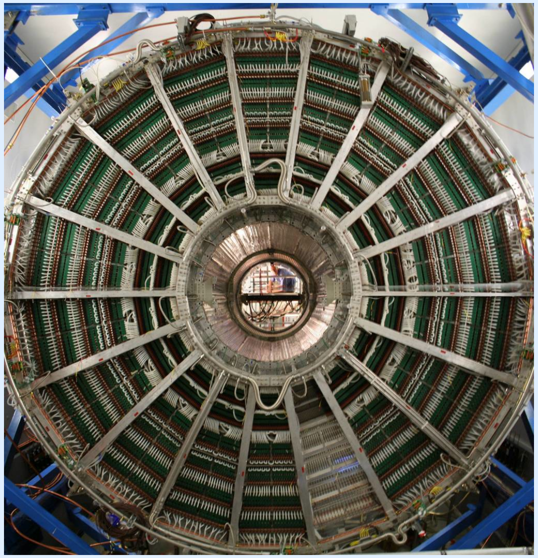
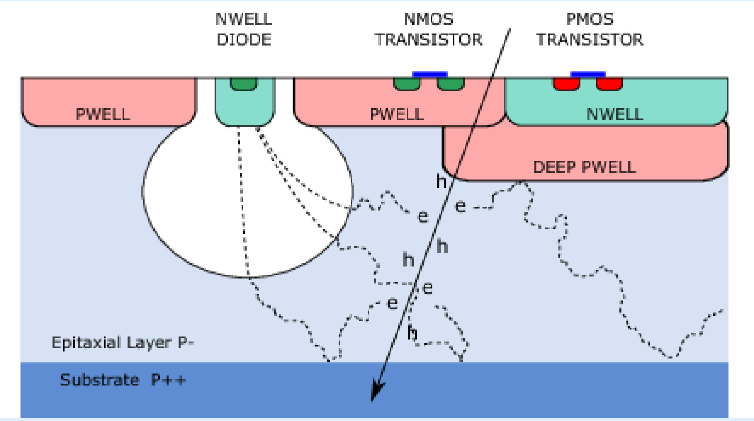
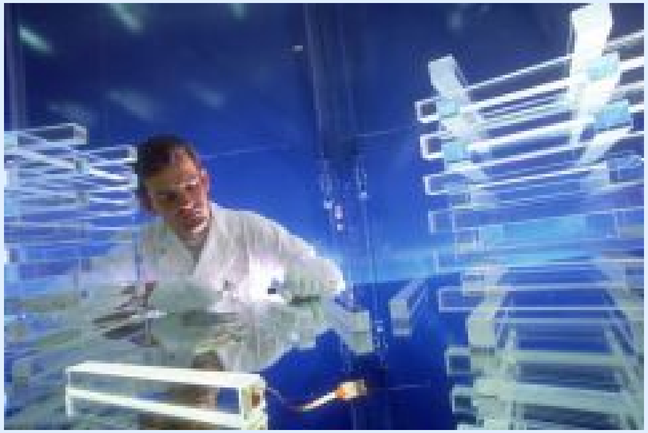






Semiconductor detectors - 2

Silvia Masciocchi,
GSI and University of Heidelberg

SS2017, Heidelberg
May 31, 2017

Overview semiconductor detectors

- **Principle of operation of semiconductor detectors**
  - **Properties of semiconductors (band structure)**
  - **Intrinsic material**
  - **Extrinsic (doped) semiconductors**
  - **p-n junction**

LAST WEEK

- Signal generation
- Ionization yield and Fano factor
- Energy measurement with semiconductor detectors
- Position measurement with semiconductor detectors

TODAY

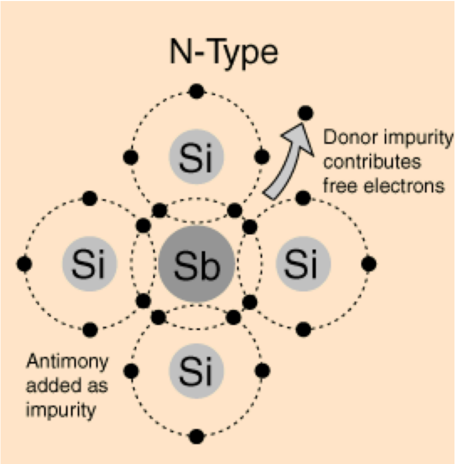
  - Micro-strip detectors
  - Pixels
  - Silicon drift detectors
  - Charge-coupled devices (CCDs)
- Radiation damage

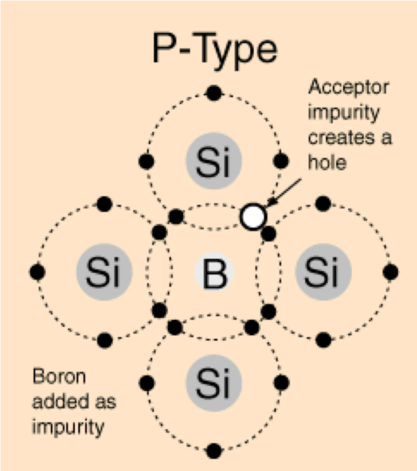
JUNE 14 !!!

Intrinsic and doped semiconductors

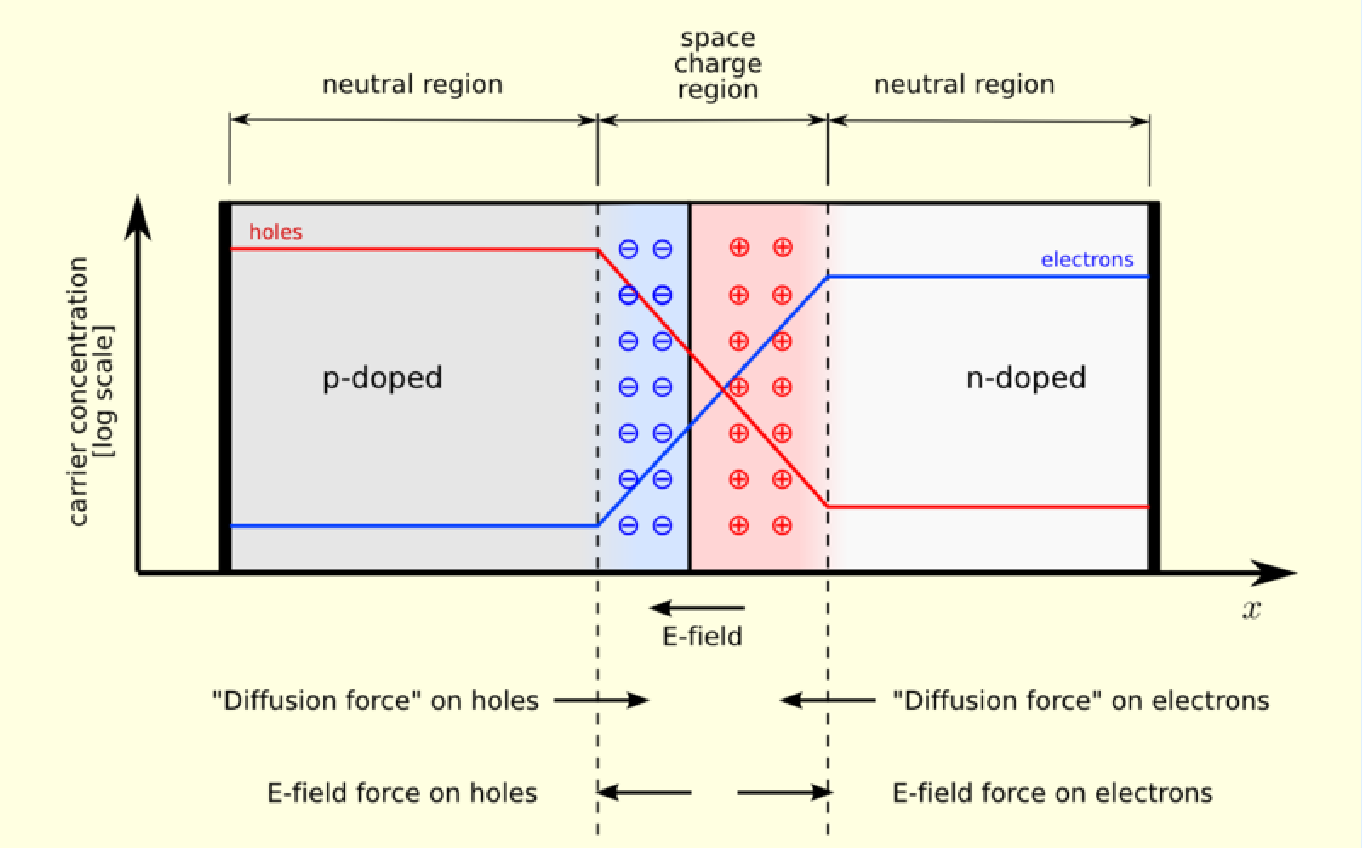
REMINDER

- Doping is the replacement of a small number of atoms in the lattice by atoms of neighboring columns from the atomic table (with one valence electron more or less compared to the basic material – usually tetravalent, Si, Ge)
- The doping atoms create energy levels within the band gap and therefore alter the conductivity
- An undoped semiconductor is called an intrinsic semiconductor
- A doped semiconductor is called an extrinsic semiconductor
- In an intrinsic semiconductor, for each electron in the conduction band there is a hole in the valence band. In extrinsic semiconductors there is a surplus of electrons (n-type) or holes (p-type)





p-n junction

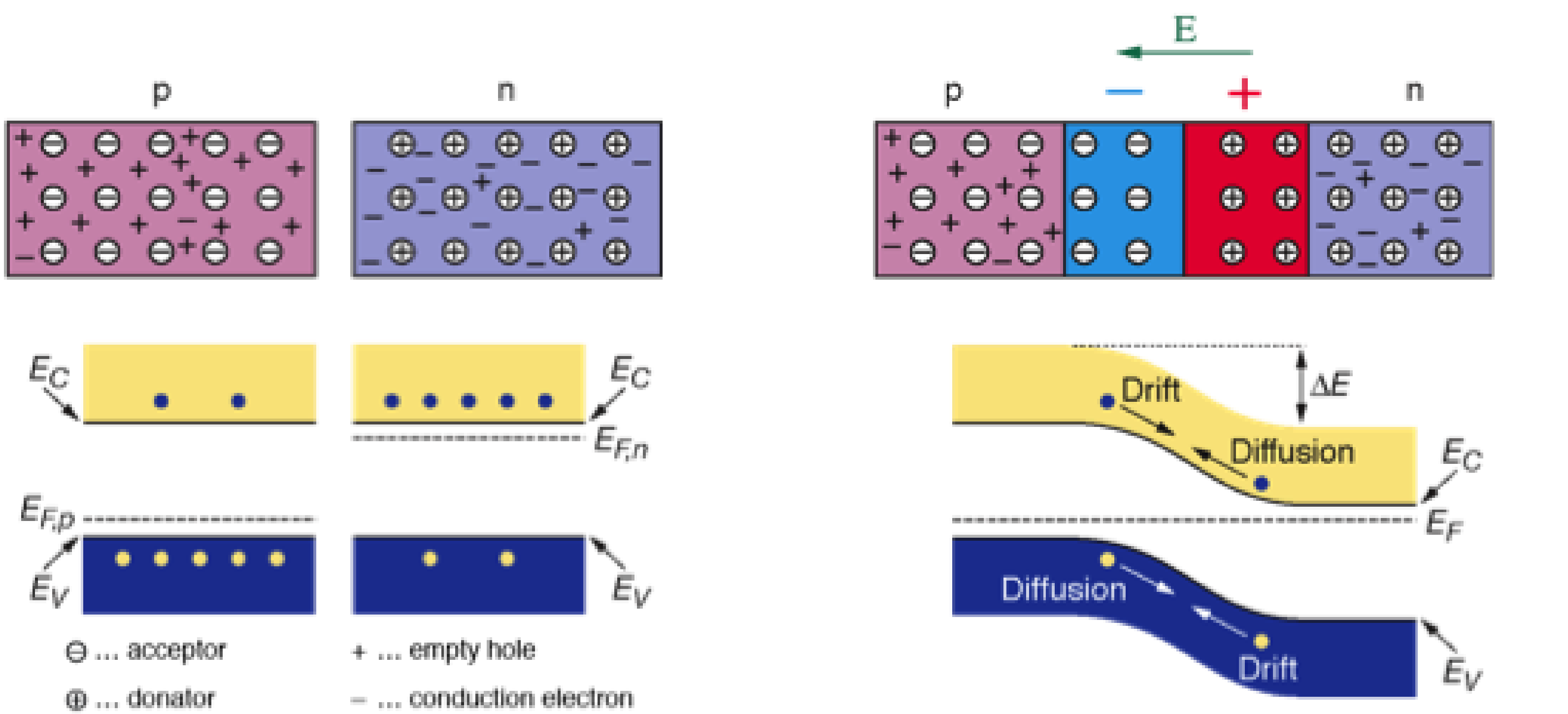

neutral region
space charge region
neutral region
holes
electrons
p-doped
n-doped
carrier concentration [log scale]
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

p-n junction

REMINDER

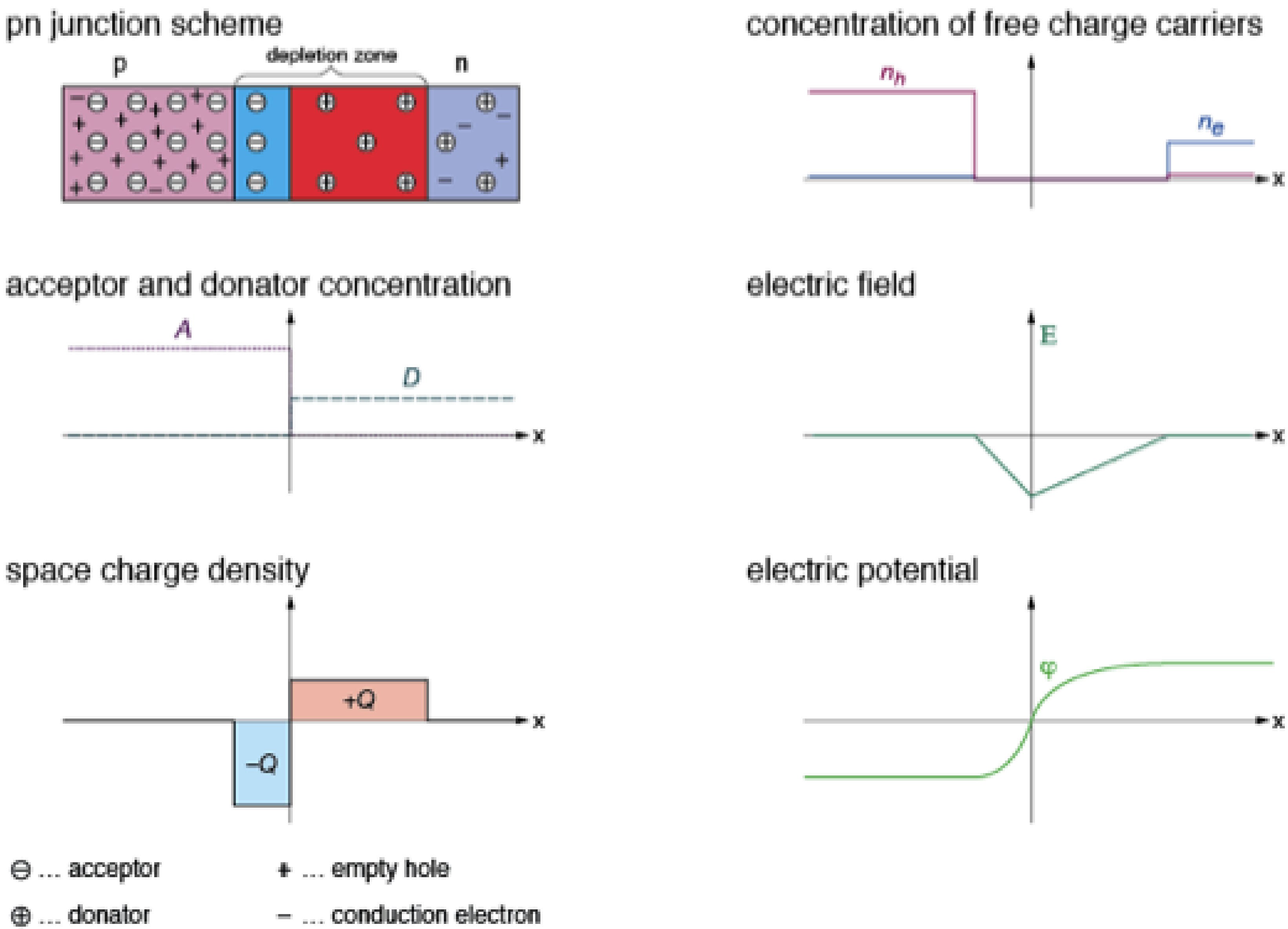
At the interface of an n-type and p-type semiconductor the difference in the fermi levels cause diffusion of surplus carries to the other material until thermal equilibrium is reached. At this point the fermi level is equal. The remaining ions create a space charge and an electric field stopping further diffusion (contact potential).

The stable space charge region is free of charge carries and is called the depletion zone.



p-n junction

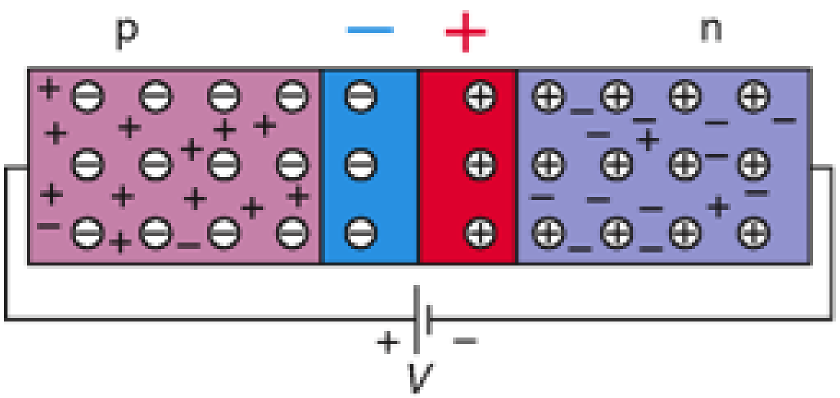
REMINDER



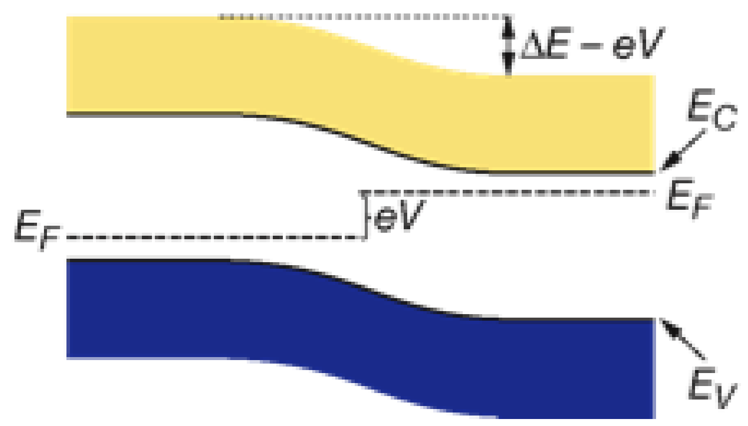
p-n junction: forward bias

REMINDER

Applying an external voltage V with the anode to p and the cathode to n e- and holes are refilled to the depletion zone. The depletion zone becomes narrower.



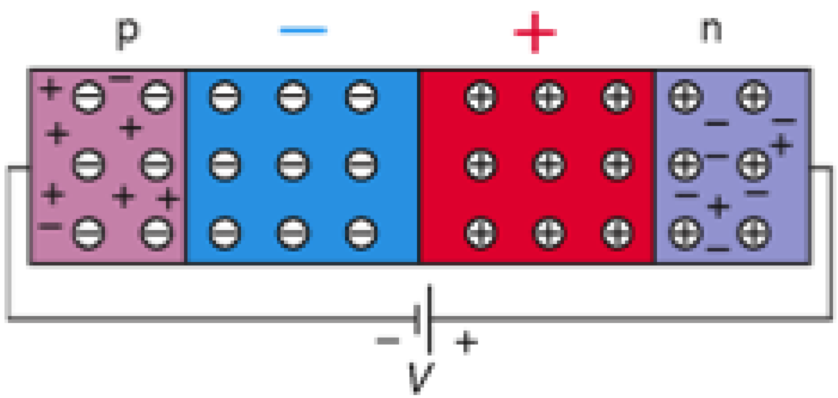
The potential barrier becomes smaller by eV and diffusion across the junction becomes easier. The current across the junction increases significantly.



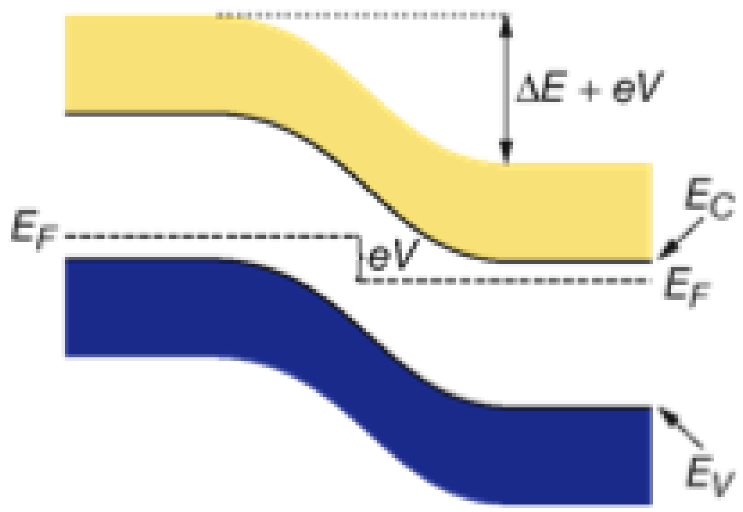
p-n junction: reverse bias

REMINDER

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.



The potential barrier becomes higher by *eV* and diffusion across the junction is suppressed. The current across the junction is very small “leakage current”.

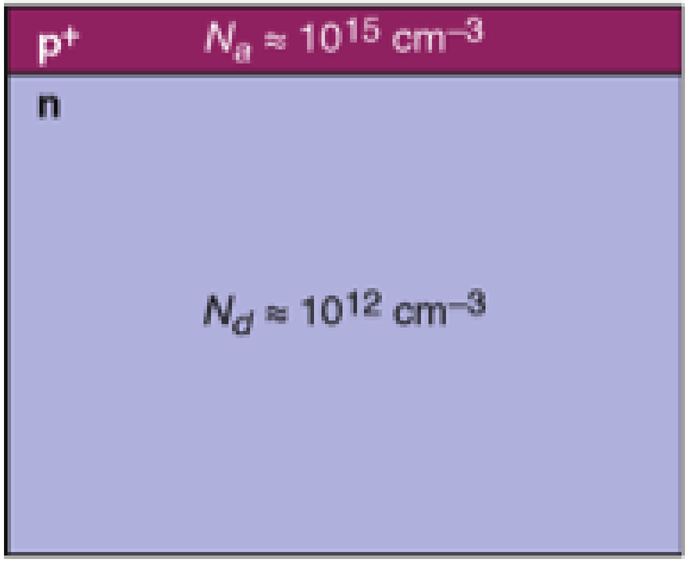


p-n junction

REMINDER

Example of a typical p⁺-n junction in a silicon detector:

Effective doping concentration $N_a = 10^{15}$ cm^{-3} in p⁺ region and $N_d = 10^{12}$ cm^{-3} in n bulk.



Without external voltage:

$W_p = 0.02$ µm

$W_n = 23$ µm

Applying a reverse bias voltage of 100 V:

$W_p = 0.4$ µm

$W_n = 363$ µm

Width of depletion zone in n bulk:

$$\boxed{W \approx \sqrt{2\varepsilon_0 \varepsilon_r \mu \rho |V|}}$$

$$\rho = \frac{1}{e \mu N_{eff}}$$

V … External voltage

ρ … specific resistivity

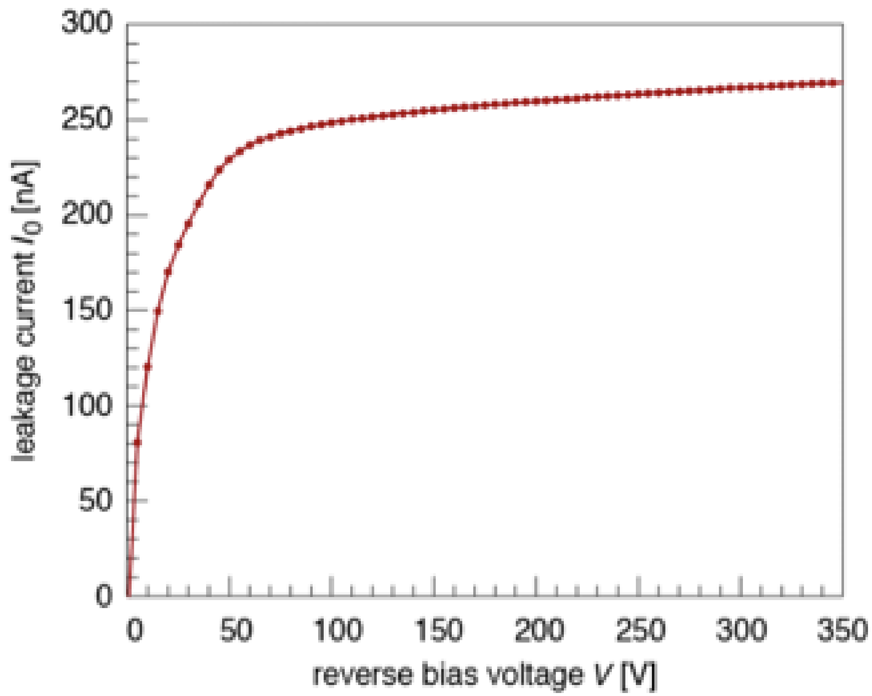
μ … mobility of majority charge carriers

N_{eff} … effective doping concentration

p-n junction: leakage current

- Movement of minority carriers (small)
- Thermally generated electron-hole pairs originating from recombination and trapping centers in the depletion region
- Surface channels (surface chemistry, contaminants, type of mounting, etc.)

It is essential to keep the leakage current low! That is the reference noise level with respect to which the desired SIGNALs have to be measured!!! (S/N)

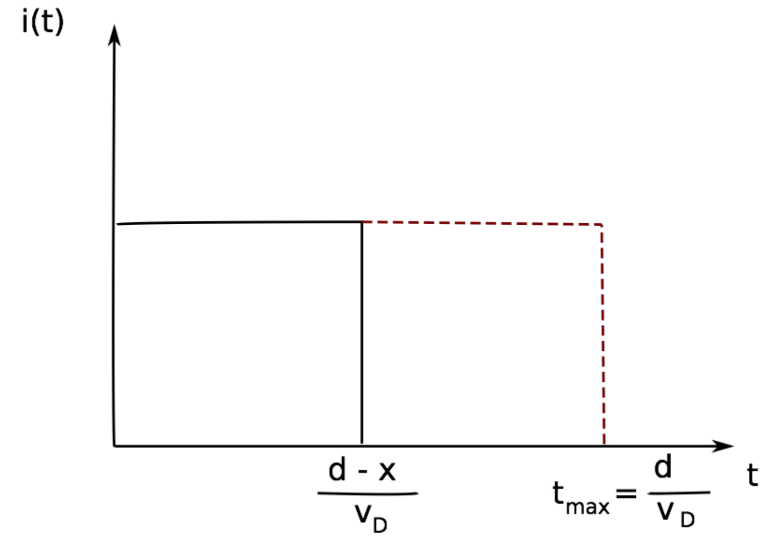


Signal generation in semiconductor detectors

Similar to ionization chambers: under constant E field, each drifting electron contributes to signal current while drifting

$$dq = \frac{e\,dx}{d}$$

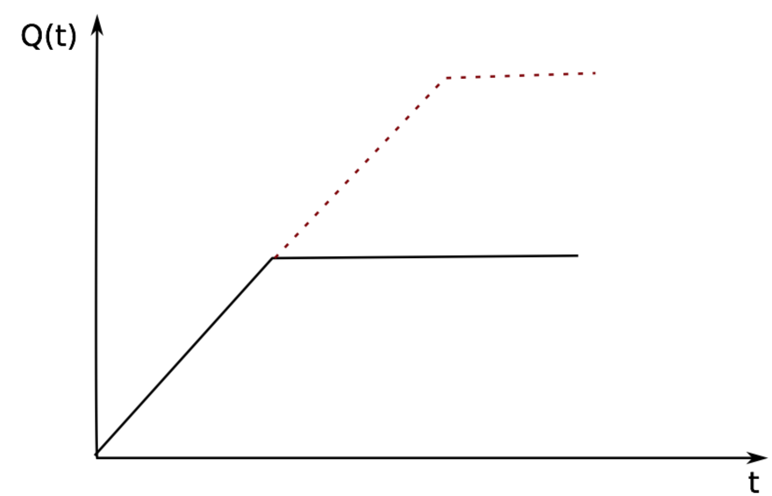
$$i = \frac{dq}{dt} = e\frac{dx}{d}\frac{1}{dx/v_D} = e\frac{v_D}{d}$$



d = width of depletion zone
x = location where electron was generated
→ **capacitor charges:**

$$Q = e\frac{v_D}{d}\cdot t = e\frac{v_D}{d}\frac{d-x}{v_D}$$

Assume a line of charges across the depletion zone (constant ionization along the track) →
$Q_{electrons} = N_0e/2$, $Q_{holes} = N_0e/2$ → $Q_{tot} = N_0e$



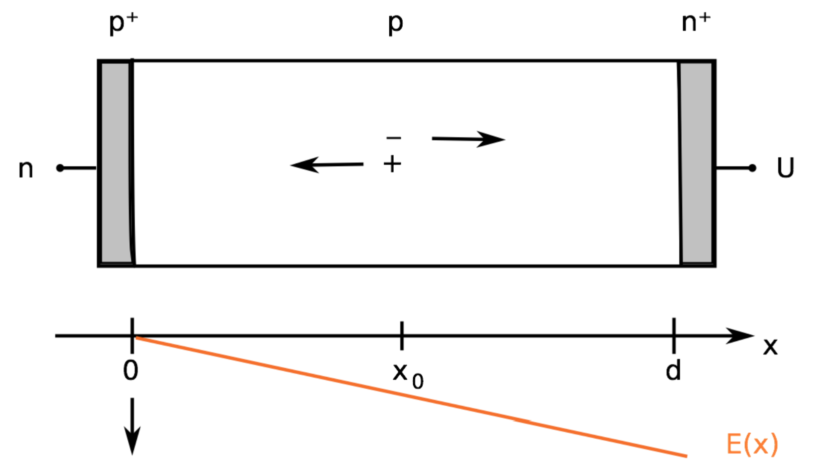
Signal generation in semiconductor detectors

More realistically: E-field depends on x

Simple Ansatz: $$|\vec{E}| = \frac{e N_A}{\epsilon \epsilon_0} \cdot x$$

With: $$\sigma = \frac{1}{\rho} = e N_A \mu_+ \qquad \tau = \frac{\epsilon \epsilon_0}{\sigma}$$

$$|\vec{E}| = \frac{x}{\mu_+ \tau} \qquad (\tau \approx 1\,\mathrm{ns})$$



For an electrons generated at location x inside the depletion zone and mobilities independent from E:

$$v_- = -\mu_- E = \frac{\mu_-}{\mu_+} \frac{x}{\tau} \quad \Rightarrow \quad x = x_0 \exp\left(\frac{\mu_- t}{\mu_+ \tau}\right)$$

Total drift time of electrons:

$$t_d = \tau \frac{\mu_+}{\mu_-} \ln\left(\frac{d}{x_0}\right)$$

Charge signal for t < t_d:

$$Q_-(t) = -\frac{e}{d} \int \frac{dx}{dt} dt = \frac{e}{d} x_0 \left(1 - \exp\left(\frac{\mu_- t}{\mu_+ \tau}\right)\right)$$

Analogously for holes

$$v_+ = \mu_+ E = -\frac{x}{\tau} \quad \Rightarrow \quad x = x_0 \exp(-t/\tau)$$

$$Q_+(t) = -\tfrac{e}{d} x_0 \left(1 - \exp(-t/\tau)\right)$$

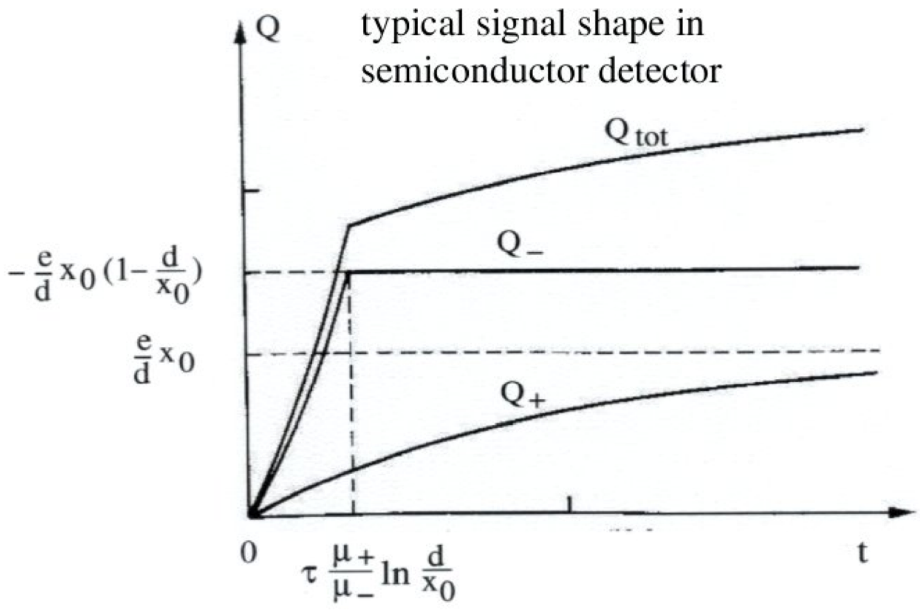
Signal generation in semiconductor detectors

Total charge signal:

$$Q_{-}(t_d) + Q_{+}(+\infty) = -e$$

Signal rise time essentially determined by:

$$\tau = \rho \cdot \epsilon \cdot \epsilon_0$$



In reality a bit more complicated:

- Track not exactly a line charge (distributed over typically 50 µm width)
- $\mu_{\pm} \neq$ constant
- Some loss of charges due to recombination at impurities

For silicon: τ = ρ · 10^{-12} s (ρ in Ωcm), ρ = 1000 Ωcm → τ = 1 ns

Ionization yield and Fano factor

Ionization yield and resolution

	$E_0^{300\ \mathrm{K}}$	$E_0^{77\ \mathrm{K}}$	E_{gap}
Si	3.6 eV	3.8 eV	1.1 eV
Ge	-	2.9 eV	0.7 eV

Mean energy per electron-hole pair:

~1/3 in ionization, ~2/3 in excitation of crystal lattice

$$\text{Energy loss } \Delta E \quad \Rightarrow \quad \begin{cases} \text{lattice vibrations:} & \text{generation of phonons} \\ & \text{typical quantum energy } E_x = 0.037\ \text{eV} \\ \text{ionization:} & \text{characteristic energy } E_i = E_{\mathrm{gap}} = 1.1\ \text{eV in Si} \\ \text{total:} & \Delta E = E_i N_i + E_x N_x \end{cases}$$

For both processes, we assume a Poisson distribution: $\sigma_i = \sqrt{N_i}$, $\sigma_x = \sqrt{N_x}$

For a FIXED energy loss ΔE, the sharing between ionization and lattice excitations varies as:

On average:

Using $N_x = (\Delta E - E_i N_i)/E_x$

Ionization yield and Fano factor

In case of ideal charge collection without losses:

$N_i = \Delta E / E_0 \rightarrow$

$$\sigma_i = \frac{E_x}{E_i}\sqrt{\frac{\Delta E}{E_x} - \frac{E_i}{E_x}\frac{\Delta E}{E_0}} = \underbrace{\sqrt{\frac{\Delta E}{E_0}}}_{\sqrt{N_i}} \underbrace{\sqrt{\frac{E_x}{E_i}\left(\frac{E_0}{E_i} - 1\right)}}_{\sqrt{F}}$$

F: Fano factor

Si: $E_0 \simeq 3.6$ eV $F \simeq 0.1$

Ge: $E_0 \simeq 2.9$ eV $F \simeq 0.1$

$\sigma_i = \sqrt{N_i}\,\sqrt{F}$ smaller than the naïve expectation!

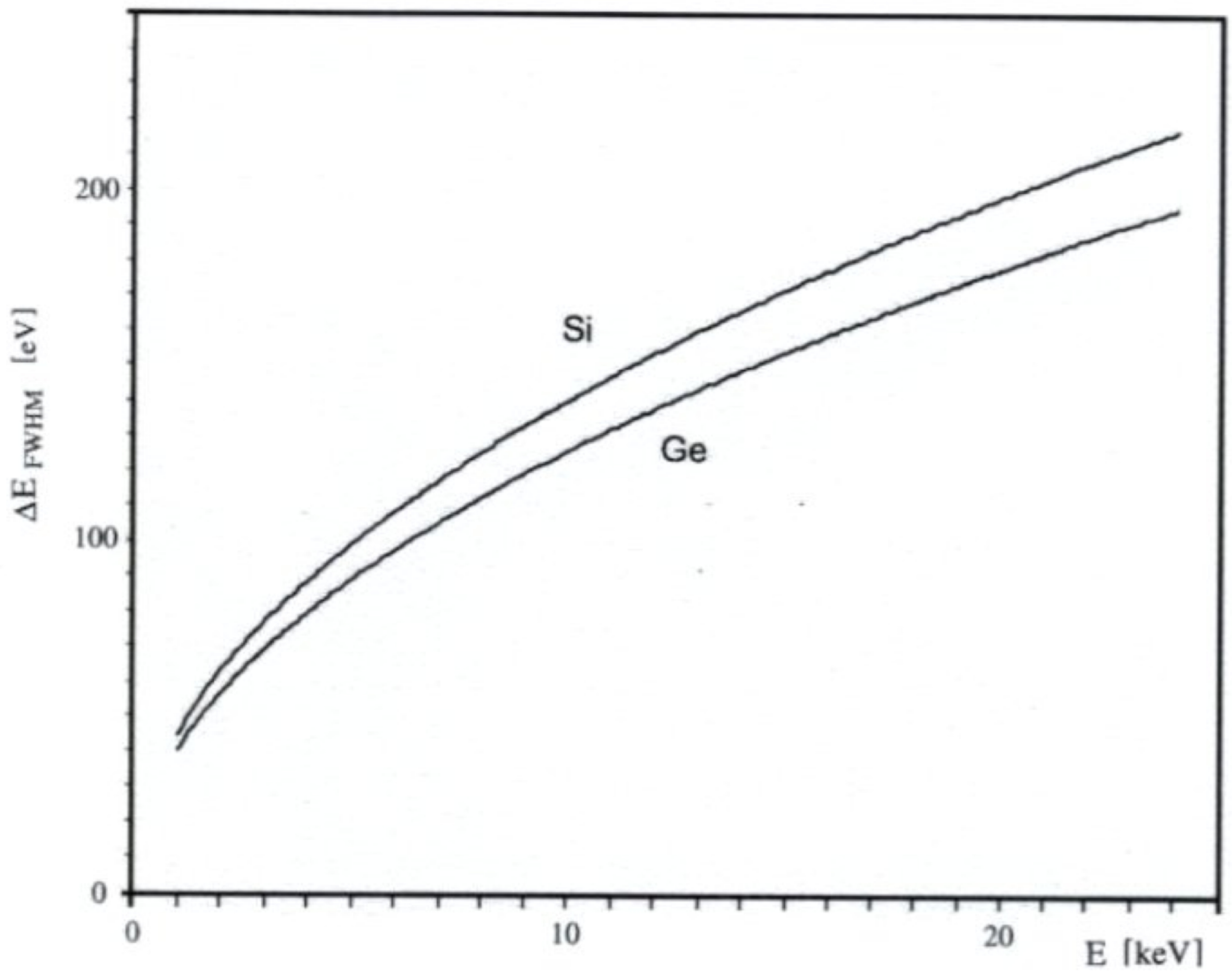
Due to energy conservation, fluctuations are reduced for a given energy loss ΔE (the total absorbed energy does not fluctuate)

Relative energy resolution:

$$\boxed{\frac{\sigma_i}{N_i} = \frac{\sqrt{N_i F}}{N_i} = \frac{\sqrt{F}}{\sqrt{N_i}} = \frac{\sqrt{F E_0}}{\sqrt{\Delta E}} = \frac{\sigma_{\Delta E}}{\Delta E}}$$

Example: photon of 5 keV, $E_\gamma = \Delta E$, $\sigma_{\Delta E} = 40$eV ≃ 1% instead of 2.7% w/o Fano factor

Energy resolution



Statistics of charge carriers generated + noise + non-uniformities in charge-collection efficiency

Energy measurements

- Particularly suited for low energies: e.g. α-particles, low energy electrons, X- and γ- rays
- Via dE/dx in thin detectors

  or full stopping in thick detectors

We will consider:

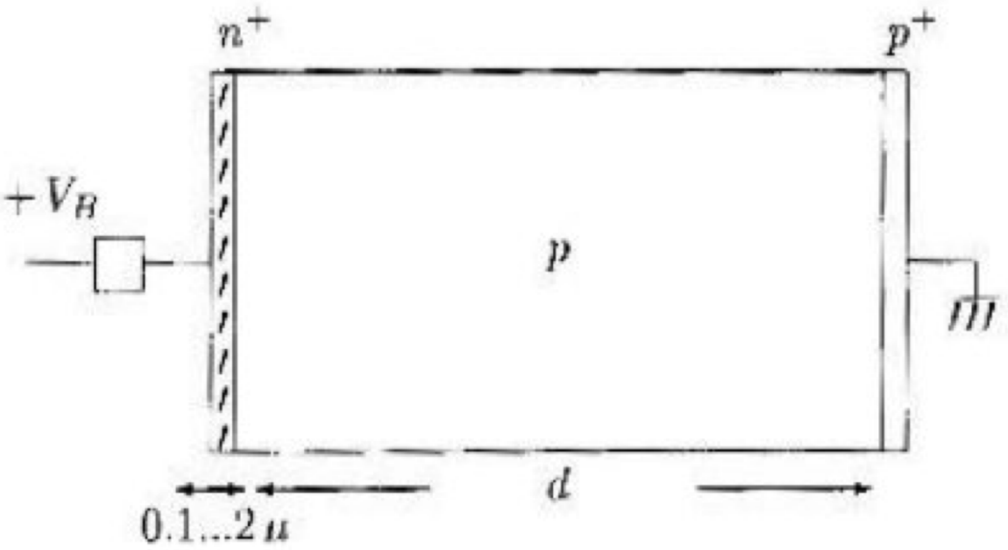
- Ion implanted or diffusion barrier detectors
- Surface barrier detectors
- p-i-n detectors: Ge(Li), Si(Li)
- High purity of intrinsic Ge detectors
- (Bolometers)

Ion implanted or diffusion barrier detectors

p-type material (usually 300 µm) with n^+ and p^+ surface contacts, obtained by:

- Ion implantation (50 nm), or
- Diffusion doping (0.1 – 1 µm)

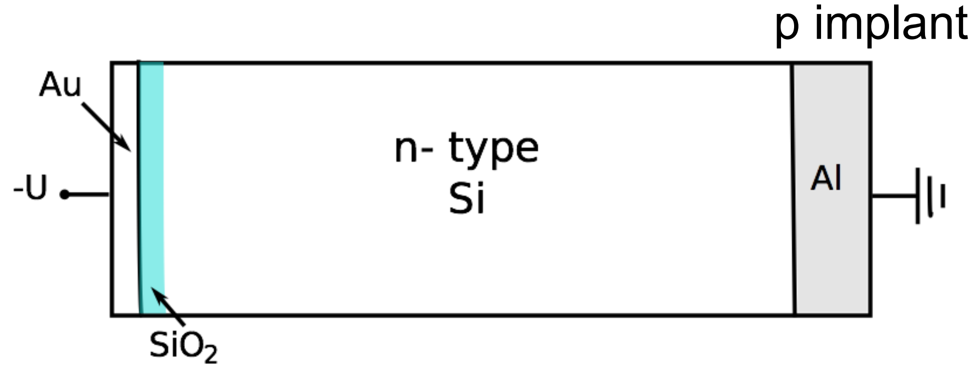
U^+ applied at n^+ side
→ p zone fully depleted
Depletion layer = p-zone



Disadvantage: the n^+ contact layer acts as dead material for the entering particles

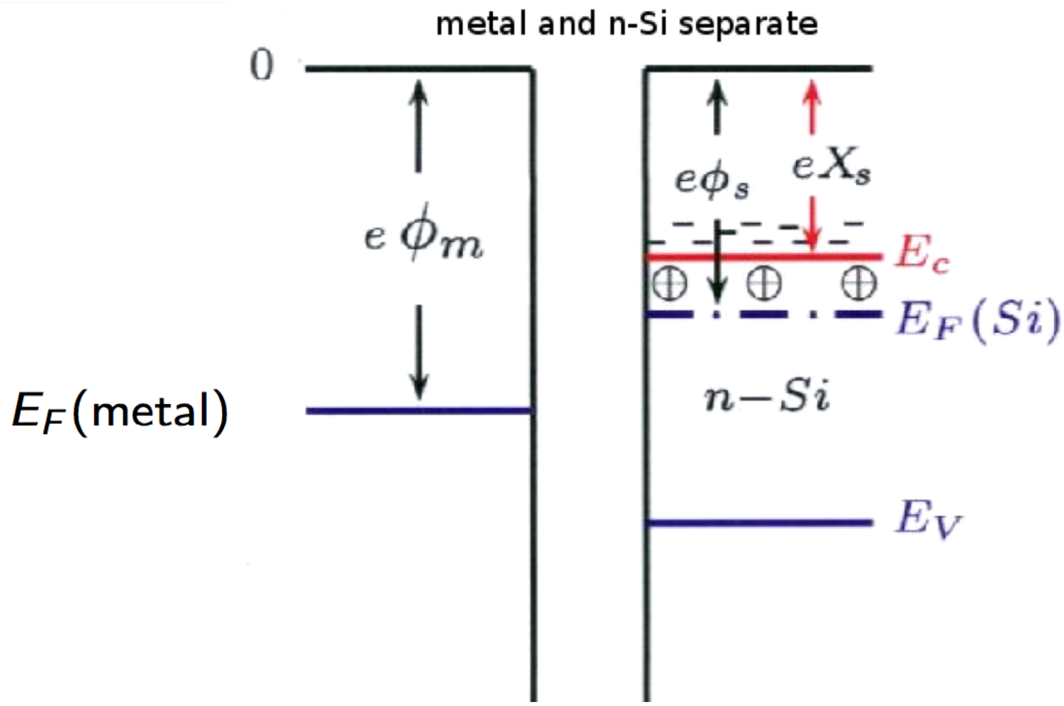
- Part of the energy loss will not be measures → additional fluctuations (limit in resolution)
- Very soft particles or short range particles like α's may not reach the depletion layer at all

Surface barrier detectors



Contacts are realized by evaporating very thin layers of metal
(40 µg / cm² ≡ 20 nm)

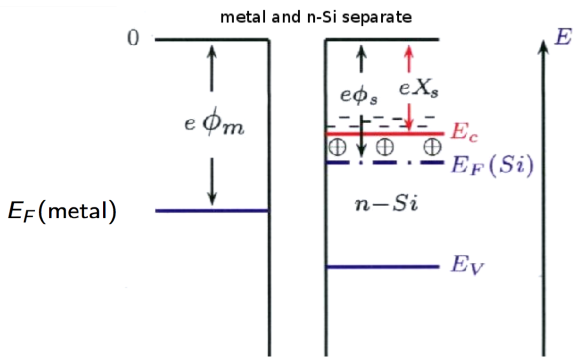
2-band model of a Schottky diode:

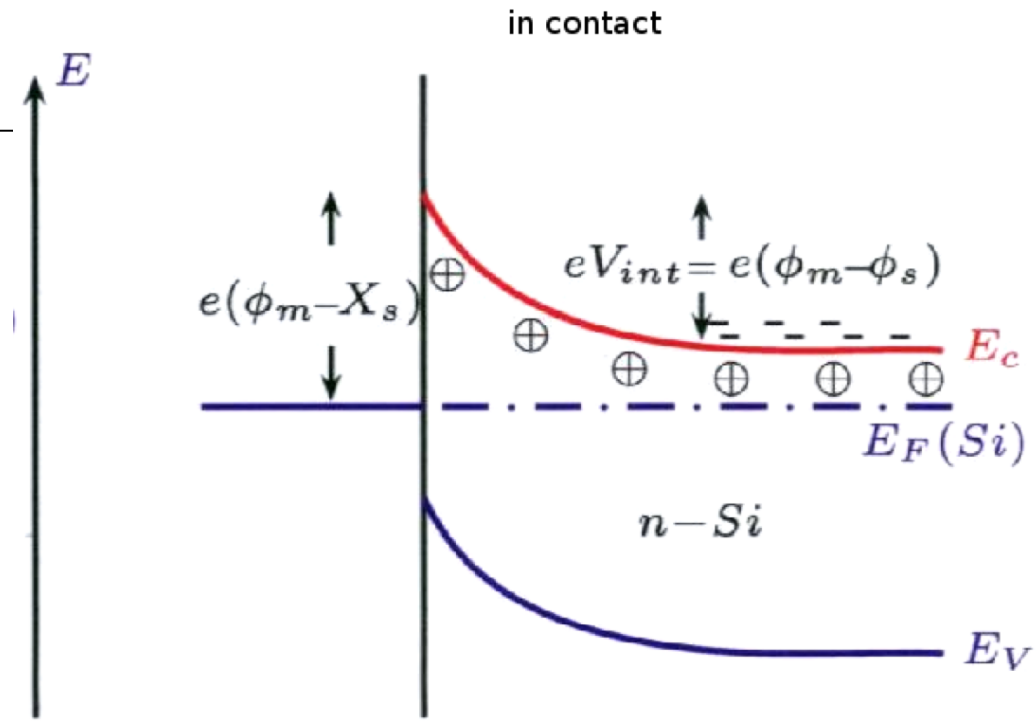


- $e\varphi_m$ metal work function (= work to extract an electron)
- $e\varphi_S$ work function semiconductor (< $e\varphi_m$, otherwise the interface would be conducting)
- eX_S electron affinity semiconductor (energy spent or released when an electron is added)

Bring metal in contact with n-Si: electrons diffuse from Si into metal until $E_F^{metal} = E_F^{Si}$ → strong E-field at the surface

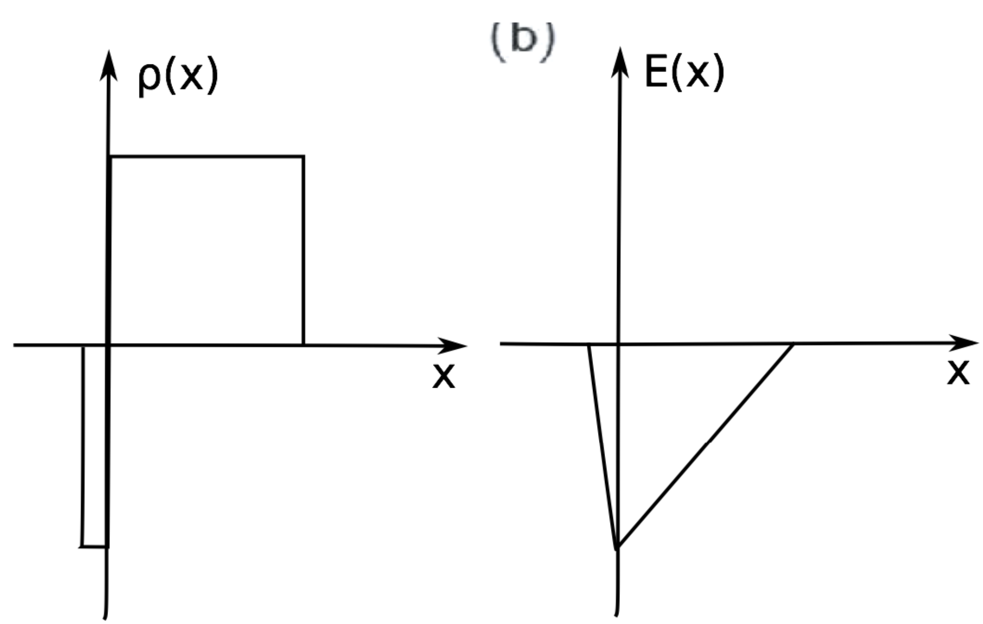
Surface barrier detectors





Metal-semiconductor junction acts as a diode, region with high resistance.

- $eV_{int} = e(\Phi_m - \Phi_S)$: potential barrier at surface for electrons in conduction band in Si
- Applying –U at metal: the barrier is increased → no tunneling (dark current. Only current due to ionization



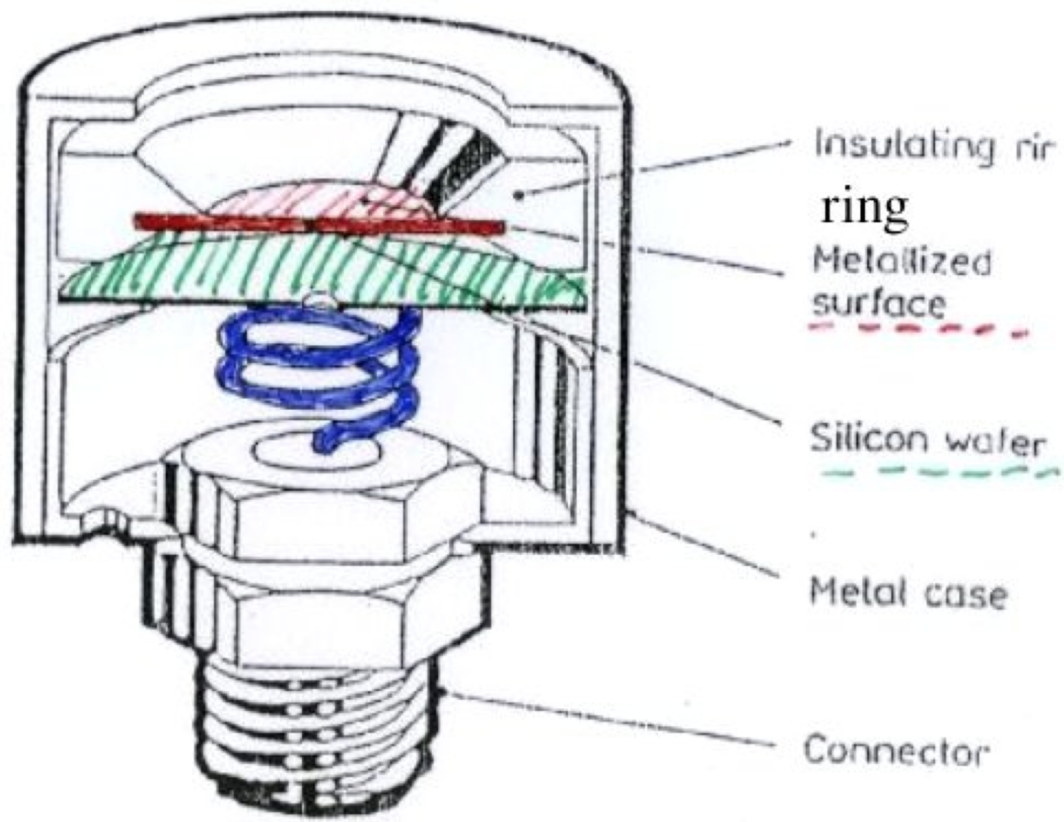
Depletion layer in n–Si up to several mm thick!
Used since the 1960ies for particle detection

Surface barrier detectors

Advantage of surface barrier detector:

- Simple fabrication process
- Very thin entrance window:
  - Energy loss negligible
  - For detection of photons down to eV energy range

    But usually thickness too small for γ-ray detection above 100 keV, i.e. good for X-rays



Careful:

- They are sensitive to light (thin gold layer cannot stop it): need a light-tight enclosure
- Sensitive surface, not to be touched or contaminated

High resistivity

For energy measurements (particularly of γ rays – above 100 keV) need for very high resistivity materials, because:

Depletion layer = constant ·

Dark current must be kept low

Typical values:

- n-type semiconductor: 20,000 Ωcm
- Intrinsic material: ~230,000 Ωcm
  - Problem is to have good enough purity in large volumes
- Compensated materials (see next case): ~100,000 Ωcm

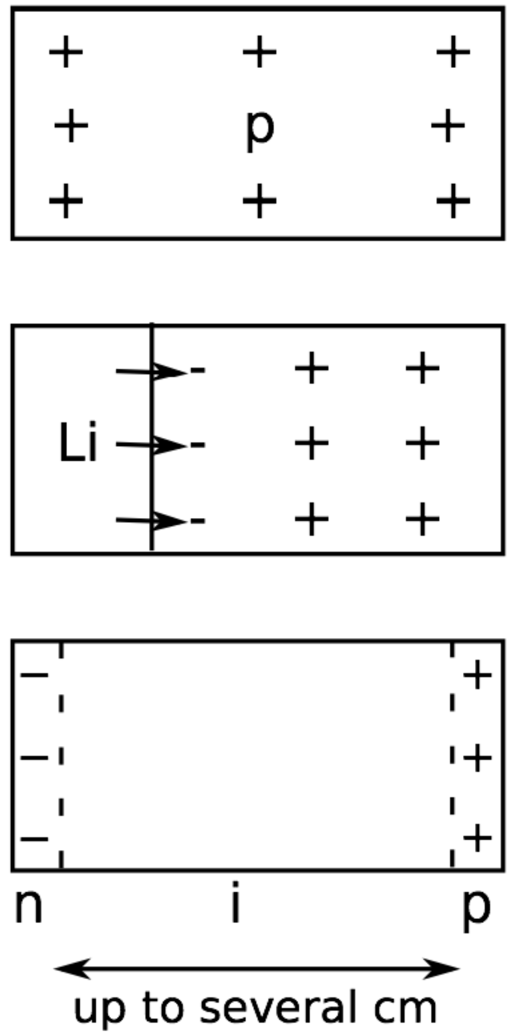
p-i-n detectors: Ge(Li), Si(Li)

Way to get beyond a few mm thickness:

From the 1960ies: create a thick (1-2 cm) depletion layer with **COMPENSATED** material (very high resistivity)

E. M. Pell

- Start with high-purity p-type Ge or Si (acceptor is typically Boron)
- Bring in contact with liquid Li bath (350-400 °C) the lithium diffuses into Ge/Si
- Apply external field → positive Li-ions drift far into the crystal and compensate Boron ions locally



Typically 10^9 /cm^3 Li atoms

p-Si + Li$^+$ ≃ neutral

$\rho = 2 \cdot 10^5$ Ωcm possible

i.e. like true intrinsic material

Achieve high resistivity!

p-i-n detectors: Ge(Li), Si(Li)

Needs to be **cooled PERMANENTLY**! (liquid N2) to avoid separation of Li impurities by diffusion!

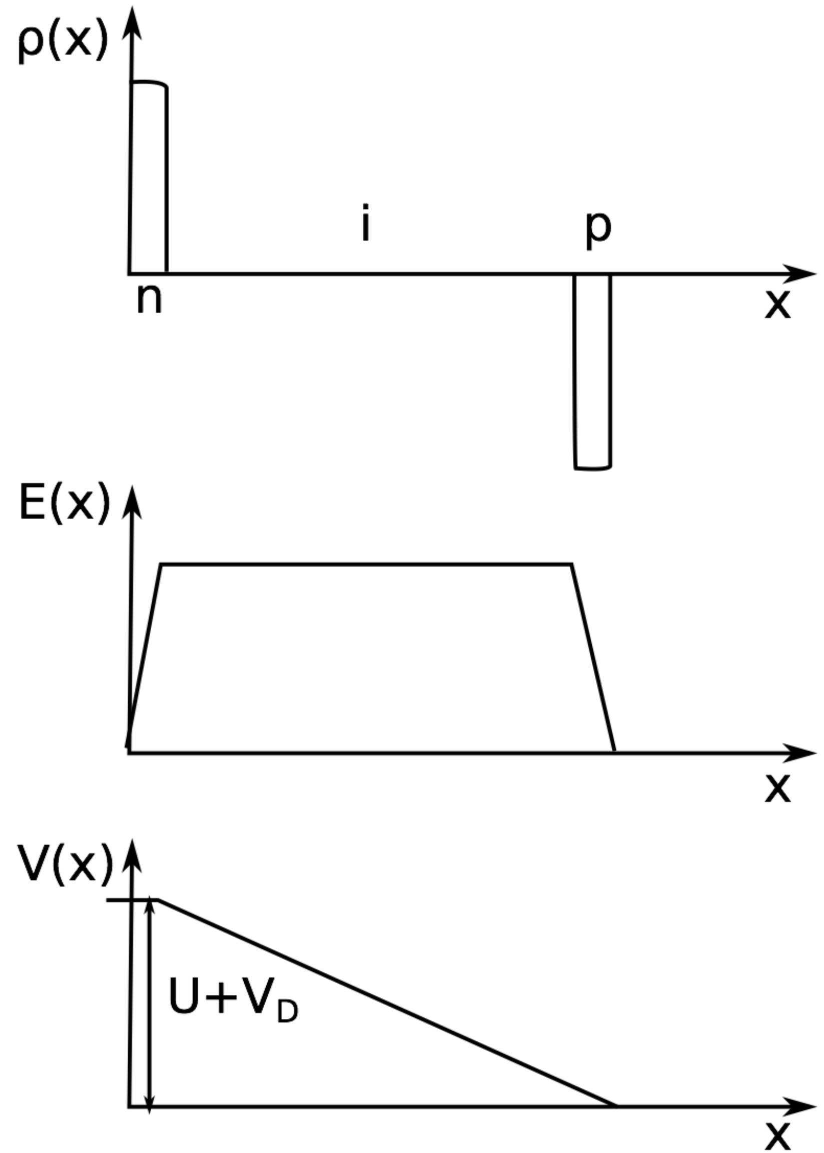
Application: **γ spectroscopy**

Larger cross section for photoelectric effect in Ge wrt Si:

→ Ge(Li) preferred!

However: full energy peak contains only order of 10% of the signal in a 50 cm^3 crystal (30% in a 170 cm^3 crystal)

- Resolution much better than NaI (sodium iodide - scintillator)
- Efficiency significantly lower



external voltage U and diffusion voltage V_D

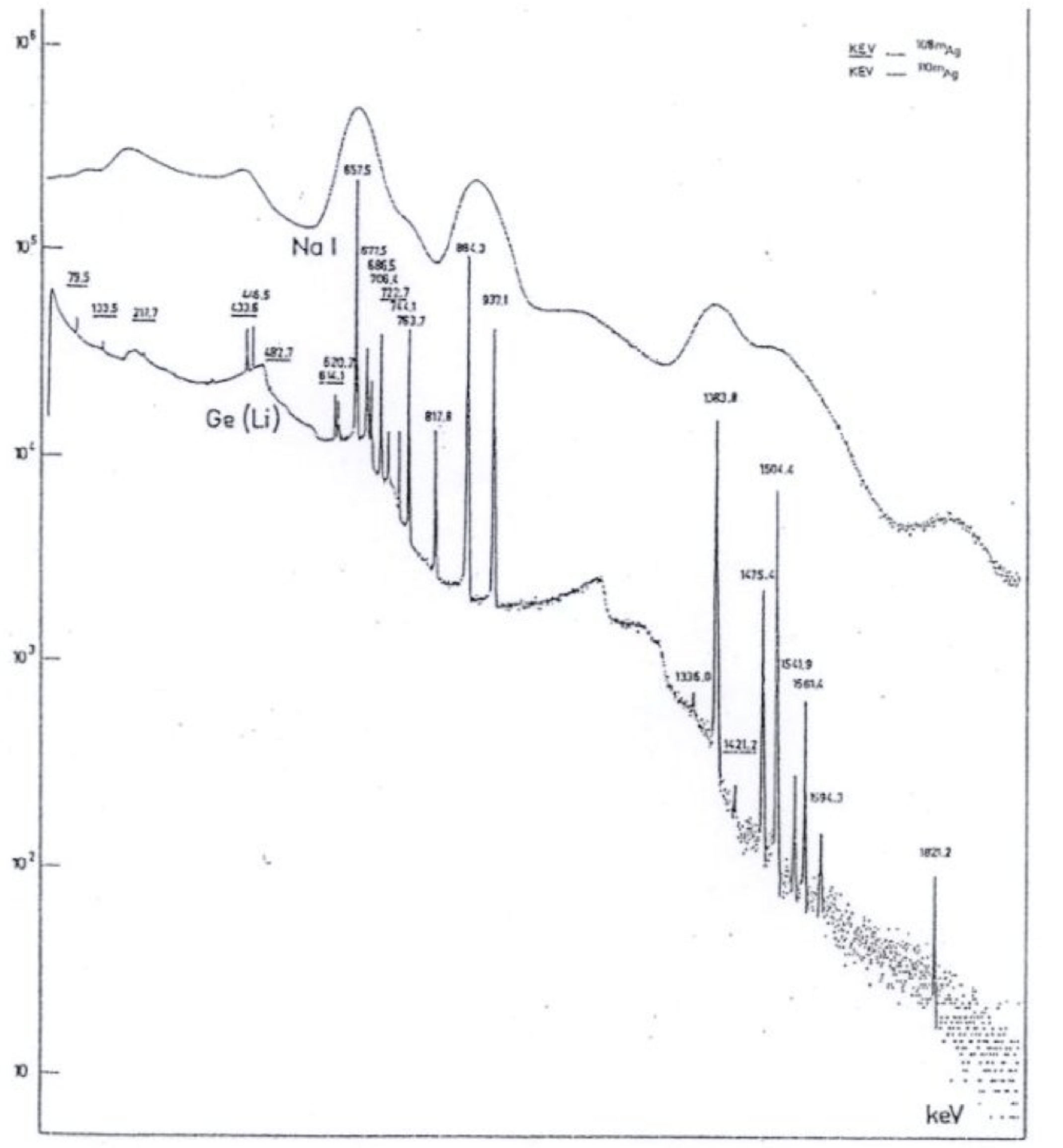
p-i-n detectors: Ge(Li), Si(Li)

Ge(Li) detectors: a revolution in γ spectroscopy in the mid 1960ies

Comparison of spectra obtained with NaI (state of the art technique until then) and Ge(Li)

Decays of ^{108m}Ag and ^{110m}Ag

Energies of peaks are labeled in keV



High purity or intrinsic Germanium detectors

From the late 1970ies: improvements in material quality

Keep dark current low not by compensating impurities but by making the material **VERY CLEAN** itself

Extremely pure Ge obtained by repeating the purification process (zone melting) $\rightarrow$ $\leq 10^9$ impurities per cm^3

Intrinsic later like compensated zone in Ge(Li), similar sizes possible

Advantage: cooling only needed during use, to reduce the noise

Other applications:

- Low energy electrons
- Strongly ionizing particles
- dE/dx for particle identification

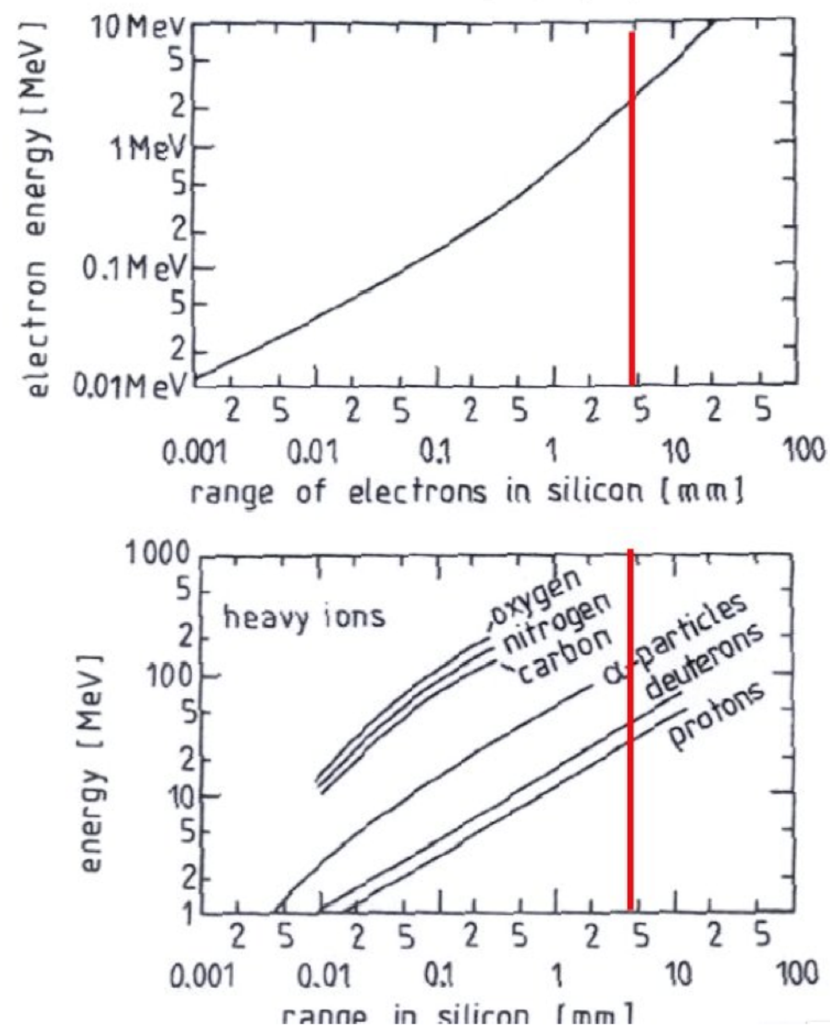
High purity or intrinsic Germanium detectors

The energy range addressed by a device is determined by the range of particles compared to the size of the detector

Range of electrons, p, d, α, etc. in Si

Particles stopped in 5mm Si(Li) detectors:

- α up to 120 MeV kintic energy
- p up to 30 MeV
- e up to 3 MeV



energy-range relation for electrons (top) and more massive particles (bottom)

Bolometers

How to increase further the energy resolution?

Use even finer steps for energy absorption = break-up of Cooper pairs in a semiconductor, operate at cryogenic temperatures

Instead of current, one can measure the temperature rise due to the absorption of e.g. an X-ray → couple the absorber with extremely low heat capacity (HgCdTe) with semiconductor thermistor

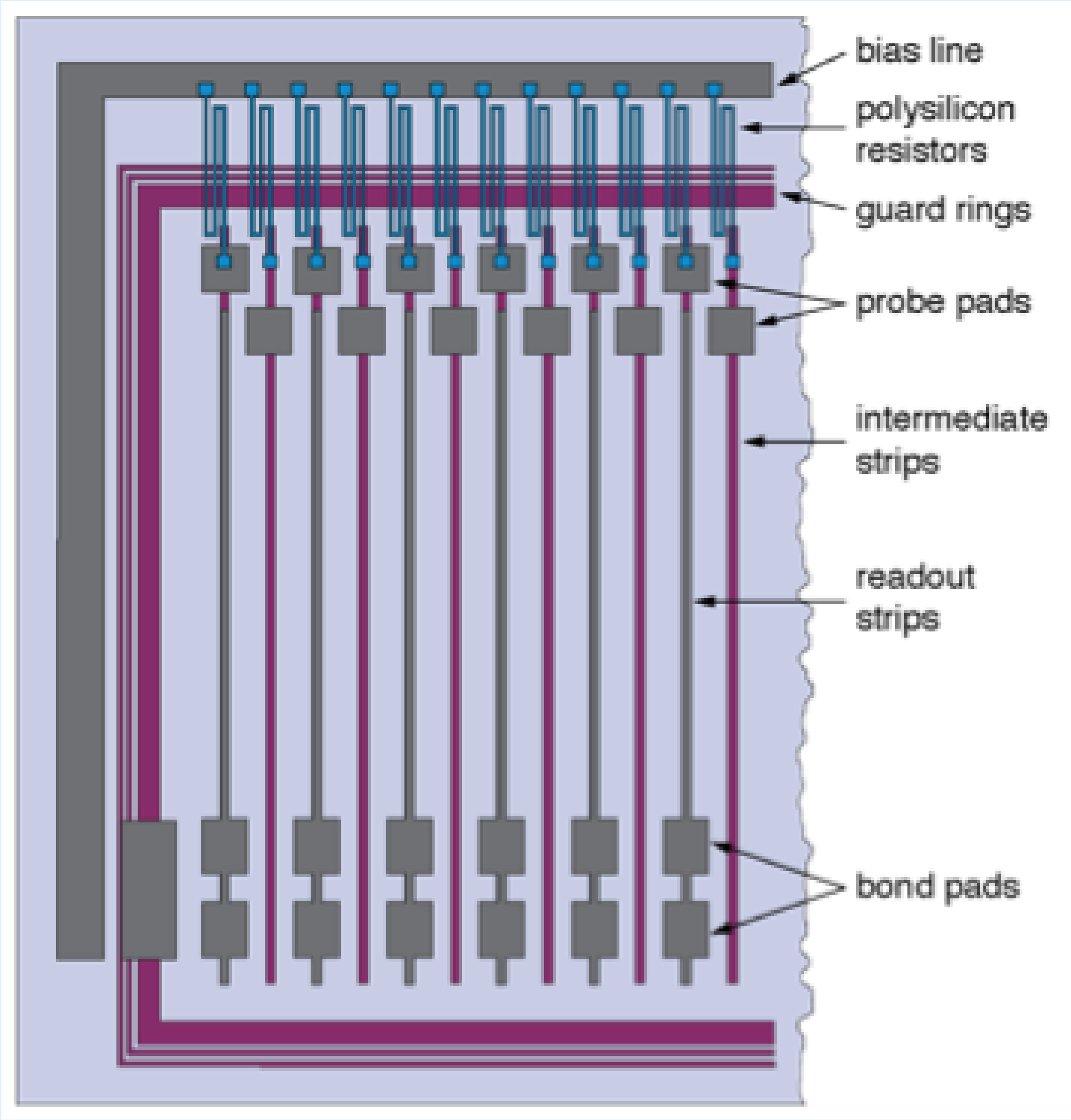
→ excellent energy resolution!!

17 eV for 5.9 keV X-ray, i.e. $\Delta E/E = 2.9\ 10^{-3}$

But low rate capacity

Applications: dark matter searches, astrophysical neutrinos, magnetic monopole searches, neutrino mass

Position sensitive detectors

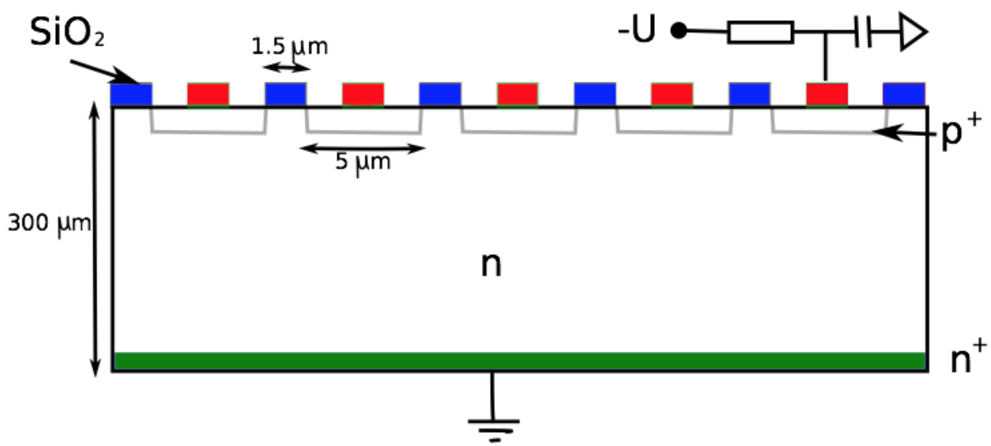


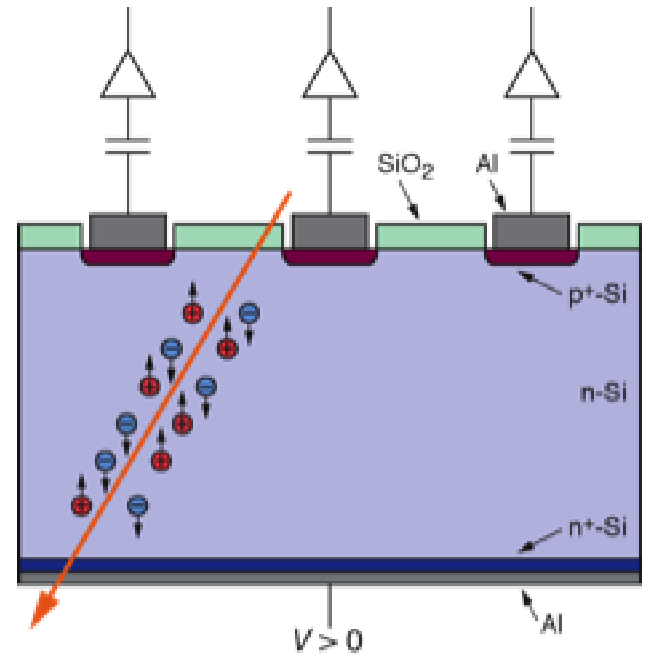
Detectors for position measurements

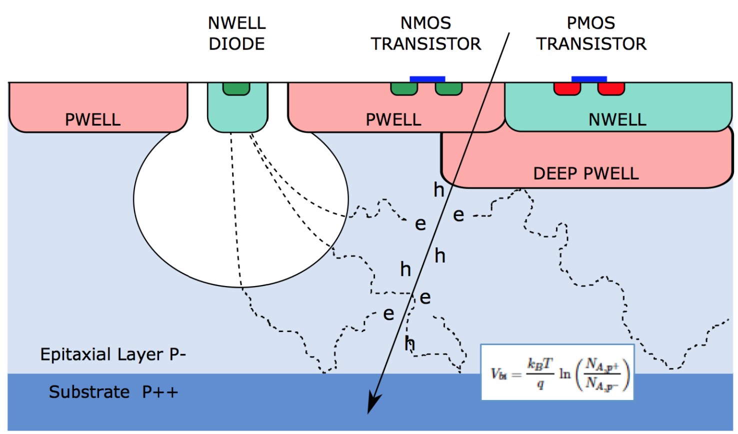
Segment the readout electrodes into strips, pads, pixels

First use in 1980ies

By now standard part of high energy experiments since LEP (CERN) and Tevatron (Fermilab) era





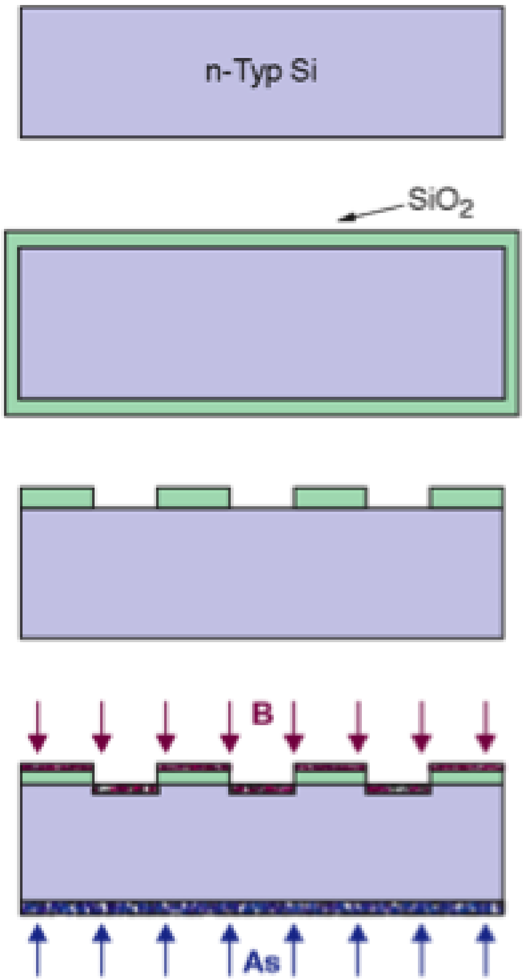


History of semiconductor detectors

- 1951: First detector was a germanium-pn-diode (McKay).
- 1960: p-i-n semiconductor detectors for - und -spectroscopy (E.M. Pell)
- 1960ies: Semiconductor detectors from germanium but also silicon are more and more important for the energy measurement in nuclear physics.
- 1980: First silicon surface barrier micro strip detector (E. Heijne)
- 1983: First use of a planar silicon strip detector in a fix target experiment - NA11 at CERN. (J. Kemmer)
- 1980ies and after: micro structured silicon detectors gain rapid importance for tracking detectors in high energy physics experiments!

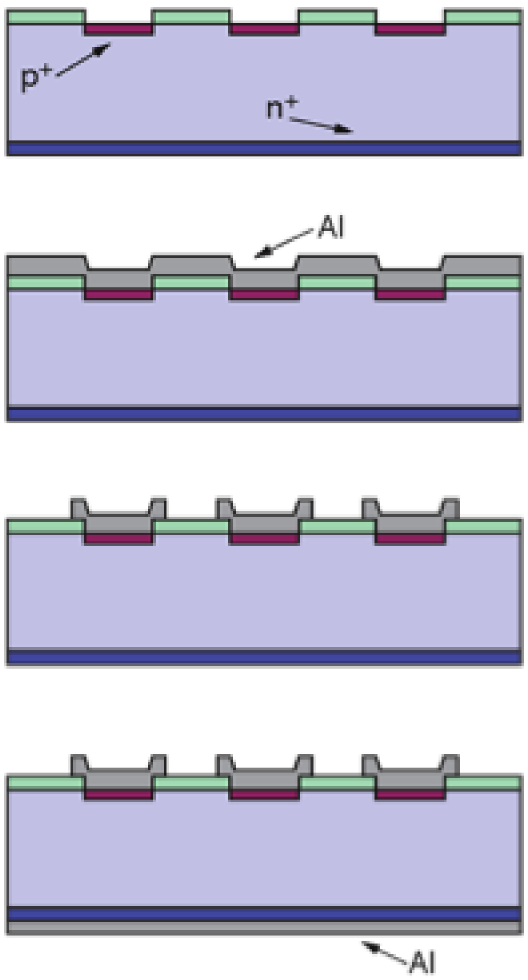
Manufacturing by planar process - 1

1. Starting Point: single-crystal n-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: Arsenic, 30 keV, $N_D \approx 5{\cdot}10^{15}$ cm^{-2}



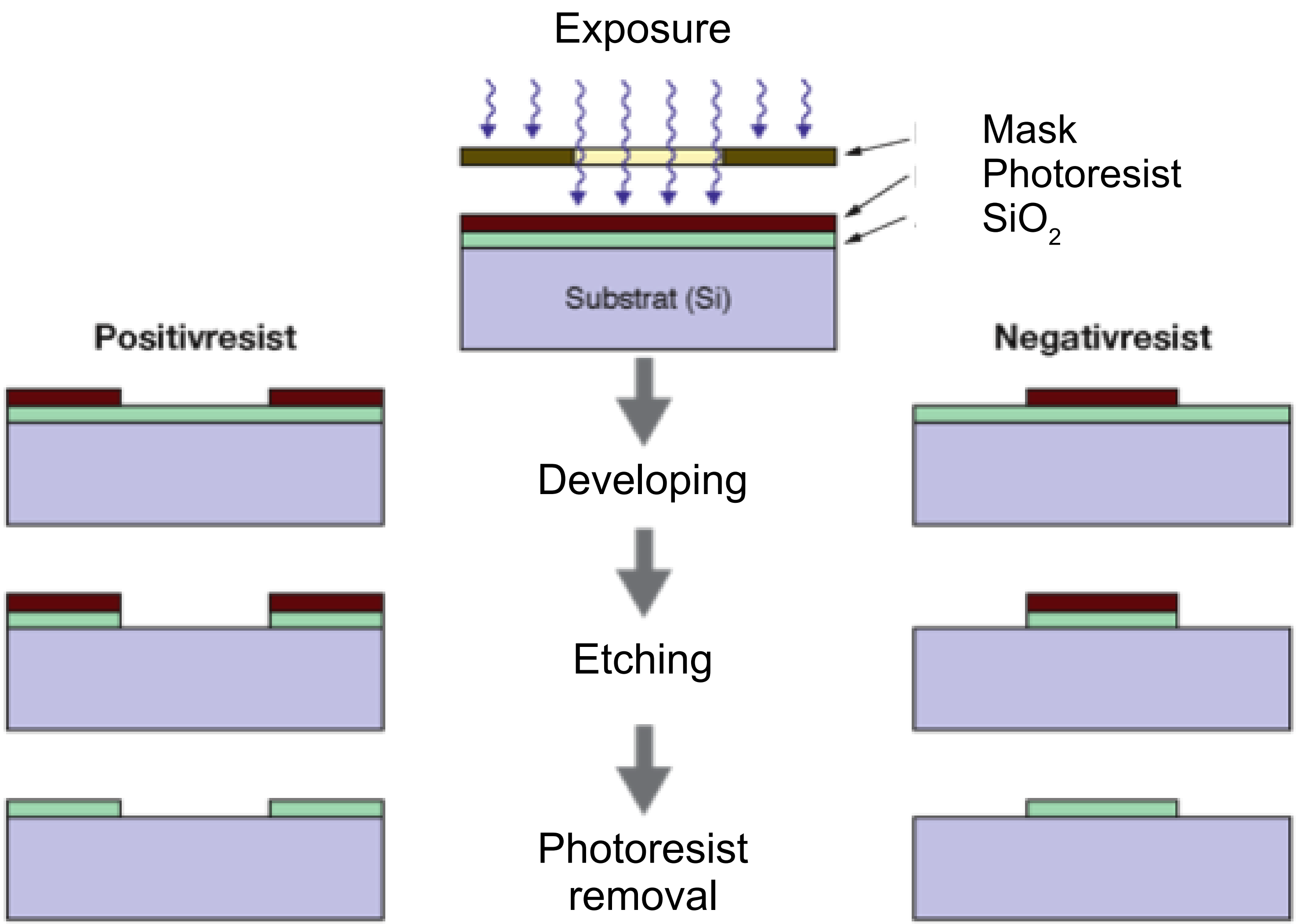
Manufacturing by planar process - 2

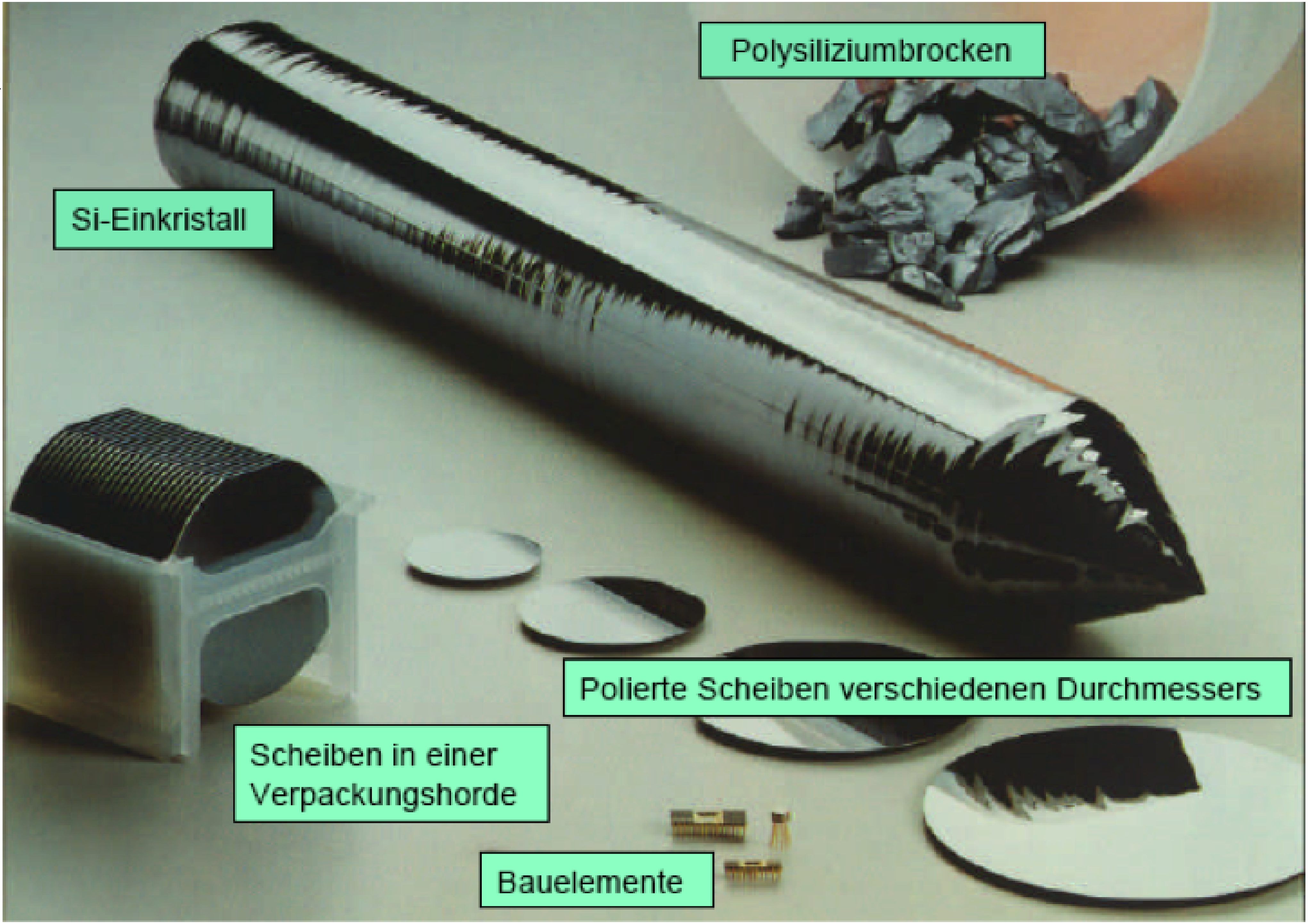
5. After ion implantation: Curing of damage via thermal annealing at approx. 600°C, (activation of dopant atoms by incorporation into silicon lattice)
6. Metallization of front side: sputtering or CVD
7. Removing of excess metal by photolitography: etching of non-covered areas
8. Full-area metallization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



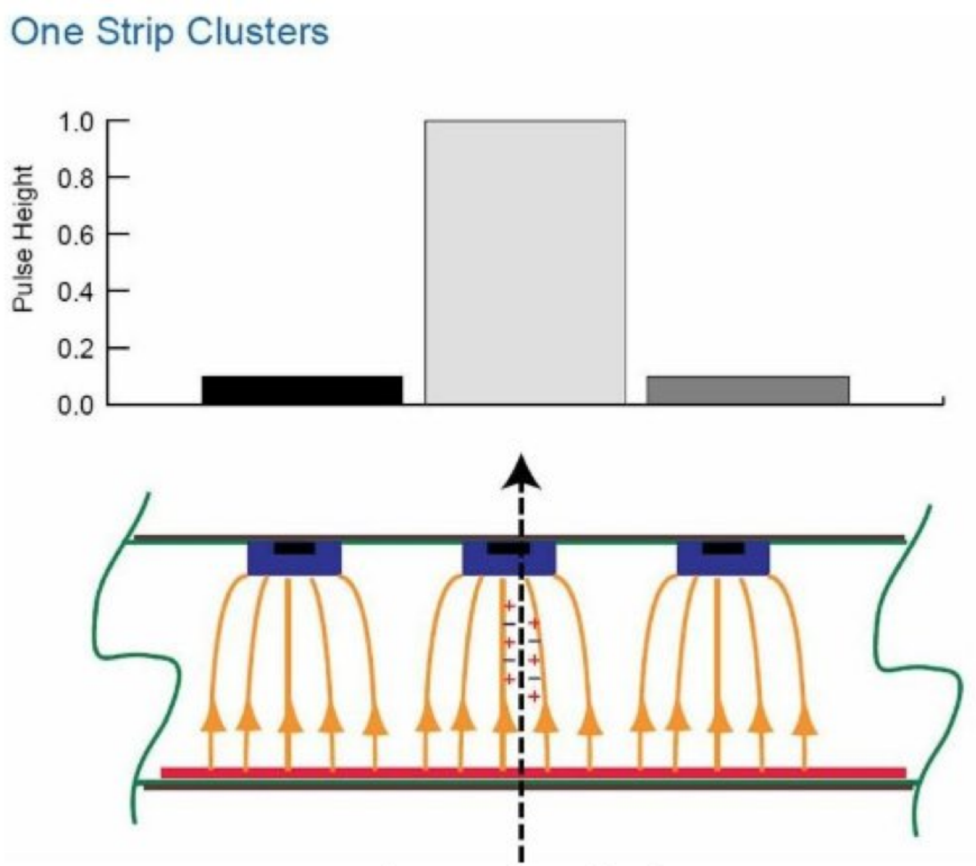
CVD = chemical vapor deposition

Lithography



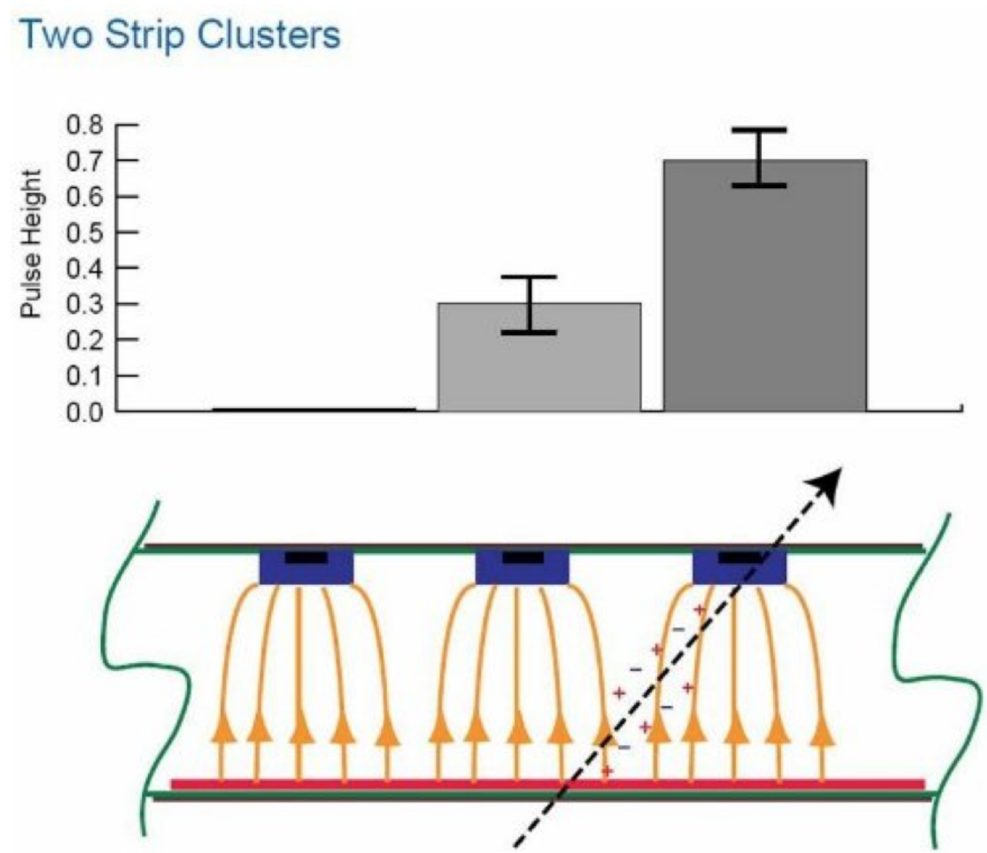

Polysiliziumbrocken
Si-Einkristall
Polierte Scheiben verschiedenen Durchmessers
Scheiben in einer Verpackungshorde
Bauelemente

Position measurement



Δs: strip pitch

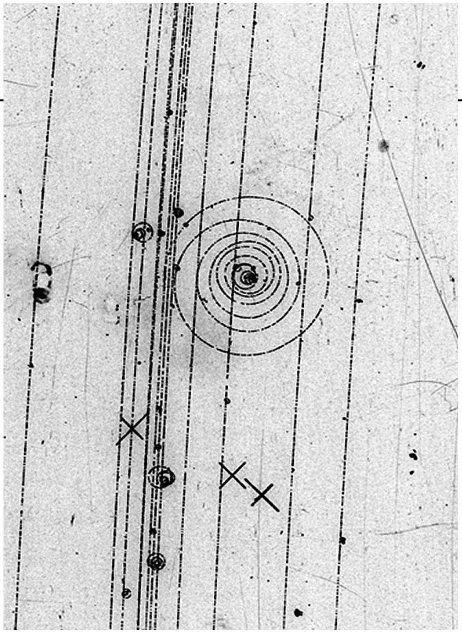
$$\sigma_x = \Delta s / \sqrt{12}$$



centroid resolution

$$\sigma_x \approx (\Delta s/2)(N/S)$$

Position resolution: limits



1. δ-electrons

can shift the center of gravity of the track

N_p primary ionization - includes δ-electron, which travels over a range r_δ

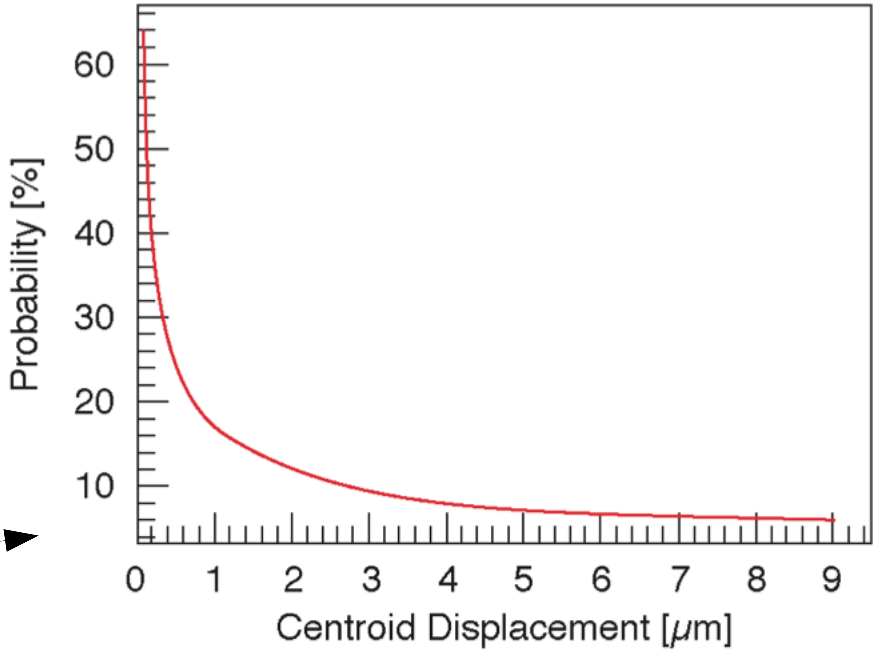
The δ-electron has energy such that it produces further N_δ electron-hole pairs.

Assuming it moves perpendicular to the track:

Example: 100 μm Si, 5 GeV pion → 240 eV/μm → N_p = 6700

10% probability for δ with T_δ>20 keV and r_δ = 5 μm → Δx ≈ 1 μm

Worse for 300 μm Si, see figure



Position resolution: limits

2. Noise

Position measurement requires S $\gg$ N

- If signal only on one strip or one pad, resolution is σx = pitch / $\sqrt{12}$, independent of S/N
- If signal spreads of more strips → more precise position by center-of-gravity method, but influenced by S/N

3. Diffusion

Smearing of charge cloud (transverse diffusion)

Initially helps to distribute signal over more than one strip

But 2-track resolution and S/N deteriorate with diffusion

4. Magnetic field

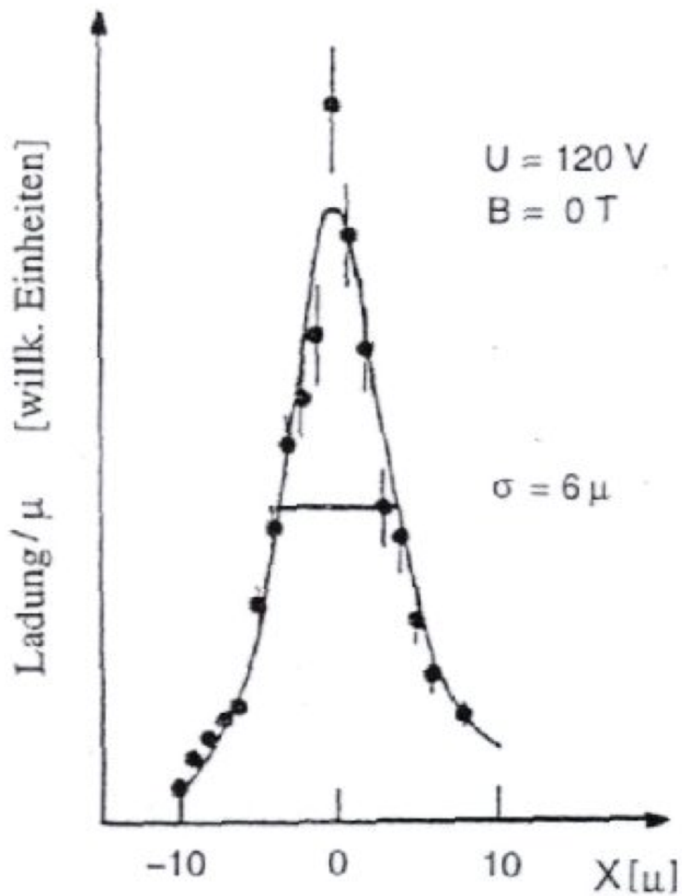
Lorentz force acts on drifting electrons and holes: track signal is displaced if E not parallel to B, increasing displacement with drift length (see next)

Position resolution: limits

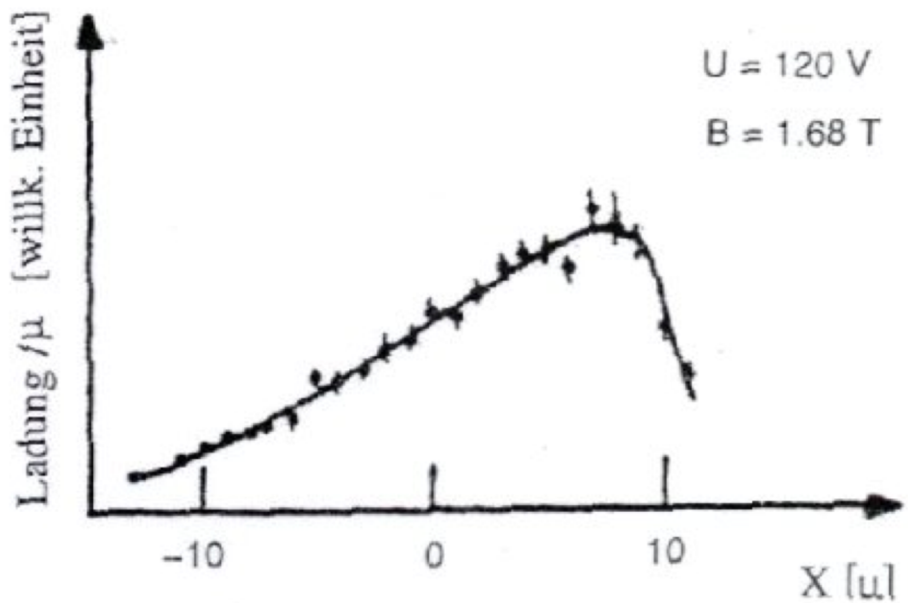
Magnetic field

charge distribution registered for a semiconductor detector with or without magnetic field

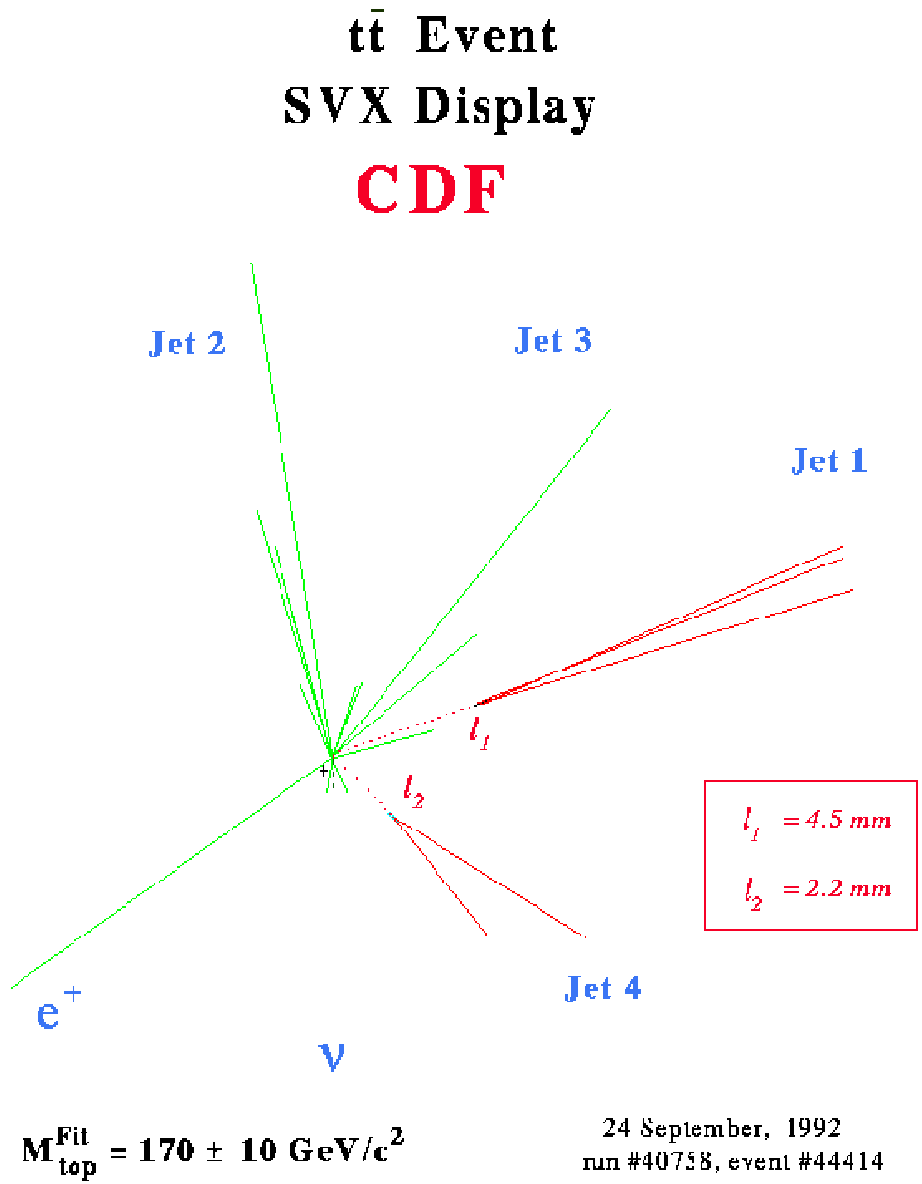
no field



$B = 1.68\ T$



Position resolution: vertex reconstruction

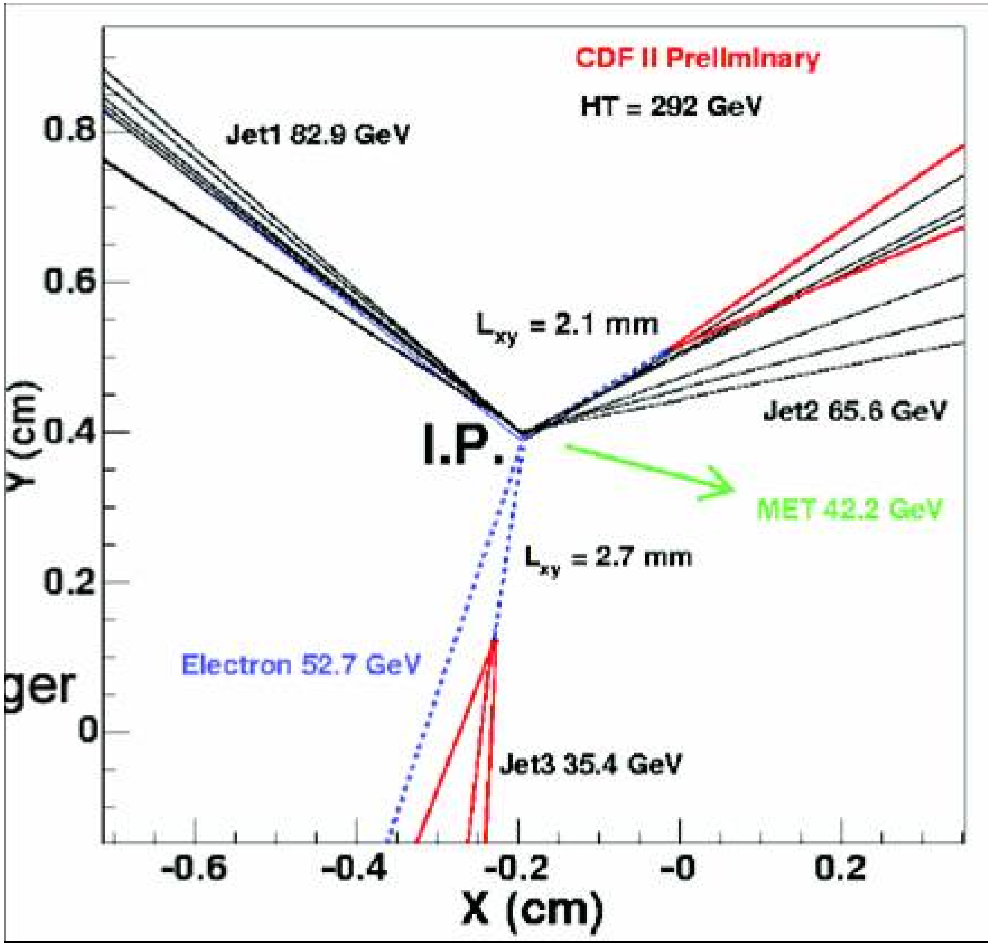


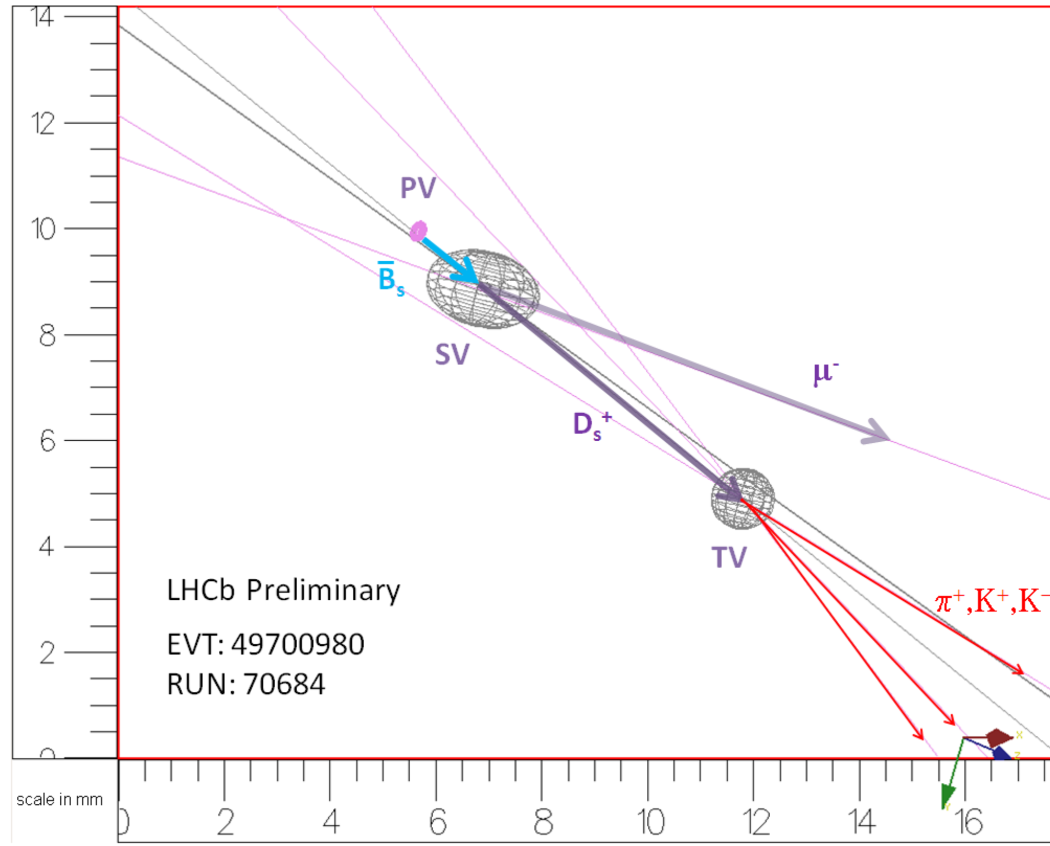
CDF (Tevatron, Fermilab)

Two beauty-jets from a $t\bar{t}$-decay

$$p + \bar{p} \rightarrow t\bar{t} + X$$
$$\hookrightarrow \bar{b} + W^+$$
$$\hookrightarrow e^+ + \nu_e$$
$$\hookrightarrow b + W^-$$
$$\hookrightarrow q\bar{q} \text{ (2 jets)}$$

Position resolution: vertex reconstruction





Position resolution: multiple scattering

Essential for the selection of decay particle trajectories:

Impact parameter: closest distance of primary vertex from the extrapolated track

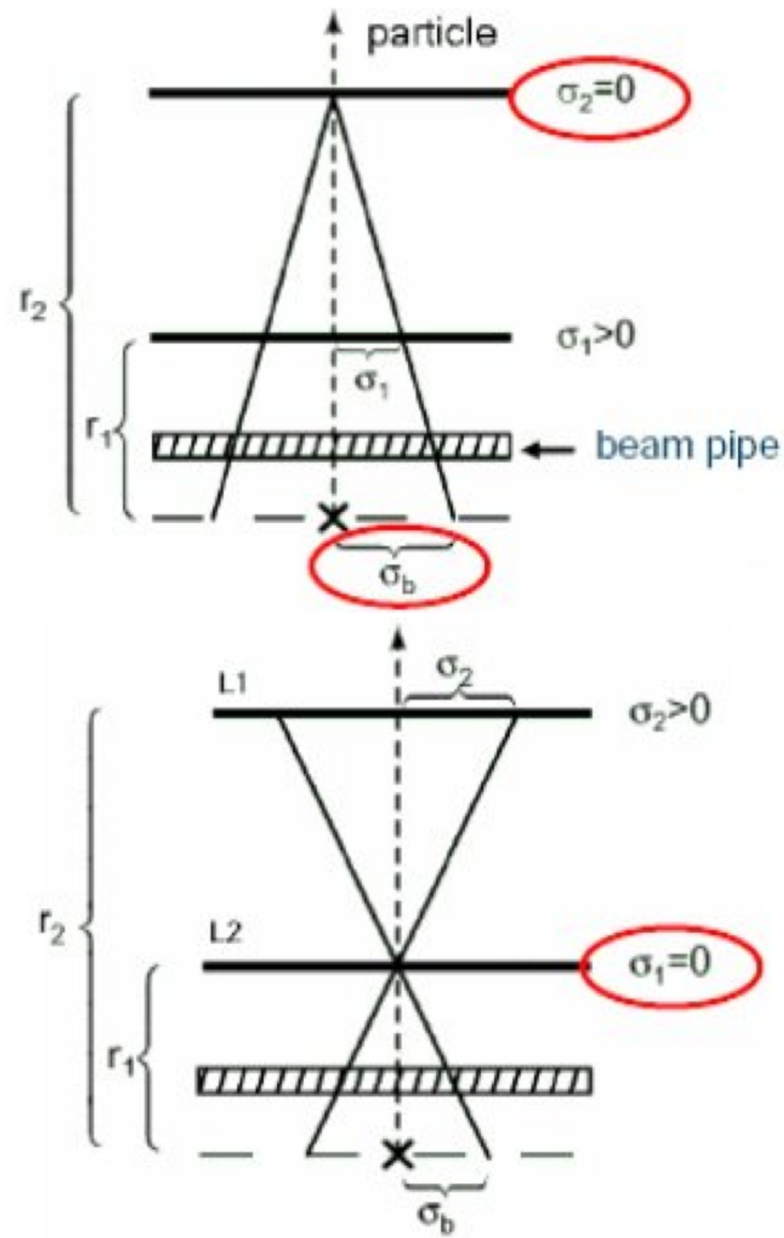
$$\frac{\sigma_b}{\sigma_1} = \frac{r_2}{r_2 - r_1}$$

$$\boxed{\sigma^2 = \left(\frac{r_1}{r_2 - r_1}\sigma_2\right)^2 + \left(\frac{r_2}{r_2 - r_1}\sigma_1\right)^2 + \sigma_{MS}^2}$$

$$\frac{\sigma_b}{\sigma_2} = \frac{r_1}{r_2 - r_1}$$

Optimum resolution for:

- **r_1 small**
- **r_2 large**
- **σ_1, σ_2 small**
- **σ_{MS} as small as possible, by as little material as possible**

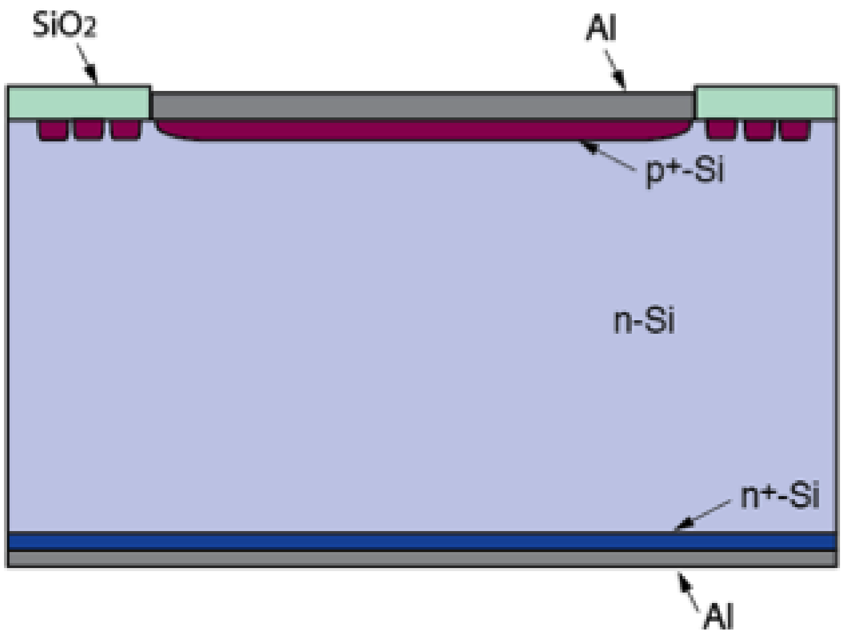


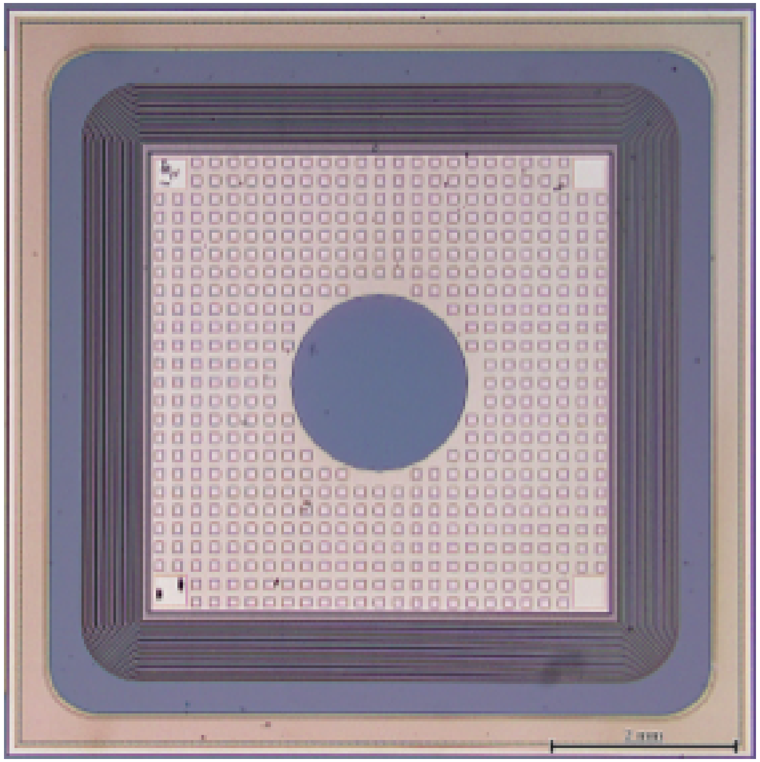
Detector structures

.... just the beginning

Pad detector

The most simple detector is a large surface diode with guard ring(s)

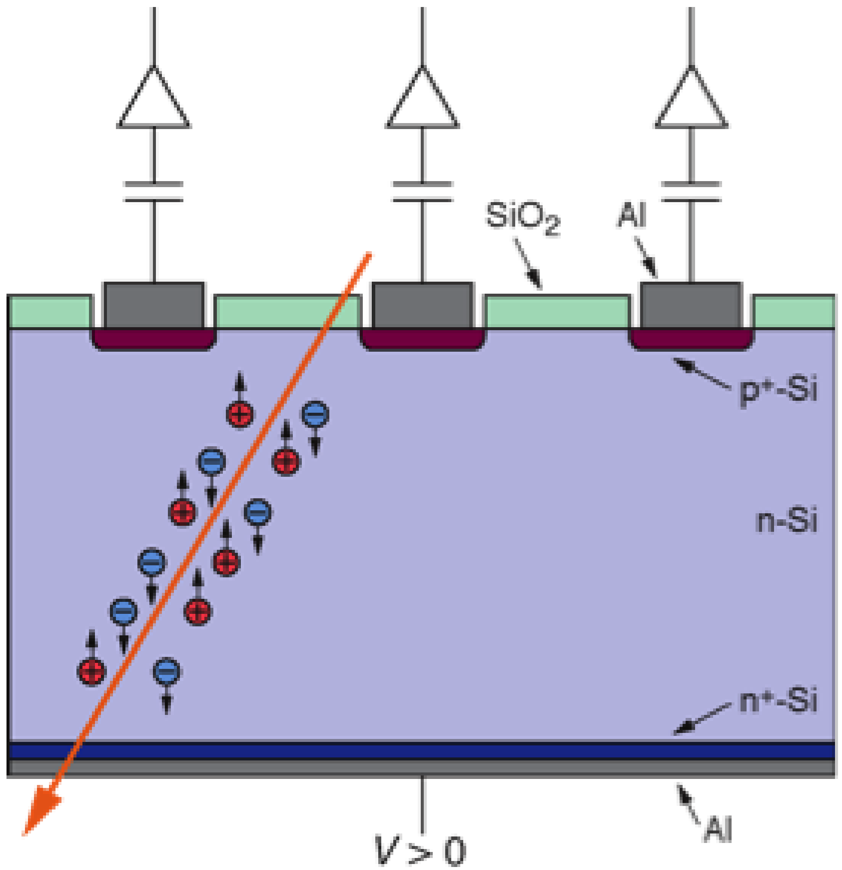




Microstrip detectors

Through going charged particles create e-h+ pairs in the depletion zone (about 30,000 pairs in standard detector thickness). These charges drift to the electrodes. The drift (current) creates the signal which is amplified by an amplifier connected to each strip. From the signals on the individual strips the position of the through going particle is deduced.

A typical n-type Si strip detector:



- p+n junction:
  $N_a \approx 10^{15}$ cm^{-3}, $N_d \approx 1\text{–}5 \cdot 10^{12}$ cm^{-3}
- n-type bulk: > 2 kΩcm
  thickness 300 μm
- Operating voltage < 200 V
- n+ layer on backplane to improve ohmic contact
- Aluminum metallization

Overview semiconductor detectors

- **Principle of operation of semiconductor detectors**
  - **Properties of semiconductors (band structure)**
  - **Intrinsic material**
  - **Extrinsic (doped) semiconductors**
  - **p-n junction**

LAST WEEK

- Signal generation
- Ionization yield and Fano factor
- Energy measurement with semiconductor detectors

TODAY

- **Position measurement with semiconductor detectors**
  - **Micro-strip detectors: single- and double-sided, biasing schemes**
  - **Pixels: hybrid, monolithic active pixels, DEPFET**
  - **Silicon drift detectors**
  - **Charge-coupled devices (CCDs)**
  - **3D detectors**
- **Radiation damage**

JUNE 14 !!!