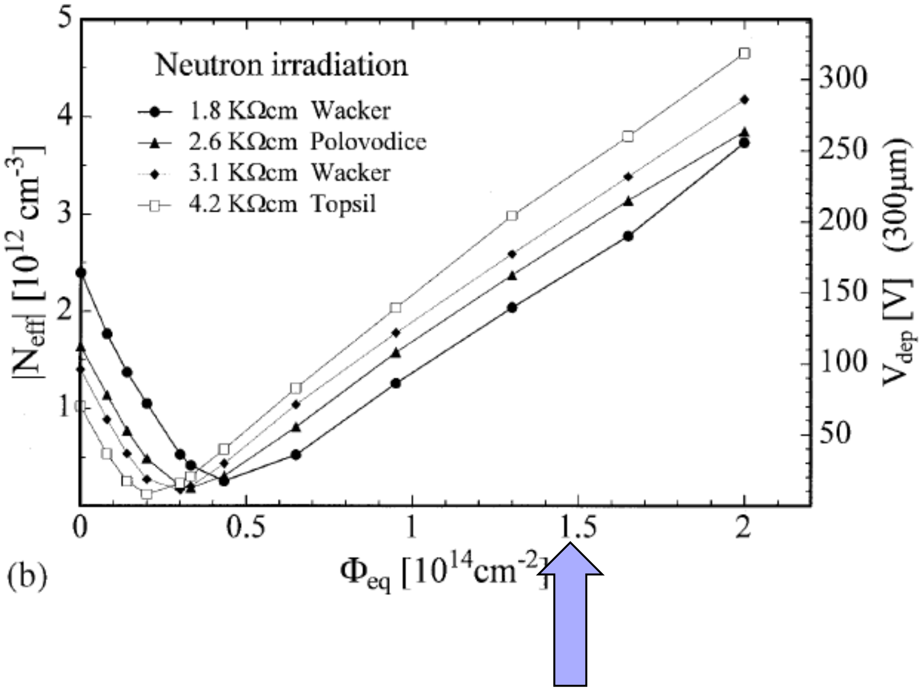
- incomplete donor removal – not all initial donors are removed
- no influence of any impurity – after neutron irradiations all materials behave the same!

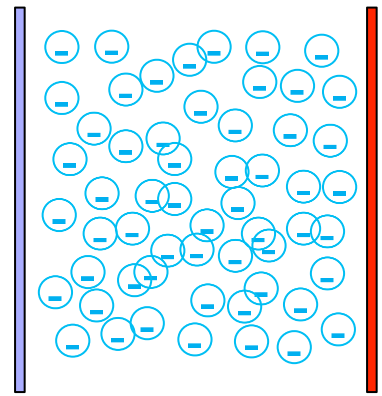
$$N_{eff} \sim g_{eff}\,\Phi_{eq}$$

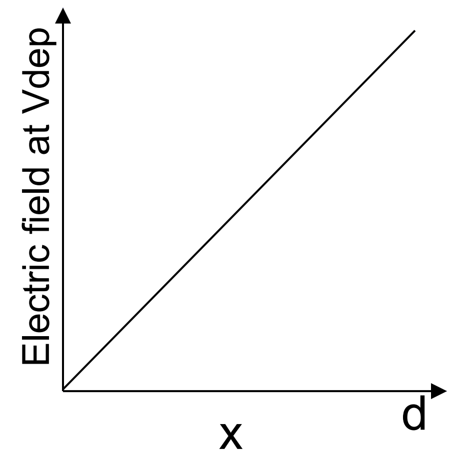
$$g_{eff} \sim 0.017\ \mathrm{cm}^{-1}$$

Evolution of V_{FD} with neutron fluence …









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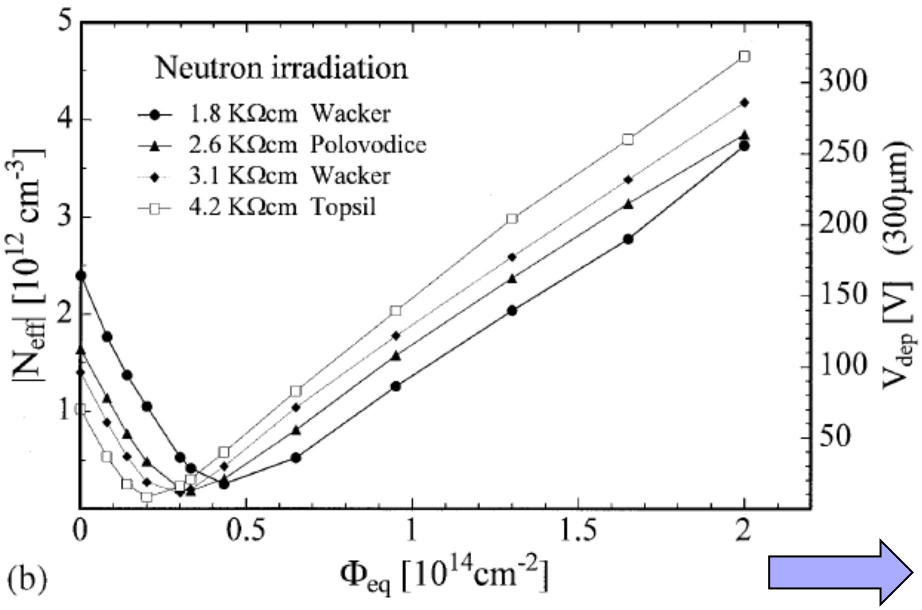
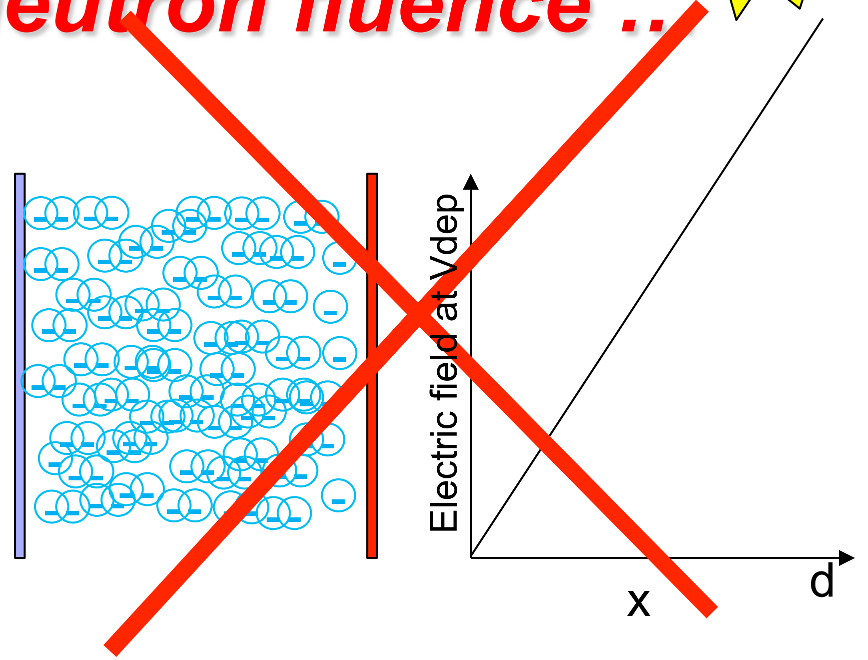
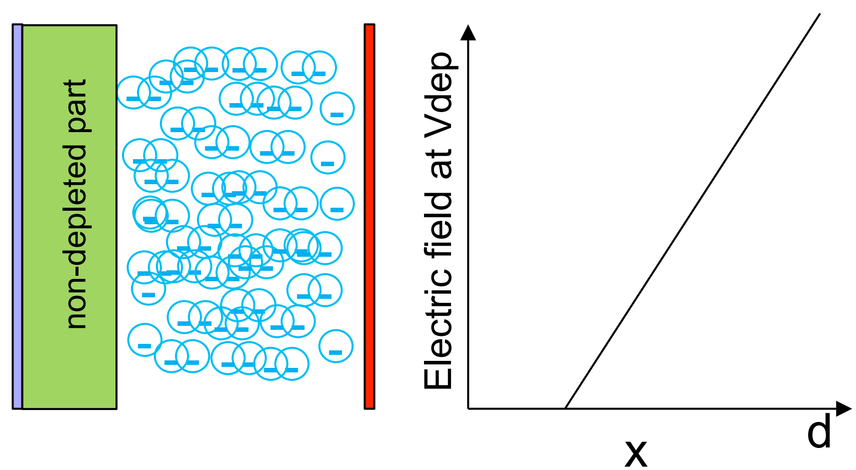
Evolution of V_{FD} with neutron fluence ..

Silicon





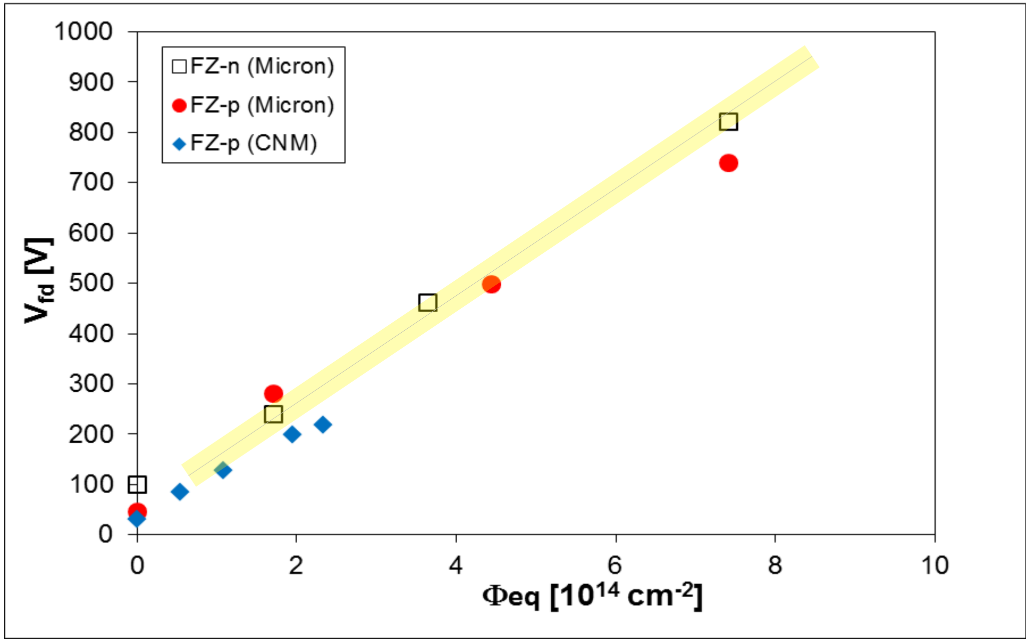
Reduce the voltage = not fully depleted detector



Detector is not fully efficient and has to run partially depleted. Huge problem for n-type detectors.

Silicon

What about the p-type material?



p-type FZ material:

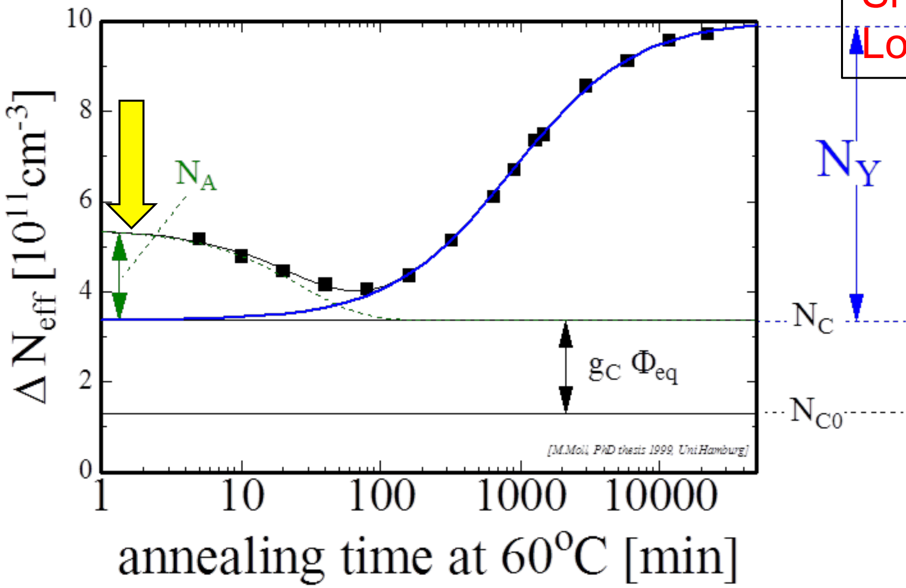
- No inversion (material stays always effectively p-type)
- There is some initial acceptor removal, but is not so well studied
- The rate with which the negative space charge is introduced is comparable to n-type detectors

p-type material is more suitable for building detector for very harsh radiation environments

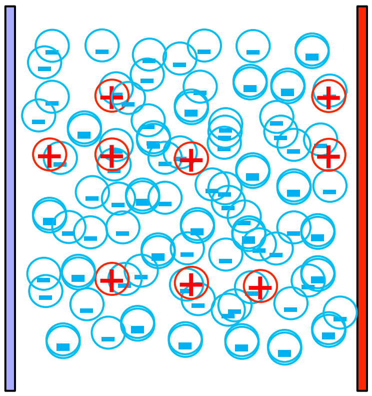
- High field region always stays close to the electrodes (weighting field effect)
- Carrier arriving at n^+ contact are electrons which are faster – less trapping

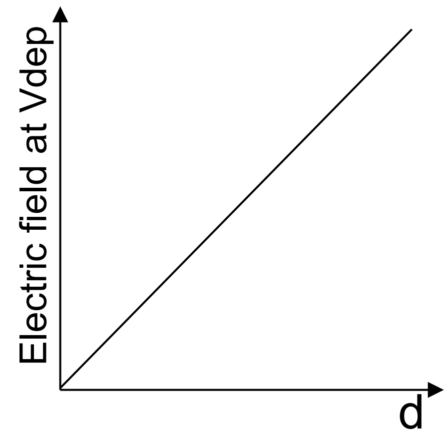
Evolution with time - Hamburg model

Silicon



Short term : reduction of negative space charge
Long term: introduction of negative space charge





- **Short term:** "Beneficial annealing"-N_A
- **Long term:** "Reverse annealing"-N_Y

  - time constant depends on temperature:
    - ~ 500 years (-10°C)
    - ~ 500 days (20°C)
    - ~ 21 hours (60°C)
  - **Consequence:** Detectors must be cooled even when the experiment is not running!

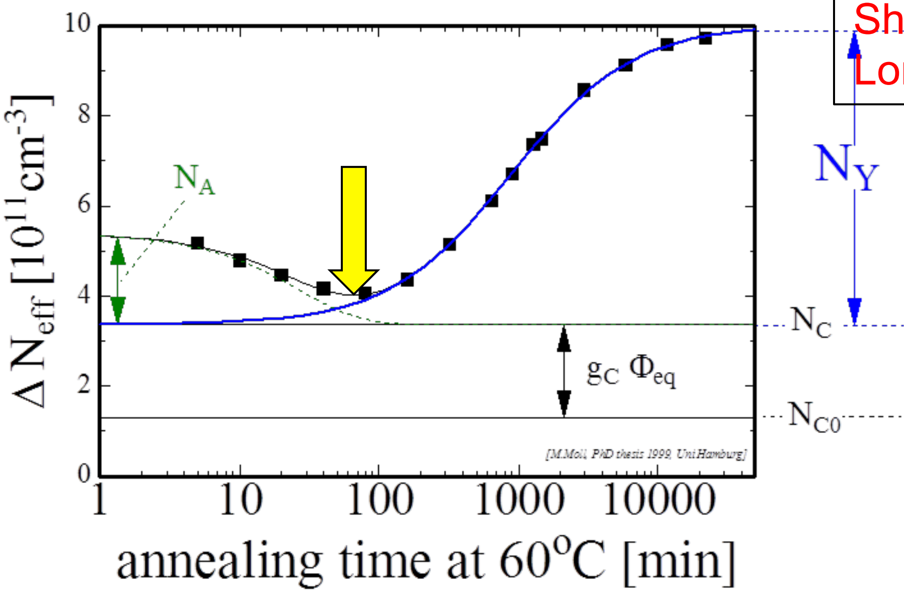
$$\Delta N_{eff} = N_{eff,0} - N_{eff}$$

$$\Delta N_{eff} = N_A(t,\Phi_{eq}) + N_c + N_Y(t,\Phi_{eq})$$

$$\Delta N_{eff} = N_a \exp(-t/\tau_{ba}) + N_c + N_Y(1-\exp(-t/\tau_{ra}))$$

Silicon

Evolution with time - Hamburg model



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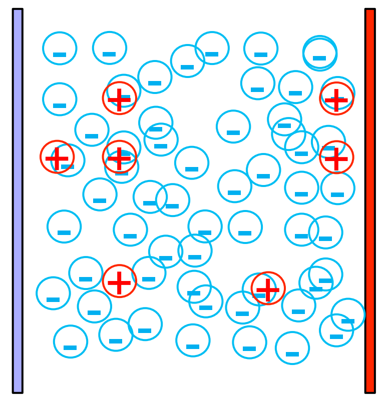

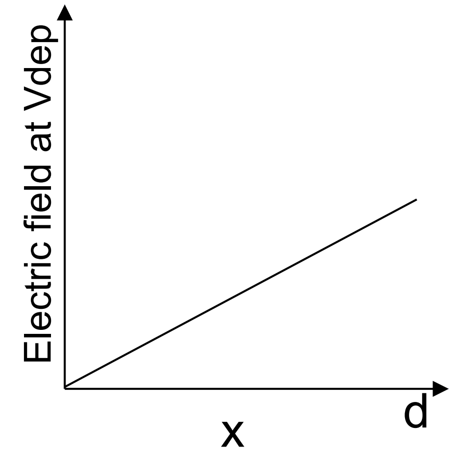

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Silicon

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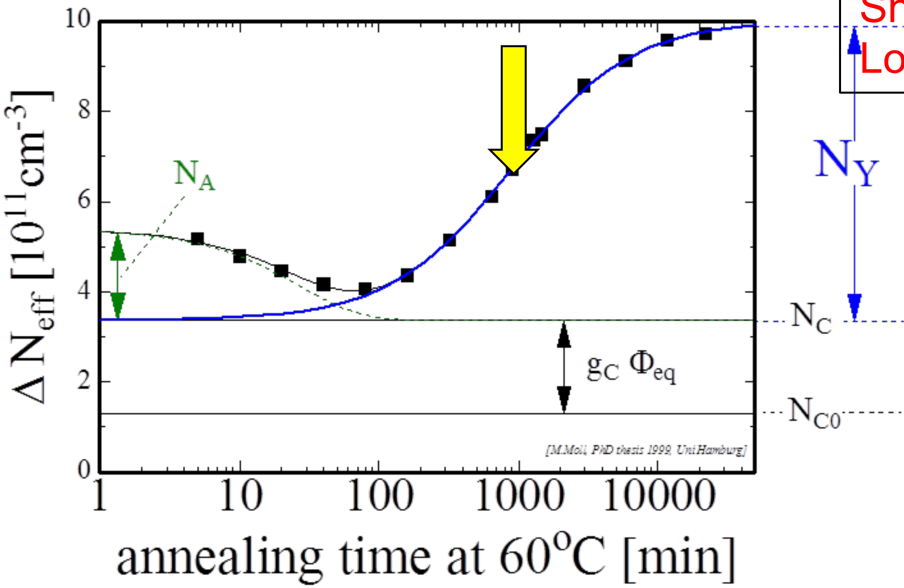

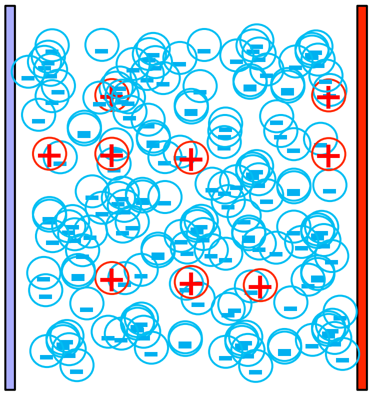

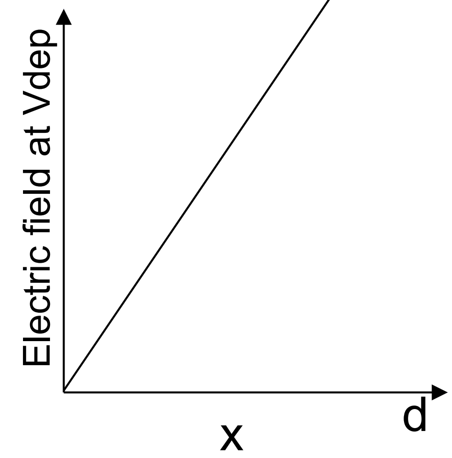

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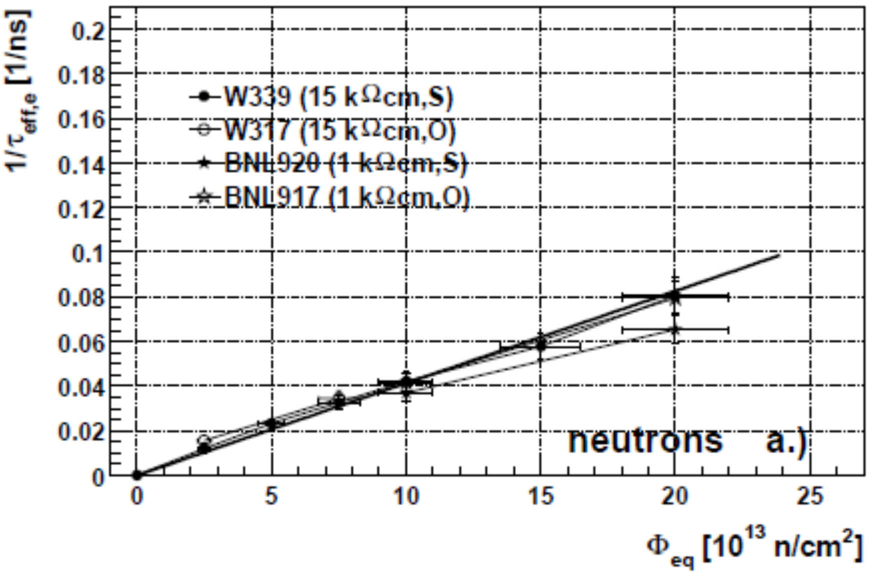
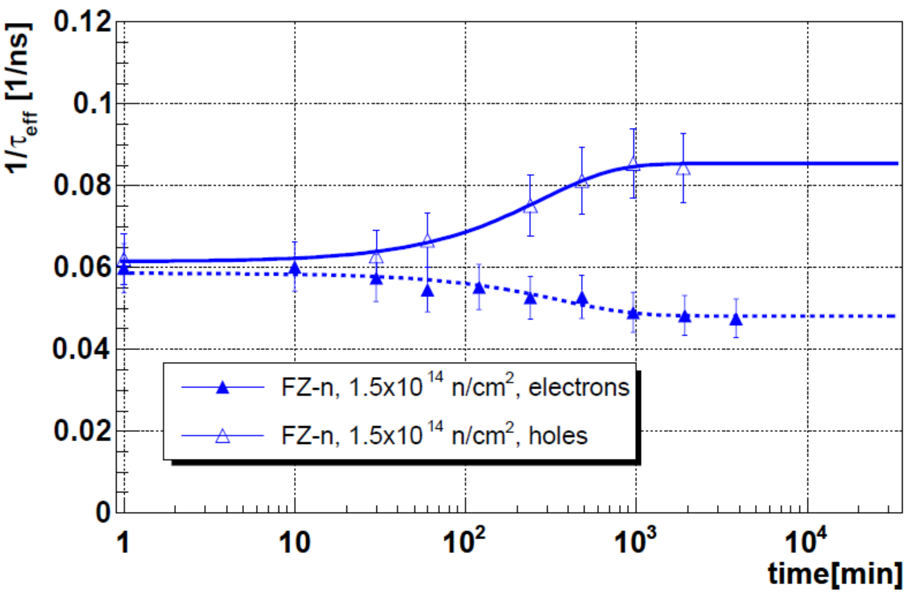
Trapping of drifting charge

Silicon



β(-10°C, t=min Vfd) [10^{-16} cm²/ns]	reactor neutrons
Electrons	3.5 ± 0.6
Holes	4.7 ± 1

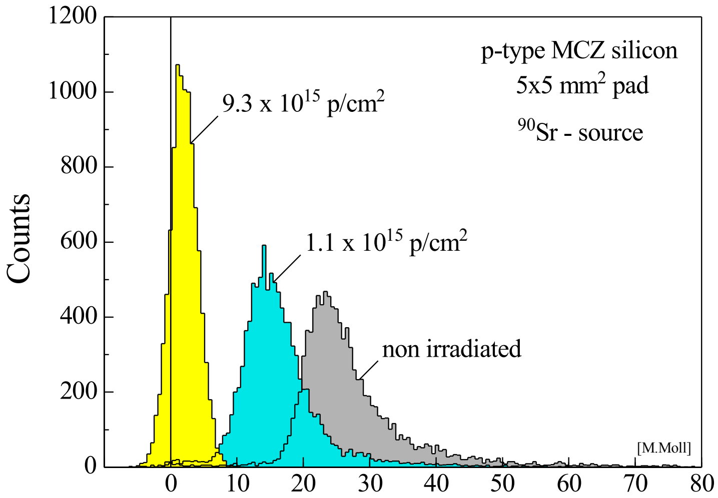
$$\frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(T,t)\,\Phi_{eq}$$



The $\beta_{e,h}$ was so far found independent on material;
- resistivity
- [O], [C]
- type (p,n)
- wafer production (FZ, Cz, epitaxial)
- somewhat lower trapping at Φ_{eq}>10^{15} cm^{-2}
- **$\beta_{e,h}$ ~ 0 for ^{60}Co irradiated samples**

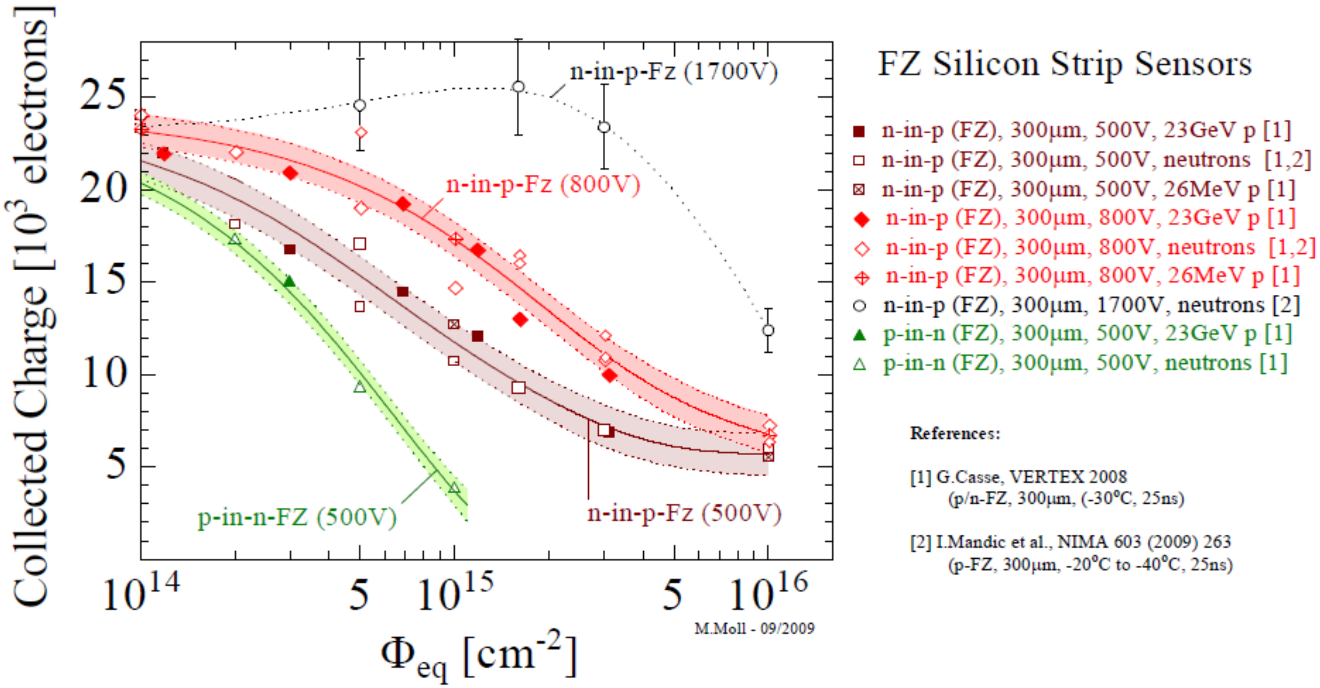
The trapping probability:
- gets smaller with time for electrons
- gets larger with time for holes

Charge collection efficiency



The consequence of irradiation is less charge more noise. What can we do?

- We can influence electric field in silicon by adding Oxygen but only for charged particles
- We can however optimize geometry – **impact of weighting field**

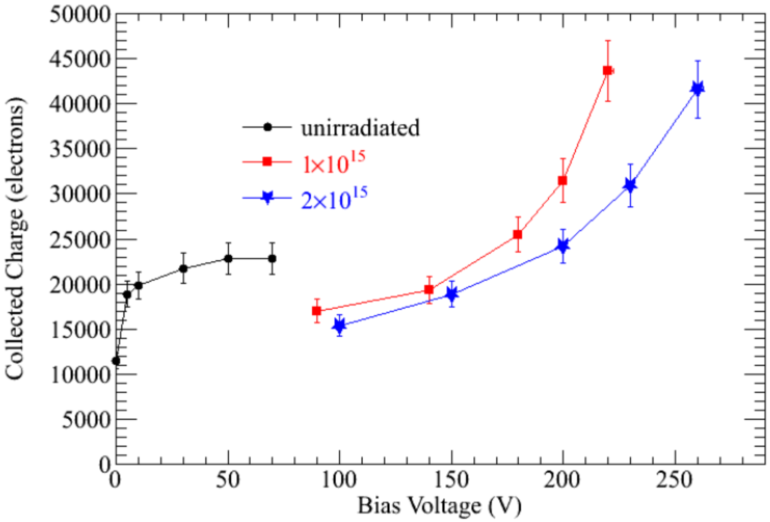


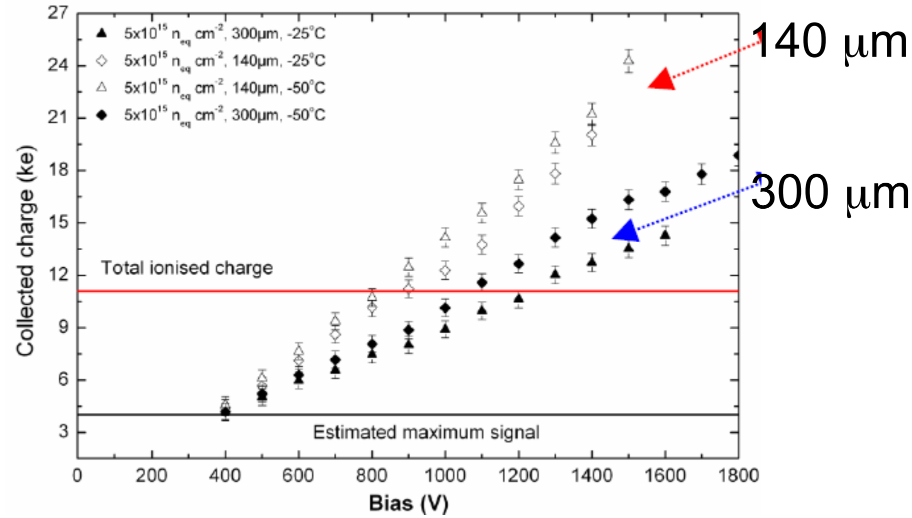
Silicon

Charge collection efficiency

At very high fluences the collected charge exceeds expectations:

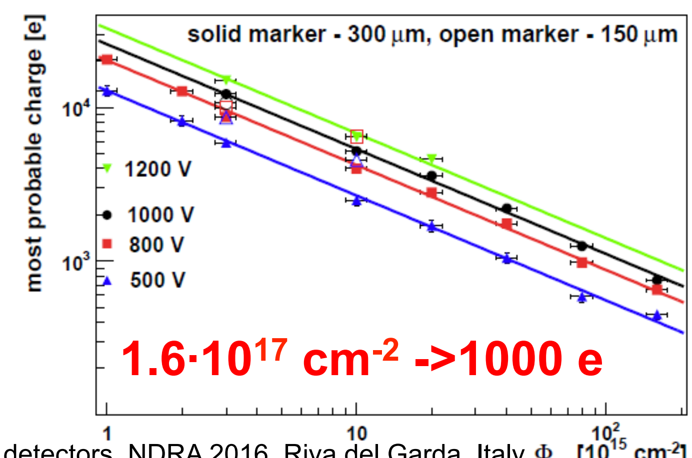
- ➢ Due to large N_{eff} the E becomes high enough for impact ionization – multiplication ☺
- ➢ The whole detector volume is active ☺



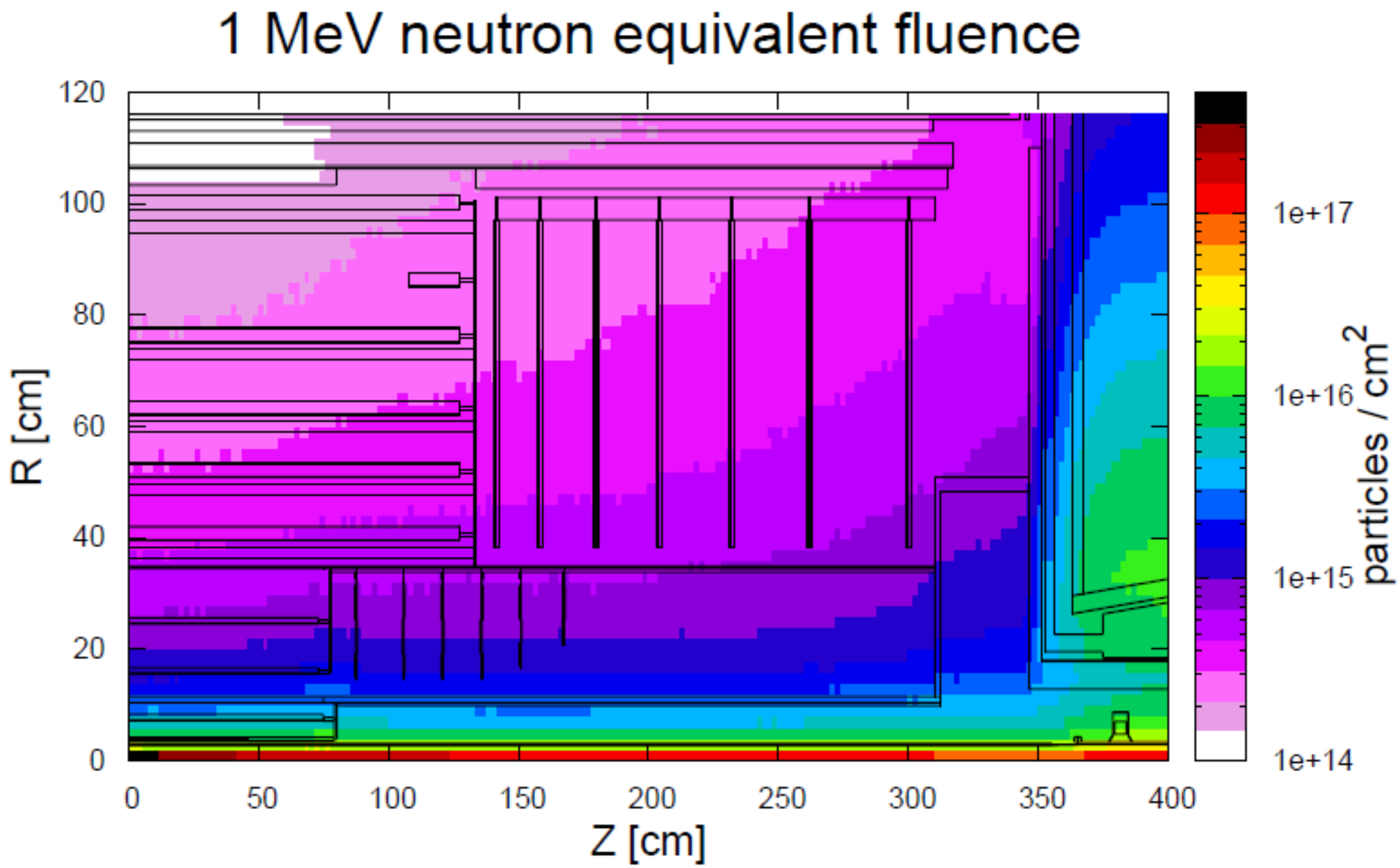


Extreme fluences:

- ❑ Silicon still works, but charge collection efficiency is significantly reduced.
- ❑ $I_{leak}(\Phi_{eq})$ saturates ☺

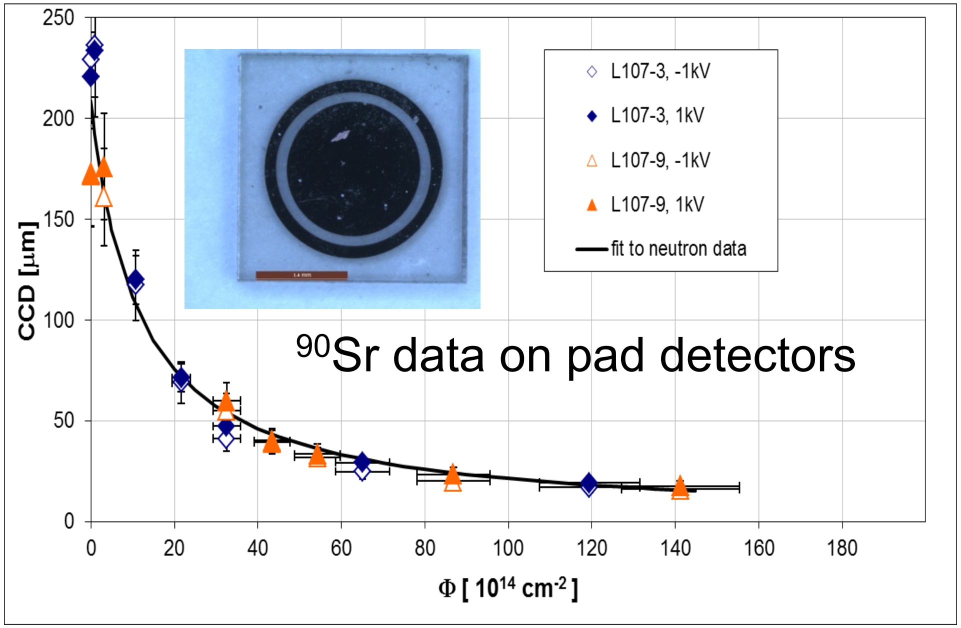


Fluence in ATLAS tracker after upgrade



Radiation damage in diamond

diamond



500 mm thick diamond pad detectors

$$\frac{1}{CCD} \approx \frac{1}{CCD_0} + k \times \Phi$$

$$Q = CCD \cdot 36 \frac{e-h}{\mu m}$$

^{90}Sr: $k \sim$ **(4.2±0.8)x10^{-18} µm^{-1}cm^{2}**
test beam data give somewhat smaller damage constant.

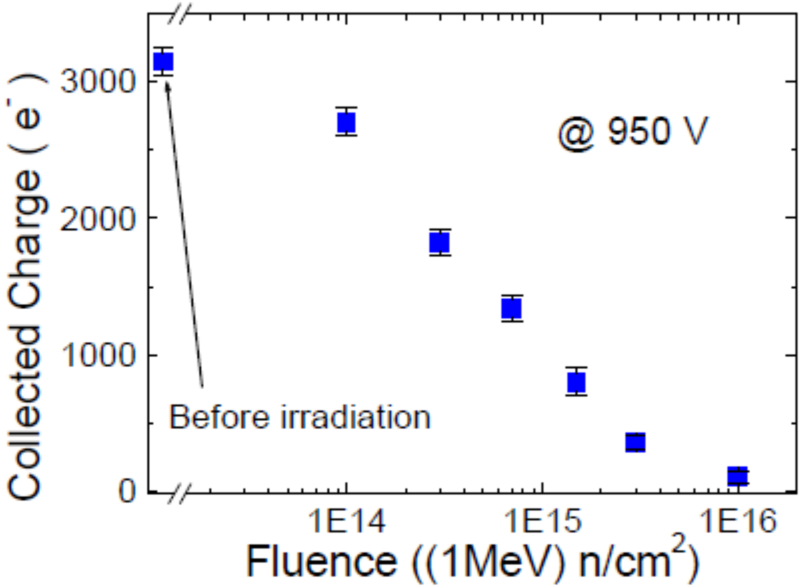
E field: complex electric field due to trap filling - space charge (long de-trapping)
Leakage current: doesn't' change after irradiation
Trapping : large and mainly responsible for degradation of charge collection efficiency.

Same damage parameter is valid also for scCVD – in terms of signal diamond is not more radiation hard than silicon.

Radiation damage in SiC

SiC

- CCE before irradiation
  - 100 % with α particles and MIPS
- CCE after irradiation (example)
  - material produced by CREE
  - 55 µm thick layer
  - neutron irradiated samples
  - tested with β particles
- Conclusion:
  - SiC is less radiation tolerant than expected



Still possible to do a particles counting but the spectrum is suppressed by trapping.

[F.Moscatelli, Bologna, December 2006]

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- Signal processing 1 and 2
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- Development of CVD Diamond Tracking Detectors for Experiments at High Luminosity Colliders
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