Principles of Semiconductor Detectors

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Outline

- **Semiconductor as detector material**
  - Detection of different types of radiation (charged particles, photons, neutrons)
  - Material properties of semiconductors
  - Electrical properties of semiconductors
- **Semiconductor detector**
  - How to make a detector
  - P-N junction and its electrical properties
- **Signal formation**
  - Ramo's theorem and its implications
  - Effects of electrode segmentation
  - Examples of induced currents and measured spectra in silicon detectors
- **Performance of segmented detectors**
  - Noise, its sources, and SNR
  - Position resolution
  - Energy resolution
  - Time resolution

- **Methods and tools**
  - TCAD simulator
  - Layout Editor
  - Silicon Foundry
  - Parametric Testing
- **Various silicon detector structures**
  - Planar (Pad, Strip, Pixel, Drift)
  - "MEMS" (3D, active edge)
  - Avalanche (LGAD, SiPM)
  - Monolithic (DEPFET, CCD, MAPS, …)
- **References**

Semiconductor as detector material

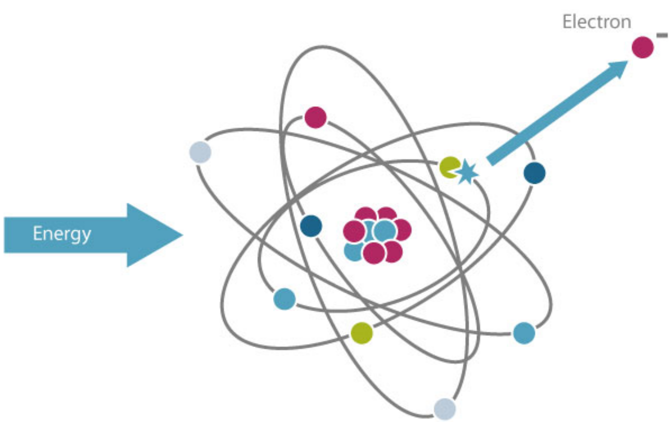
Semiconductor detector = solid state ionization chamber

Main advantages:

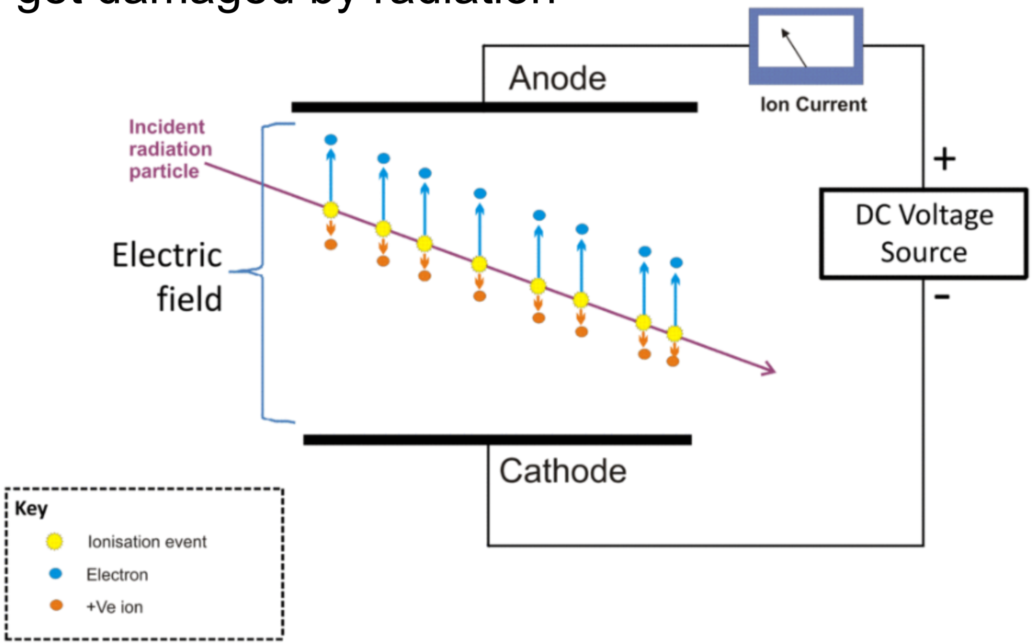
- Much lower ionization energy (eV instead of tens eV) and much larger density – more charge, i.e. "signal"
- Faster (smaller distances, larger speed of moving carriers)
- Better resolution (energy and position)

A major disadvantage:

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



ion – electron creation in gas atom

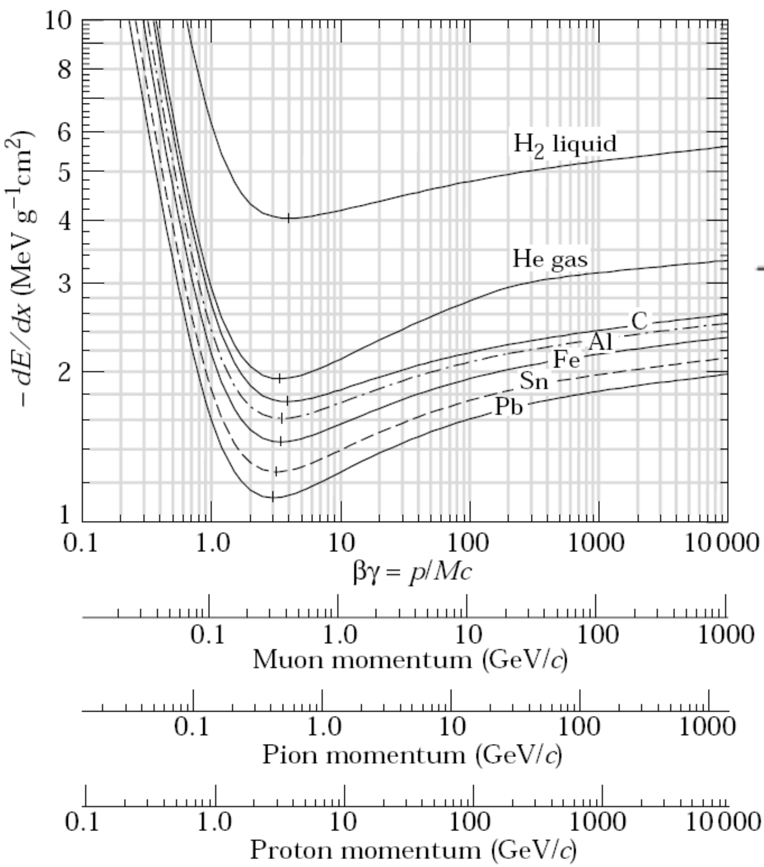


Types of radiation and choice of material

The choice of the material depends a lot on the application

To directly ionize semiconductor material, 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



Bethe Bloch formula (calculates **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 energy losses for:

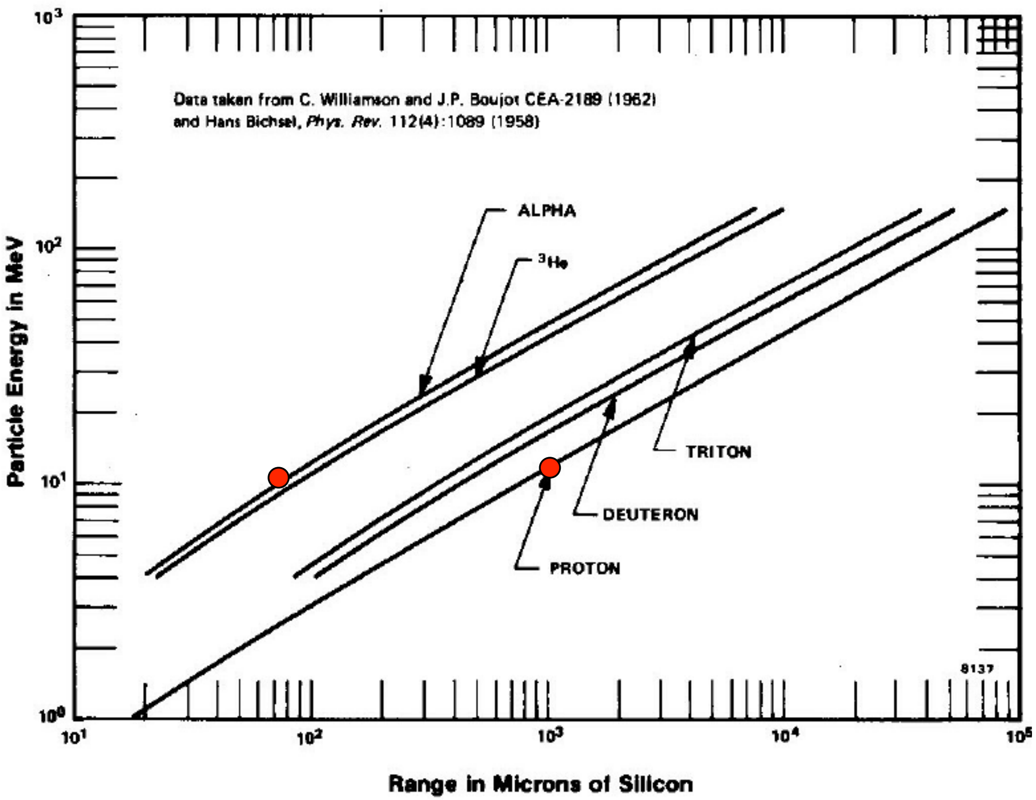
- low β=v/c<<1
- high z (i.e., α particles)
- denser material

For each material at β=0.96 there is a minimum – minimum ionizing particle (in Si: 3.87 MeV/cm)

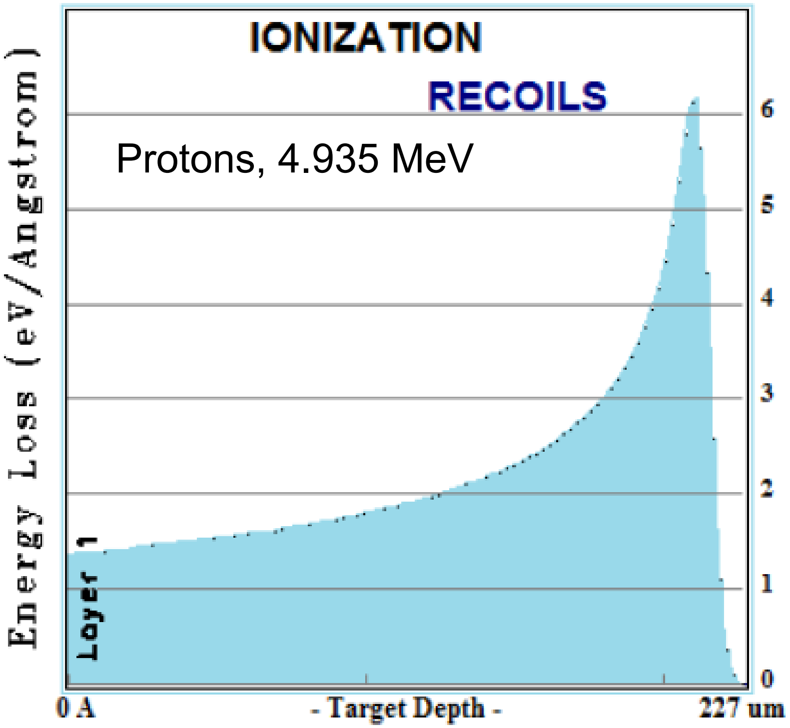
- Small ionization energy I

Range and energy deposition

At low β (non relativistic particles)

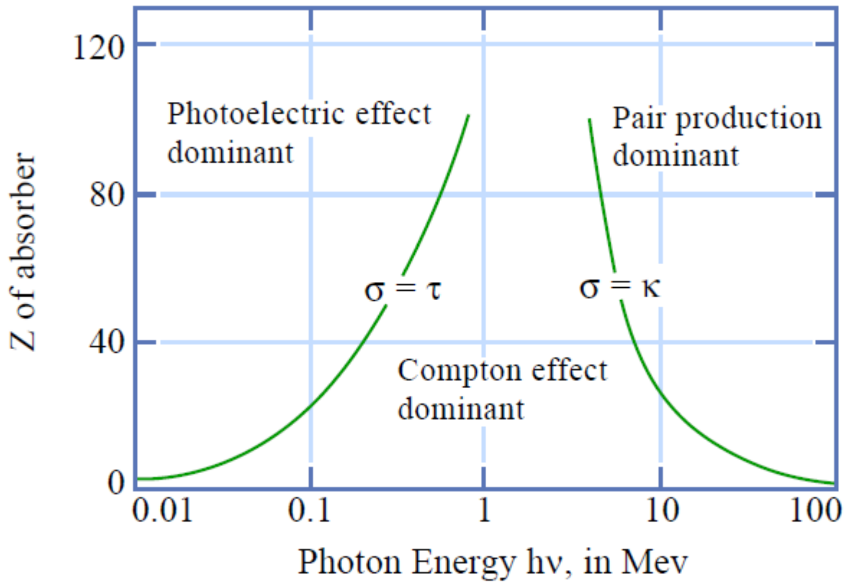


- Most energy is deposited at the end of the track, i.e., in the so-called Bragg peak



- The range depends on energy and spans from micrometers to millimeters

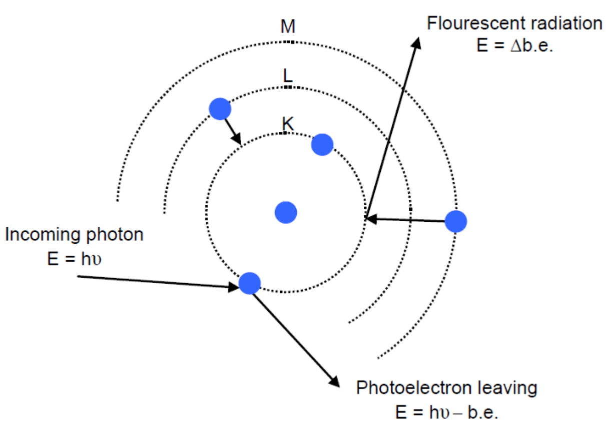
Interaction of photons with matter

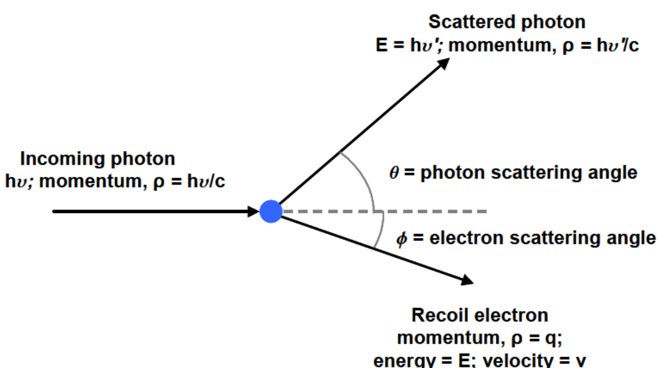


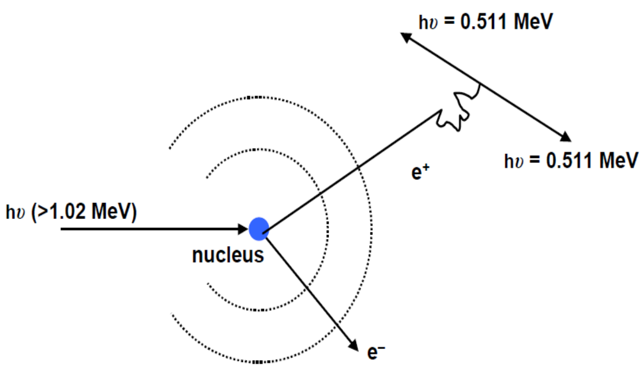
- Photoelectric effect: produces an electron, varies as ~ Z^4/E^3
- Compton effect: produces an electron and a scattered photon, varies as ~ Z
- Pair production: produces an electron and a positron, varies as ~Z^2 (threshold 2 m_ec^2)

The total interaction probability μ: $\mu = \tau + \sigma + \kappa$
τ is the photoelectric effect interaction prob.
σ is the Compton scattering interaction prob.
κ is the pair production interaction prob.

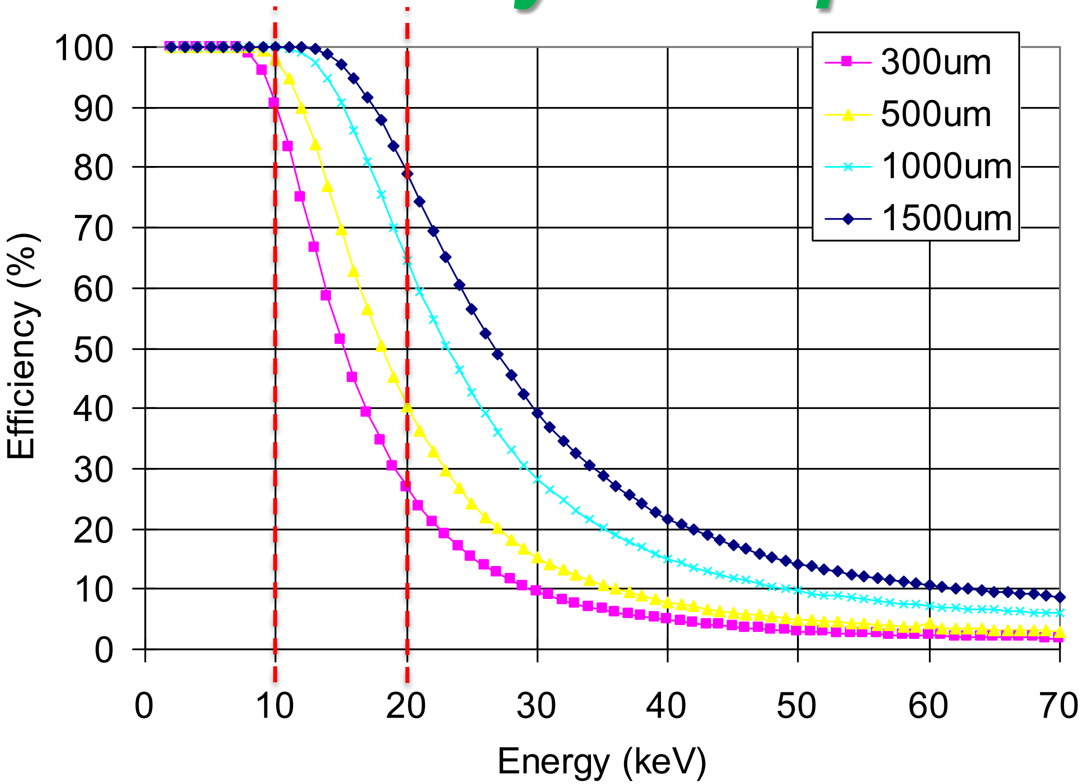
Photon flux in material exponentially decreases with μ (Lambert-Beer's law)

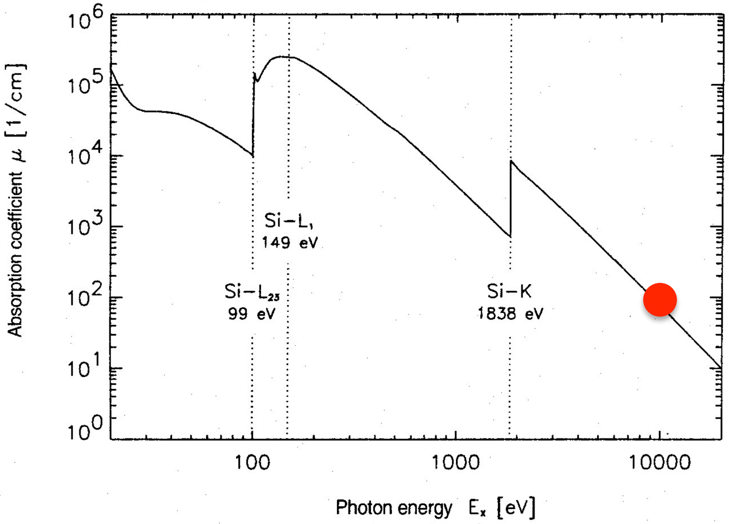


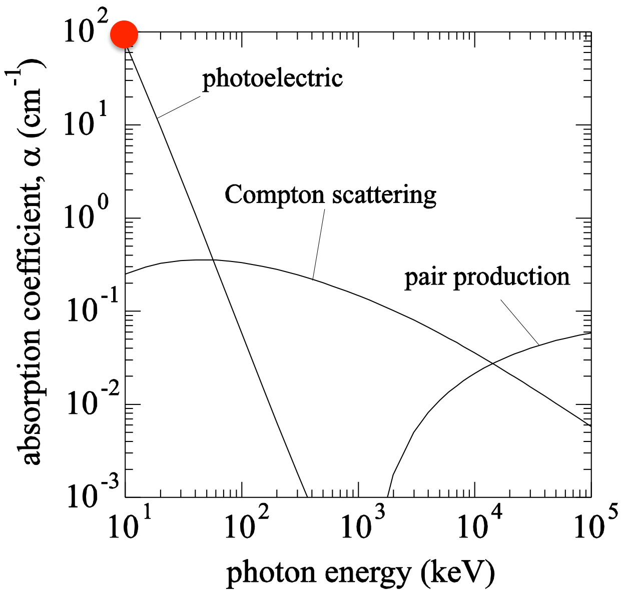




X-ray absorption efficiency in Si



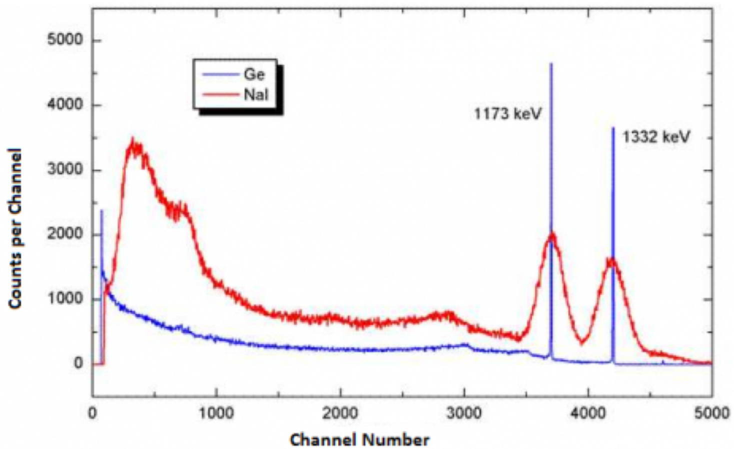




- Absorption coefficient due to photoelectric effect is high at relatively low energies
- Silicon is efficient only up to a few tens of keV
- Entrance window to be optimized for low energies

High-energy photon detection

- Silicon is not efficient for high-energy photon detection
- Other, high-Z semiconductors can be used at RT (e.g., CdTe)
- Best spectroscopic performance achieved with Germanium, but it requires cooling to low temperature (liquid nitrogen → bulky cryostat)
- As an alternative, high-energy photons can be converted into light photons by scintillators
  - radiation induced excitation of the material and return to ground state with UV or visible light photon emission
  - position resolution achievable using scintillator fibers or small columns

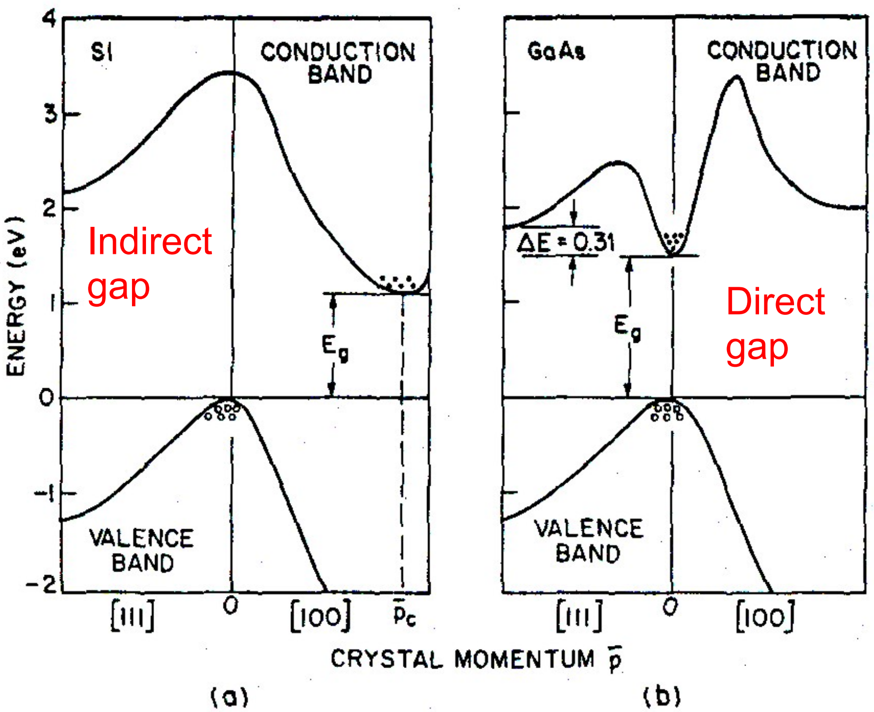


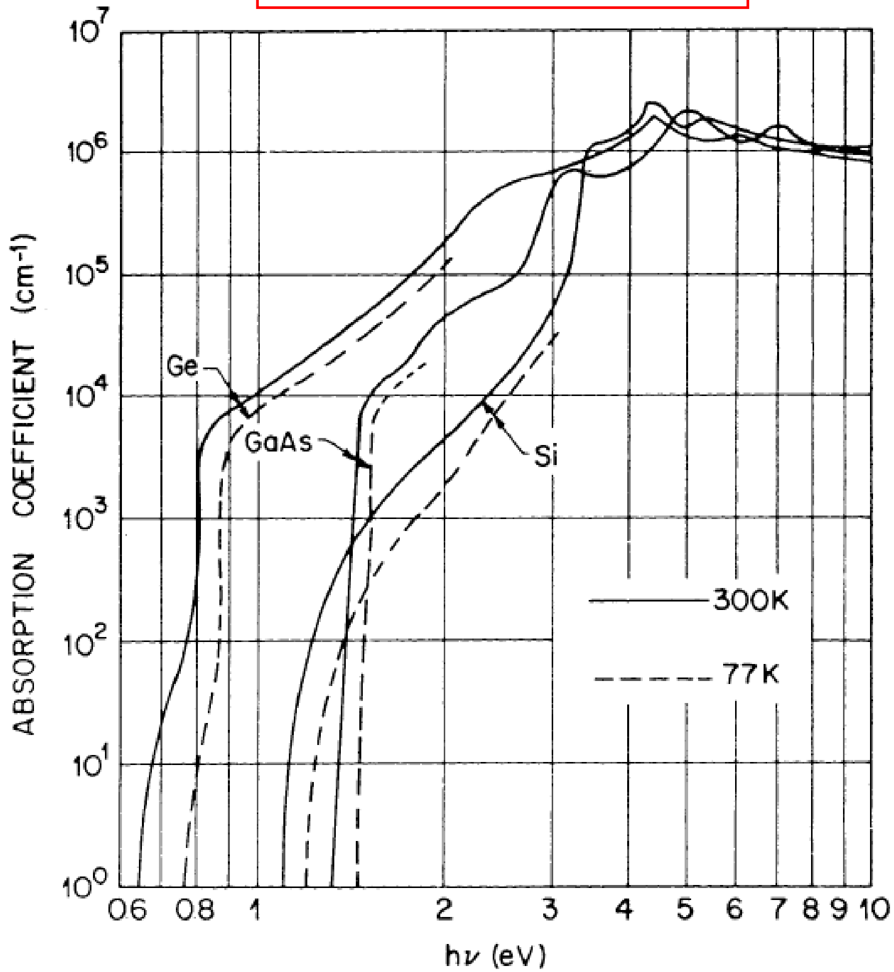
  - important parameters: efficiency, linearity, decay time, emission wavelength compatibility with photodetectors
  - weak light signals: photomultipliers or avalanche based photodetectors

Light detection

- Provided that its energy is larger than the energy gap (E_G) of the semiconductor, a light photon can be absorbed and generate an electron-hole pair
- In Silicon (indirect gap), also a phonon must be involved to ensure momentum conservation law

$$\phi(x) = \phi_0 \cdot e^{-\alpha x}$$





Interaction of neutrons with matter

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

Relative probabilities of different interactions change rapidly with E_n

Cross sections are sizable only at very low energy (slow and thermal neutrons)

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

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

- **fast neutrons:**

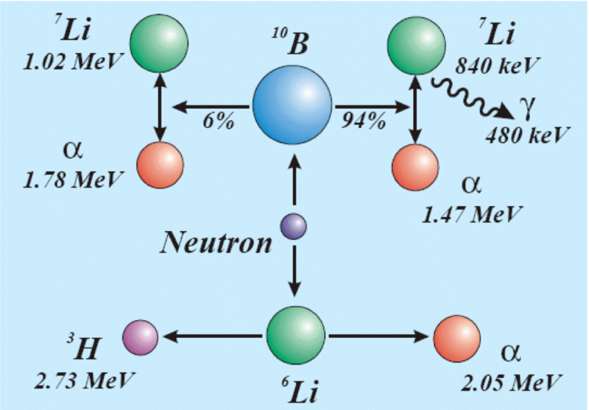
-elastic scattering probability becomes greater → large energy transfer in one collision

→ neutron loses energy and is moderated/slowed to lower energy

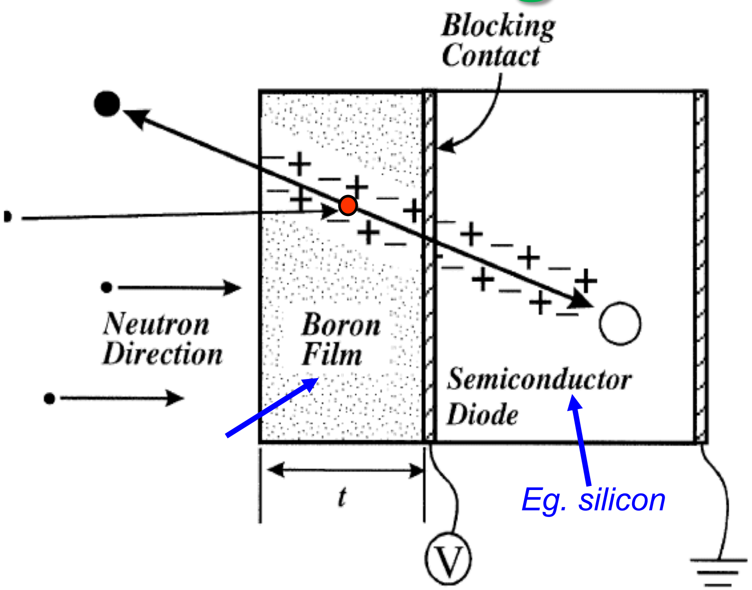
(the best moderator is hydrogen - it can get all n-energy in a single collision)

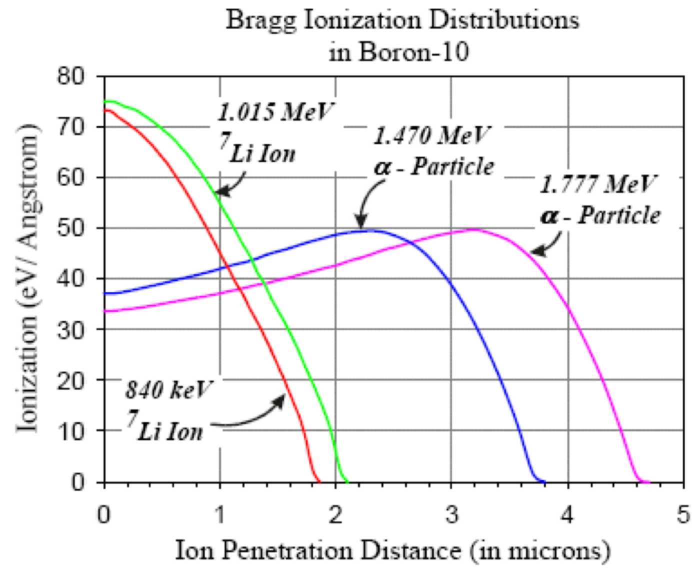
- Inelastic scattering at high energies (break up of target nuclei)

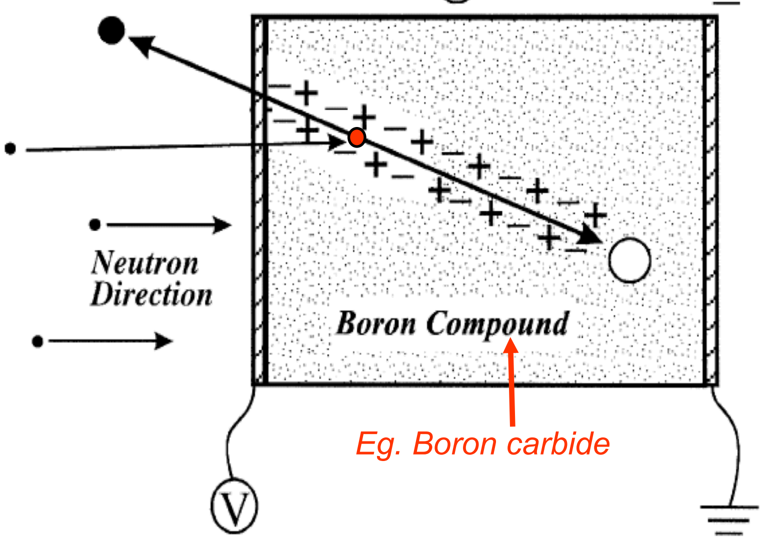
Slow neutrons – converter is incorporated with semiconductor detector (e.g., ^{6}Li or ^{10}B).
Fast neutrons : hydrogen rich converter – direct moderator followed by converter



Detecting neutrons with semiconductors







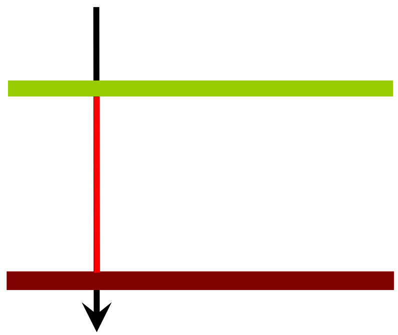
Boron coated silicon detectors have an intrinsic efficiency limit of ~4%:

- ✘ 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.

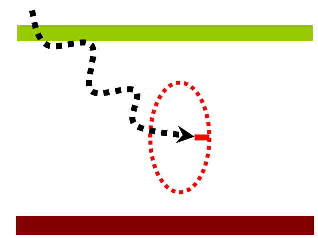
Charge generation in a detector

ionizing particle track



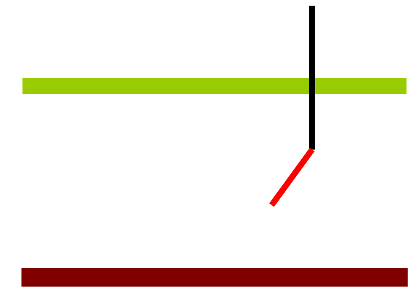
- deposition of e-h pairs along the track
- average 32000 e-h in 300 μm of Si for m.i.p.
- energy loss is distributed (shown later)

Single–photon generation



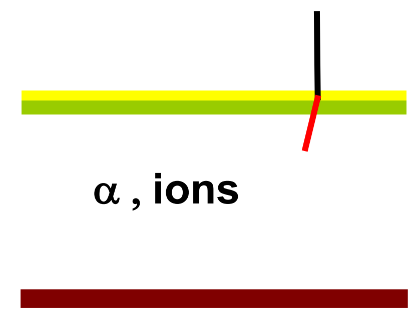
- deposition of e-h pairs close to the point of conversion
- efficiency depends on thickness

α, ions



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

neutrons

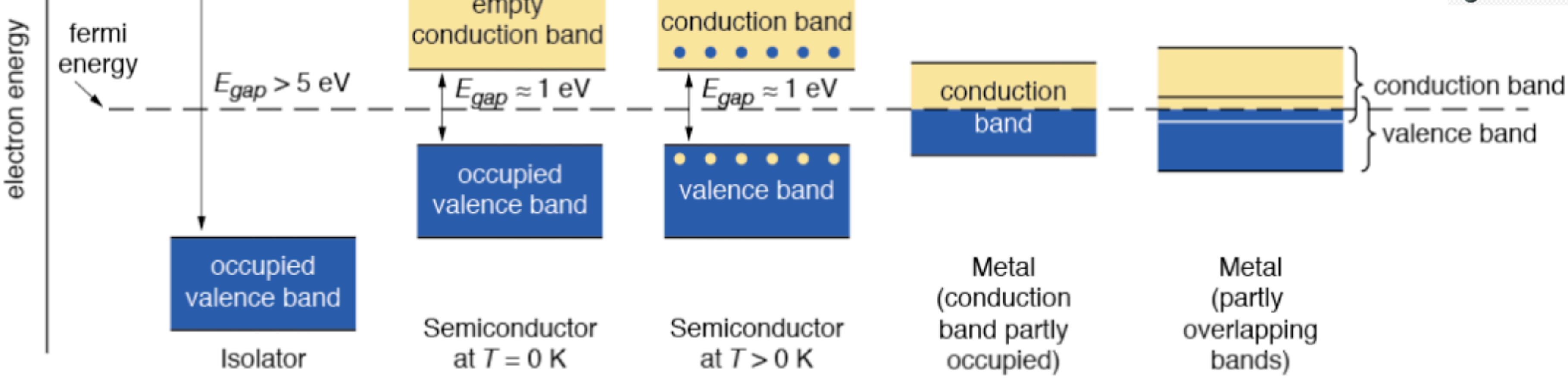


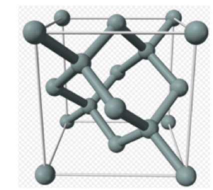
- deposition of e-h pairs near (few μm away) converter – limited efficiency, but detector can be thin

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

Energy bands in crystalline materials

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





In pure silicon the intrinsic carrier concentration is **~1.45·10^{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 electrons 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 (as compared to E_g=1.12 eV)

Charge motion

Excited charges must move in order to be detected

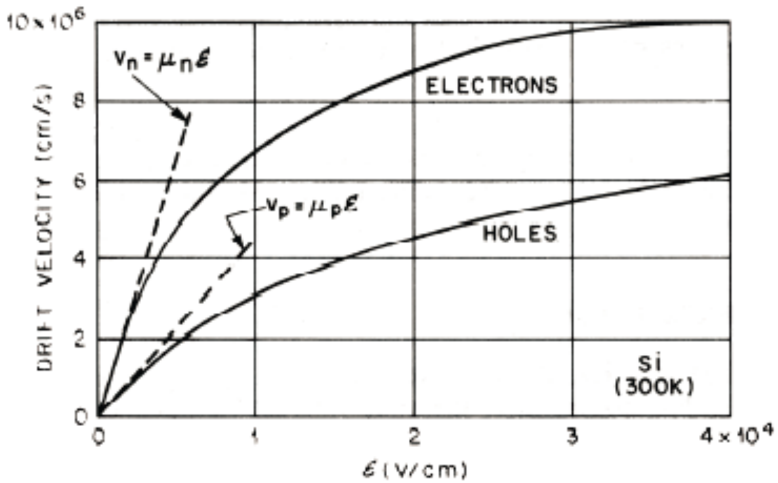
Drift velocity

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 cm^2/Vs μ_p(Si, 300 K) ≈ 450 cm^2/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.

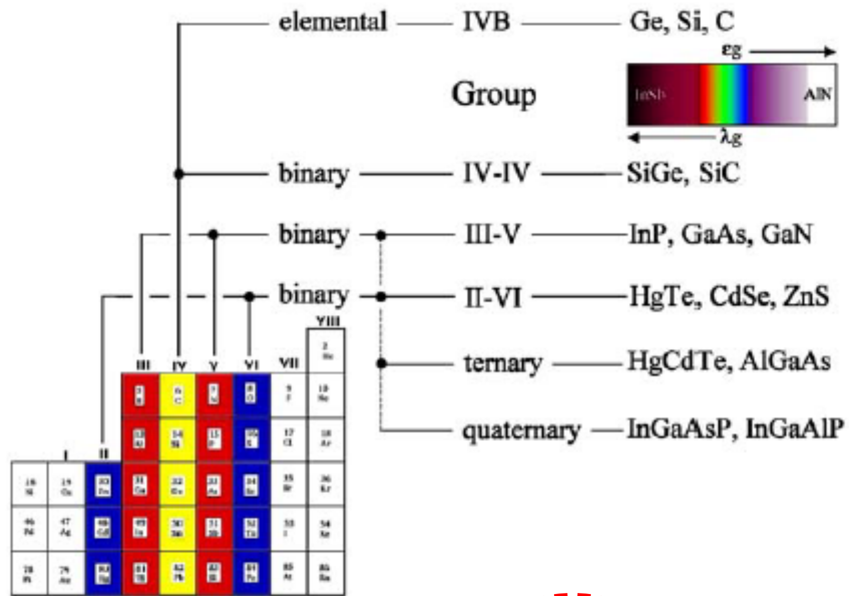
Comparison of different semiconductors

Apart from elemental semiconductors, there are compound semiconductors – mainly used for γ, X-ray detection due to high Z

$$\boxed{I_0 \cong a \cdot E_g + b}$$ Empirical law

The other fraction of the energy lost goes to phonons!

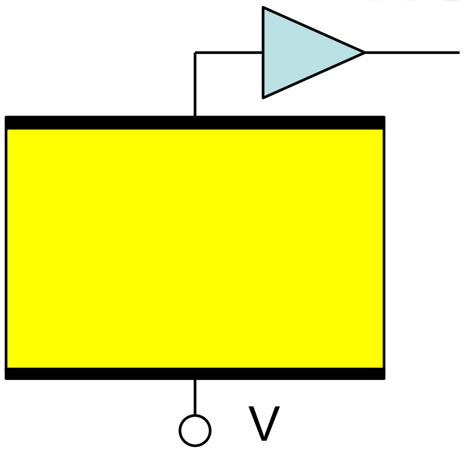
Silicon is by far most studied, understood, manufactured and used (I_0=3.62 eV).



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?



A semiconductor is sandwiched between two metal 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-hole pairs ➔ low ionization energy ➔ small band gap!

✘ Low noise

➔ very few intrinsic charge carriers ➔ large band gap!

Semiconductor as detector material?

A simple calculation for silicon with mean ionization energy ***I_0 = 3.62 eV*** *and 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: $$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6\,\mathrm{eV/cm} \cdot 0.03\,\mathrm{cm}}{3.62\,\mathrm{eV}} \approx 3.2 \cdot 10^4\ \mathrm{e^-h^+ - pairs}$$

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

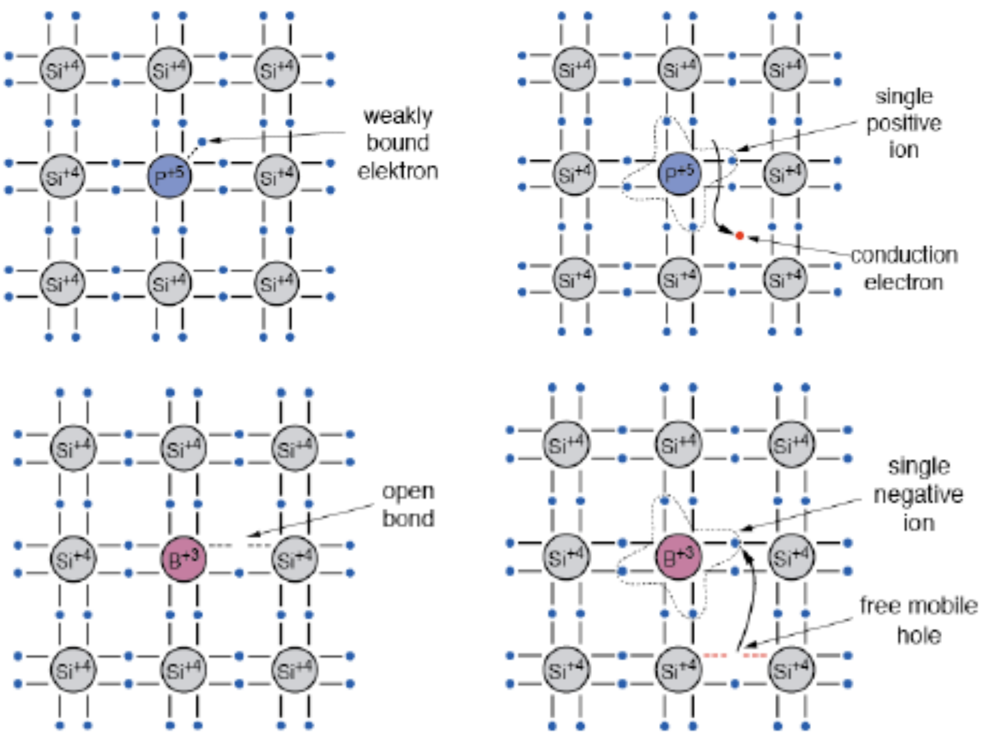
Number of thermally generated e^-–h^+-pairs is 4 orders of magnitude larger than signal!

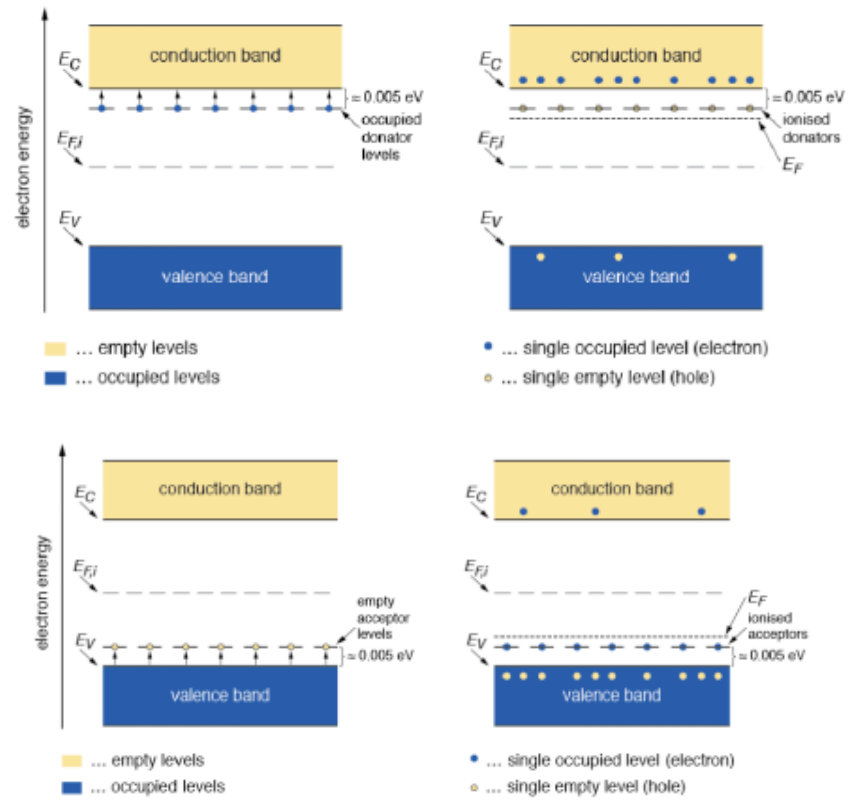
How to reduce it?

- For silicon and other materials with small band-gap one has to reduce the intrinsic carrier charge by:
  - cooling – $n_i \propto \exp(-\frac{E_g}{2k_BT})$
  - **forming a reverse biased P-N junction !**
- For wide band-gap semiconductors (e.g., diamond) the resistivity can be large enough so that they can be operated with ohmic (or Schottky) contacts

Extrinsic semiconductors: n & 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**.

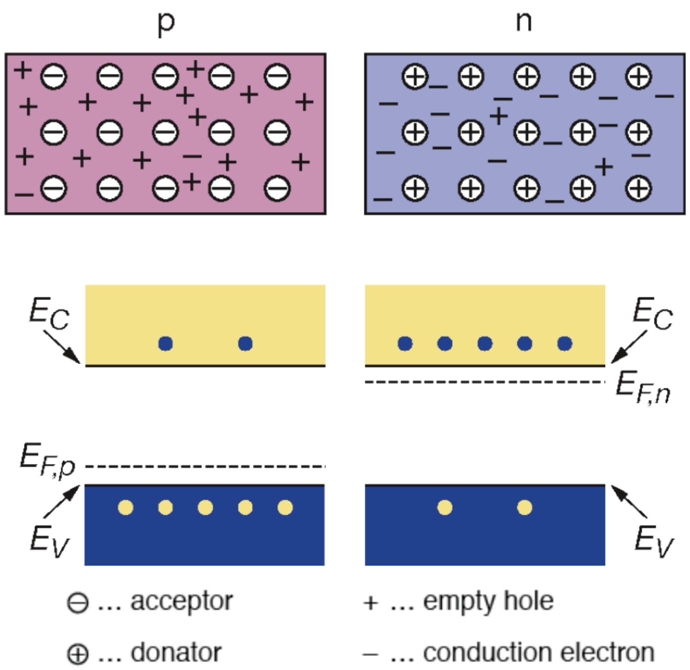


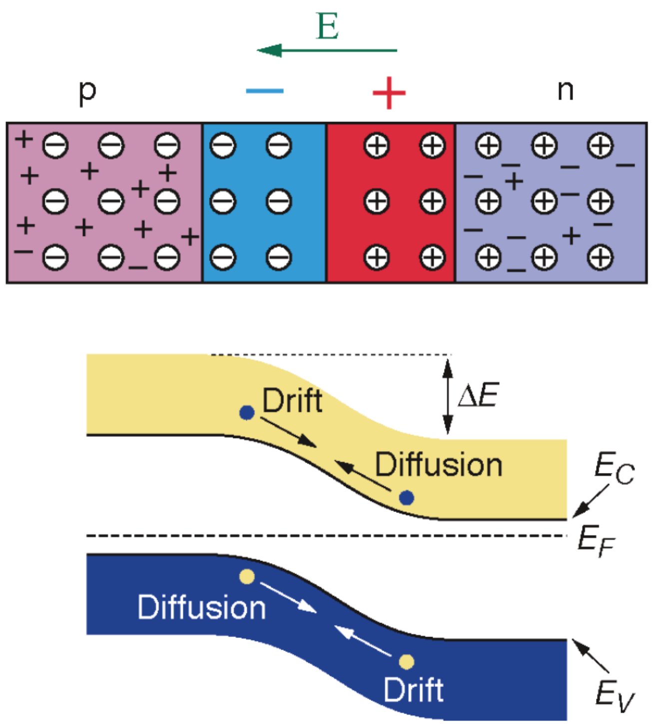


p doping with an element 3 atom (e.g., **B, Al, Ga, In**). One valence bond remains open. This open bond attracts electrons from the neighbour atoms. The doping atom is called **acceptor.** The acceptor atom in the lattice is a negatively charged ion: **N_{eff} is negative**.

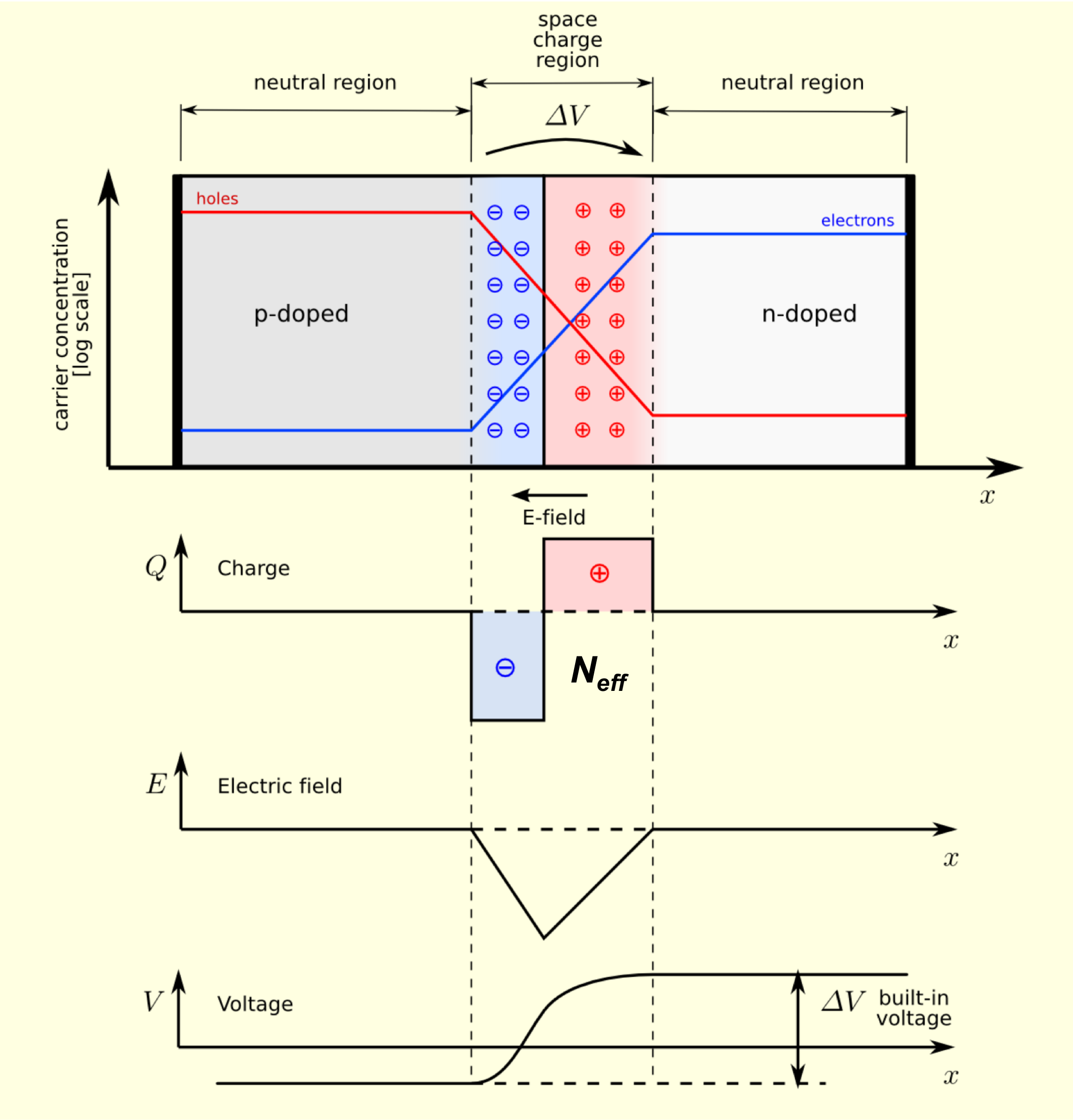
Creating a p-n junction

At the interface of an n-type and p-type semiconductor the difference in the Fermi levels cause diffusion of surplus carriers 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 carriers and is called the depletion zone.





Electric field in p-n junction



Electric field and electric potential follow from Poisson equation (with proper boundary conditions). Under the assumption of space charge region fully depleted from mobile charges:

$$\frac{d^2V}{dx^2} = -\frac{dE}{dx} = -\frac{e_0 \cdot N_{eff}(x)}{\varepsilon_s \varepsilon_0}$$

1st integration: electric field
2nd integration: electric potential

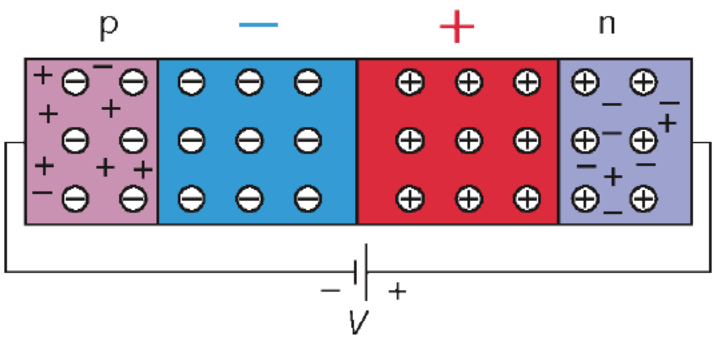
$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

V_{bi} = potential difference between open contacts. Usually one side is far more doped than the other *(e.g., $N_A > N_D$)*

Reverse biased p-n junction

Applying an external voltage V with the cathode to p and the anode to n, more electrons and holes are pulled out of the depletion zone.
→ The depletion region width becomes larger.

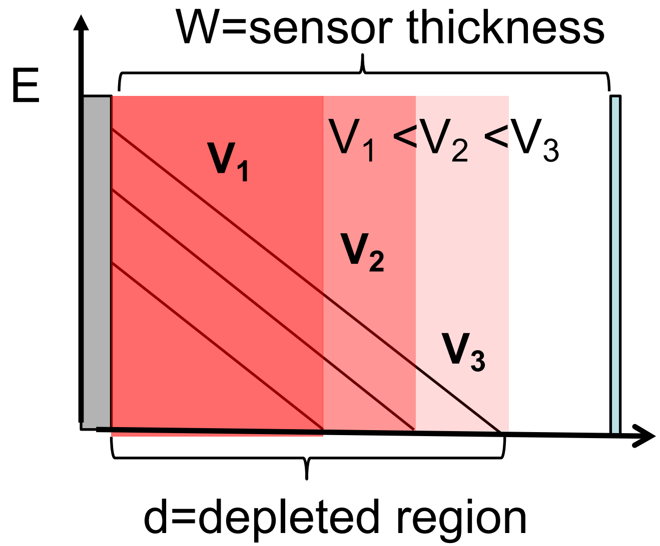
p-n junction with reverse bias



One side of the junction is usually much more heavily doped than the other:

N_A=10^{18} cm^{-3} , W_p=0.027 μm
N_D=10^{12} cm^{-3} , d~W_n=26.9 μm at built-in voltage

$$d \cong \sqrt{\frac{2\varepsilon_s\varepsilon_0(V+V_{bi})}{qN_D}}$$



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

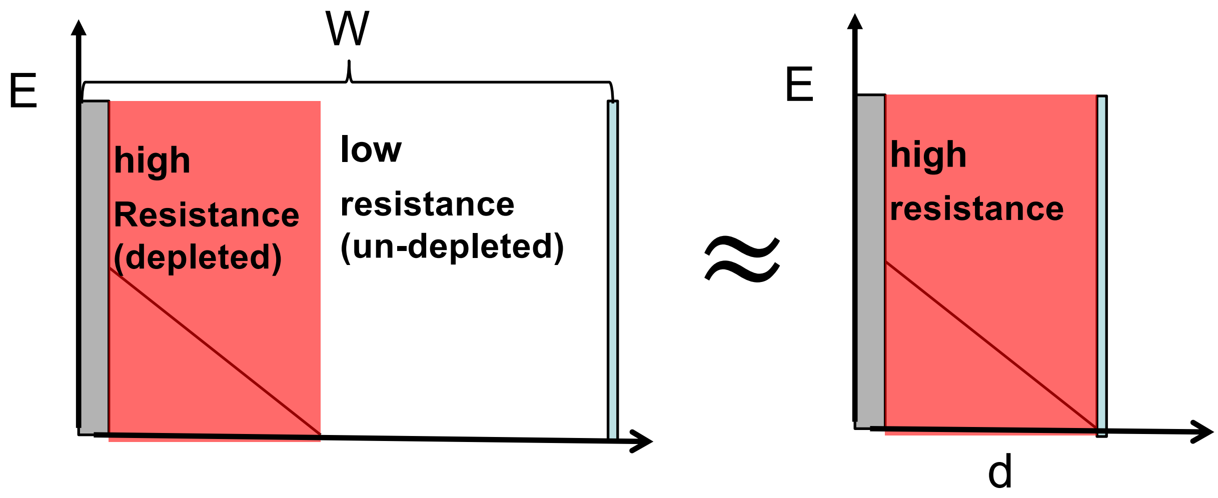
$$V_{FD} \cong \frac{W^2 qN_D}{2\varepsilon_s\varepsilon_0} - V_{bi}$$

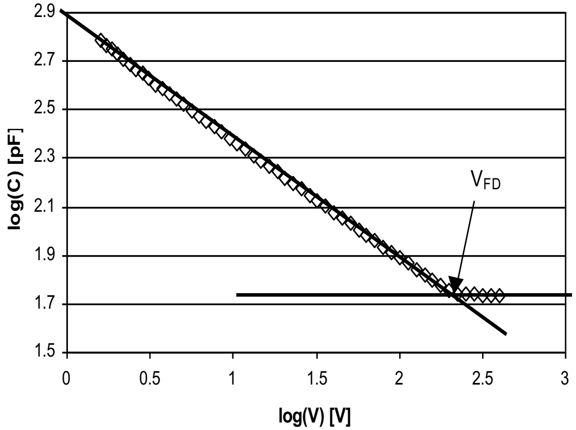
At V_{BD} the electric field becomes so strong that the detector breaks down
(high field - impact ionization – many carriers – breakdown)

Electrical properties - capacitance

$$C = \varepsilon_s \varepsilon_0 \frac{S}{d}$$

At: $V \geq V_{FD}$ $C_{geom} = \varepsilon_s \varepsilon_0 \dfrac{S}{W}$ ⟶ d from *C(V)*





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

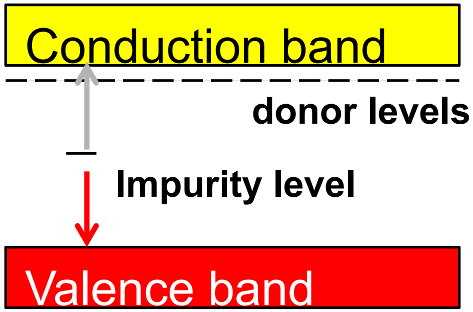
Capacitance of the electrode plays a mayor role in electronics noise

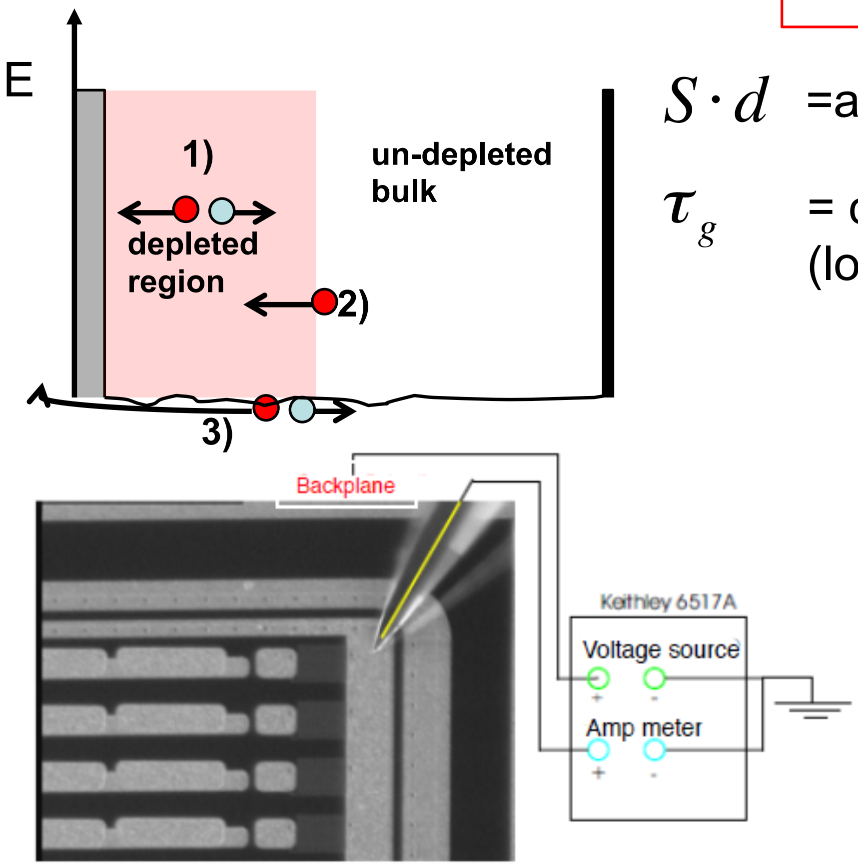
Leakage current/dark current

It is present in any semiconductor and comes from:

1) Generation at mid-gap impurities
2) Diffusion from un-depleted bulk
3) Edge and surface effects

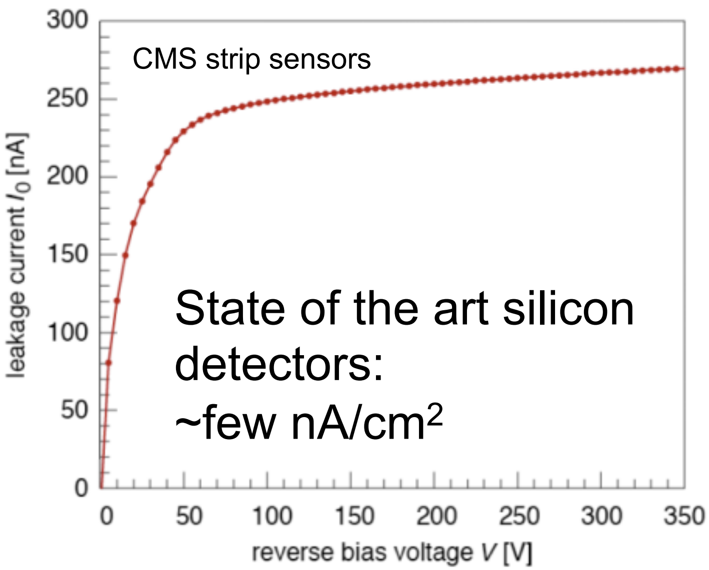
$$\boxed{I_g = \frac{e_0 n_i}{\tau_g} \cdot S \cdot d}$$





$S \cdot d$ =active (depleted) volume

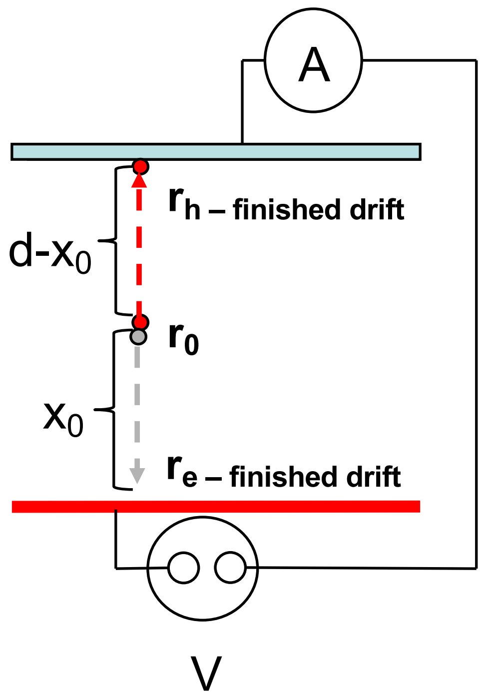
τ_g = carrier generation lifetime (long for good quality material)



State of the art silicon detectors: ~few nA/cm²

Signal formation

Signal formation – pad detector



- First look at the simple pad detector (fully depleted) with electrodes connected to low impedance.
- Whenever generated charge moves in the detector it induces current at the electrodes according to Ramo's theorem (electrons and holes don't need to reach electrodes, they couple to electrodes and induce mirror charges):

S. Ramo, Proc. I.R.E. 27 (1939) 584,
E. Gatti et al., NIM 193 (1982) 651.

For a simple pad detector: $I = q\dfrac{v}{d}$

$$Q = \int_0^t I\,dt = q\int_0^t \frac{v}{d}\,dt = q\cdot\frac{x-x_0}{d}$$

$$Q_{e-h} = Q_e + Q_h = -e_0\cdot\left(\frac{0-x_0}{d}\right) + e_0\cdot\left(\frac{d-x_0}{d}\right) = e_0$$

- 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 dependence of the signal on starting point of the drift.

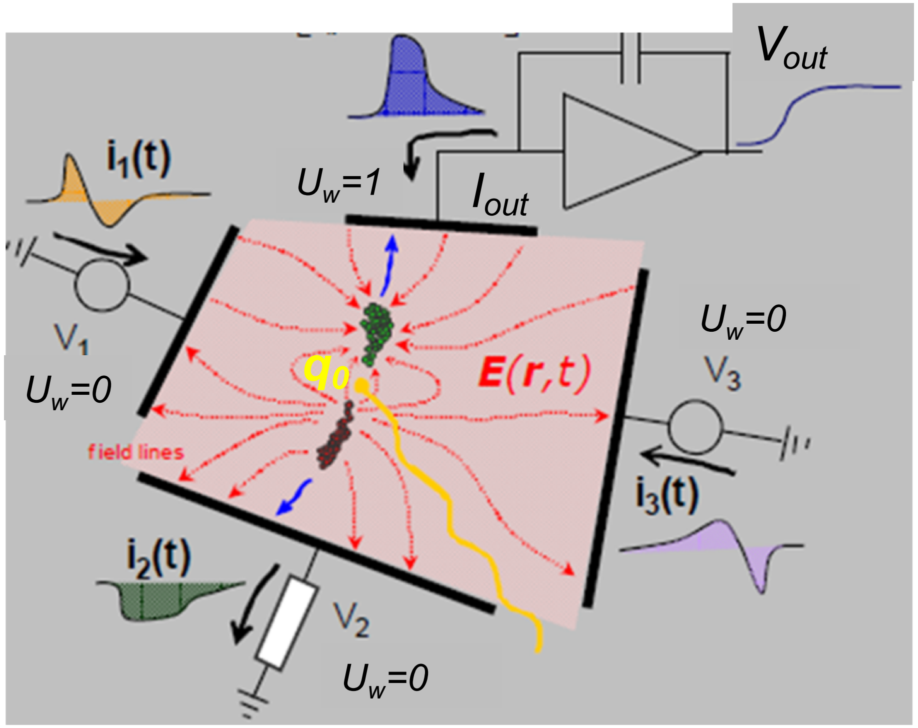
Signal formation – segmented detectors

- Induction of current at the considered electrode is done through the concept of weighting field
- The related concept of weighting potential is obtained by setting the potential of the electrode to 1 and the potentials of all other electrodes to 0.

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

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

$$\vec{E}_w = -\nabla U_W$$



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

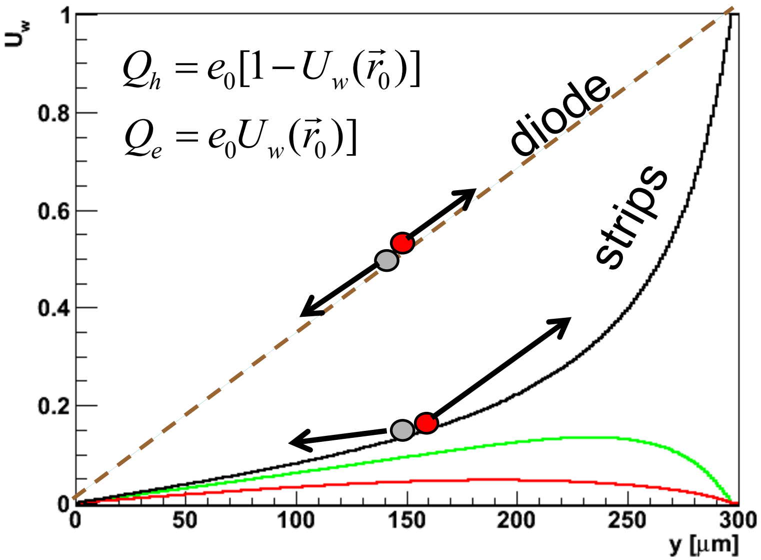
$$\boxed{Q_{e,h} = e_0[U_w(\vec{r}) - U_w(\vec{r}_0)]}$$

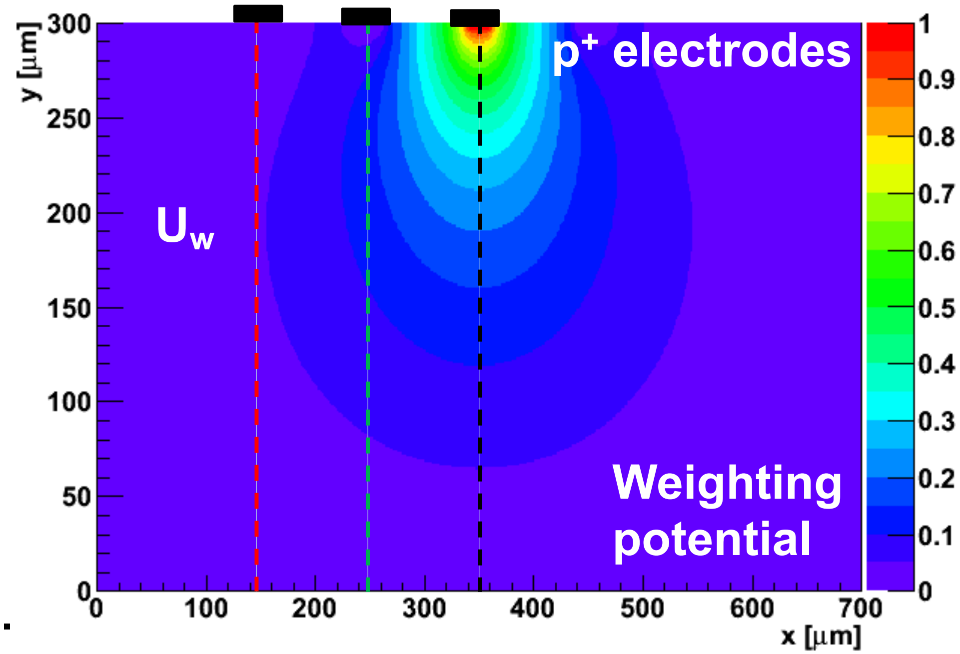
$$Q_{e-h} = Q_e + Q_h$$

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

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

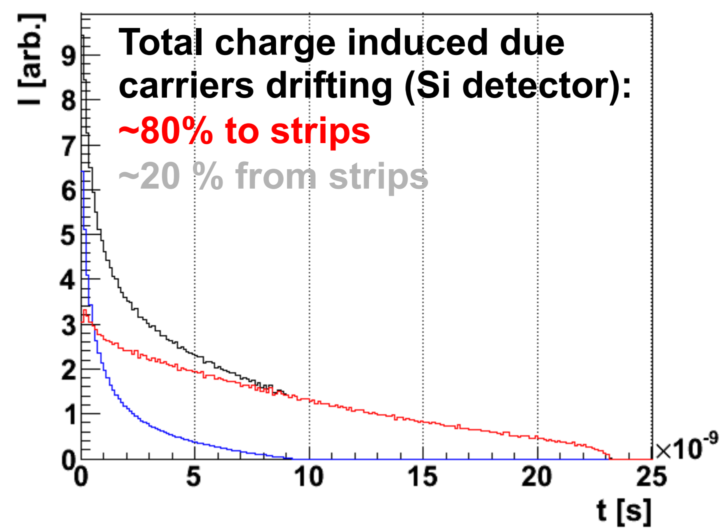
U_w in strip detector and diode



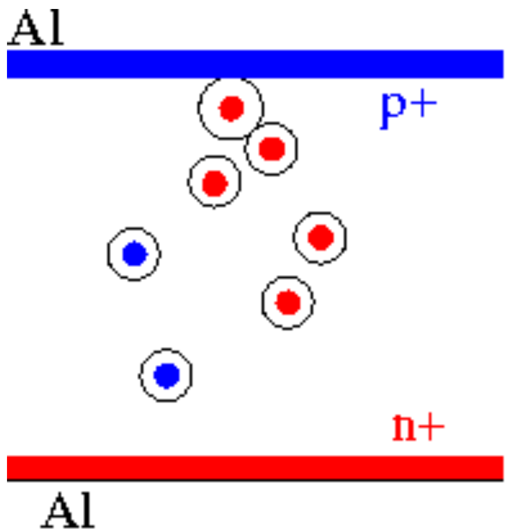


The dashed lines denote the U_w along the line.

- 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 (bipolar pulses).



Incomplete drift



Ramo's theorem corrected for trapping:

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

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 crystal growth (energy levels in the band gap) - not in silicon detectors though
  - Charges trapped at the defects introduced by irradiation
- Integration time of the current is smaller than the drift time (ballistic deficit)

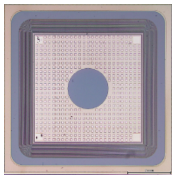
Mean Free Path - can be directly related to induced charge

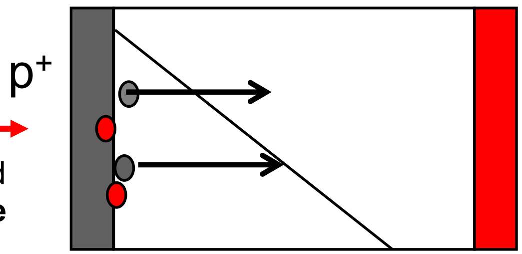
$$\lambda_{e,h} = \tau_{eff,e,h}\,\mu_{e,h} \cdot E$$

often taken as a figure of merit

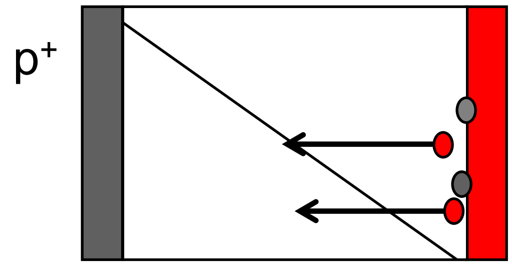
E. Butz and M. Bruzzi tomorrow

Example of measured induced currents



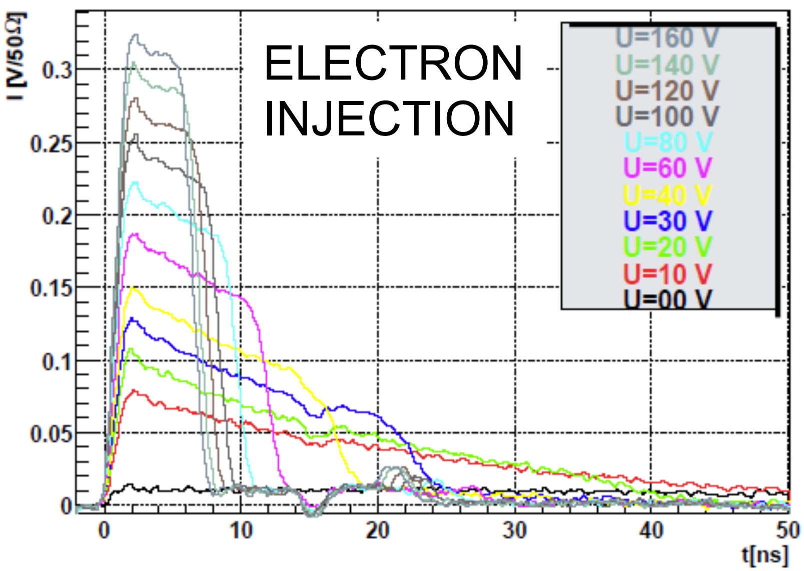


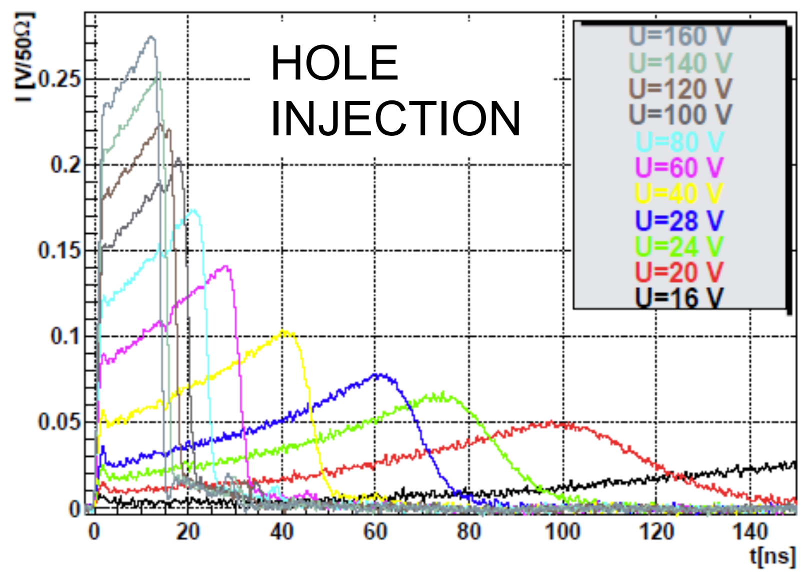
Illumination by a red
660 nm laser pulse
or α particle



Illumination by a red
660 nm laser pulse

or α particle



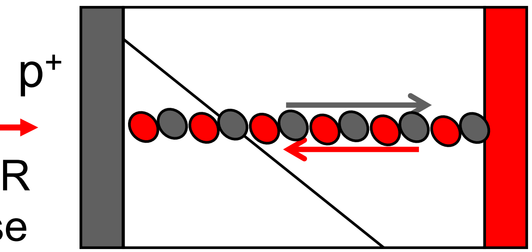


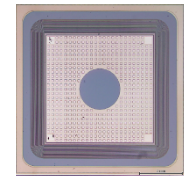
p-n pad detector (15 kΩ cm, n type, 300 μm thick)

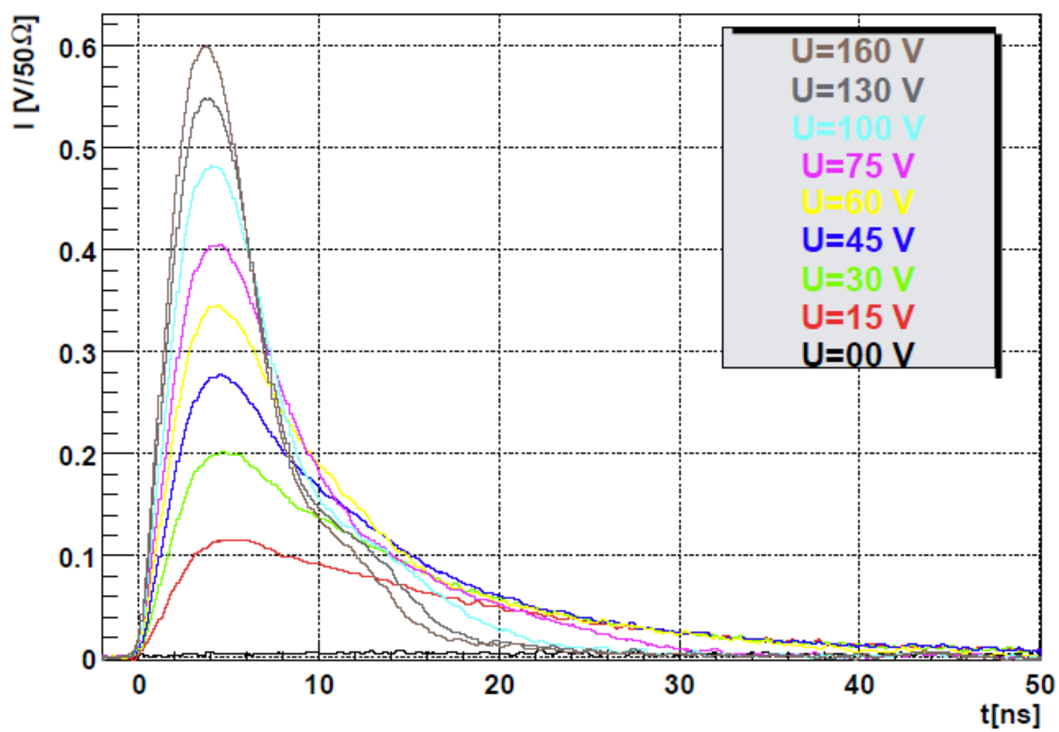
Remember – the shape of *I* gives you the shape of *electric field* !

Example of measured induced currents

Illumination by an IR 1065 nm laser pulse

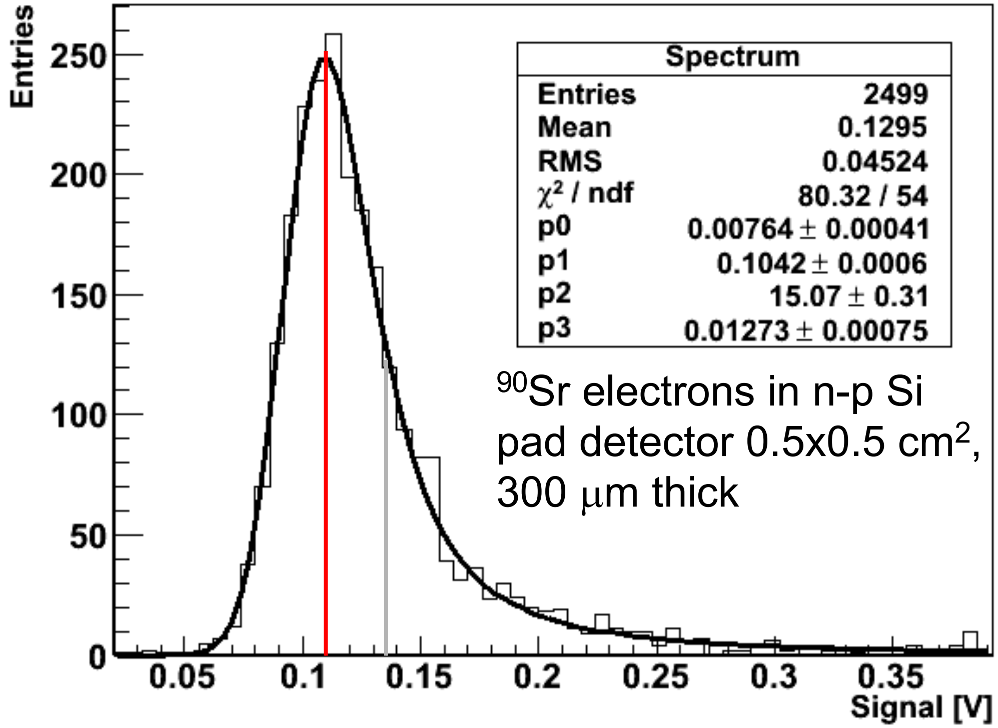


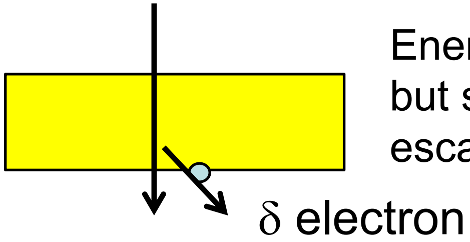




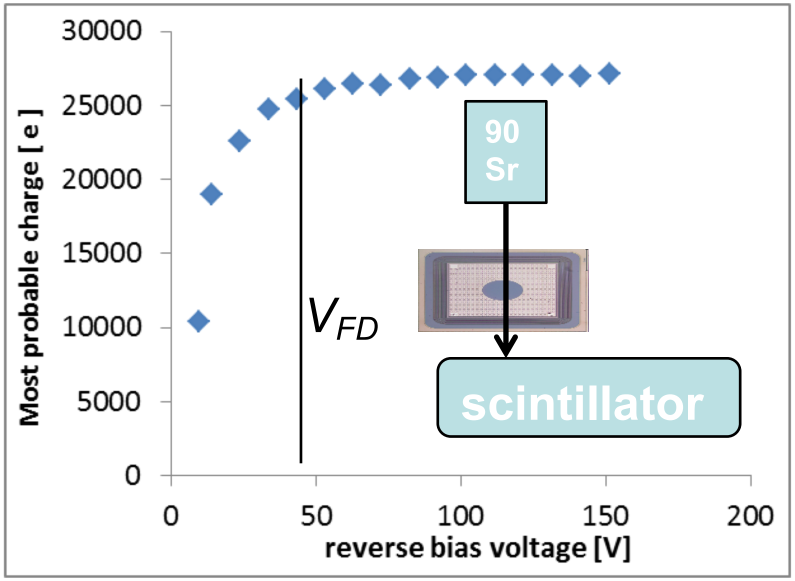
Example : mip particles in Si

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 escapes with δ electron



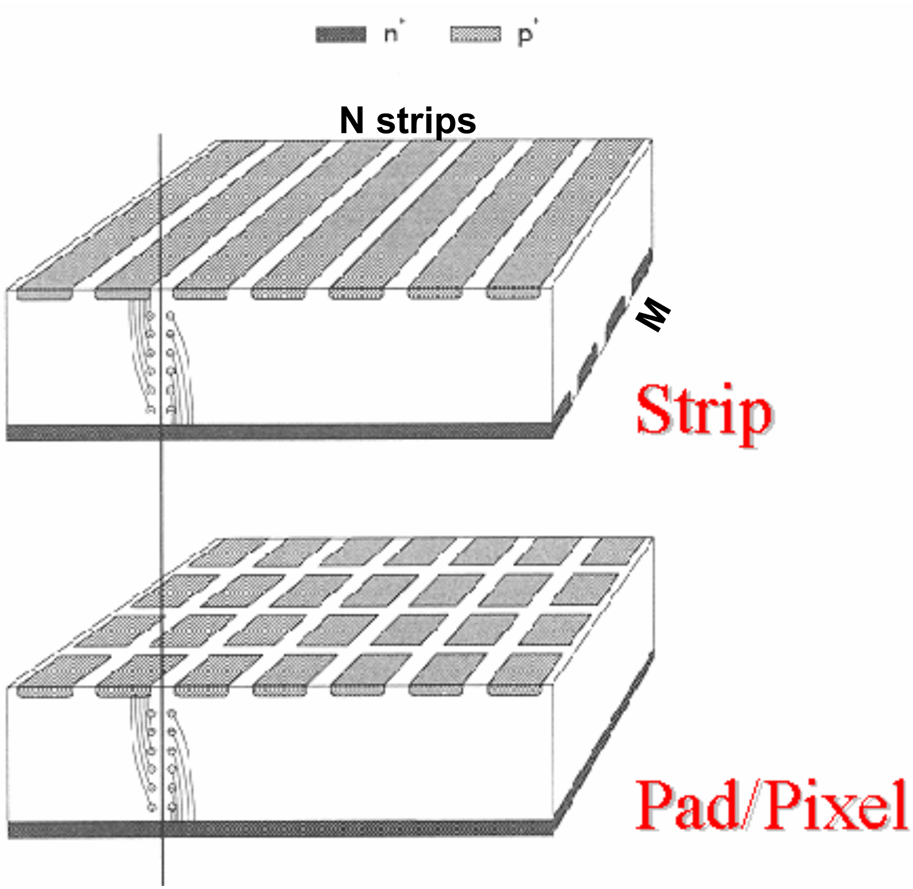
- Mip signal (MPV): 72 e/μm, 22600 in 300μm:
- Medium/mean signal 300 μm: 32400 (~30% higher)

Performance of segmented detectors

Properties of segmented detectors

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

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

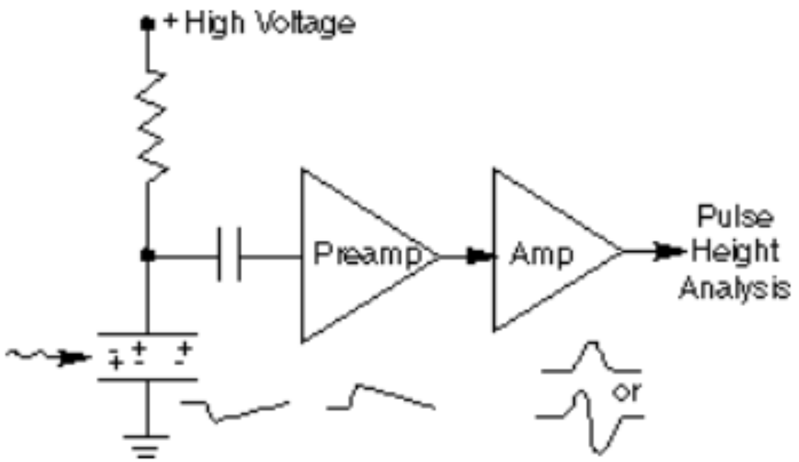


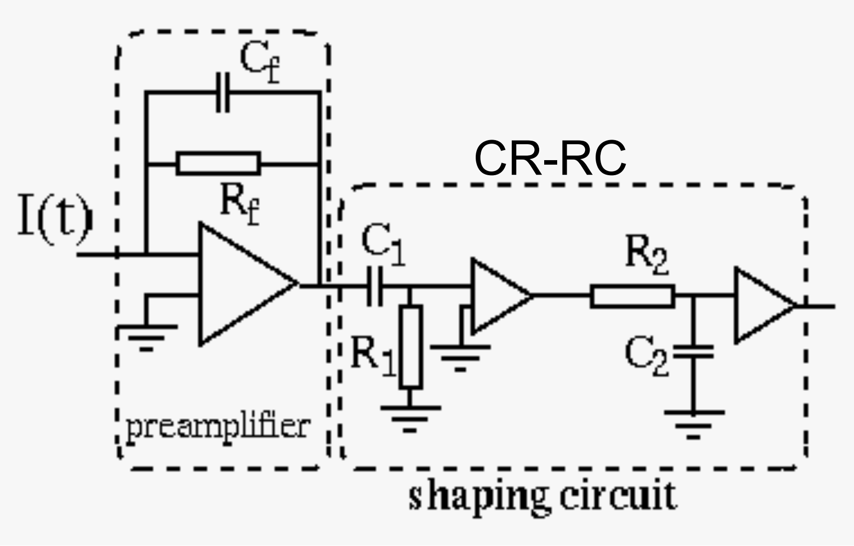
- Strips are not suitable for high rate applications (ambiguous determination for several simultaneous hits)

- 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-out with charge-sensitive amplifiers followed by pulse shaping circuits to optimize the noise performance

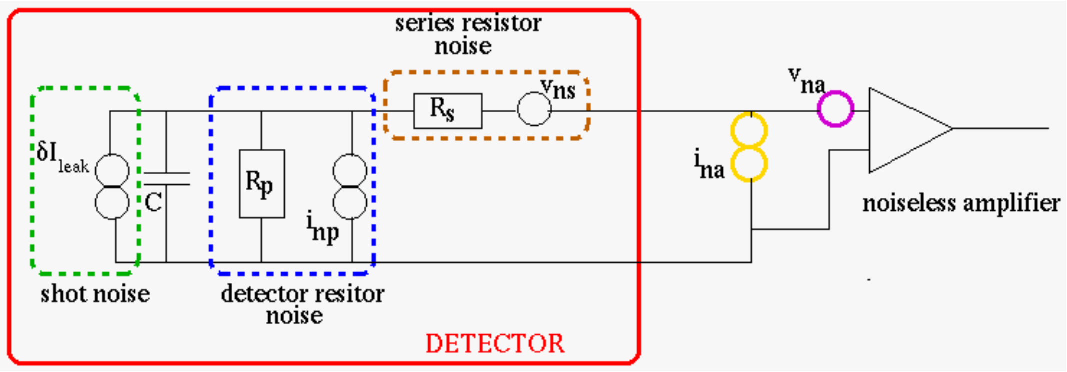




- The most important parameter is Signal-To-Noise ratio (SNR)
- **The noise** in a silicon detector system depends on various parameters: geometry of the detector, the biasing scheme, the readout electronics, etc.
- Noise is typically expressed in terms of "Equivalent Noise Charge" (ENC). This is the amount of charge at the input terminal of the detection system that would give rise to a unitary S/N

Equivalent Noise Charge

- Regarding the origin of the noise from the detector we talk about voltage (series noise) 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 (e.g., bias resistor)
  - Voltage noise (v_n = noise voltage) – increases with detector capacitance:
    - Series resistance noise - ENC_{Rs}



V. Re lecture on Wednesday

Amplifier 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

Position resolution (1)

The position resolution is the main parameter of detectors for tracking and imaging systems – excellent for semiconductor detectors.
It depends on various factors: device physics and the design of the system.

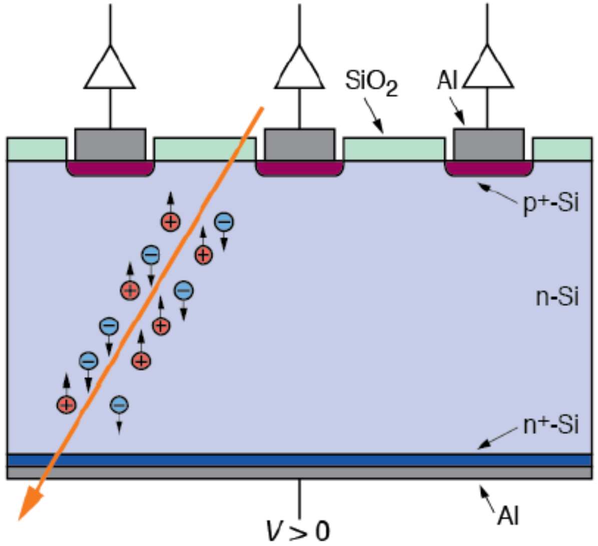
Physics processes:

- 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 parameters:

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

Strip/Pixel charge determines position of the hit

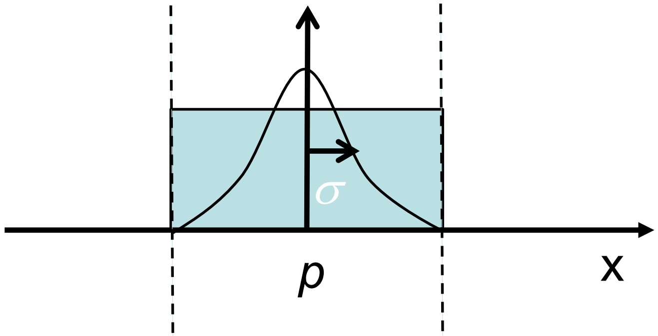


Position resolution (2)

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 i-strip, Q_i=signal at the i-strip

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

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

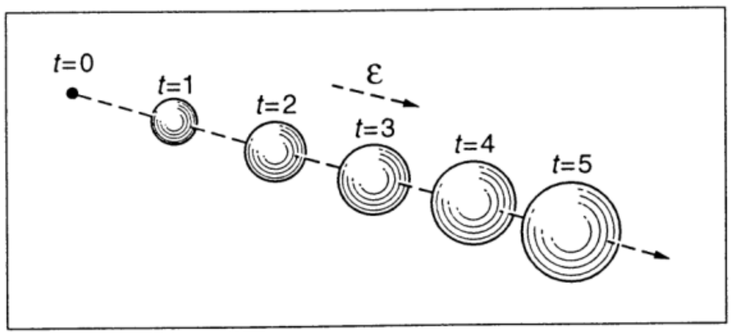
$$\sigma \propto \frac{p}{S/N}$$

Position resolution: diffusion

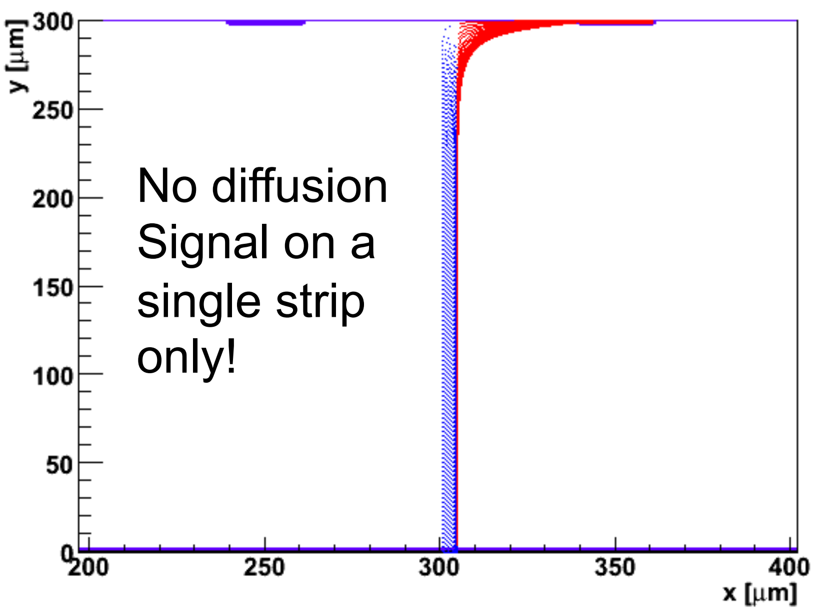
Electrons and holes in the detector move by drift and **diffusion.**
The width (rms) of the charge cloud increases with time *t* as :
Note: $D \propto \mu$ *and* $t \propto 1/\mu$, *hence* σ_D *is equal for* e^- *and* h^+.

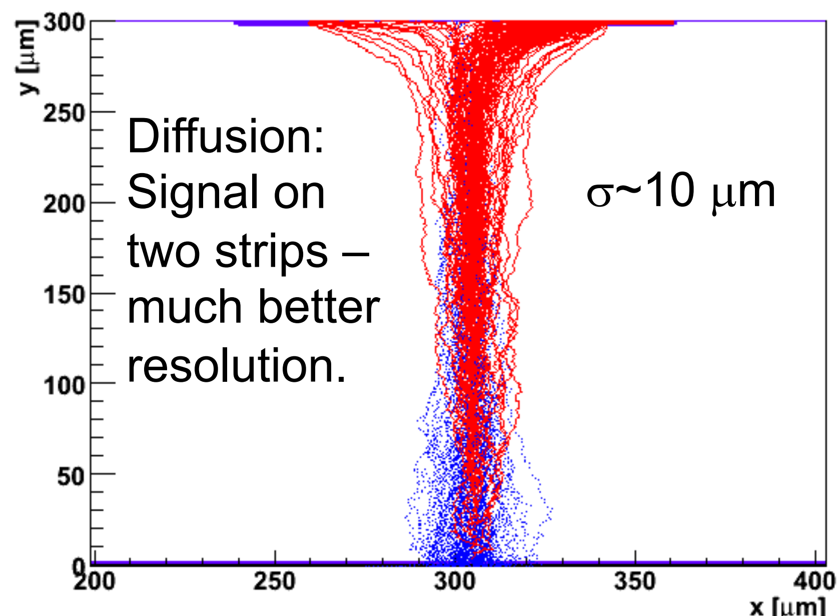
$$\sigma_D = \sqrt{2Dt}$$

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



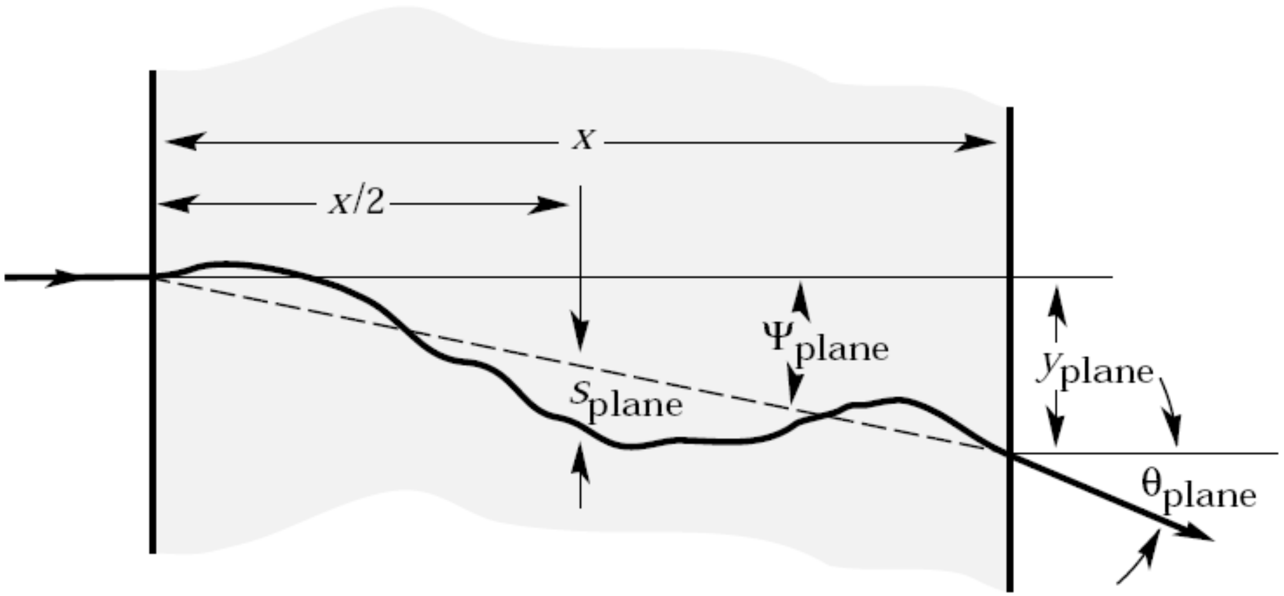
σ_D width of the charge carrier distribution
t **drift time**
D **diffusion coefficient**
k_B Boltzmann constant
T temperature
e_0 electron charge
μ charge carrier mobility





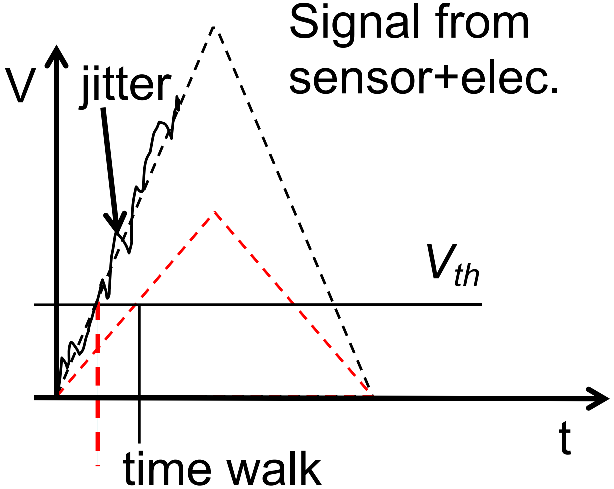
Position resolution : Multiple scattering

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



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

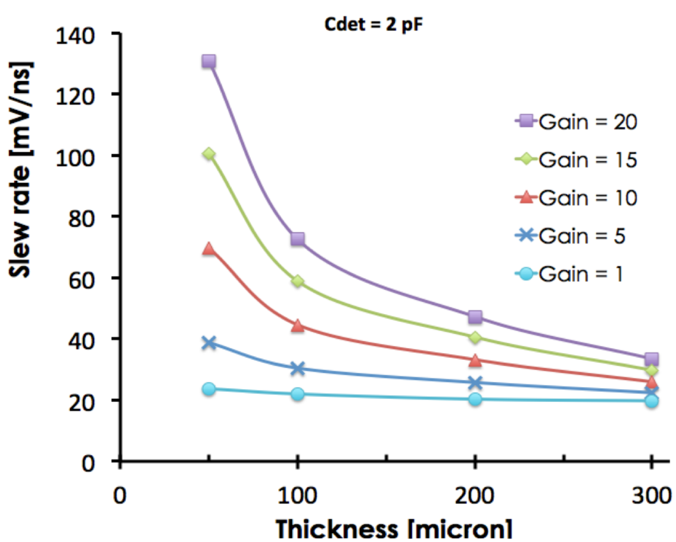
Time resolution

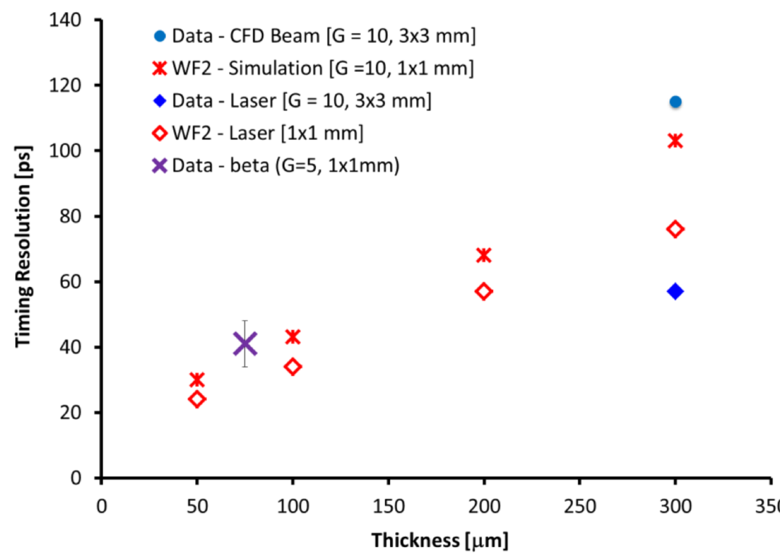


More from N. Cartiglia tomorrow

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

time walk ↑ noise jitter ↑ TDC ↑





Energy resolution of detectors

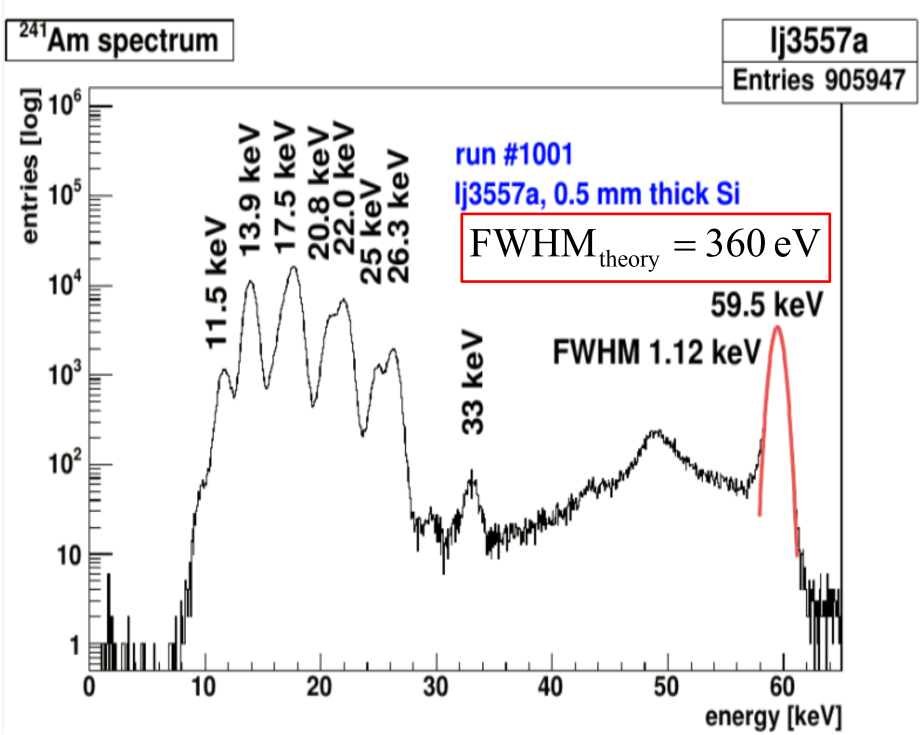
Energy resolution is determined by:

Physics processes:

- Statistical fluctuations of the deposited energy
  - Fano factor (F accounts for corrections to Poisson statistics)
  - 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:

$$\boxed{\frac{\delta E}{E} = 2.35\frac{\sqrt{FI_0}}{\sqrt{E}}}$$

Fano factors:

Si = 0.11

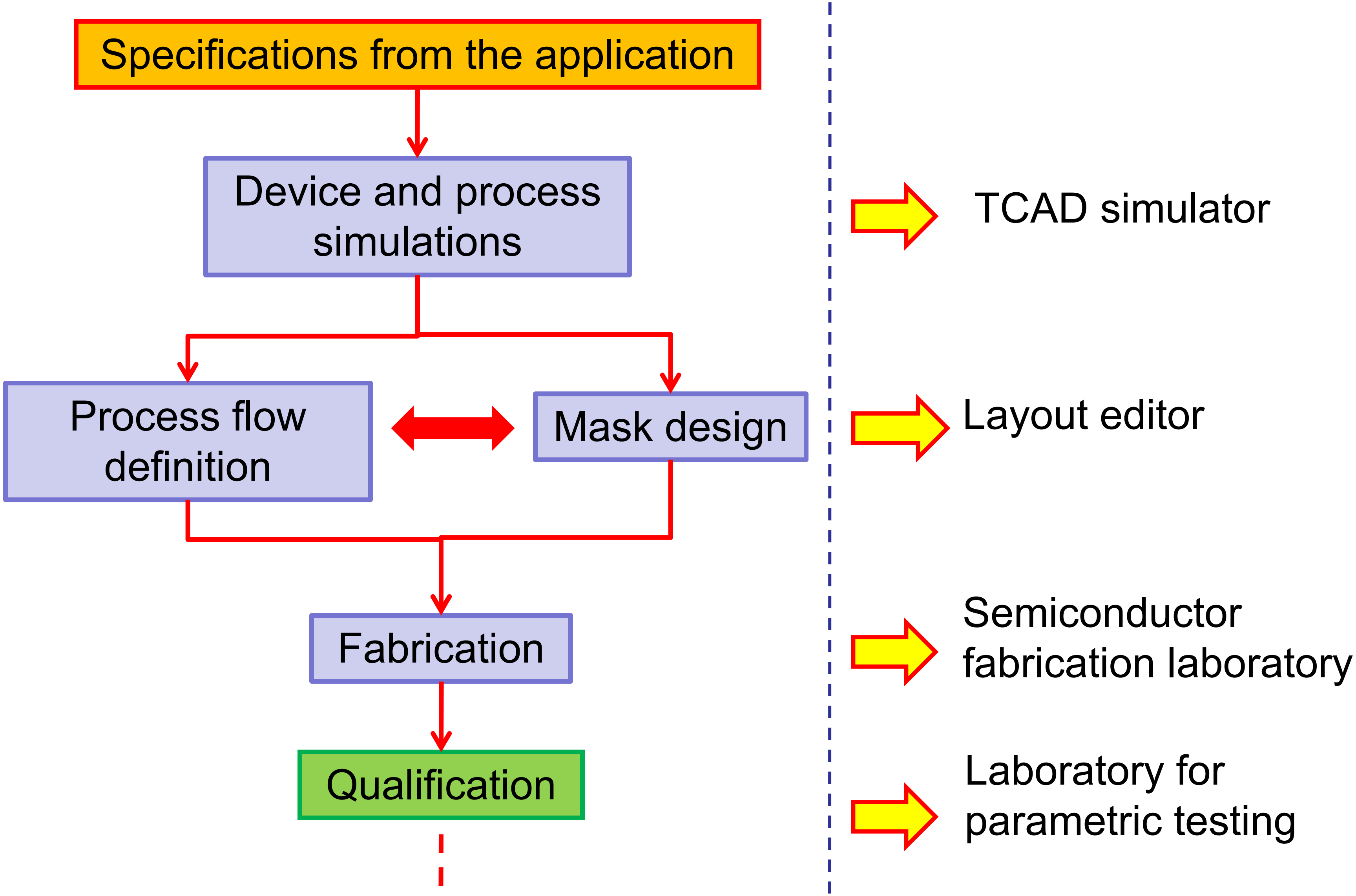
CdZnTe= 0.09

Diamond=0.08

Methods and tools

Methods

Tools



TCAD simulator

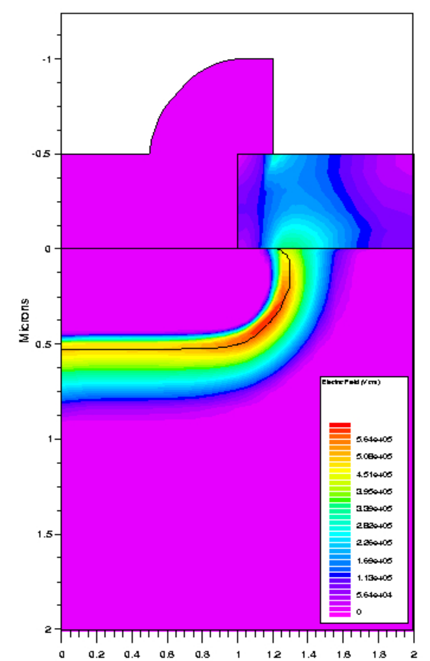
Process simulator
physical modeling of semiconductor fabrication processes

- ion implantation
- high-temperature processes
- topography simulation
- …

Device simulator
physical modeling of electrical behavior of a semiconductor device

- static properties
- dynamic behaviour
- response to radiation
- mixed-mode simulations.

Example: electric field distribution

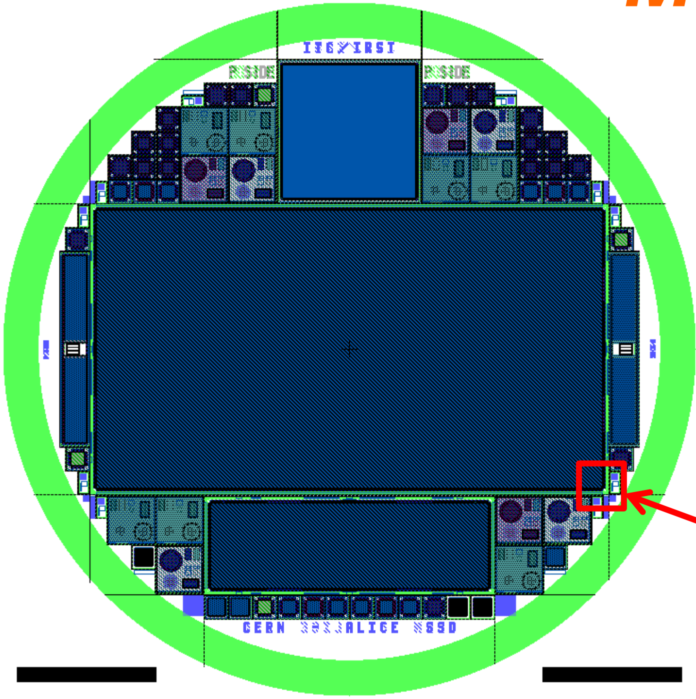


Physically-based simulation provides 2 main advantages:
- it is predictive
- it provides insight

Objective: Minimize long, costly real world experimentation in terms of fabrication and testing

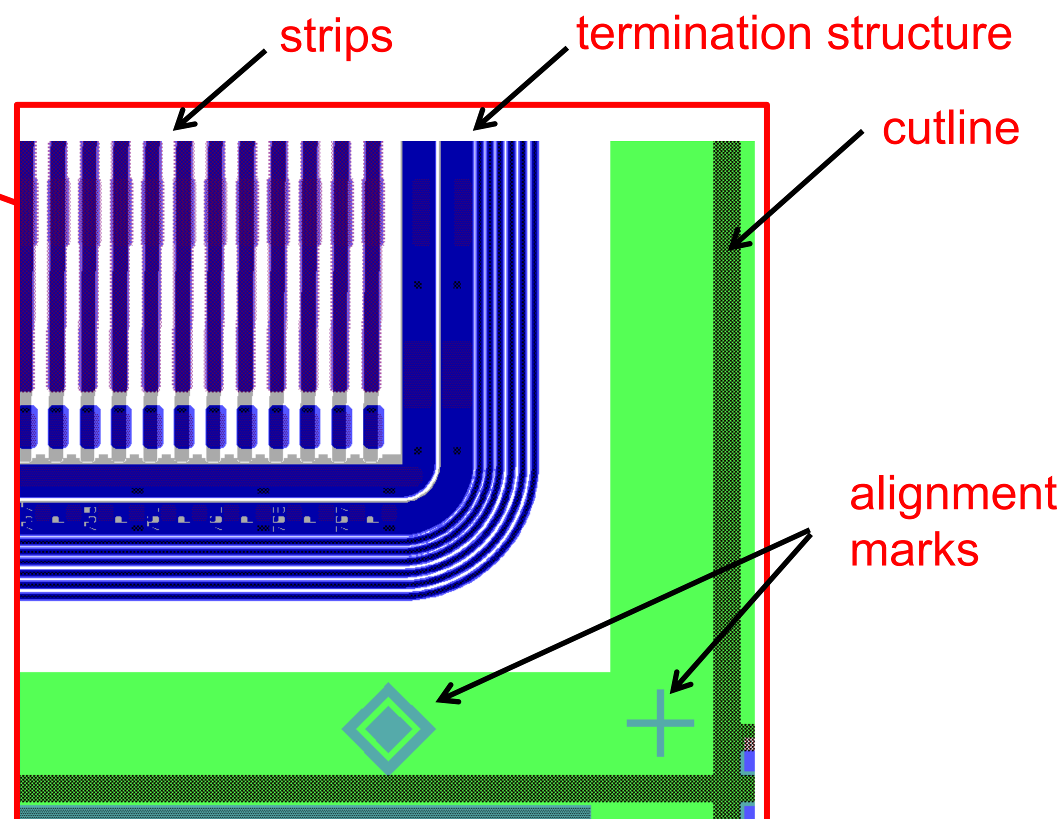
Mask layout editor

Software which allows the design of the geometry of the levels (masks) involved in the fabrication process of a given device.



Full wafer view of all the layers (12) of a double-sided silicon strip detector

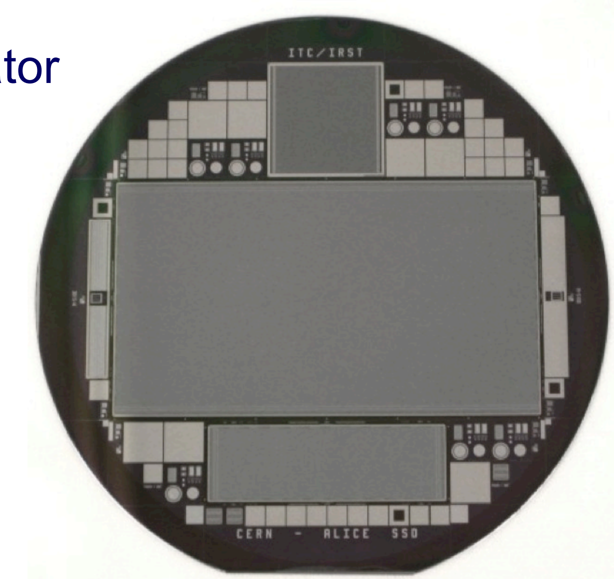
Detail view of the detector corner (only front side layers, 5)



light gray = p implant
green = n implant
dark gray = contact vias
blue = metal
violet = passivation vias

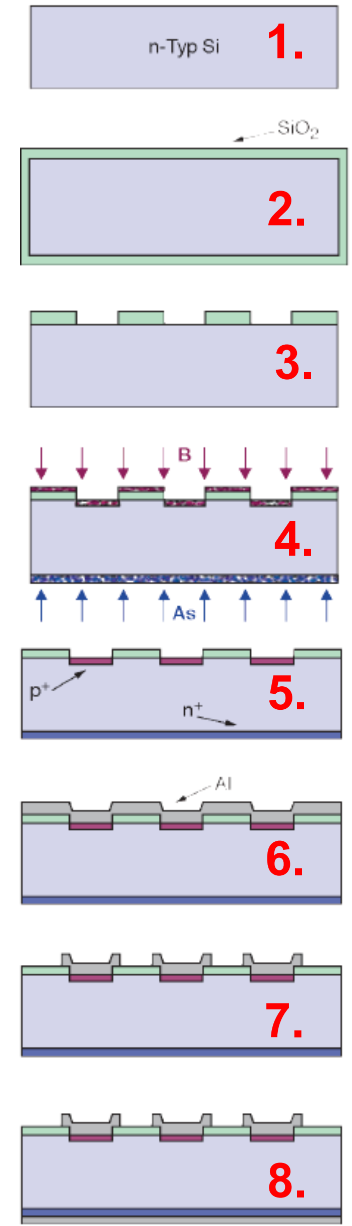
Silicon foundry

EQUIPMENT
- Ion Implanter
- Furnaces
  * dry/wet oxidation
  * oxide and nitride deposition
  * polysilicon deposition
  * B & P diffusion
  * annealing/sintering
- Litho (Mask Aligner)
- Dry & Wet Etching
- Sputtering & Evaporator
- …



Main issues in sensor technology:
- Large Area (Yield …)
- Low defect density
- Low leakage current

Fabrication of a silicon detector



1. Starting Point: single-crystal n(p)-doped wafer ($N_D \approx 1 \cdot 10^{12}$ cm^{-3})

2. Surface passivation by SiO_2-layer (approx. 200 nm thick). E.g. growing by (dry) thermal oxidation at ~1000 ° 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, $N_A \approx 5 \cdot 10^{15}$ 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 a temperature of at least 600° C, (activation of dopant atoms by incorporation into silicon lattice)

6. Metallization of front side: sputtering or evaporation

7. Removing of excess metal by photolithography: etching of non-covered areas

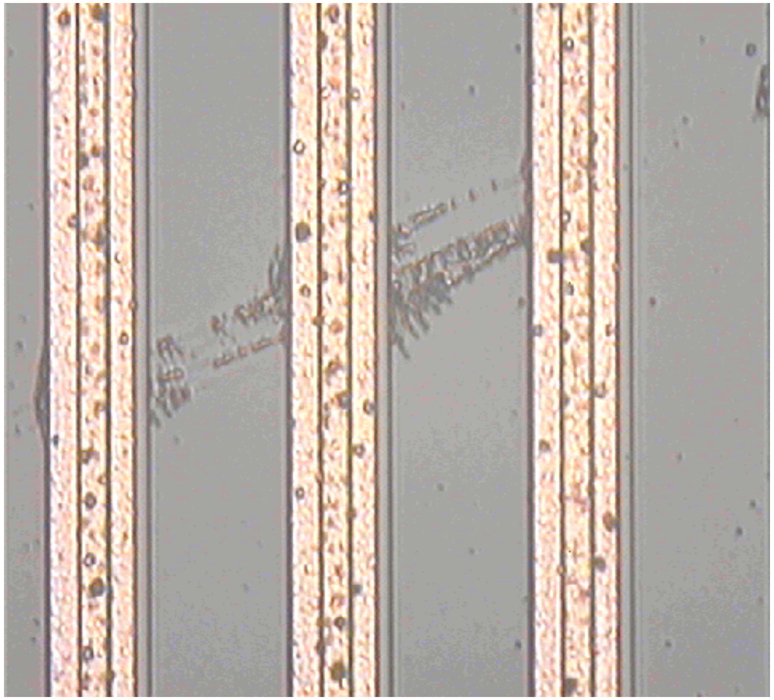
8. Full-area metallization of backplane with sintering at approx. 450° C for better contact between metal and silicon

Last step: wafer dicing (cutting)

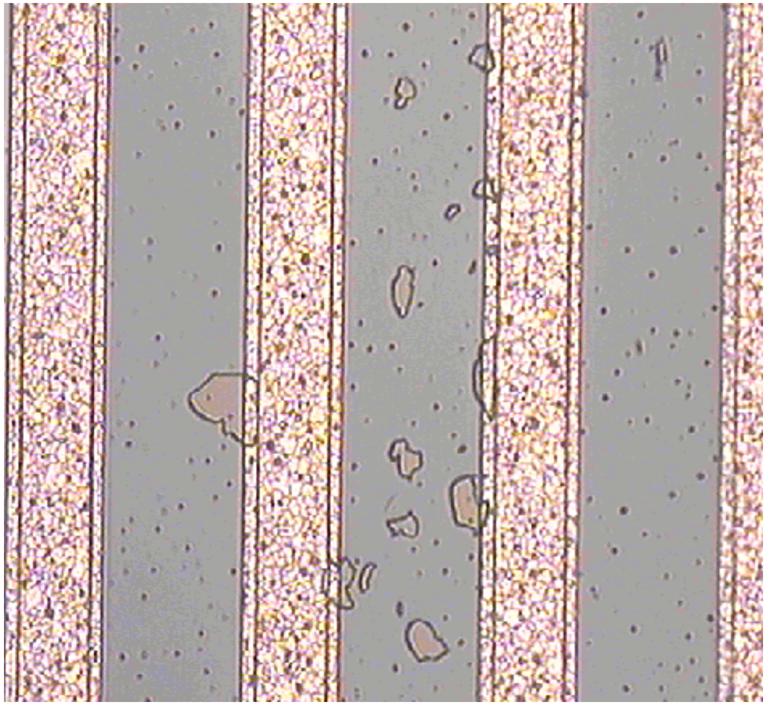
J. Kemmer, NIM 169 (1980) 499.

This example: DC coupled micro-strip detector.

Optical inspection
(looking for defects)



Microscratch
(bad handling)

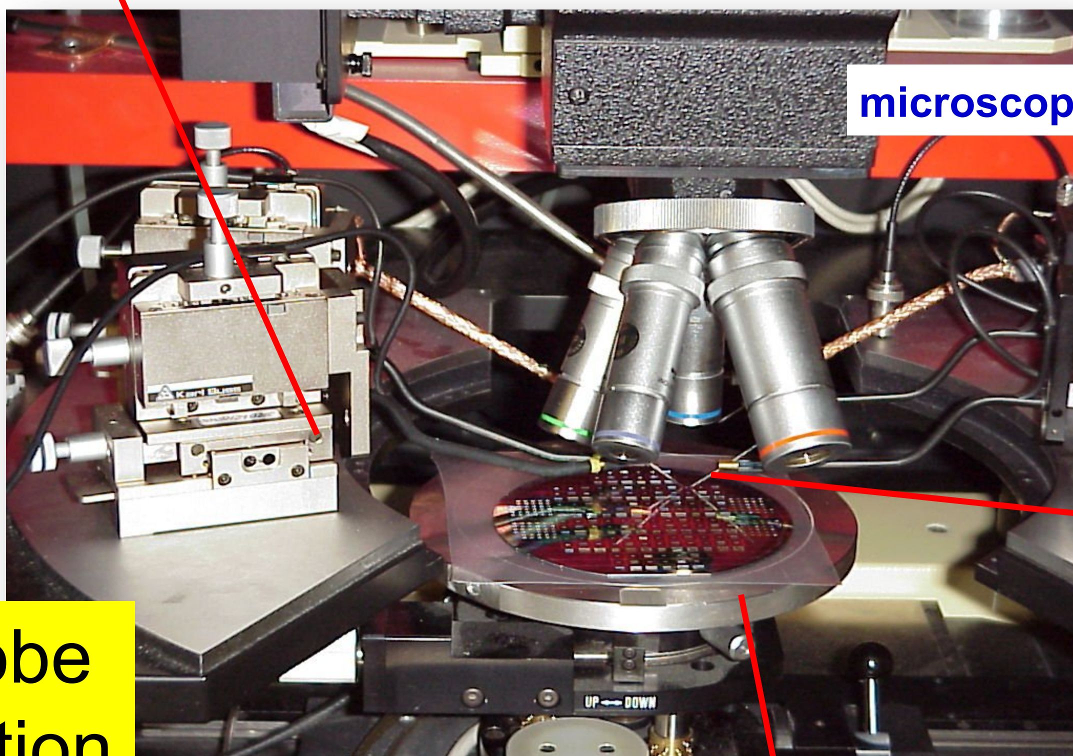


Parasitic implant
(litho problem)

Laboratory for parametric testing

Monitor the process quality and device functioning.
Usually done at the wafer level with a probe station.

micromanipulators (XYZ fine movements)



micron-sized probe tips

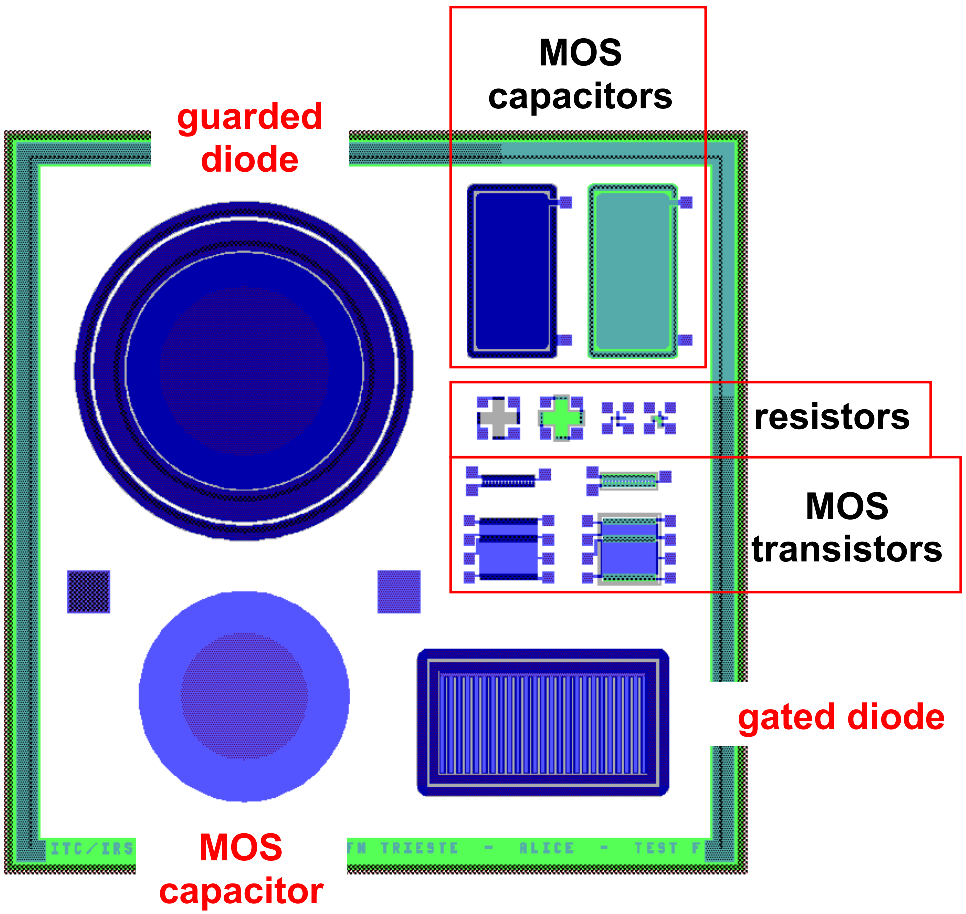
wafer support "chuck" (XYZ movements)

Basic instrumentation:

- Semiconductor parameter analyzer (with programmable channels - SMU)
- LCR meter

Parametric Tests

On dedicated test structures to qualify the process



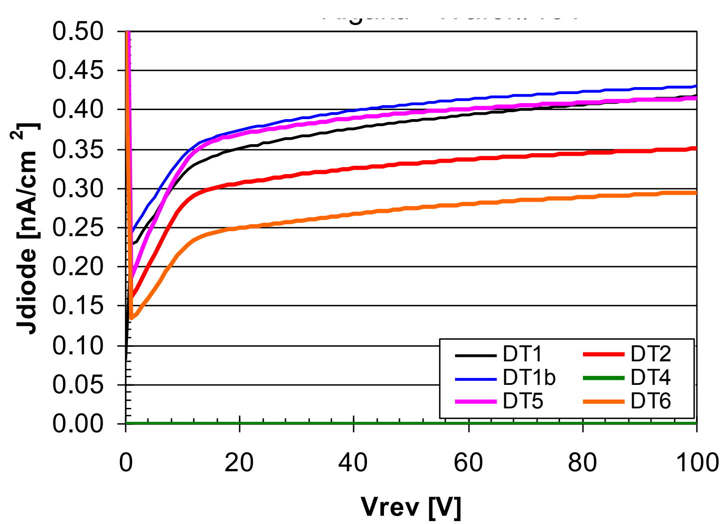
On the detector

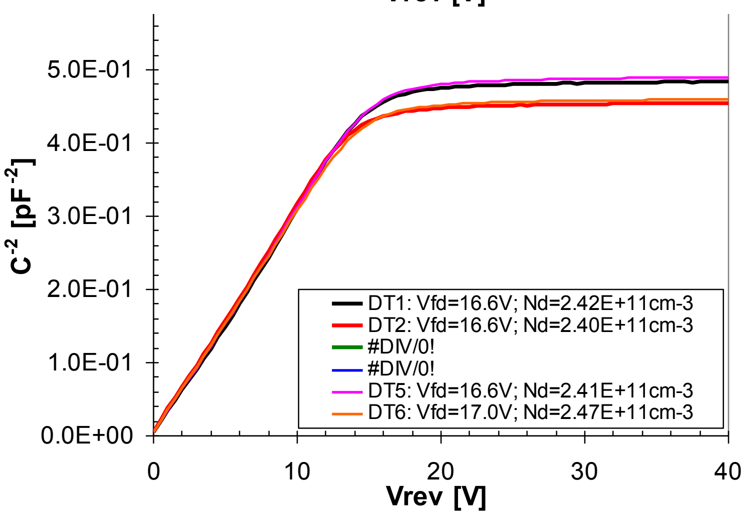
- Leakage current of the single strips
- Resistor value of the single strip
- coupling capacitor value of the single strip
- strip capacitance

Need of (semi)automatic probe station

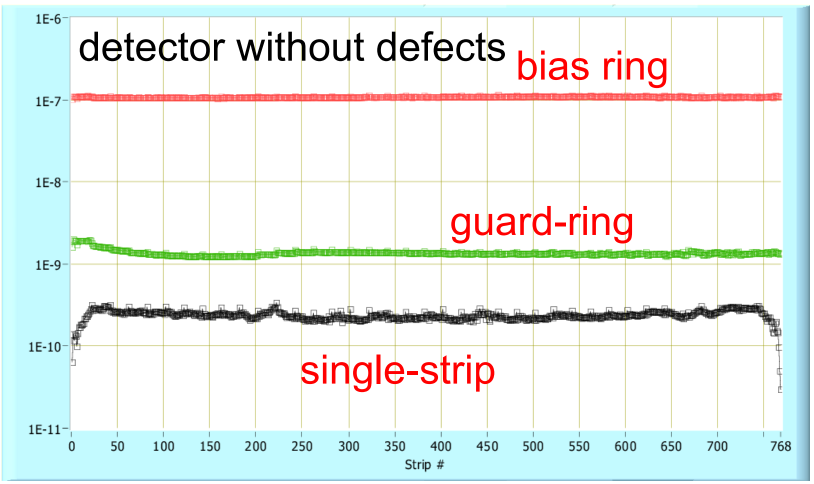
Example of test results

Diode I-V and C-V curves:
low leakage current, low depletion voltage





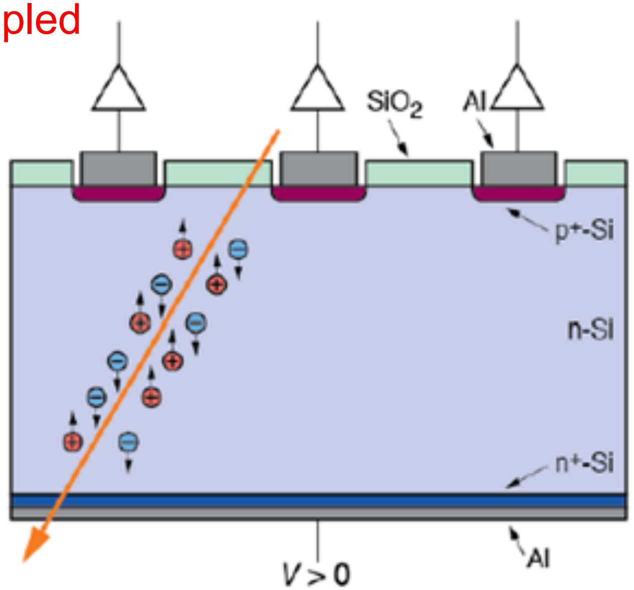
Detector scan: measurement of the leakage current of each strip for 2 detectors @ 60V reverse bias



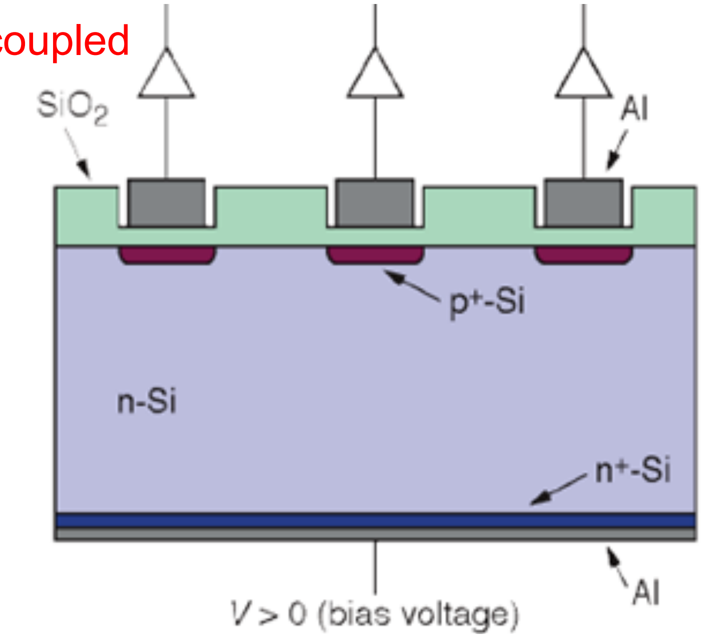
Various silicon detector structures

Silicon strip detectors

1) DC coupled



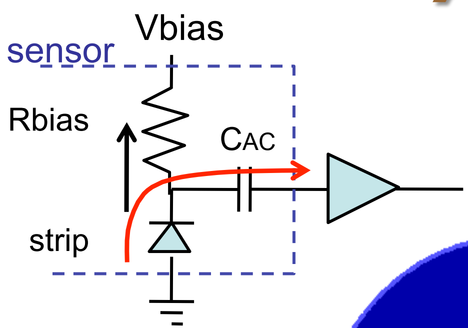
2) AC coupled



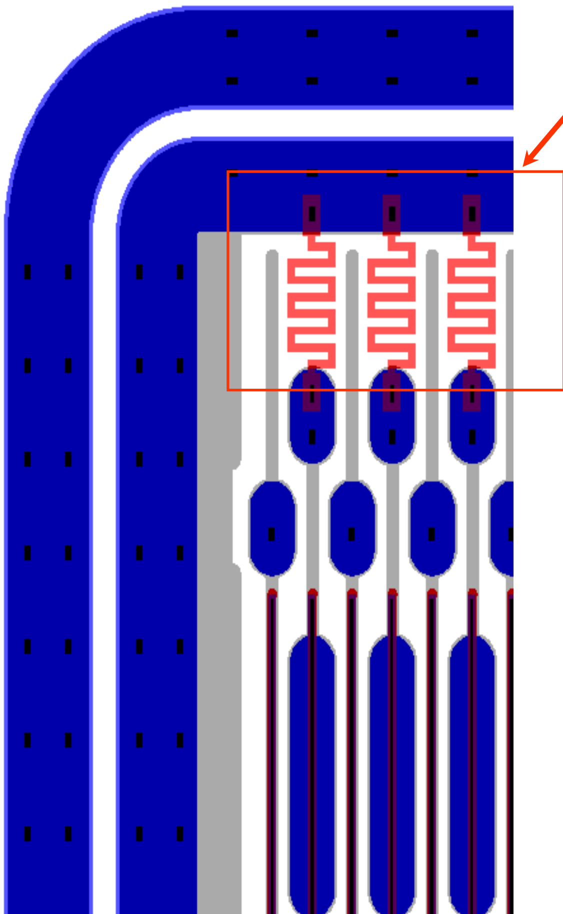
- p-n junction (or n-p junction)
- $N_a \approx 10^{19}$ cm^{-3}, $N_d \approx 1 \cdot 10^{12}$ cm^{-3}
  (vice versa for n-p type detector)
- n-type bulk: ρ > 0.5 kΩcm
  p-type bulk: ρ >2 kΩcm ➔ thickness 100's μm
- Operating voltage: from 10's V up to 1000 V
- Highly doped layer n$^+$ (p$^+$) on backplane to improve ohmic contact

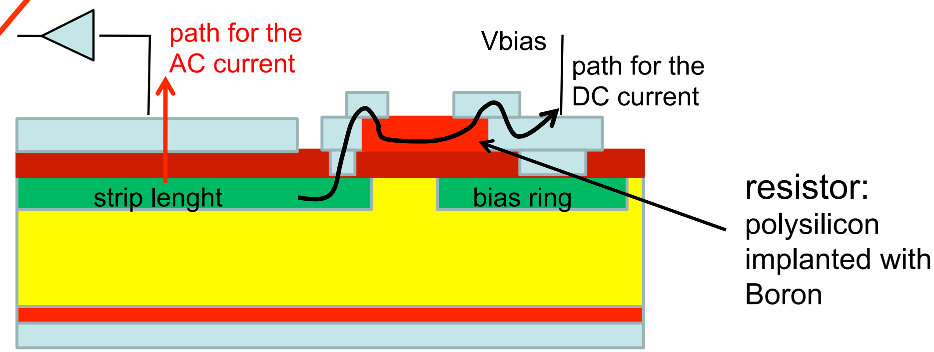
- **AC coupled strips:**
  - Capacitors integrated in the process (SiO_2 and/or Si_3/N_4)
  - Electronics doesn't have to sink current
- Implants biased by highly resistive poly-Si resistors to ground (other bias solutions possible)

AC coupled strip detectors

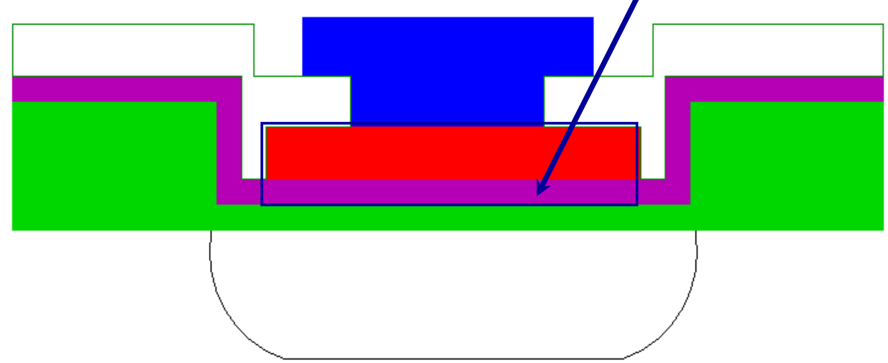


High Ohmic poly-Si
bias resistors (1 – 10 MΩ)

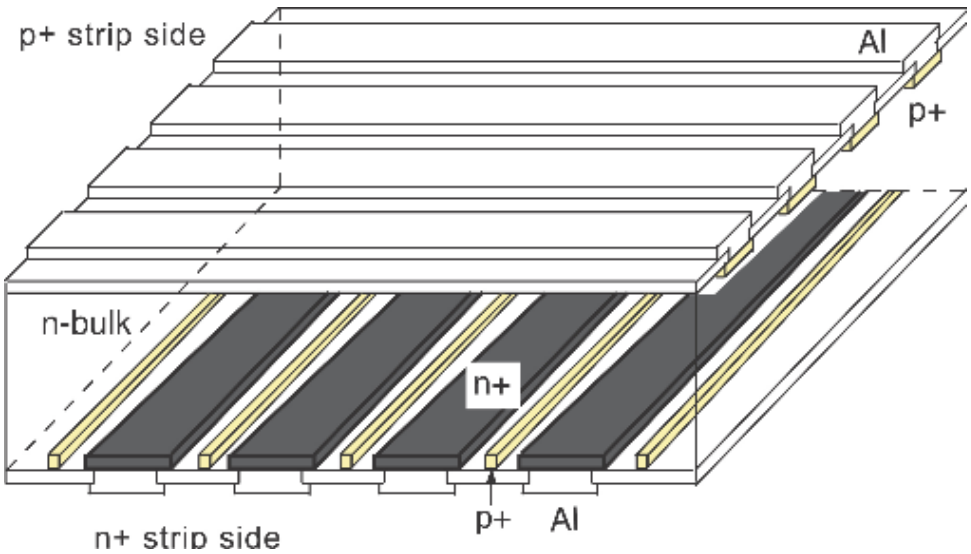




Stacked dielectric (oxide/nitride)
coupling capacitors

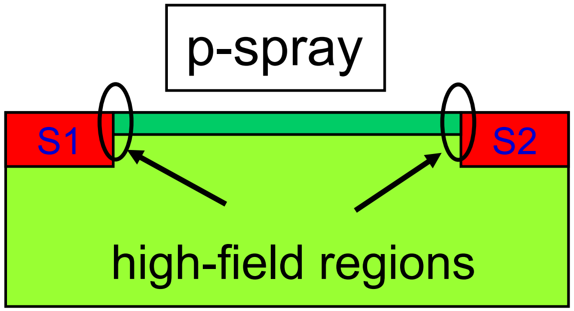


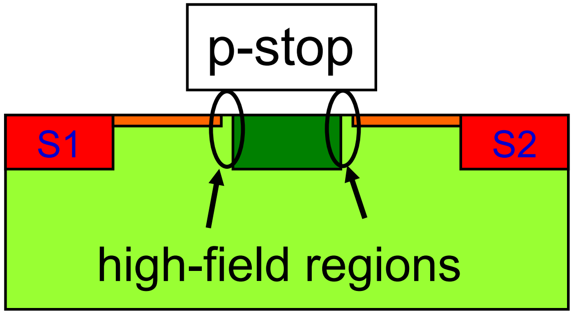
Double-sided strip detectors

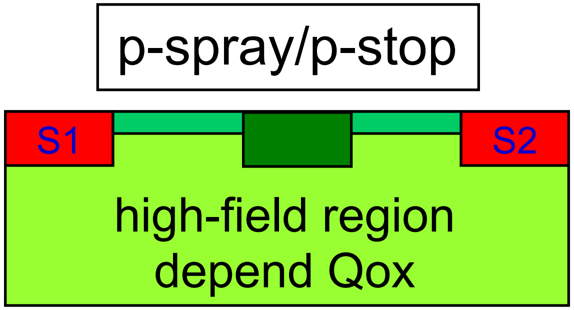


- Diode segmentation on both sides
- Orthogonal or stereo (small angle) configurations
- The X-Y position of the passage of the ionizing particle is given by the location of the strips showing a signal
- AC coupling is mandatory on one side to separate HV bias from LV input to the amplifiers (usually ohmic side)
- Double-sided process – high cost

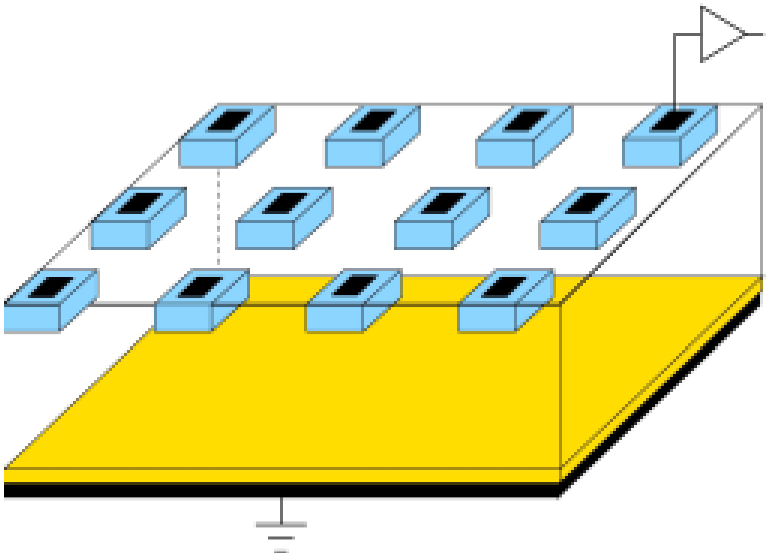
N^+ Strip isolation problem on the ohmic side … need p-type isolation implant







Pixel detectors



• 2-D Diode segmentation on one side
• The X-Y position of the passage of the ionizing particle is given by the location of the pixel(s) showing the signal

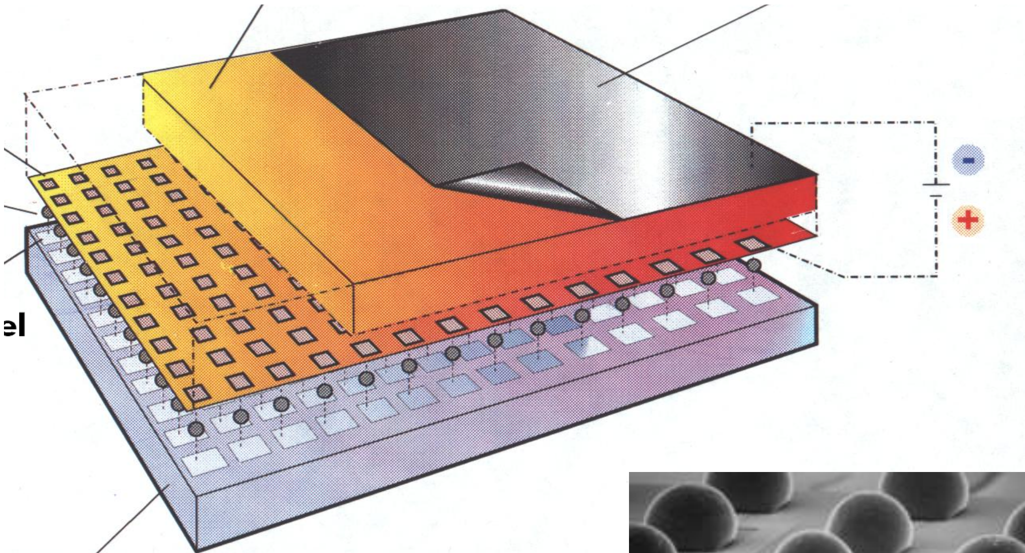
• Usually no need for patterning on the opposite side (easier fabrication technology), but much higher interconnection complexity

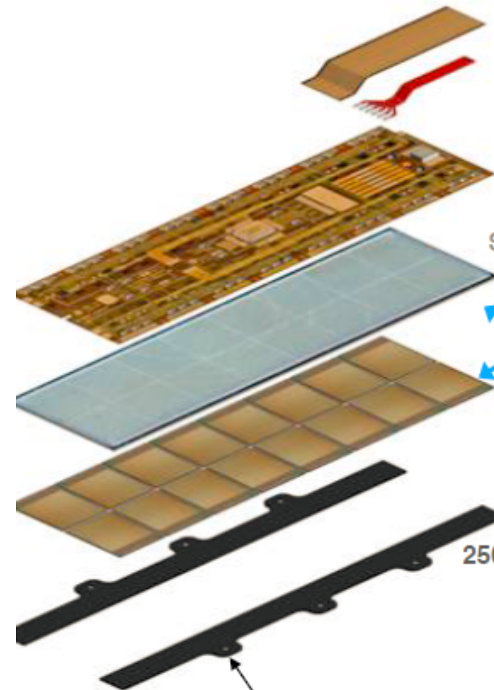
• Two solutions:

→ hybrid pixel + electronics approach (bump bonding and flip – chip)

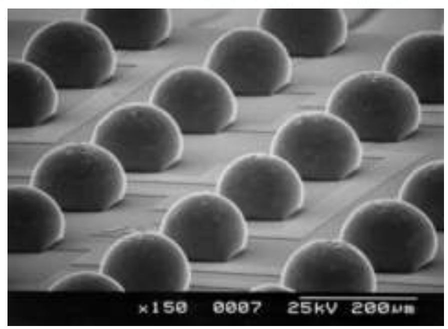
→ monolithic pixel detectors (with embedded electronics)

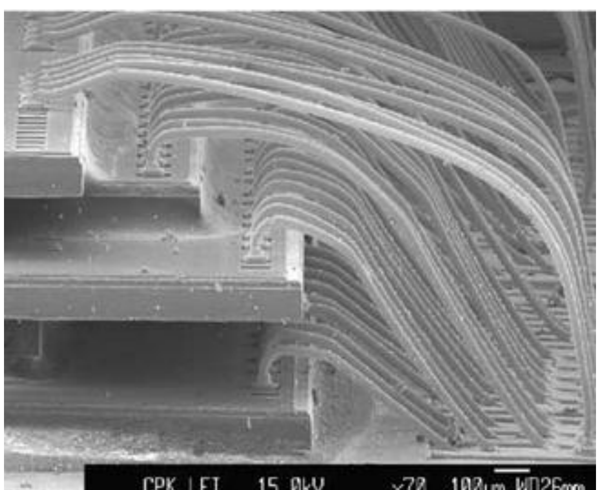
Hybrid pixel detectors

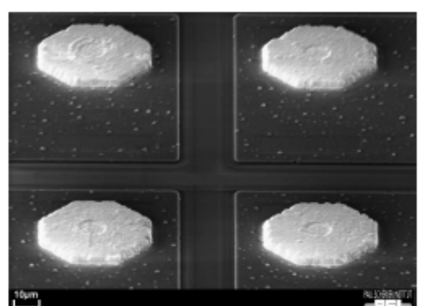


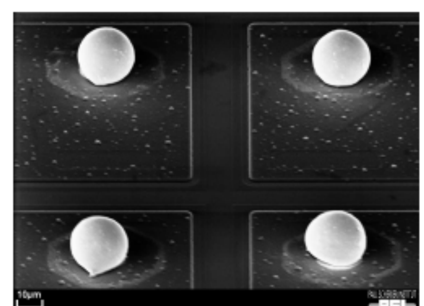


R. Horisberger





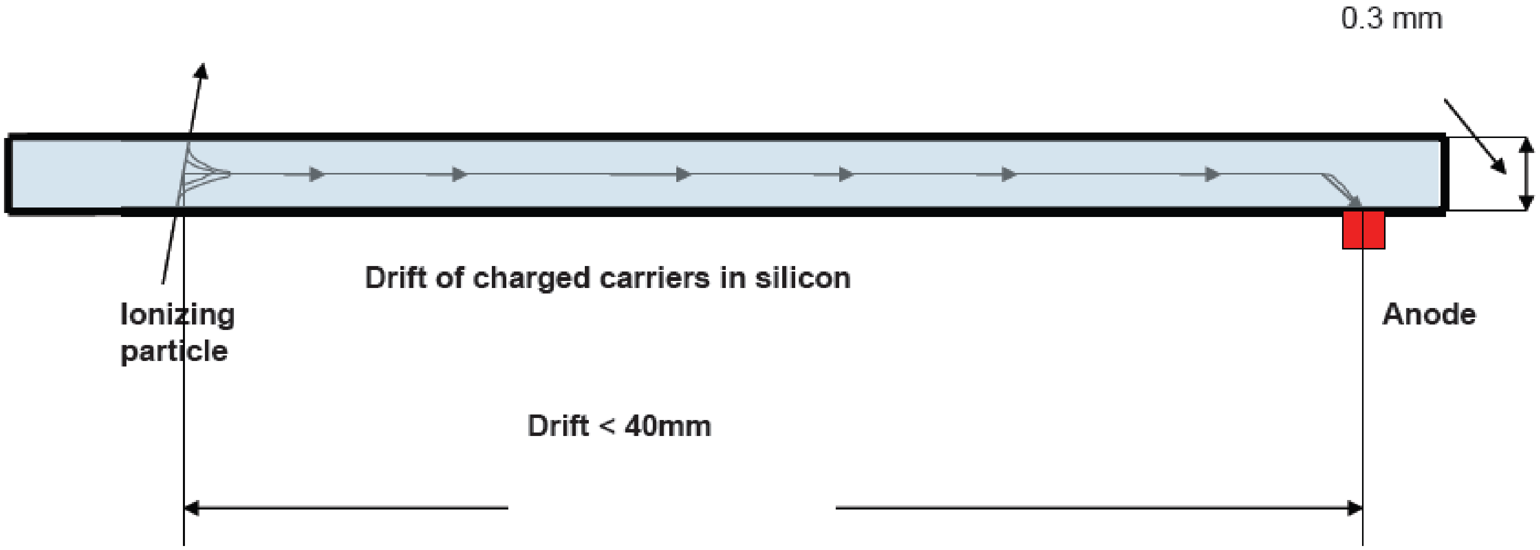




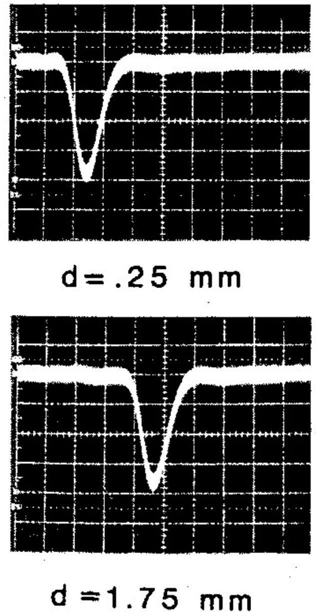
Silicon Drift Detector

Invented by Emilio Gatti and Pavel Rehak, 1983

Concept: transport of charged carriers in thin fully depleted semiconductor detectors in a direction parallel to the detector surface.

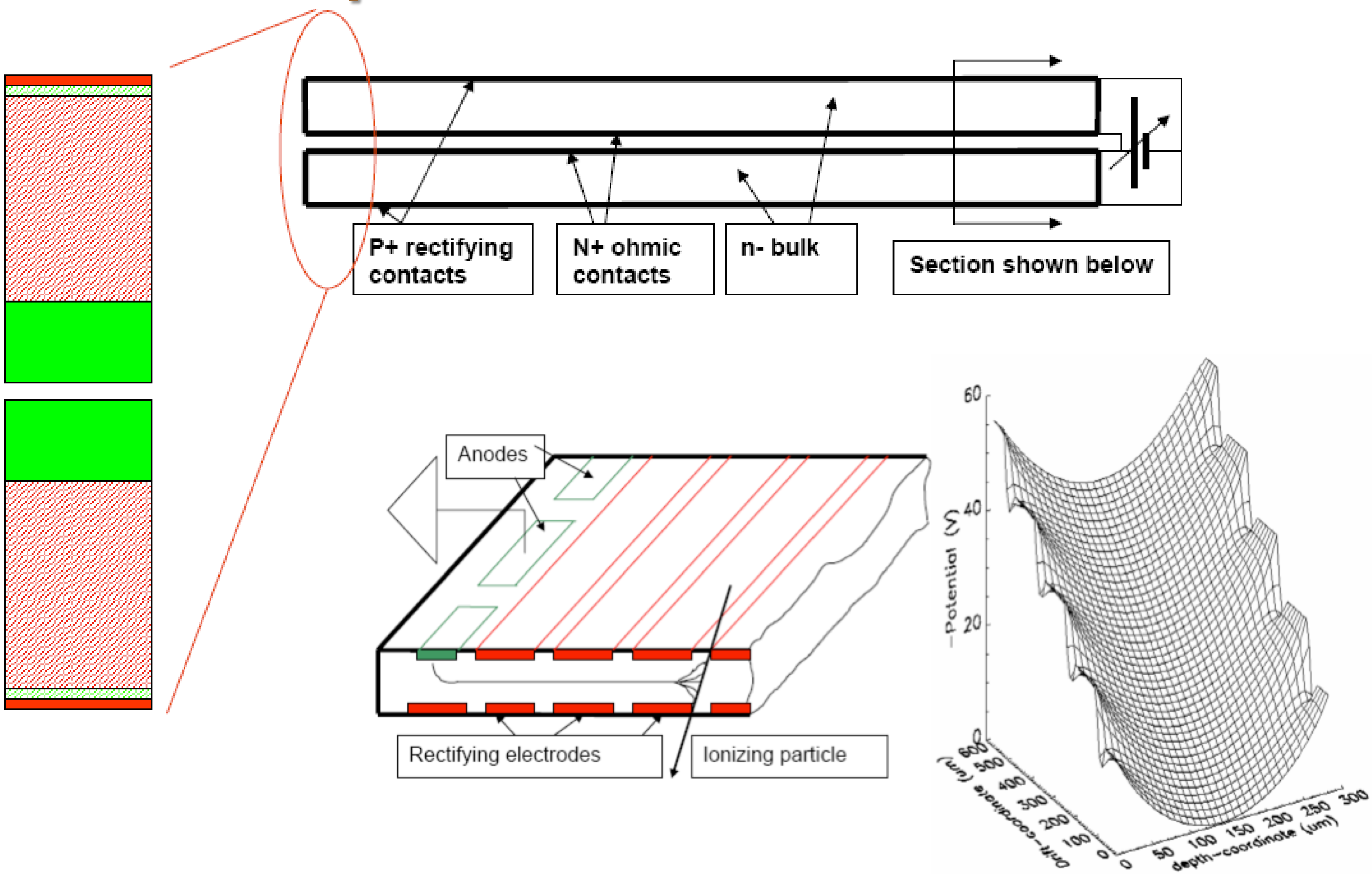


First signals from SDD, BNL 1984



E. Gatti and P. Rehak, “Semiconductor drift chamber — An application of a novel charge transport scheme”, NIM 225 (1984) 608

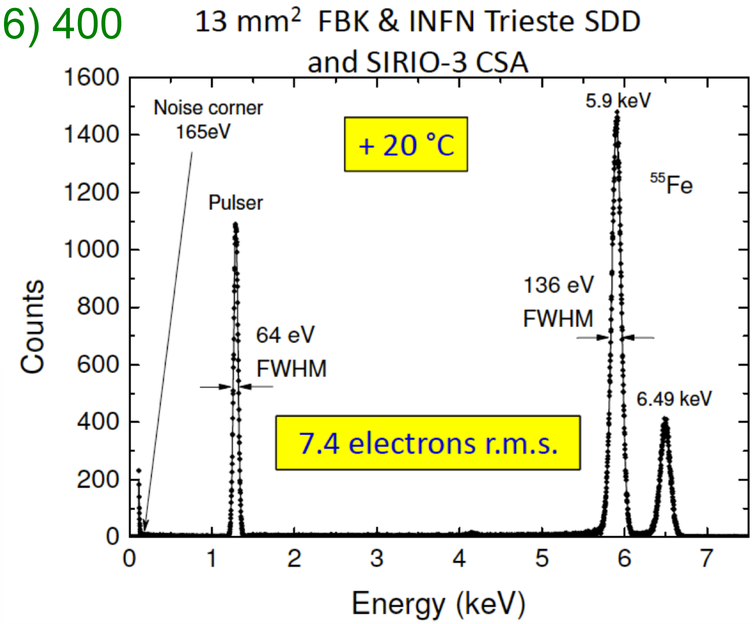
Depletion from two sides

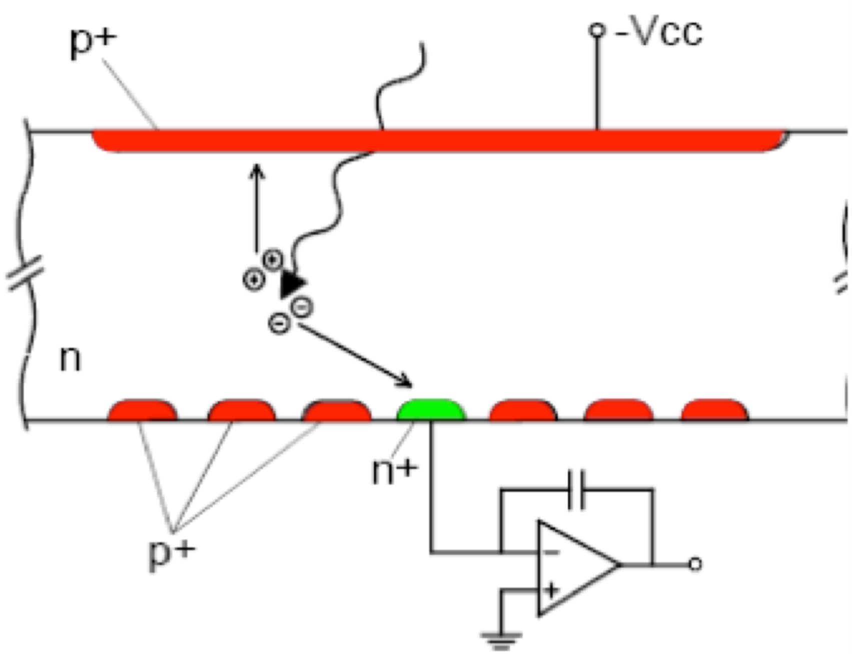


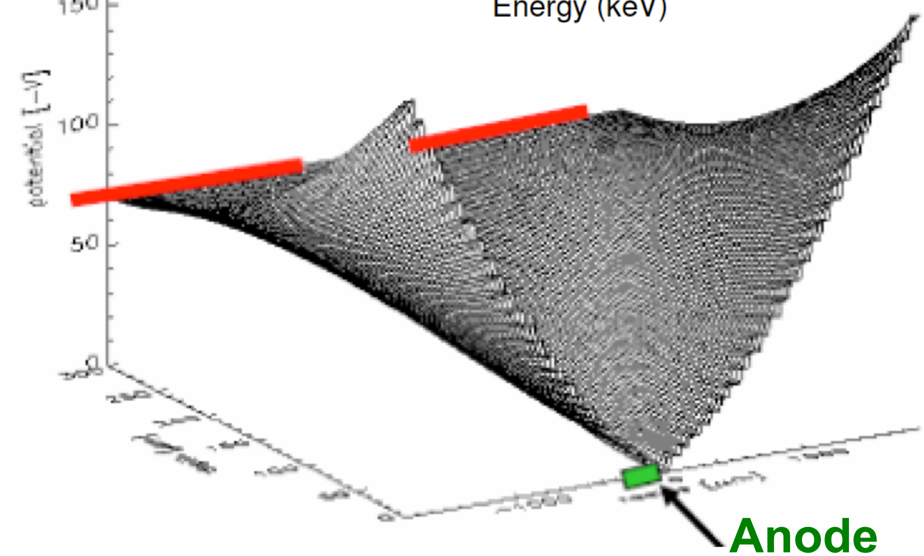
SDD for spectroscopy

G. Bertuccio et al, IEEE TNS 63 (2016) 400

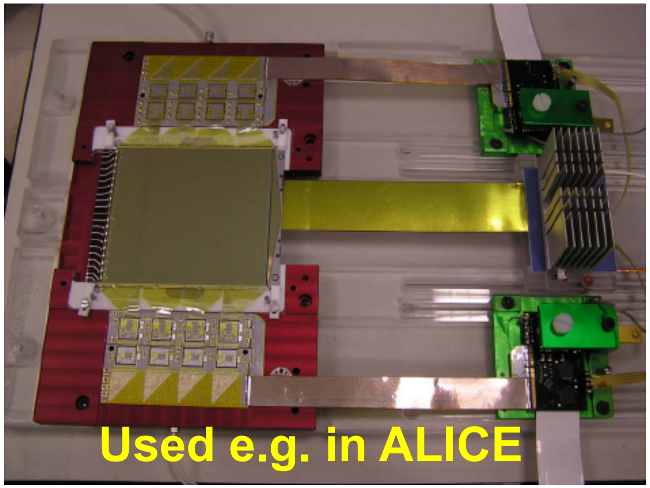
- The electrons are collected by the small central anode, characterized by a low output capacitance (~100 fF), which is independent on the active area of the detector.
- Lateral drift electrodes on anode side only
- Thin uniform entrance window on opposite side







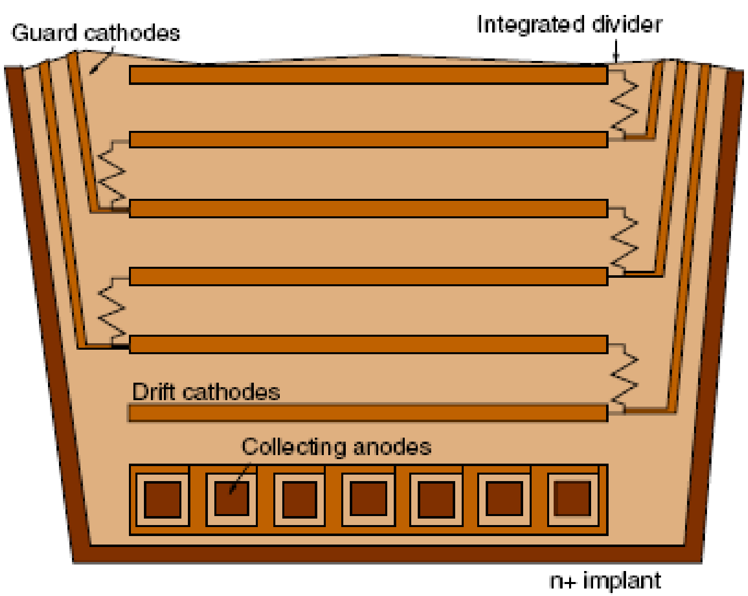
Linear SDD

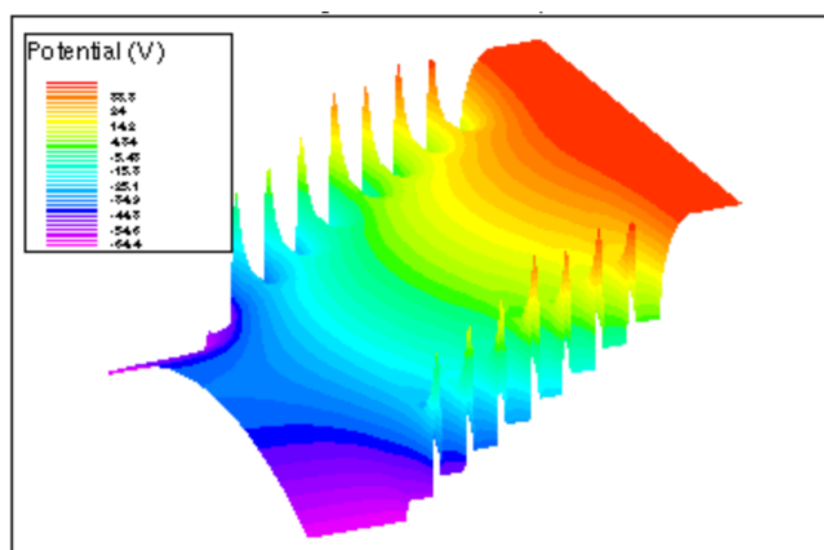


- Anode segmentation
- Determination of both coordinates by using also time of arrival with small number of readout channels (anode readout)
- No extra material in the active area

BUT

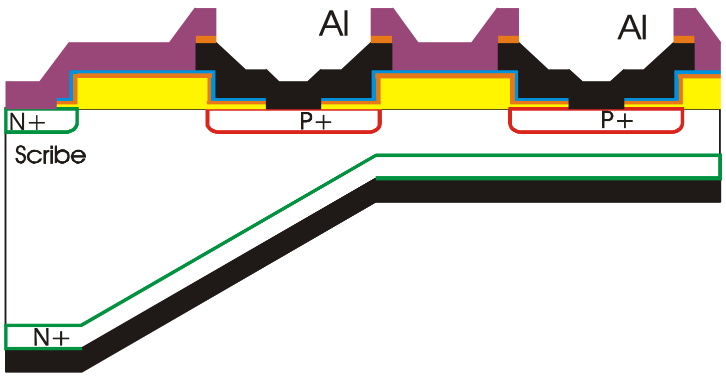
- … relatively slow (drift speed ~1 cm/μs)

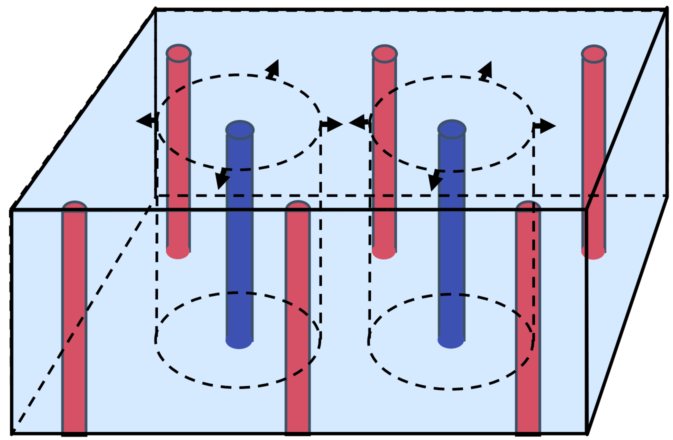


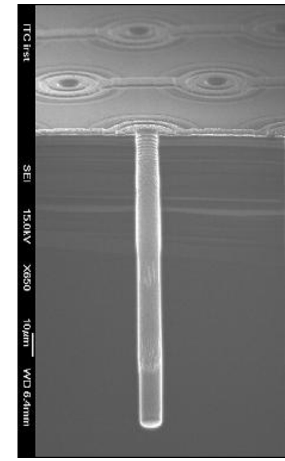


Microfabricated "MEMS" detectors

Use Si bulk etching to exploit third dimension in silicon

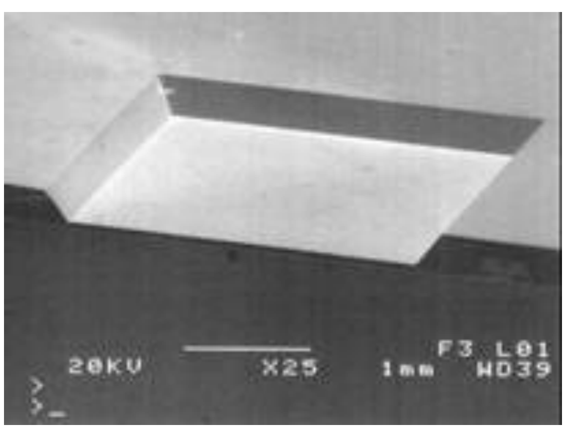


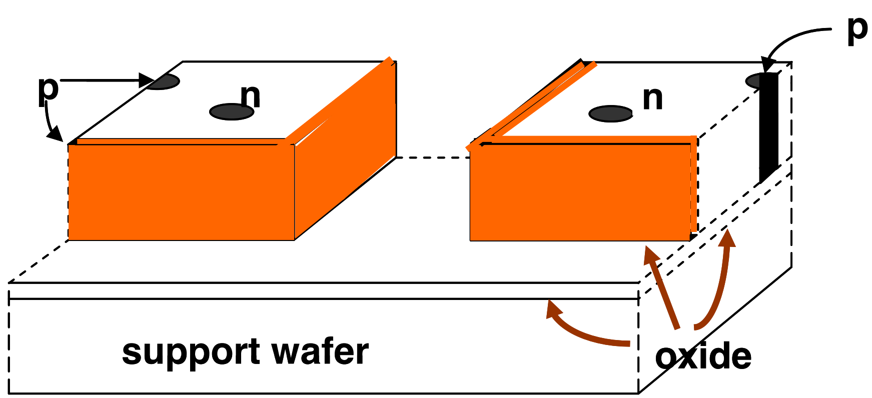


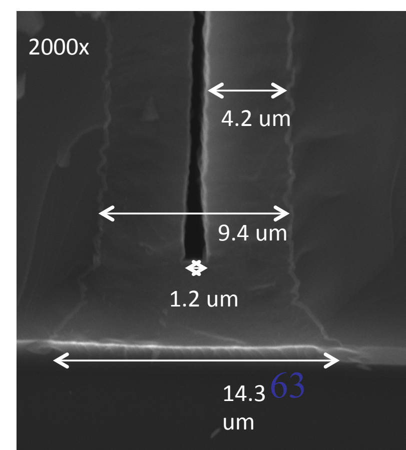


Locally thinned detectors

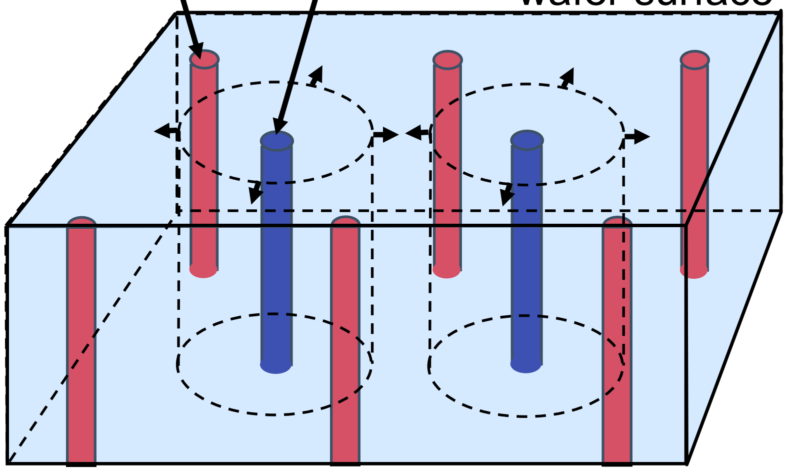
3D and active edge detectors



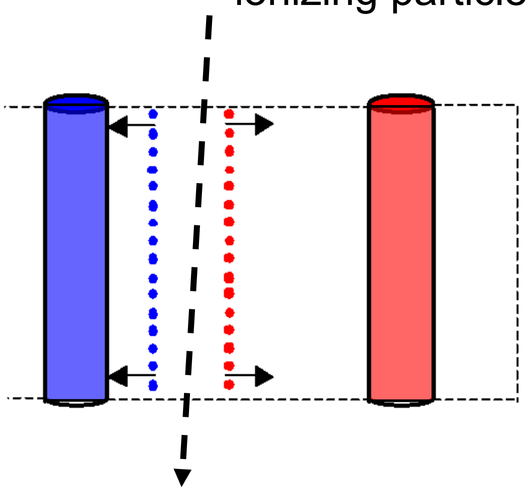




3D detectors



S. Parker et al. NIMA395 (1997)

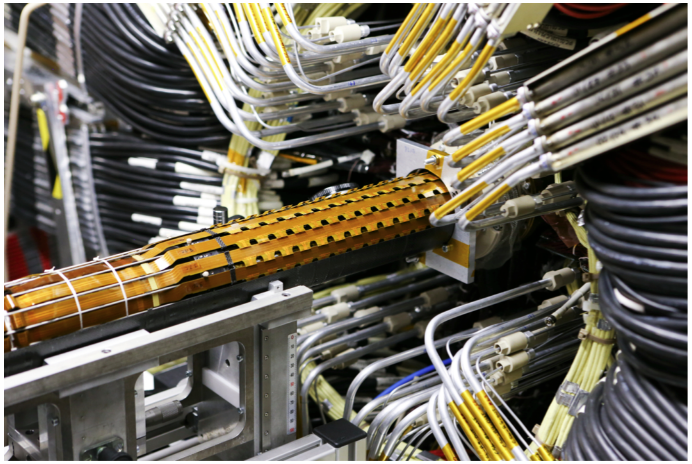


- Distance between *n* and p electrodes can be made short (~50 μm)

➡ extremely radiation hard detector

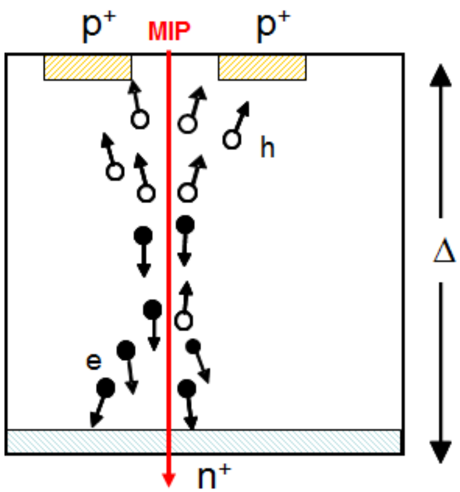
- First HEP application: the ATLAS Insertable B-Layer (IBL)

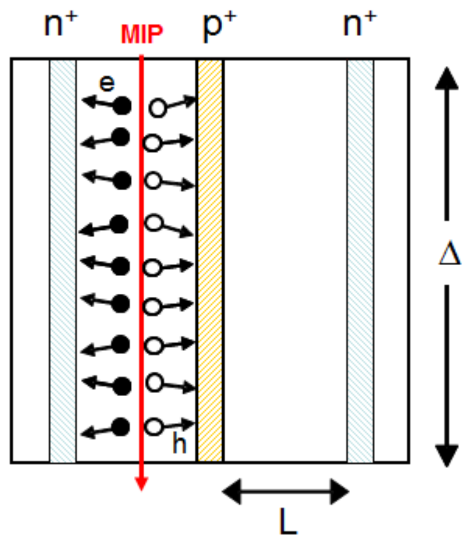
C. Da Via et. al. NIMA 694 (2012), 321



3D vs planar

Electrode distance (L) and active substrate thickness (Δ) are decoupled → L<<Δ by layout



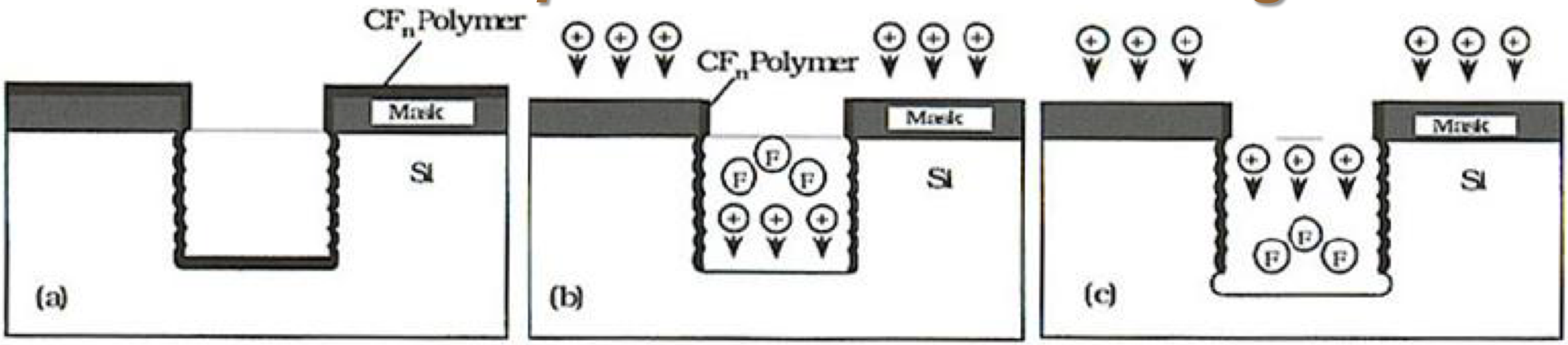


3D ADVANTAGES:
- Low depletion voltage (low power diss.)
- Short charge collection distance:
  - Fast response time
  - Less trapping probability after irr.
- Lateral drift → cell "shielding" effect:
  - Lower charge sharing
  - Low sensitivity to magnetic field
- **Active edges**

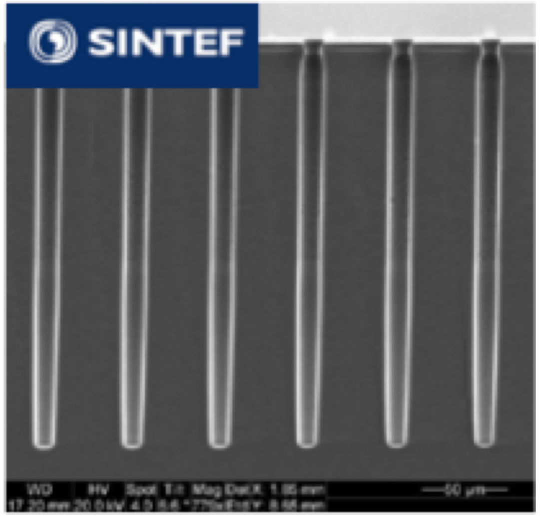
→ **HIGH RADIATION HARDNESS**

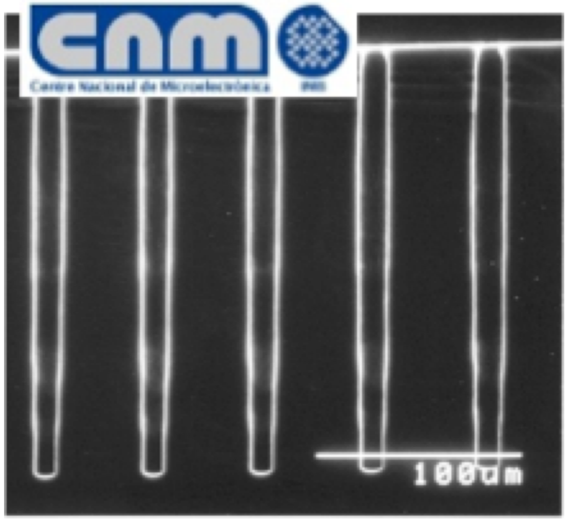
DISADVANTAGES:
- Non uniform spatial response (electrodes and low field regions)
- Higher capacitance with respect to planar (~3-5x for ~ 200 μm thickness)
- Complicated technology (cost, yield)

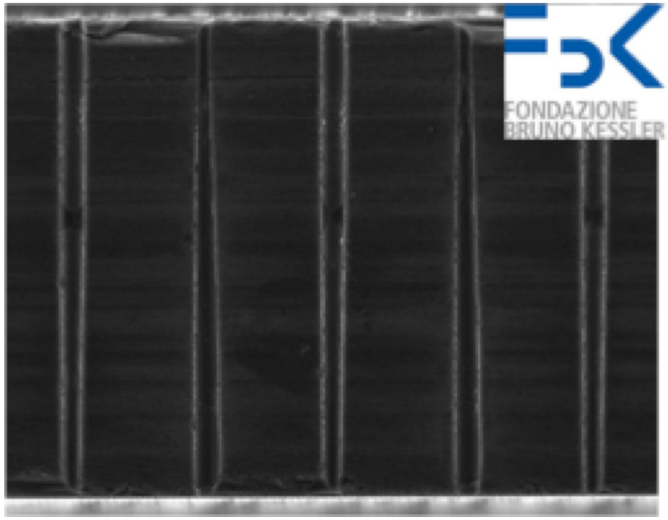
Deep Reactive Ion Etching



- Key technological step: DRIE by the Bosch process
- Alternating etch cycles (SF_6) and passivation cycles (C_4F_8)
- High aspect ratio (~30:1 or even better for trenches) and good uniformity



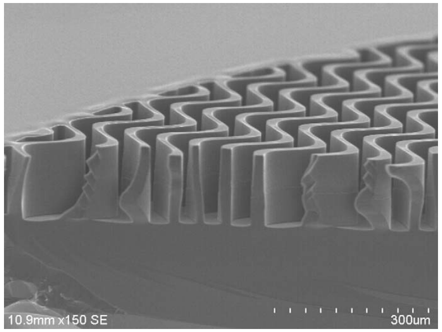




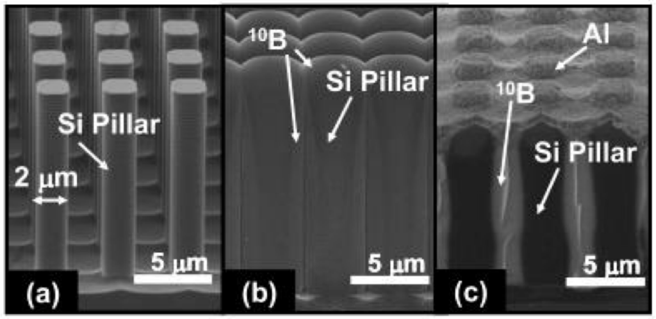
3D (perforated) neutron detectors

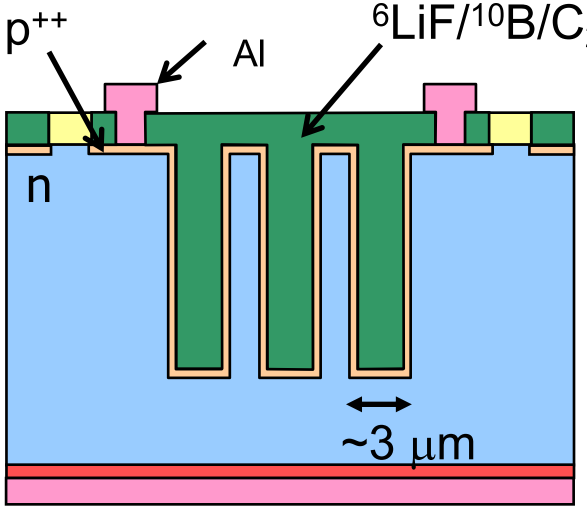
- Normal incidence intrinsic efficiency of ~50%
- Can be made position sensitive
- Careful design of the trenches to optimize for:
  - Capacitance
  - Electric and weighting field (signal)
  - Conversion efficiency (depending on converter material)
- Good n,γ separation

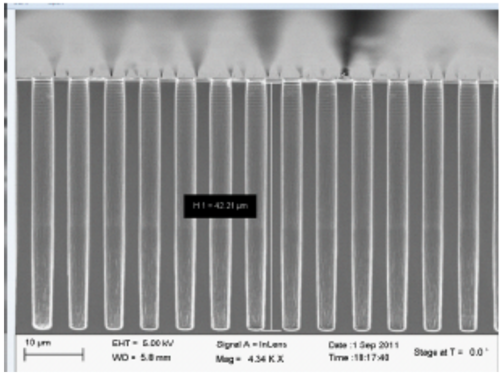
D. McGregor et al, J. Cryst. Growth 379 (2013)99

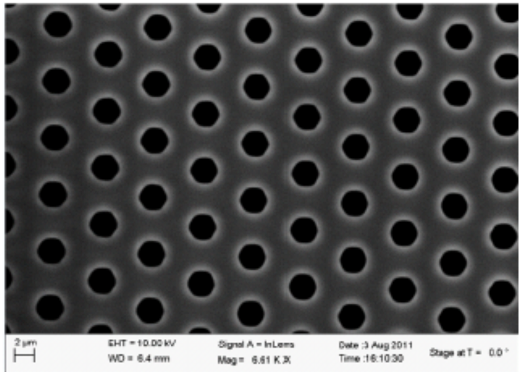


R. J. Nikolic et al, Proc. SPIE –Vol 6013

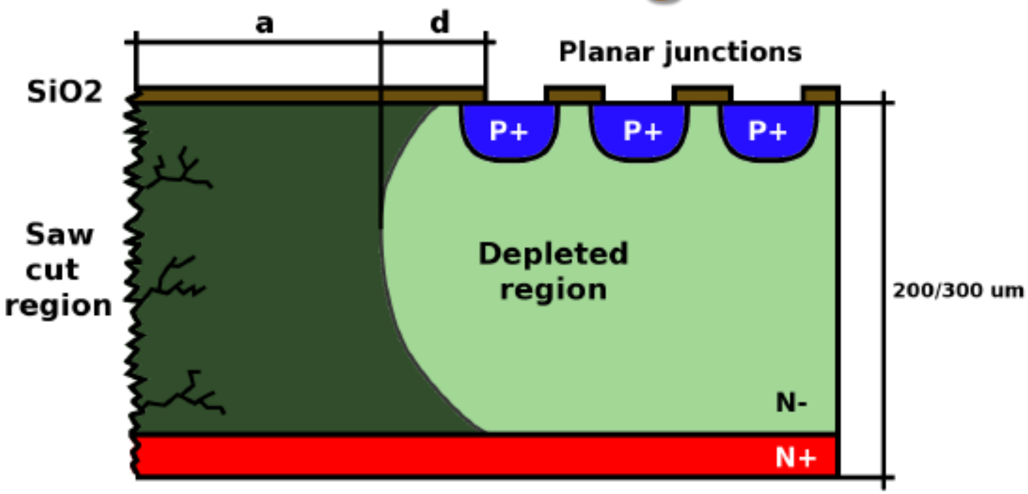


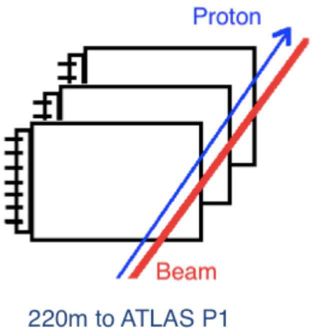


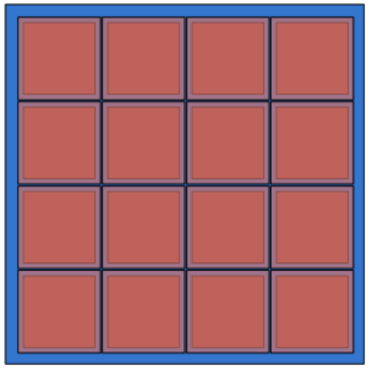




Edge termination







- In standard designs with saw-cut dicing, there's risk of high leakage current injection from the damaged cut region.
- Need to account for:
  - Lateral depletion region (d)
  - Additional safety margin (a), also used to host multiple guard rings in most designs for higher V_{bd} and better stability

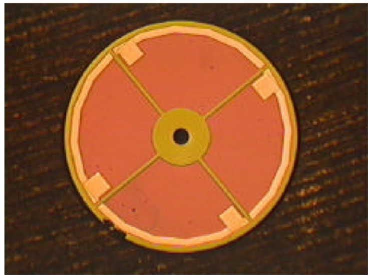
➡ Wide dead area at the edge: a+d ~ 0.5 – 1 mm

- But many applications in HEP and X-ray imaging call for slim edges !

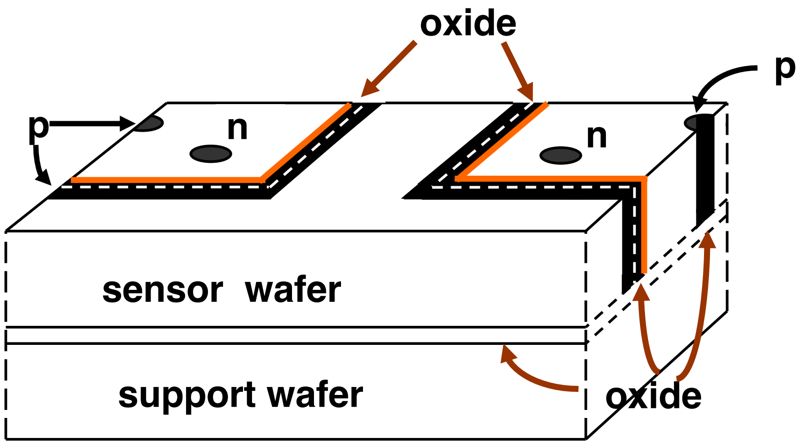
Active edge: concept

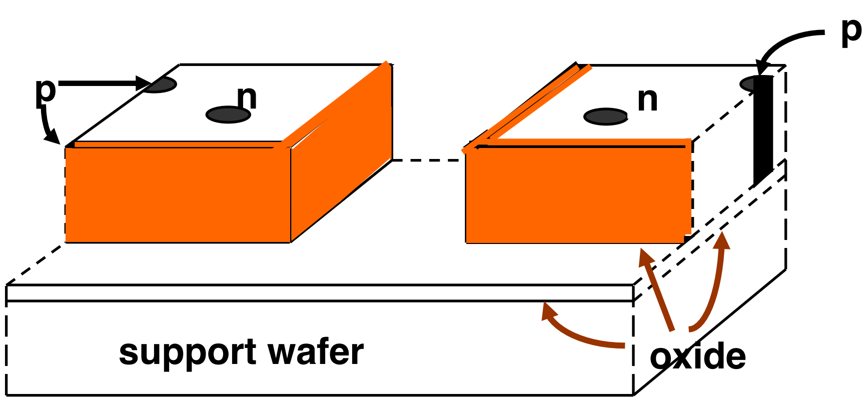
- First introduced at Stanford as an extension of 3D sensor technology, later applied also to planar sensors
- Cut lines are not sawed but etched with DRIE & doped

to act as electrodes, arbitrary shapes possible



- Process is of course more complicated:
  - Need of support wafer → wafer bonding and final removal
  - Several DRIE steps (3-4 for 3D, 2 for planar)



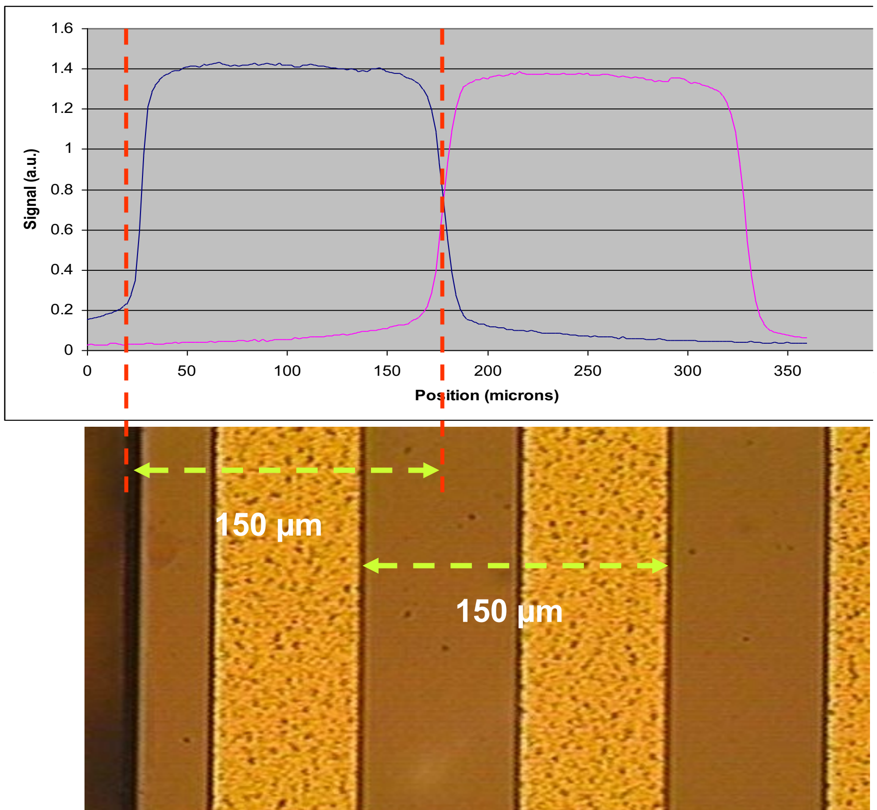


C. Kenney et al., IEEE TNS 48 (2001) 2405

C. Kenney et al., NIMA 565 (2006) 272

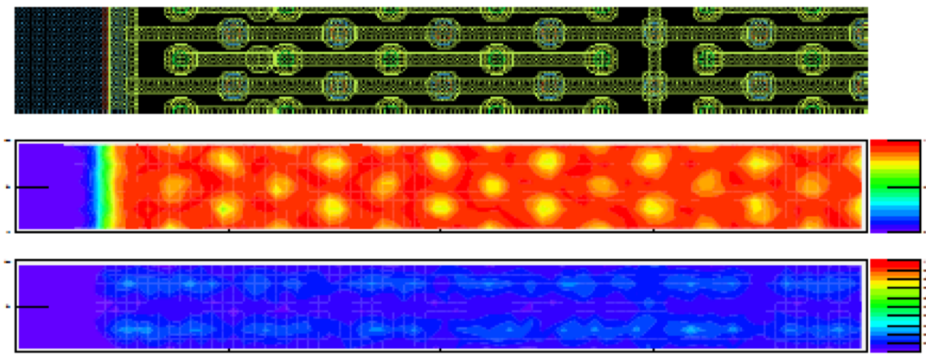
Active edge: sensitivity

Planar active-edge strip sensors tested with 12.5 keV X-ray beam (FWHM 2 μm) at the Advanced Light Source (LBL)

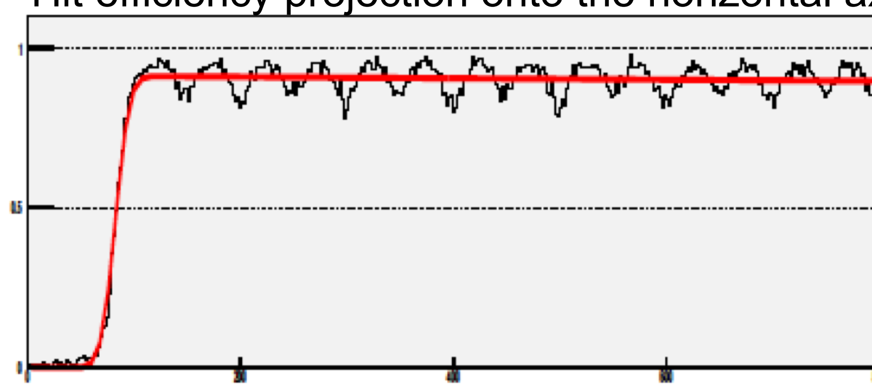


C. Kenney et al., NIMA 582 (2007) 178

3D active-edge pixel sensors coupled to FEI3 and tested with a 180 GeV/c pion beam at CERN



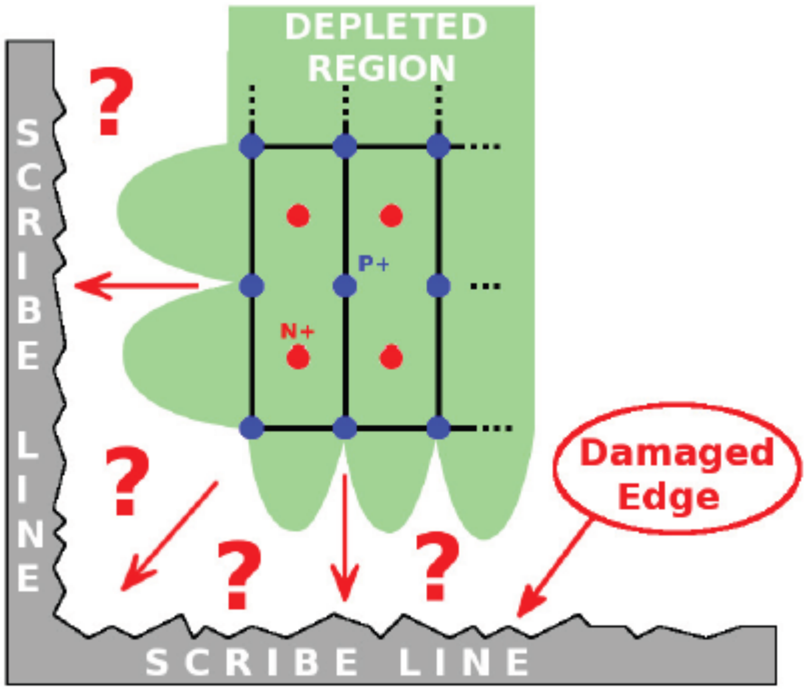
Hit efficiency projection onto the horizontal axis



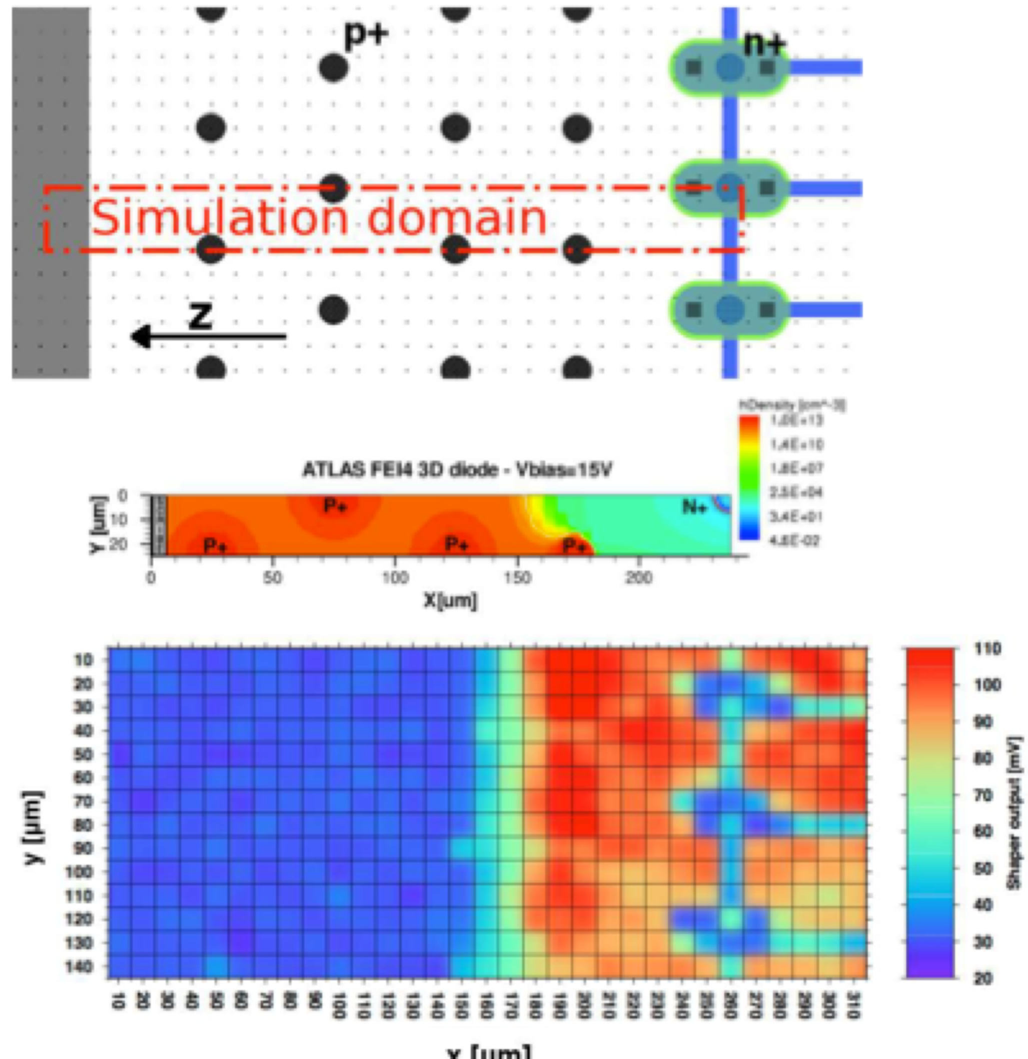
O. Røhne, IEEE NSS 2008, N27-8

C. Da Via, et al. IEEE TNS 56(2) (2009) 505

Another slim edge solution



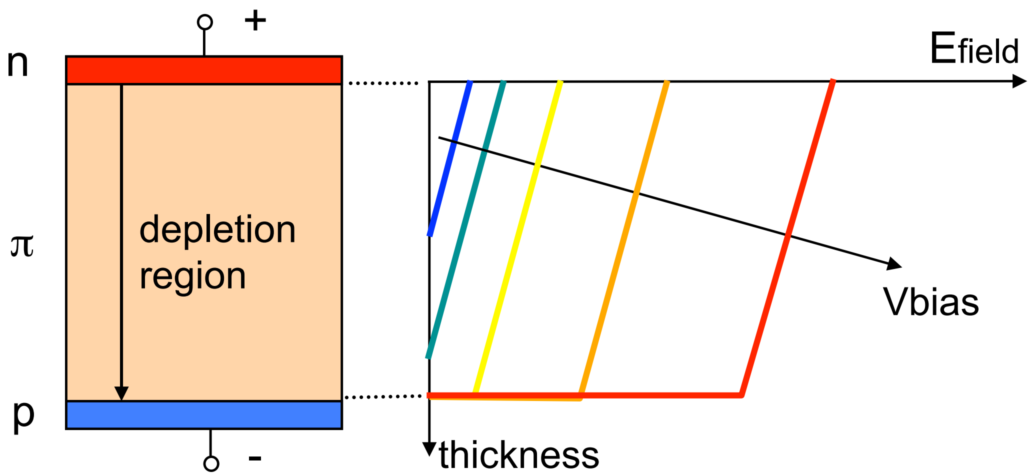
Layout, simulation and laser map

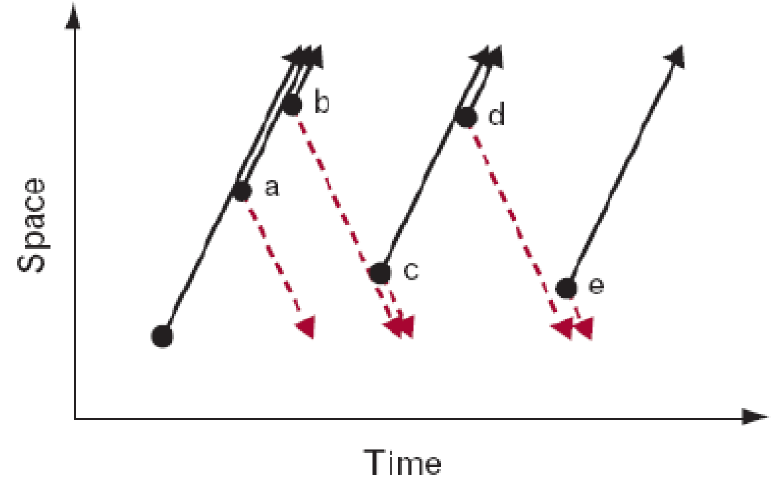


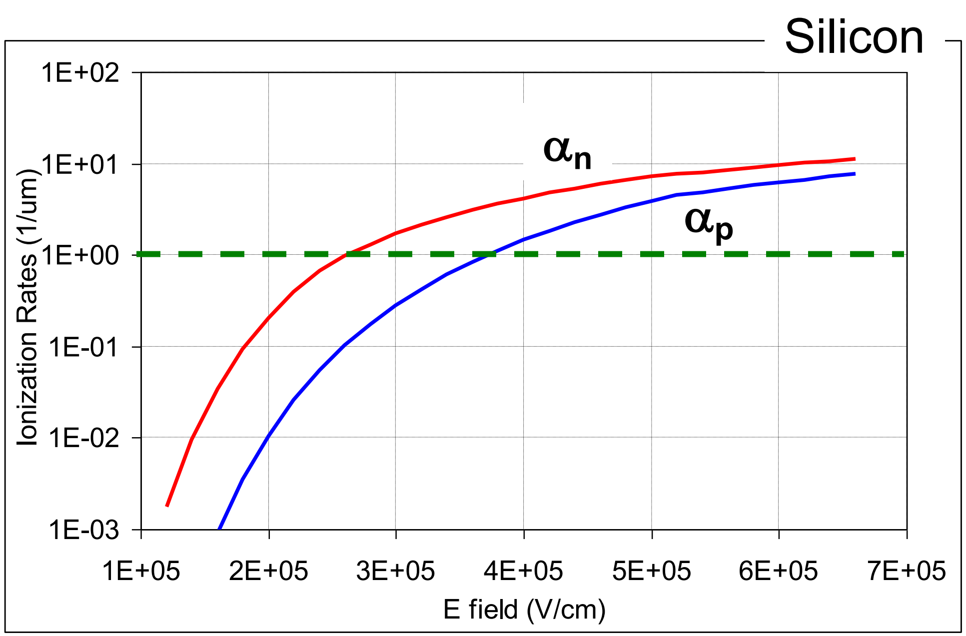
- … if a support wafer is not available
- Diamond saw cut still needed
- How to reduce the dead area ?
- Terminating structures ?
  (e.g., 3D guard ring)
- Multiple fence of ohmic columns …

M. Povoli, et al. JINST 7 (2012) C01015

Impact ionization



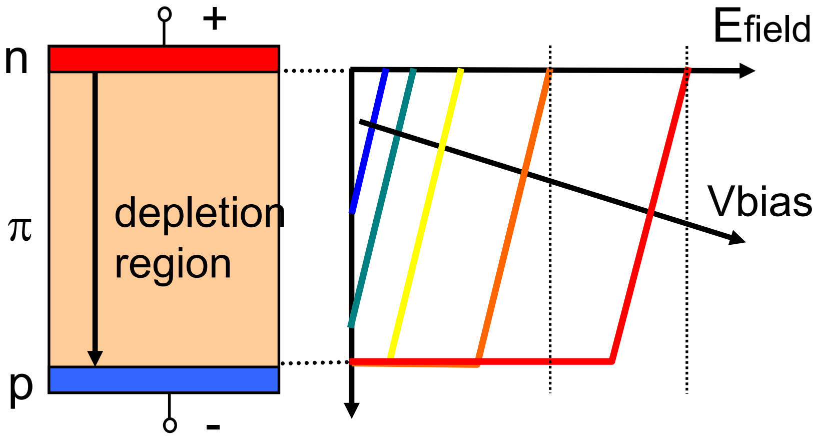




Impact ionization:
carrier has enough kinetic energy to break a bond, i.e. to move an electron from valence to conduction band

Ionization rates:
number of pairs created by a carrier per unit distance travelled
$\Rightarrow$ a field of ~3x10^5 V/cm is needed to create on average a pair in 1μm travelled.

Reverse current in a diode

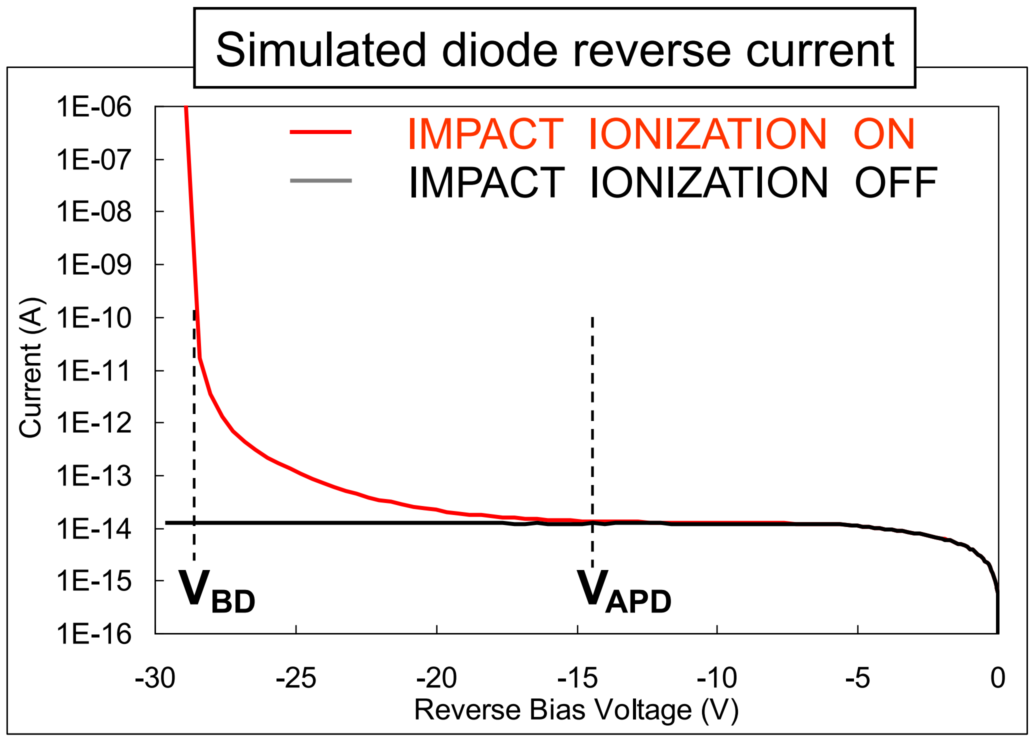


Low field region (V<V_{APD})

Leakage current is given by generation in the depletion region:

$$I = q * G * W_{dep} = q * ni * 1/\tau_g *W_{dep}$$

It reaches a constant value when fully depleted

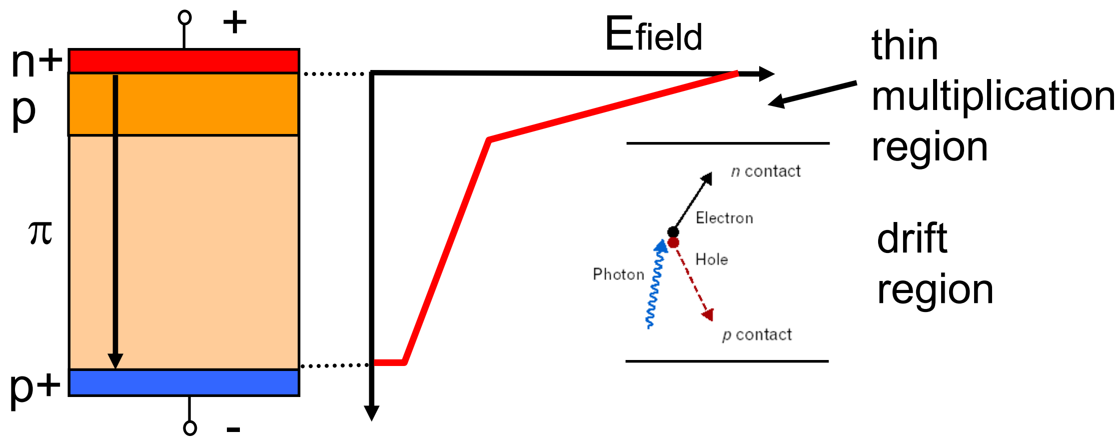


High field region (V>V_{APD})

Leakage current deviates from the expected constant value because some carriers "impact ionize"
A finite "*GAIN*" could be defined

Very high field region (V>V_{BD})
For even higher fields the phenomenon becomes uncontrolled and the current rises indefinetely (in principle)
"*Infinite GAIN*"

Realistic structure of an APD



- Separated absorption and ionization regions

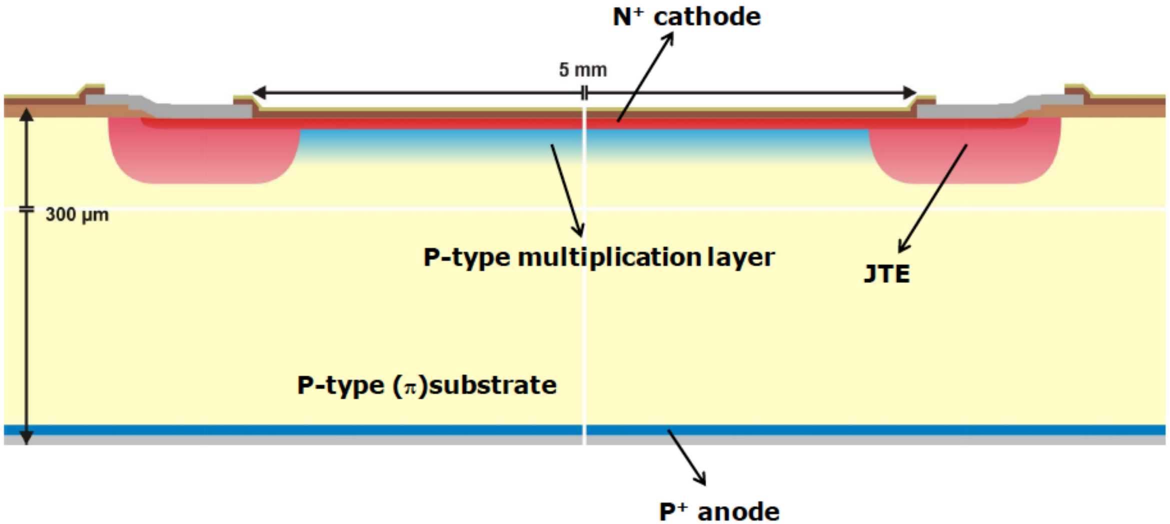
⇩

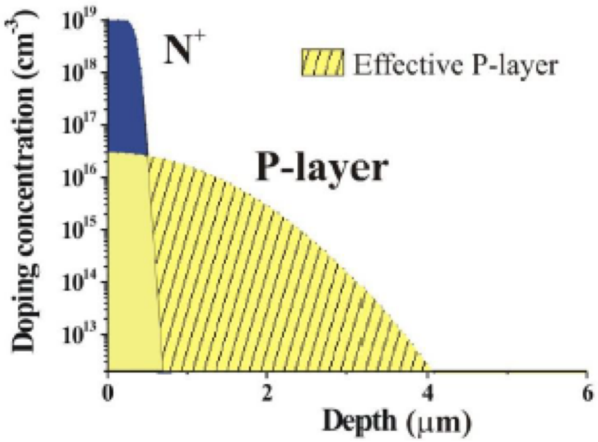
- All the electrons photo-generated in the drift region are multiplied (on average) by the same factor (excess noise reduced)

- $V < V_{APD}$
  => photodiode 1 collected pair/generated pair
- $V_{APD} < V < V_{BD}$
  => APD <M> (10-100) collected pairs/generated pairs
- $V > V_{BD}$
  => Geiger-mode APD in principle ∞ collected pairs/generated pairs

GM-APD can detect even a single photon (SPAD)

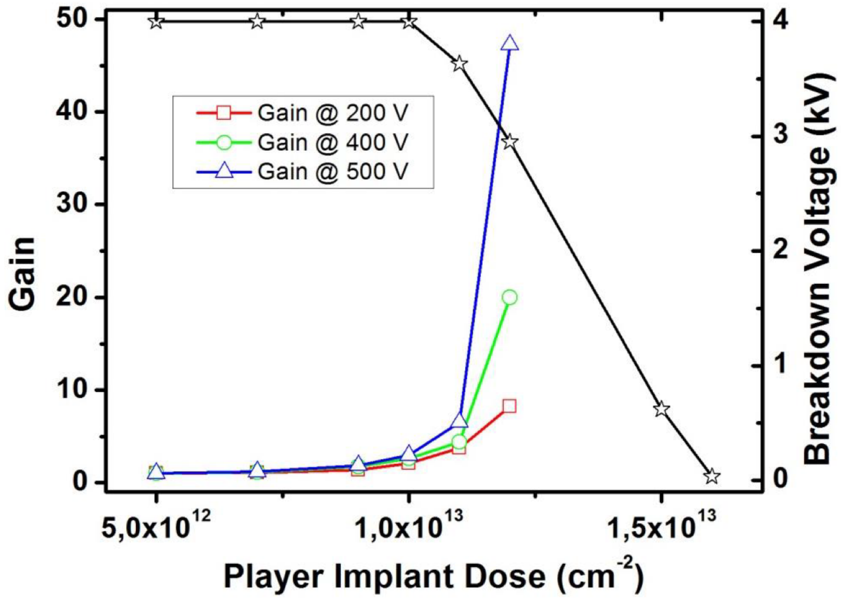
Low Gain Avalanche Detector (LGAD)





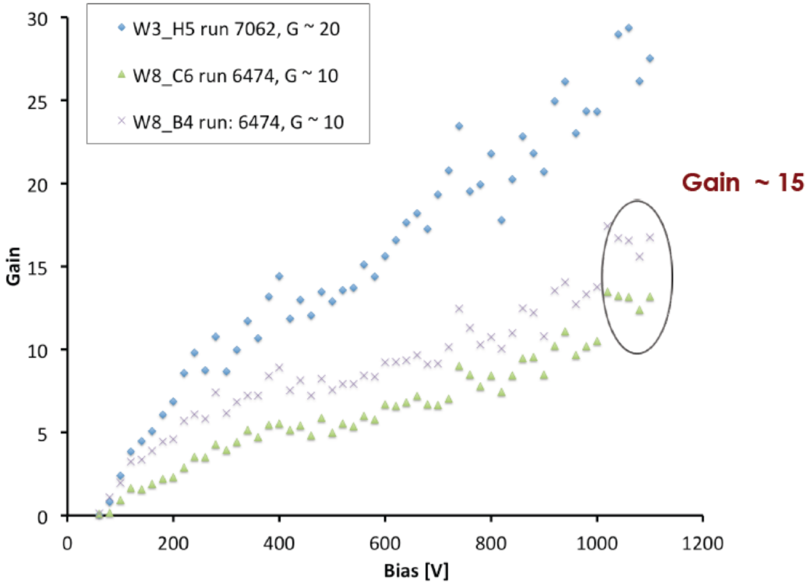
G. Pellegrini, et al., HSTD9 (2013)

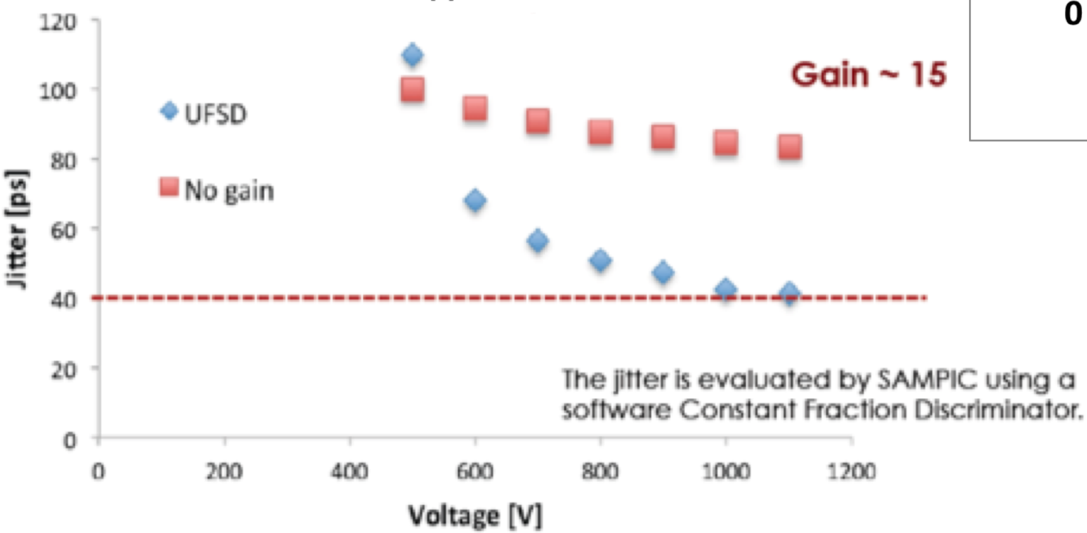
- APDs for ionizing particles
- Low gain for low excess noise and compatibility with existing electronics
- Gain vs breakdown voltage trade-off: high sensitivity to the implant dose of the multiplication layer …
- JTE to prevent from edge breakdown



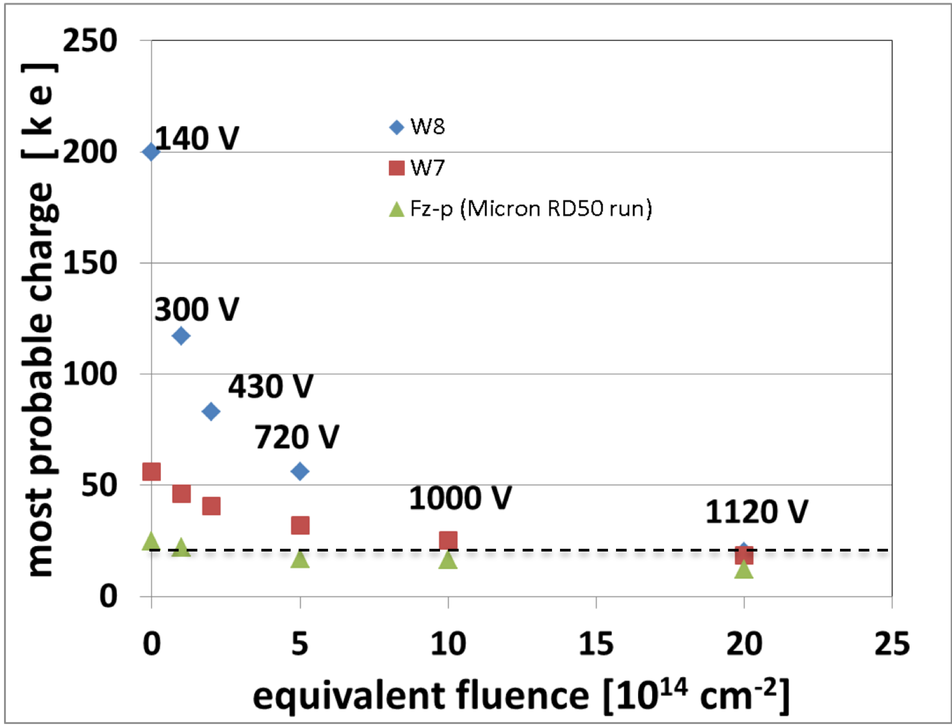
LGAD performance

N. Cartiglia et al., 24th RD50 Meeting, 2014





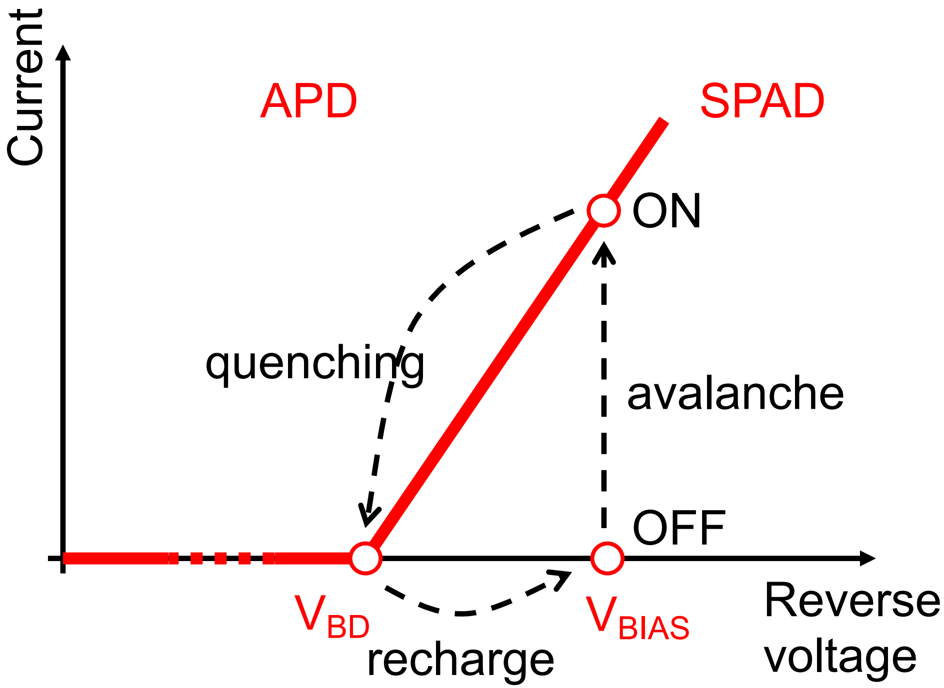
G. Kramberger et al., 24th RD50 Meeting, 2014



- It works well before irradiation
- It largely improves timing res.
- But multiplication tends to vanishe after irradiation …

More from N. Cartiglia tomorrow

SPAD



Main figures of merit

- Photon Detection Probability
- Fill factor (for arrays)
- Timing resolution
- Primary noise:
  - dark counts
- Secondary noise:
  - Afterpulsing
  - optical cross-talk (for arrays)

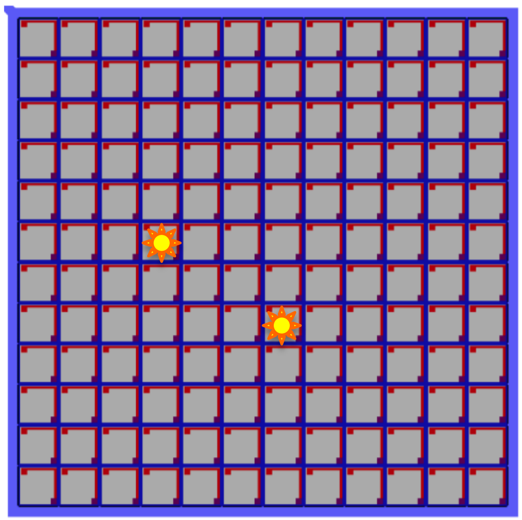
S. Cova, et al., "Evolution and prospects for single photon avalanche diodes and quenching circuits". J. Modern Optics, 51 (2004) 1267

- Need for quenching/recharge mechanisms (→ dead time)
- Strong impact of excess voltage and temperature on most parameters

More from L. Pancheri tomorrow

The Silicon PhotoMultiplier

SPADs are ON-OFF devices, i.e., they give no information on light intensity when irradiated with short (in time) bunches of photons

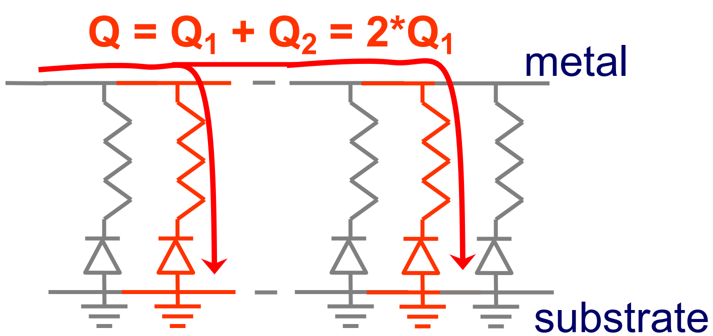


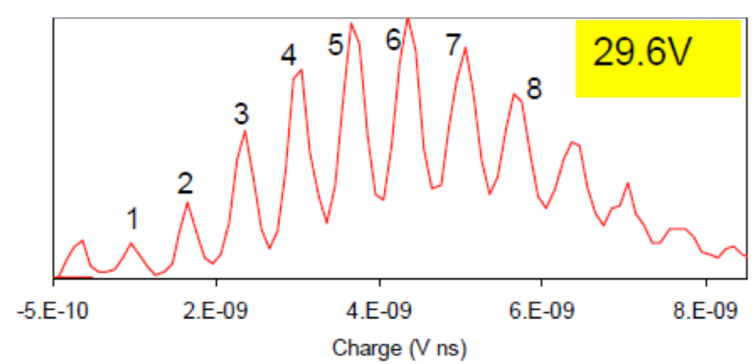
C. Piemonte et al., IEEE TNS 54 (2007) 236

SiPM

first proposed by Golovin and Sadygov in the ’90s

- A single SPAD is segmented in tiny micro SPADs connected in parallel
- Each element is independent and gives the same signal when fired by a photon
- **The output charge is proportional to the number of triggered cells that, for PDE=1, is the number of photons**





V_{eb}=2V)

Monolithic detectors

Sensor and electronics on the same substrate → no need for interconnections … two possible approaches:

1. Integrate electronics on the high resistivity substrate usually employed for sensors
   - Active volume is adequate to different types of radiation
   - Signal is large and fast
   - Transistors are not of the best quality
   - The fabrication process is highly non-standard with relatively large feature size (> 2μm)
2. Use the low resistivity substrate of standard CMOS process as sensor
   - Can use state-of-the-art deep sub-micron process
   - Proven for visible light by the success of CMOS imagers
   - Active volume is shallow
   - Signal is small and slow

Is it still true today ?

Transistors in HRS (1)

Pioneering works in late 1980's

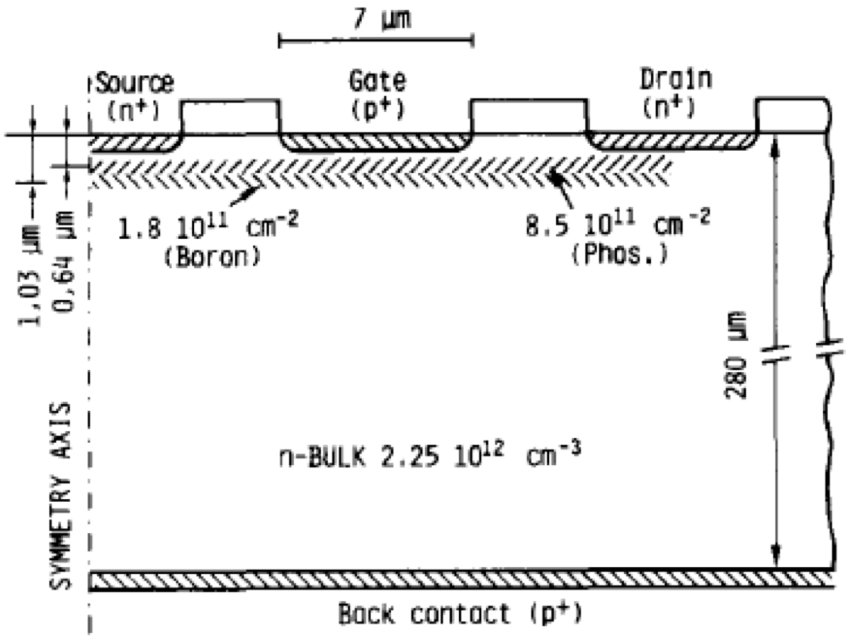
V. Radeka et al., IEEE EDL 10 (1989) 91

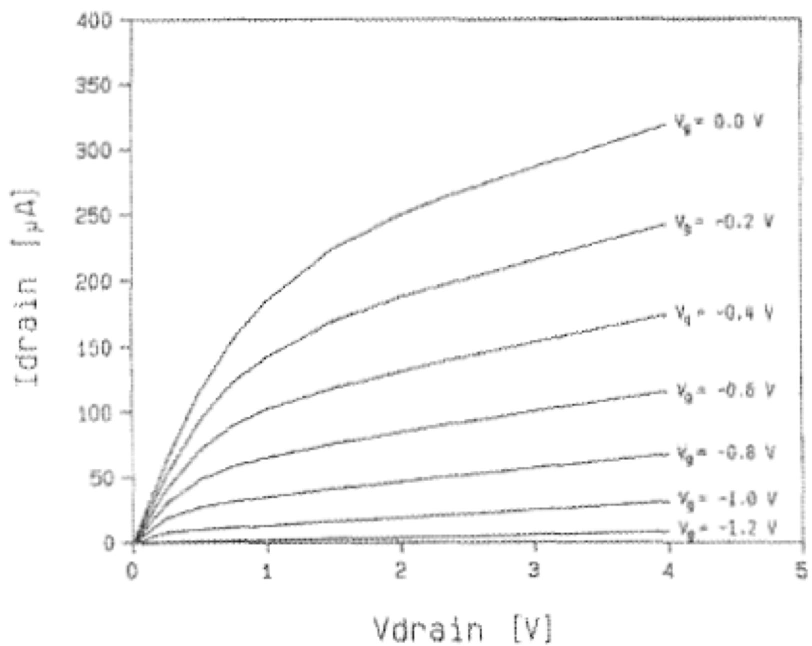
a) MPI/BNL: SSJFET for drift detectors

Fully implanted JFET: no high-temp. steps →low leakage

Good enough as a buffer, although 1/f noise is high

→ Precursor of DEPFET





Transistors in HRS (2)

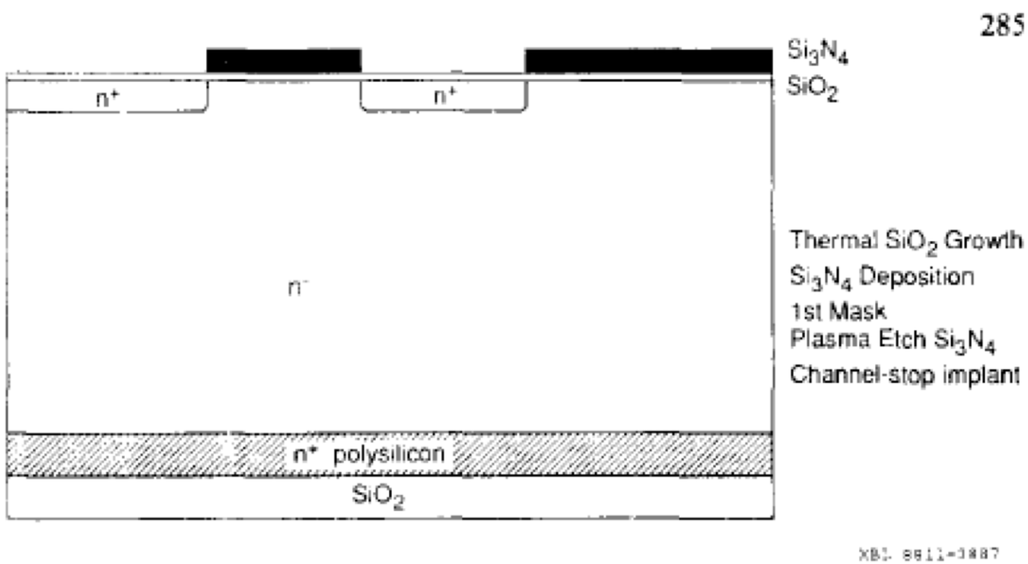
b) LBNL: MOS transistors for pixel detectors

N- and P-MOS to make integrated amplifiers

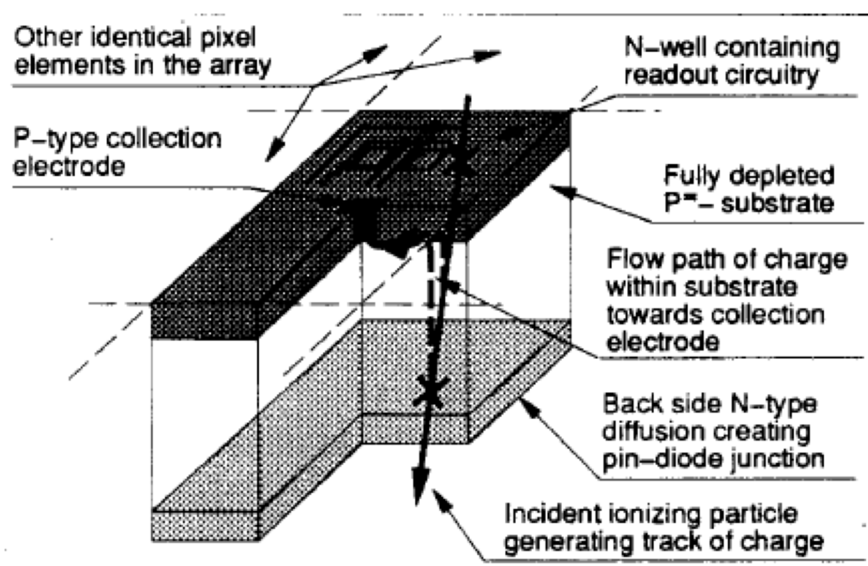
Back-side Poly-Si gettering to counteract leakage current degradation due to high-temperature thermal treatment

→ Led to very first CMOS MAPS (maybe too early)

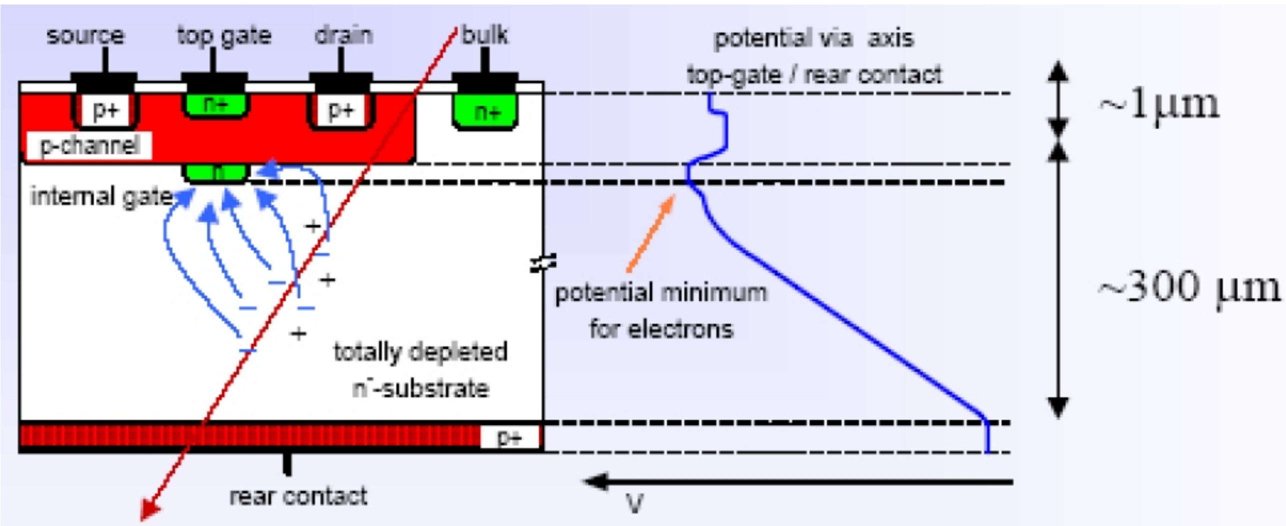
S. Holland, IEEE TNS 36 (1989) 283

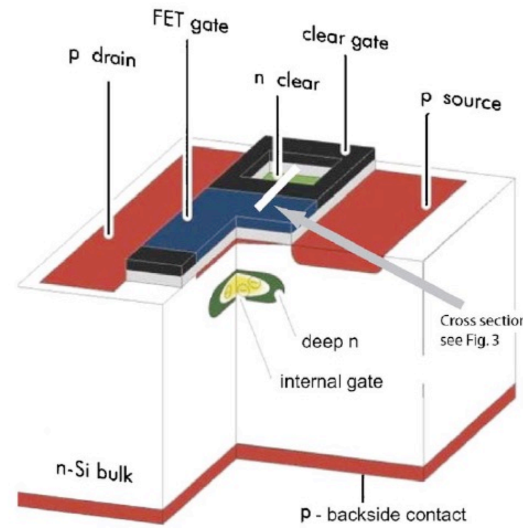


W. Snoeys et al, IEEE TNS 39 (1992) 1262



The DEPFET





J. Kemmer, G. Lutz, NIMA 253 (1987) 365

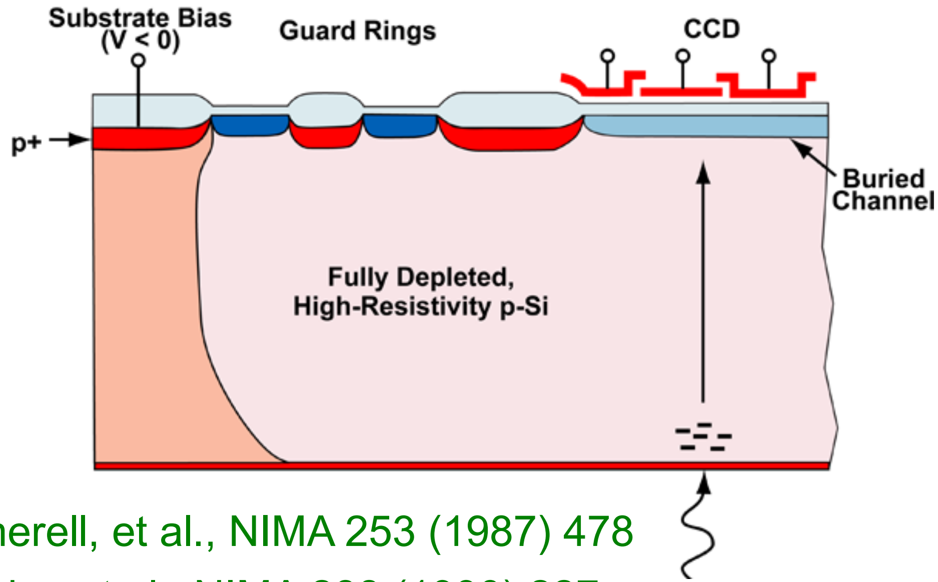
- detector has internal amplification (FET transistor incorporated)
- basically a fully depleted p-n detector with charges collected by an internal gate electrode modulating the FET current (non destructive read-out)
- An active clear mechanism is necessary to remove the electrons.

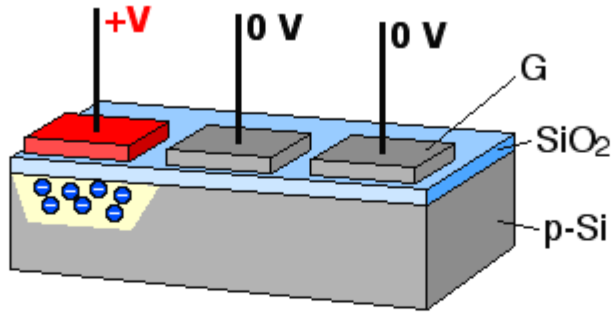
- Very low noise of only up to few e^-
- Very fast (collection by drift)
- Large signals so excellent S/N
- Pixels of ~50x50 μm^2 possible

Used in X-ray imaging (astronomy, FELs, …) and particle physics

Charged Coupled Devices

Smith & Boyle, 1969





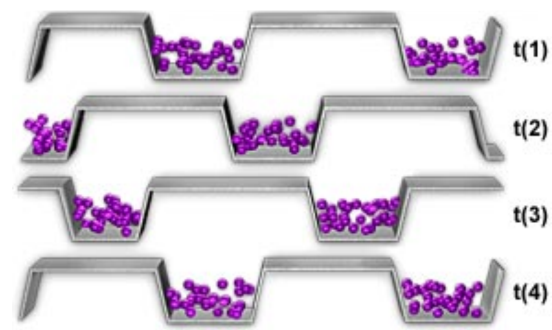
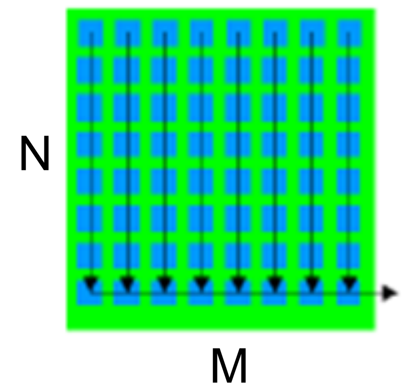


Figure 1

C. Damerell, et al., NIMA 253 (1987) 478

L. Strüder, et al., NIMA 288 (1990) 227

- Pixels are small MOS structures (but also p-n junc.)
- Depletion depth depends on type:
  - Fully depleted (particle detection)
  - Depleted only few μm underneath the electrode (optical light detection) – fill factor <100%
- Synchronized clock phases used to create potential minimum and laterally shift collected charges
- A single signal readout channel (vertical and horizontal shifting), but relatively slow (NxM shifts)
- Very low noise – up to few e^-



Monolithic Active Pixels & HV CMOS

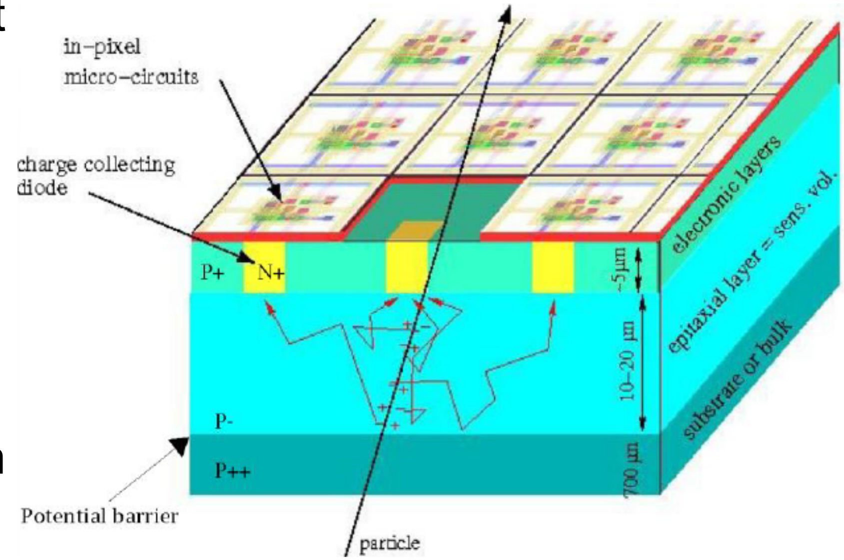
MAPs, **standard CMOS processing**. Active pixel cell with an NMOS transistor. The n^+ regions collect electrons from both ionization and light.

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

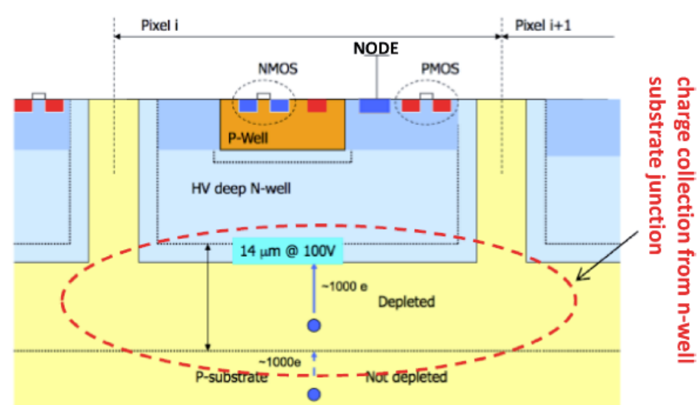
- Sensitive layer ~10-20 μm (mip → ~1000 e^-)
- Very low noise few 10 e (small pixels)
- Integrated electronics
- ALICE Inner Tracking System upgrade

BUT …

- Not so radiation hard – collection by diffusion
- Not very fast
- Technology restrictions (epitaxial layer)
- Need to exploit special features for better detectors (e.g., multiple wells)



New detector technology – HV(HR) CMOS – drift becomes dominant , the "buts" above disappear



More from M. Rolo on Wednesday

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  L. Rossi, P. Fischer, T. Rohe, N. Wermes, Springer, ISBN 3-540-28332-3

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