Chapter VIII:
Detectors based on ionization in semiconductors

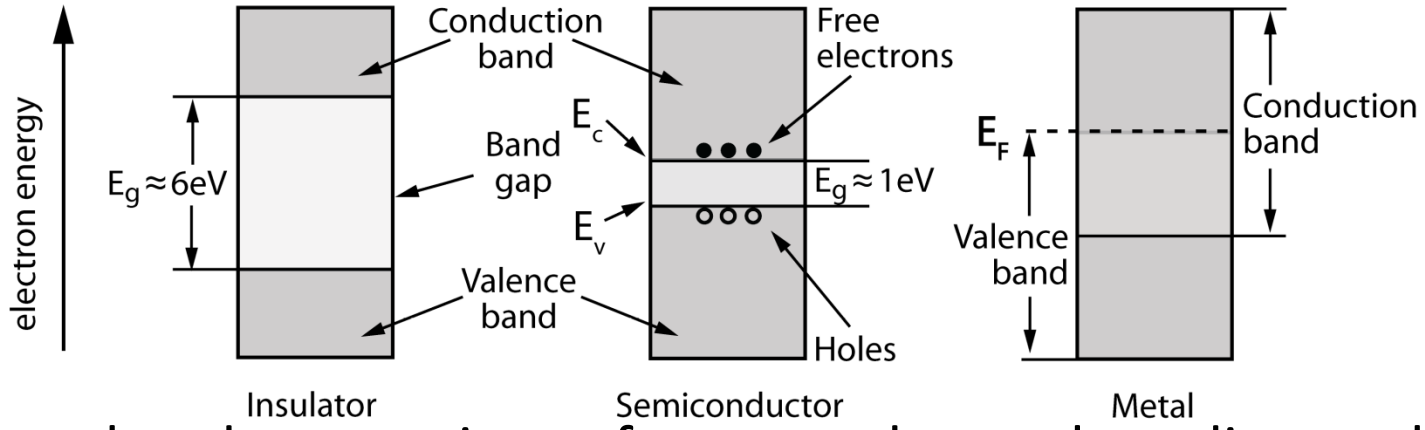
Contents

- Introduction to semiconductors
- The semiconductor junction as a detector
- Silicon detectors
- Germanium detectors
- Other semiconductor materials

Semiconductors as detectors

- Semiconductor detector → « comparable » to a gas detector in which the gaseous medium is replaced by a solid medium put between 2 electrodes
- The passage of ionizing radiation creates electron-hole pairs (instead of electron-ion pairs in gas detector) → pairs are collected by an electric field
- Semiconductor detector → solid ionization chamber
- Advantage 1 for semiconductors: energy required for one pair is $\sim$ 3 eV → 10 times smaller compared to gas detectors → largely better resolution
- Advantage 2: greater density → greater stopping power → compact in size
- 1 inconvenient: except for silicon they require low temperature to operate → additional cryogenic system

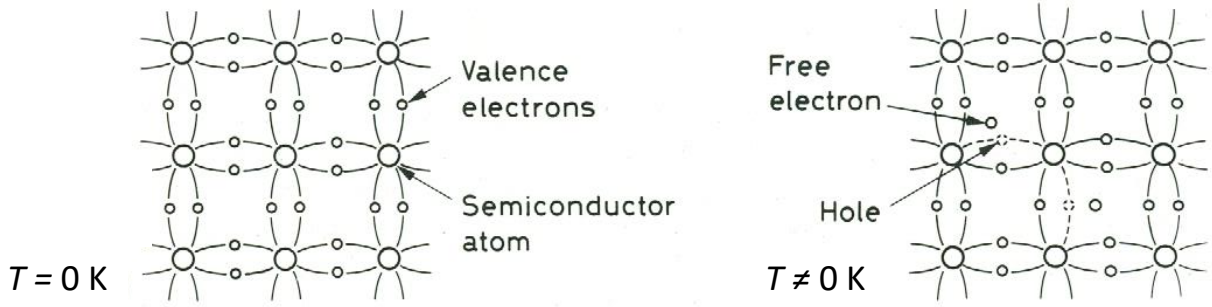
Energy band structure



- Energy bands are regions of many and very close discrete levels → continuum
- Configuration due to the periodic crystal structure → overlapping of electron wavefunctions
- Energy gap is a region without energy levels at all (width: E_g)
- e^- in the valence band are bound with the atoms
- e^- in the conduction band are free
- E_F: Fermi energy (energy of the highest occupied state at $T = 0$ K)

Charge carriers in semiconductors (1)

- At $T = 0$ K, all e^- are in the valence band→ empty conduction band → no current if an electric field is applied
- At ambient T → thermal fluctuations excite a few valence e^- to the conduction band (negative charge carrier) leaving a hole in its original position
- A neighboring valence e^- can jump from its bond to fill the hole → sequence can be repeated → hole (h^+) moves through crystal → positive charge carrier
- Charge carriers → an electric field implies a current
- In semiconductors, two source of current: movement of free e^- in the conduction band and h^+ in the valence band



Charge carriers in semiconductors (2)

- When energy is transferred to a crystal atom by a radiation incident on the semiconductor → an e^- can be excited to high energy levels inside the conduction band → presence of a h^+ inside the valence band
- Very quickly after this 1ère excitation → the e^- deexcites to the bottom of the conduction band and the ionized atom loses its excitation energy and the h^+ stays in the top of the valence band
- The energy loss during this process gives rise to the creation of phonons and to other excitations which produce other e^--h^+ pairs → creation of a lot of e^--h^+ pairs
- After $\sim 10^{-12}$ s → all the e^- are in the bottom of the conduction band and all the h^+ are in the top of valence band
- The initial energy has been shared between the e^--h^+ pairs and the crystal lattice (creation of phonons) → equivalence e^--h^+ ↔ e^--ions and phonons ↔ excitations by comparison with a gas

Intrinsic charge carriers concentration

- The probability that a particular level is occupied in thermal equilibrium is given by the Fermi-Dirac distribution (with k= 1.38 10^{-23} JK^{-1}: the Boltzmann constant)

$$f(E) = \frac{1}{\exp\left(\frac{E-E_F}{kT}\right)+1}$$

- e^--h^+ pairs are constantly generated by thermal energy and can also recombine → under stable conditions → for pure semiconductor, equilibrium concentrations of e^- and h^+ are equal: $n = p = n_i$:

$$n_i = AT^{3/2}\exp\left(\frac{-E_g}{2kT}\right)$$

with A, a constant dependent on the medium and independent on *T*

Examples: Si and Ge

- Silicon and germanium are the 2 most common semiconductors
- Both are used as detector
- Their crystal lattice is « diamond » type

$$n_i(Si) = 2.8 \times 10^{16} T^{3/2} \exp\left(\frac{-6450}{T}\right) \quad /\mathrm{cm}^{-3}$$

$$n_i(Ge) = 9.7 \times 10^{15} T^{3/2} \exp\left(\frac{-4350}{T}\right) \quad /\mathrm{cm}^{-3}$$

- Example → for T = 300 K → $n_i(Si)$ = 6.7×10^{10} cm^{-3}

Mobility for an intrinsic semiconductor

- Under the action of an applied electric field E → drift velocities for e^- and h^+ are

$$v_e = \mu_e E$$

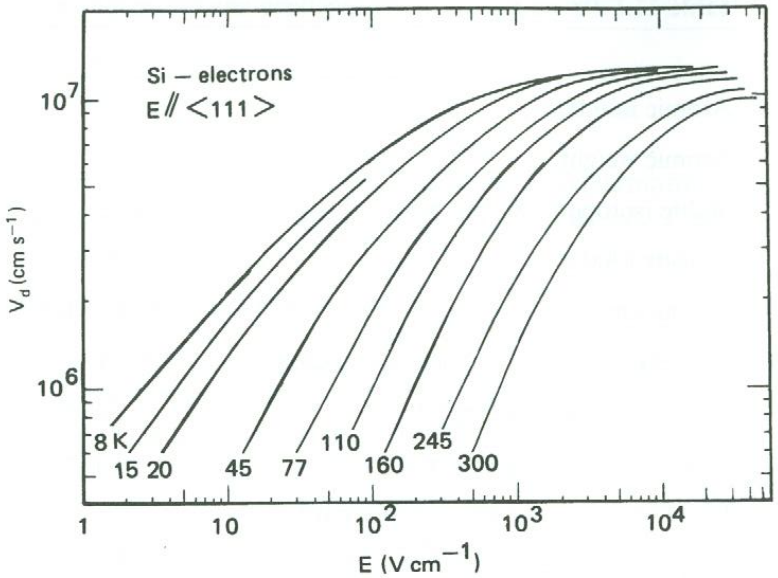
$$v_h = \mu_h E$$

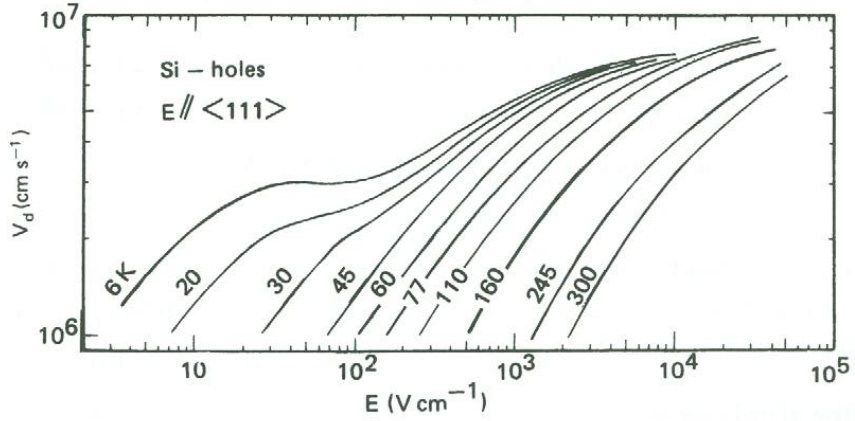
where $\mu_{e,h}$ are the mobilities of e^- and h^+ (depending on E and T → for low E: μ is independent on E, for high E: μ saturates)

- Generally $\mu_h < \mu_e$ because motion of hole necessitates transition of an electron between neighboring atoms (ratio is ≈ 2-3)
- Mobilities determine current → conductivity σ and resistivity ρ

$$\sigma = e n_i (\mu_e + \mu_h) \qquad \rho = \frac{1}{e n_i (\mu_e + \mu_h)}$$

Examples of drift velocities: Si





Some physical properties of Si and Ge

	Si	Ge
Atomic number Z	14	32
Atomic weight A	28.1	72.6
Density [g/cm^2]	2.33	5.32
Dielectric constant (relative)	12	16
Intrinsic resistivity (300 K) [Ωcm]	230000	45
Energy gap (300 K) [eV]	1.1	0.7
Energy gap (0 K) [eV]	1.21	0.785
Electron mobility (300 K) [cm^2/Vs]	1350	3900
Hole mobility (300 K) [cm^2/Vs]	480	1900

Ohmic Contacts

- An ohmic contact allows to e^- to travel in both directions
- When e^- and h^+ are created in in equal numbers in the sc → the charges split off as a function of their sign
- Some charges arrive on their electrode before the other ones and the initially neutral medium is then charged → this space charge creates an electric field implying the injection of charge at an electrode
- In our case only e^- can be injected at negative electrode to maintain the equilibrium concentrations inside the sc → multiplication of the number of e^- and apparition of a current
- The intensity of this current is no predictable → depends on the place where the pairs are created, on the mobility of the carriers and on the geometry of the internal electric field
- No possibility of use of the sc in such conditions → use of pn junctions

Doped semiconductors: n-type

- Silicon and Germanium are tetravalent
- If a pentavalent impurity (doping) atom as arsenic, phosphorus, antimony (donor element) is introduced → replacing an atom lattice → an extra electron does not fit into the valence band
- This extra e^- is weakly bound → easily excited to the conduction band → localized level just below the bottom of the conduction band
- Ionization energy of this extra level: a few 0.01 eV → comparable to thermal energy → e^- in the conduction band without h^+ in the valence band → **n-type semiconductor**
- Practically concentration of donor $N_D \gg n_i$ → electron concentration $n \approx N_D$ ($N_D \sim 10^{15}$ atoms/cm^3) →

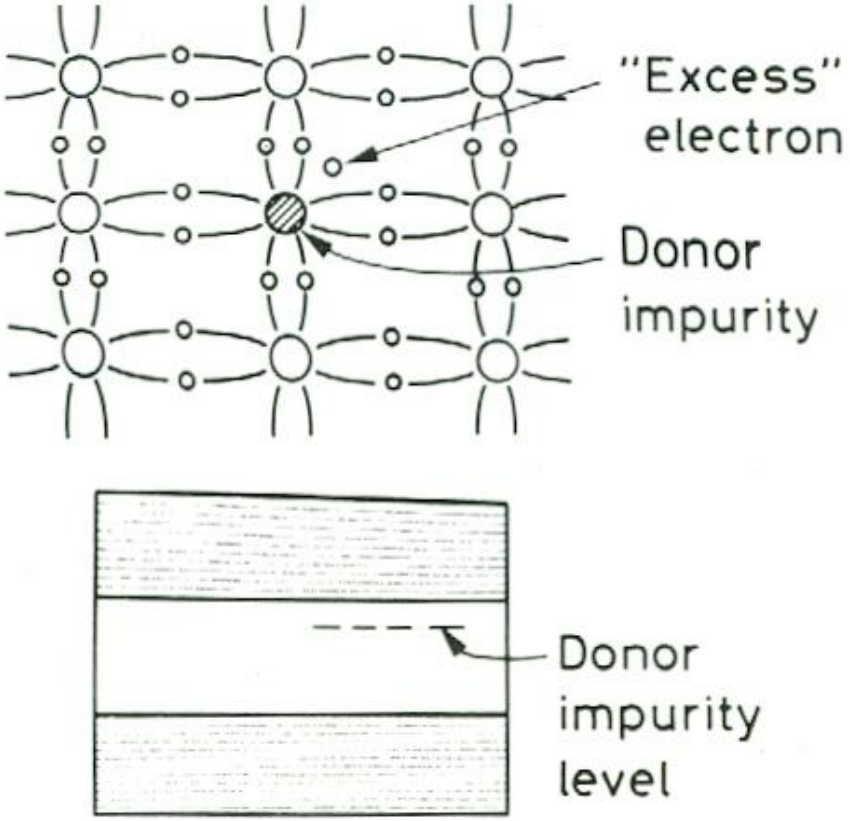
$$\sigma = eN_D\mu_e$$

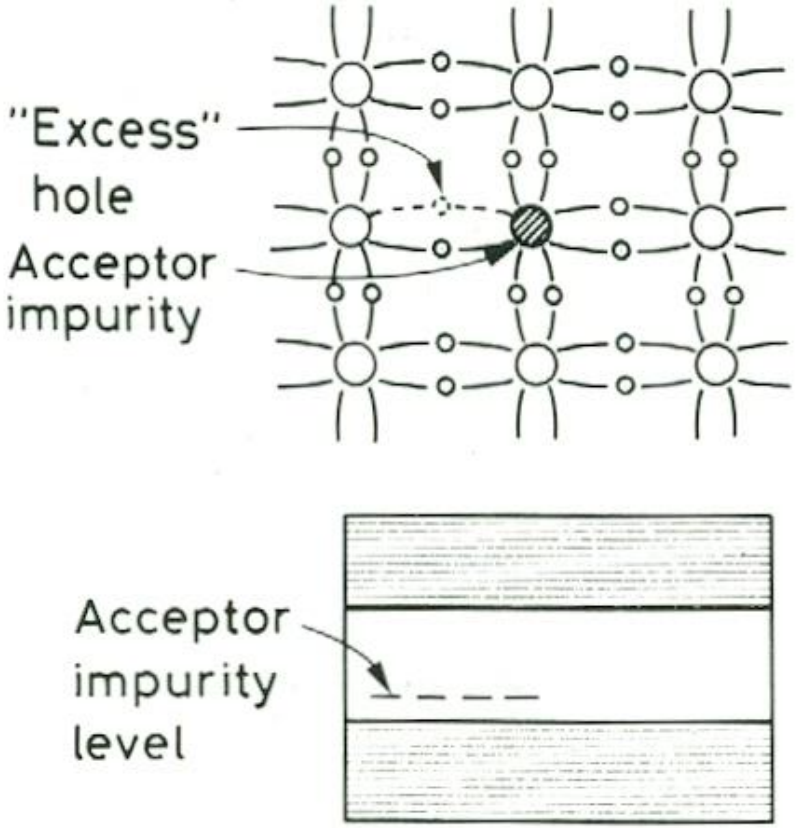
Doped semiconductors: p-type

- If a trivalent impurity atom as gallium, boron indium (acceptor element) is introduced → replacing an atom lattice → no enough electron to fill the valence band → excess of hole
- A captured e^- in this hole is less bound than normal e^- → localized level just above the top of the valence band
- e^- in the valence are easily excited to this level → extra hole in the valence band without e^- in the conduction band → **p-type semiconductor**
- Practically concentration of acceptor $N_A \gg n_i$ → hole concentration $p \approx N_A$ ($N_A \sim 10^{15}$ atoms/cm^3) →

$$\sigma = eN_A\mu_h$$

Representation of doped (extrinsic) semiconductors





Extrinsic charge carriers concentration

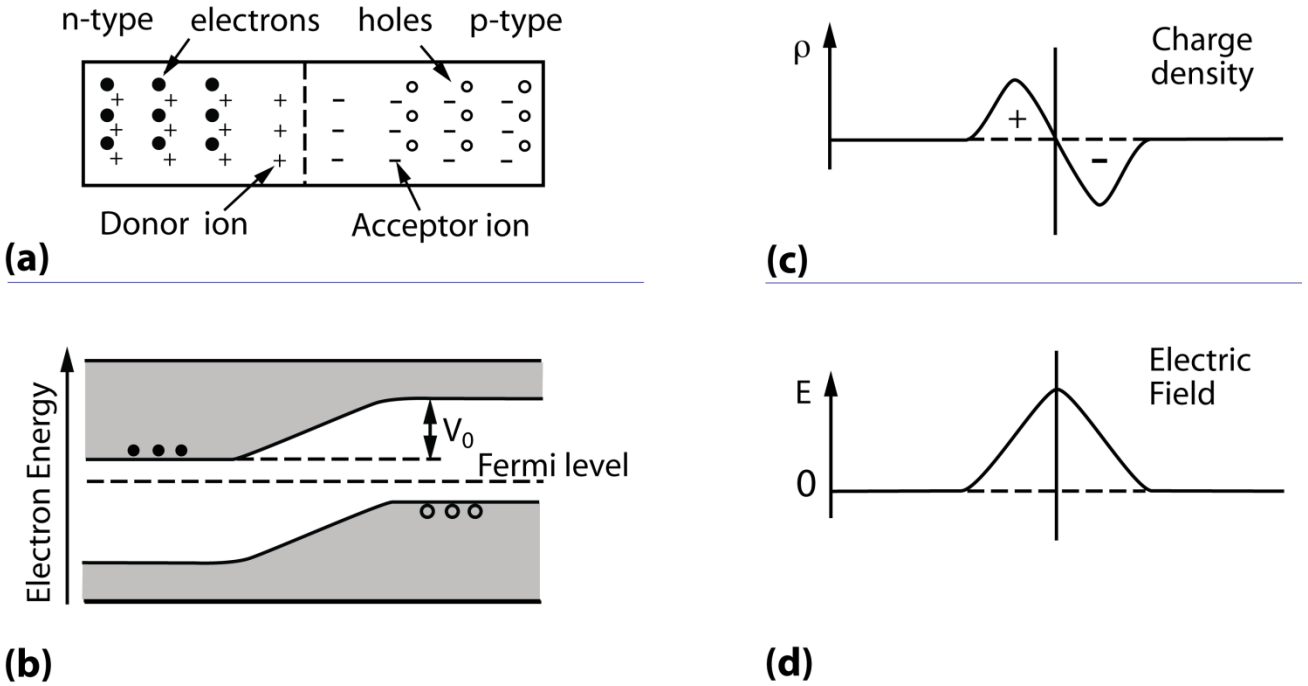
For n-type, the added concentration of e^- in the conduction band → ↗ recombination rate with holes → ↘ concentration of holes in the valence band → at equilibrium:

$$np = n_i^2$$

Example: at room T, for Si (density of $\sim 10^{22}$ atoms/cm^3), intrinsic carrier density is $\sim 10^{10}$ atoms/cm^3. If donor impurities are present with a density of $\sim 10^{17}$ atoms/cm^3, density of electrons n is $\sim 10^{17}$ atoms/cm^3 and density of holes p is $\sim 10^3$ atoms/cm^3

ATTENTION: Neutrality is assured by nuclei of impurities

pn semiconductor junction



≠ density of charge → diffusion of majority e^- from n-region to p-region and of majority h^+ from p-region to n-region → in the junction zone: recombination of e^- and h^+ → positive ions in the n-region and negative in the p-region → electric field in this region (10^3 V/cm) (called *depletion region*) → **very small solid ionization chamber**

Depletion depth (1)

- The width of the depletion zone (= *d*) depends on the concentration of n and p impurities. It can be determined from Poisson's equation (with ε the dielectric constant):

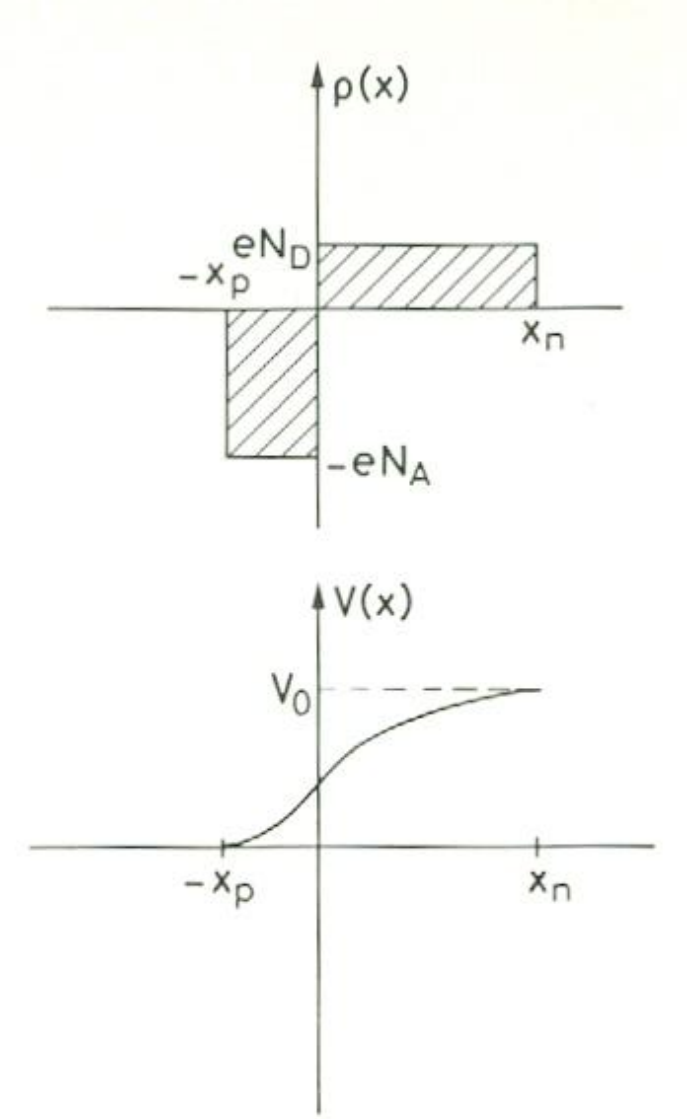
$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

- If we consider an uniform charge distribution about the junction and with x_n and x_p the extents of the depletion zone on the n- and p-sides and a contact potential V_0 →

$$\rho(x) = \begin{cases} eN_D & 0 < x < x_n \\ -eN_A & -x_p < x < 0 \end{cases}$$

- Since the charge is conserved: $N_A x_p = N_D x_n$ (with $N_A \approx p$ the acceptors concentration and $N_D \approx n$ the donors concentration)

Depletion depth (2)



Depletion depth (3)

- Integrating Poisson's equation:

$$\frac{dV}{dx} = \begin{cases} -\dfrac{eN_D}{\varepsilon}x + C_n & 0 < x < x_n \\ \dfrac{eN_A}{\varepsilon}x + C_p & -x_p < x < 0 \end{cases}$$

- Since $dV/dx = 0$ at $x = x_n$ and $x = -x_p$:

$$\frac{dV}{dx} = \begin{cases} -\dfrac{eN_D}{\varepsilon}(x - x_n) & 0 < x < x_n \\ \dfrac{eN_A}{\varepsilon}(x + x_p) & -x_p < x < 0 \end{cases}$$

- One more integration:

$$V(x) = \begin{cases} -\dfrac{eN_D}{\varepsilon}\left(\dfrac{x^2}{2} - x_n x\right) + C & 0 < x < x_n \\ \dfrac{eN_A}{\varepsilon}\left(\dfrac{x^2}{2} + x_p x\right) + C' & -x_p < x < 0 \end{cases}$$

Depletion depth (4)

- As solutions are equal at $x = 0 \rightarrow C = C'$ and as $V(x_n) = V_0$ and $V(-x_p) = 0$:

$$V_0 = \frac{eN_D}{2\varepsilon}x_n^2 + C$$
$$0 = -\frac{eN_A}{2\varepsilon}x_p^2 + C$$

- Eliminating C:

$$V_0 = \frac{e}{2\varepsilon}(N_D x_n^2 + N_A x_p^2)$$

- Using the charge conservation equation:

$$x_n = \left(\frac{2\varepsilon V_0}{eN_D[1 + N_D/N_A]}\right)^{1/2} \quad \text{and} \quad x_p = \left(\frac{2\varepsilon V_0}{eN_A[1 + N_A/N_D]}\right)^{1/2}$$

$\Rightarrow$ $d = x_n + x_p$

Depletion depth (5)

- Considering for instance $N_A \gg N_D \rightarrow x_n \gg x_p \rightarrow$

$$d \simeq x_n \simeq \left(\frac{2\varepsilon V_0}{eN_D} \right)^{1/2}$$

- Extension of the depletion zone to the n-side
- For Si with ρ = 20000 Ωcm and V_0 = 1V → d ≈ 75 µm

Reversed bias junction

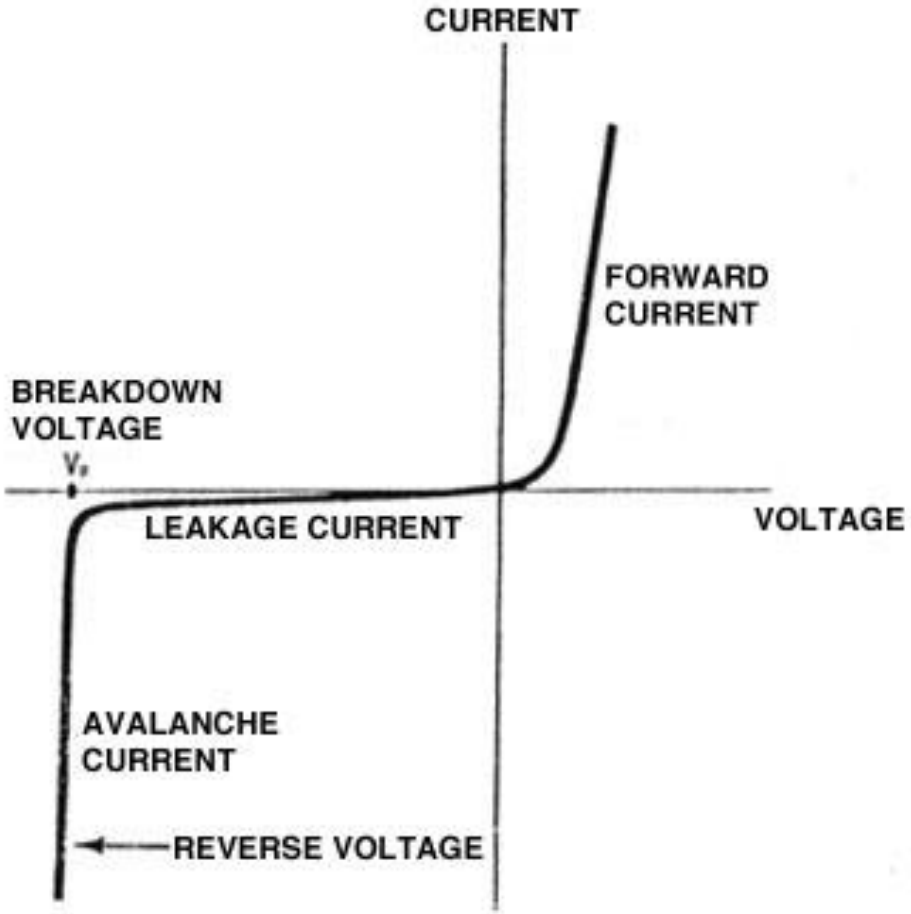
- If an external voltage is applied that removes the potential difference (forward bias) → a current will flow → no use

- If an external bias voltage V_B is applied that re-enforces the potential difference (reverse bias) → no current will flow
  1. This voltage attracts h^+ in the p-region away from the junction and similarly for the e^- in the n region → enlarge the depletion zone (use in previous equation $V_B+V_0 \approx V_B$ because $V_B \gg V_0$) → 5 mm in Si and 20 mm in Ge
  2. V_B is limited → attention to the breakdown

Breakdown

- Breakdown of the junction → abrupt increase of the inverse current when the applied inverse voltage reach a limit value (breakdown voltage)
- The breakdown is not destructive if the inverse current is limited by an external circuit to avoid an excessive overheating
- 2 breakdown mechanisms → Zener effect and avalanche effect
- Zener effect → the electric field is intense enough to extract an electron from the valence band and to move it into the conduction band → current
- Avalanche effect → a strongly accelerated electron can ionize an atom during a collision → e^- - h^+ pair → the number of free carriers increases and the phenomenon recurs with the initial carrier and the secondary carriers → carriers multiplication → current
- As a function of conditions (temperature,…) → either Zener either avalanche first occurs

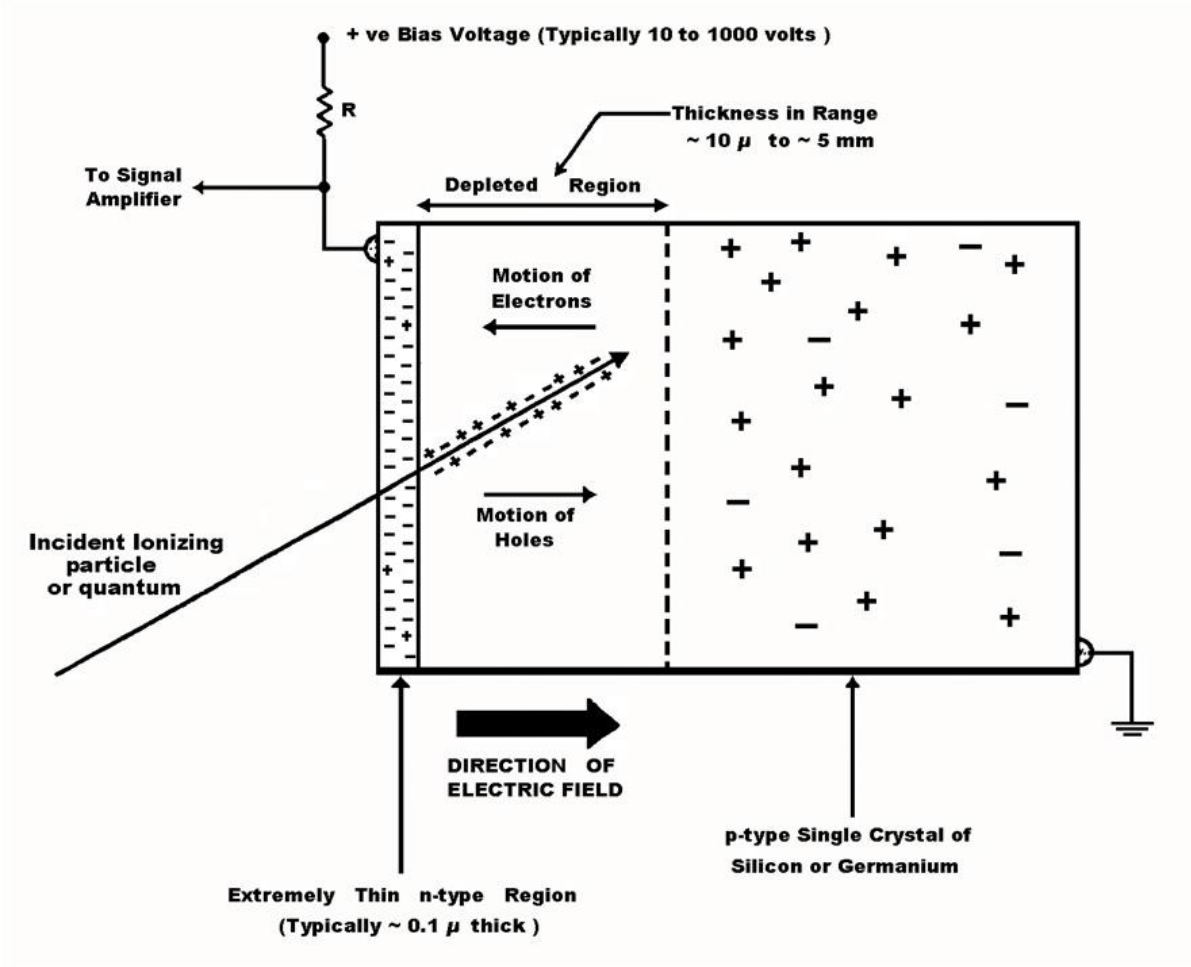
Current – voltage feature



Principles of a semiconductor detector

- A radiation crossing the depletion zone of a pn junction in reverse bias creates many e^- - h^+ pairs
- The e^- drift to the positive pole and the h^+ to the negative pole → apparition of a current as an ionization chamber → solid ionization chamber with small size
- The number of e^- - h^+ pairs is directly $\propto$ to the energy given by the radiation inside the junction → the current intensity and thus the voltage pulse over a resistance will be $\propto$ to this energy → detector for both counting and spectroscopy

Principle of semiconductor Detector

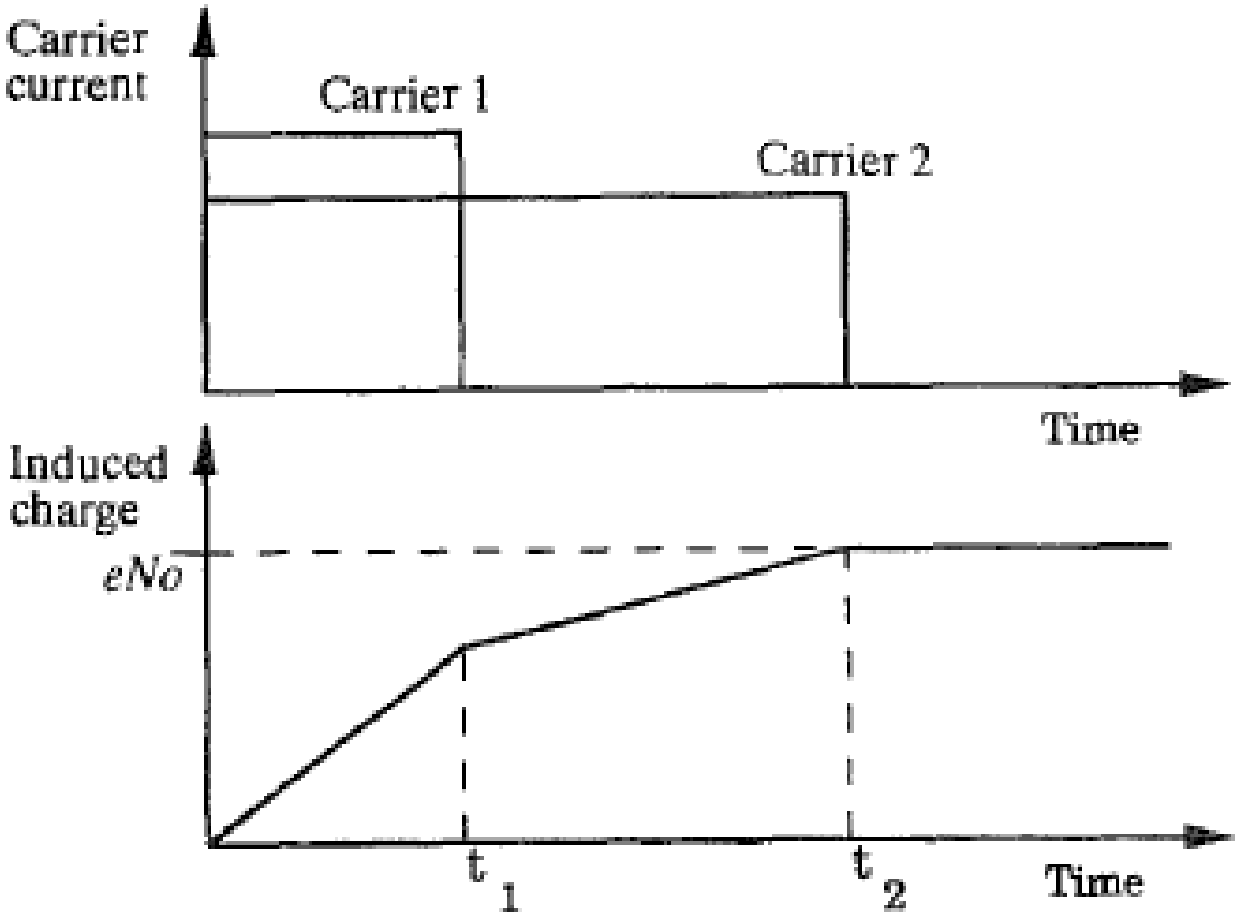


Only the charges generated in the depletion layer are collected

Charge collection (1)

- When an ionizing radiation transfers its energy inside the active volume of the detector (= depletion zone) → creation of an equal number of e^- and h^+
- Due to the electric field → drift of the carriers in opposite directions → the motion of the e^- and the h^+ forms the current which persists until the carriers are collected at the boundary of the active volume
- Exactly the same principle as for the charge collection inside a gaseous ionization chamber with 1 difference → the time scale
- The mobility of the e^- is larger than the one of the h^+ but of only a factor 2 or 3 → the collection time of the carriers are similar
- The total current includes the currents due to the 2 types of carriers

Charge collection (2)



Silicon detectors

- Operation at room temperature, except Si(Li)
- At room temperature: average energy for e^--h^+ pair creation: 3.62 eV
- Disadvantage: relatively small size of the depletion zone (≈ 5 mm) → mainly used for charged particles counting or spectroscopy (mean free path for γ too large)
- Other application → position-sensitive detector for charged particles
- Fano factor not well determined but ≈ 0.11 → typical resolution for 5.5 MeV α: 3.5 keV (or 0.063%)

Different types of Si detectors

- Diffused Junction Diodes
- Surface Barrier Detector
- Ion-Implanted Diodes
- Lithium-Drifted Silicon Diodes – Si(Li) – p-i-n Diode
- Micro-Strip Detector

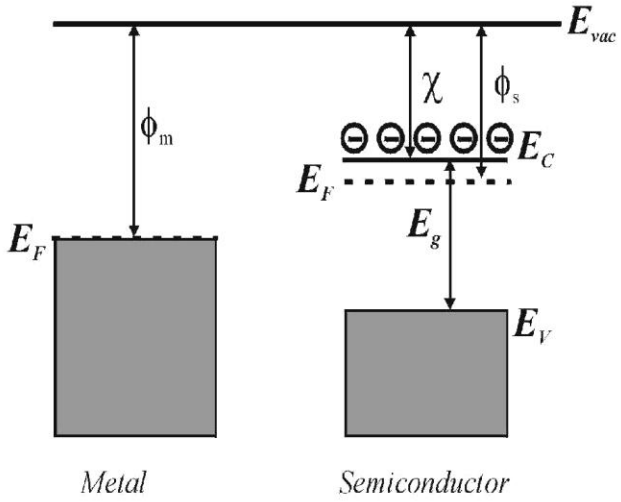
Diffused Junction Diode

- Historically: first device for detection
- We have an homogeneous crystal of p type → diffusion at high T (≈ 1000 °C) of n-type impurities (as phosphorous) → conversion of an area close of the surface into n type
- Very robust diode but surface very doped ($N_D \nearrow$) → extension of the depletion layer into the p-side → presence of a thick dead layer equivalent to the diffusion area (≈ 1 μm)
- Embarrassing for the detection of charges particles → not used currently

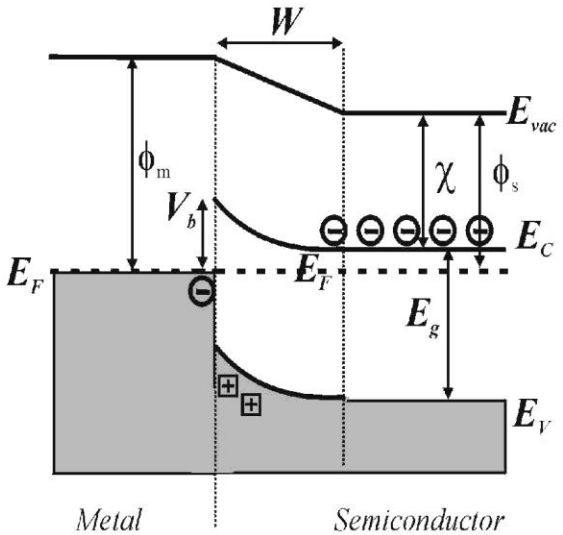
Surface Barrier Detector (SSB)

- Most used type of silicon detector
- Junction created between a semiconductor and a metal (generally → n type Si + Au or p type Si + Al)
- Due to the ≠ between the Fermi levels of the 2 media → modification of the bands in the sc → formation of a Shottky barrier
- Depletion area which can reach ≈ 5 mm
- Advantages: easy making process + small thickness dead layer $\sim$ thickness of the metal $\sim$ 20 nm
- Disadvantage: very light sensitive (metal thickness too small to stop light photons) → obligatory protection + fragile
- Remark: presence of an oxide layer at the interface

Shottky barrier



a)

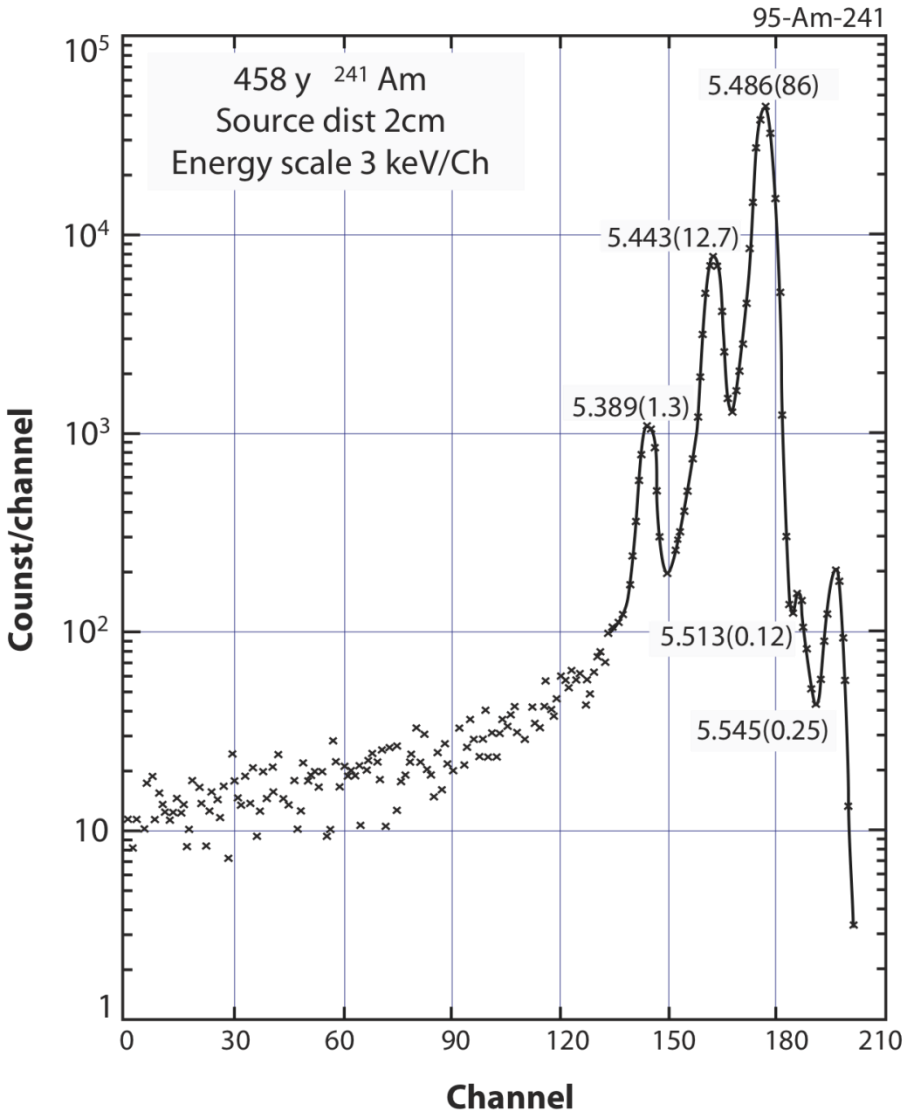


b)

- Example: metal – n type sc
- When there is contact between the metal and the sc → diffusion of the e^- from the sc to the metal (≠ between E_F) → area located at the contact in the sc empties of the e^-
- This area contains positive donors → apparition of an electric field → diffusion of the e^- is stopped
- Depletion region equivalent to the a pn contact
- 2 differences → weaker contact potential and depletion region only extended into the sc

Example of measurement with a SSB

Energy spectrum of alpha particles emitted by a source of ^{241}Am and recorded by a surface barrier silicon detector



Ion-Implanted junction

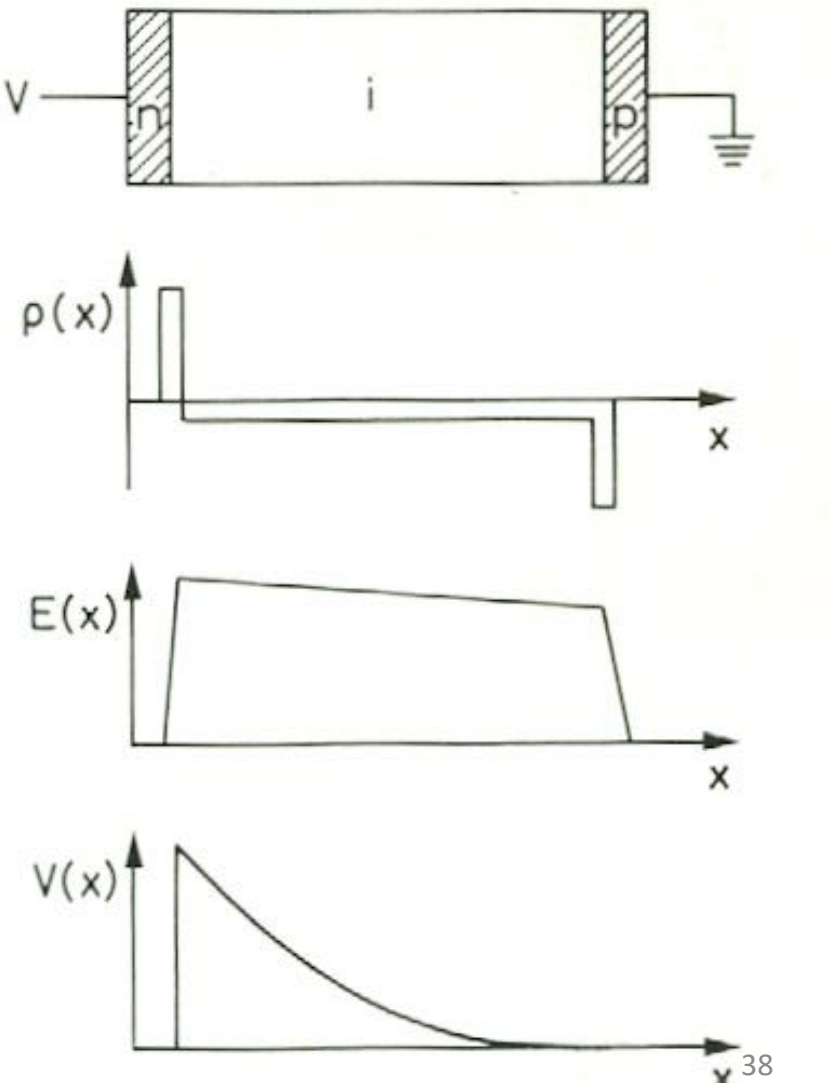
- The sc surface (n or p type) is bombarded by an ions beam (donors or acceptors) → impurities are injected into the sc
- By adjusting the energy of the ions of the beam → monitoring of the penetration depth, of the impurities concentration and of their depth profile
- Perfect control → very stable detector, very thin dead layer ($\sim$ 35 nm) → best current detector → used particularly in physics of high energies
- Disadvantage: high price

Lithium-Drifted Silicon Diode – Si(Li) – p-i-n Diode (1)

- The problem of previous diodes is the small depletion zone
- Solution → use of compensated material (i) sandwiched between p and n types coats → p-i-n
- Compensated semiconductor → the impurities of a given type can be compensated by injection of impurities of the other type such as $N_D = N_A$ → exactly the same quantity of donors and acceptors
- We retain most of the characteristics of intrinsic materials → in particular no space charge in the i zone

Lithium-Drifted Silicon Diode – Si(Li) – p-i-n Diode (2)

- No space charge → almost constant *E*
- The thickness of the compensated zone can reach ≈ 15 mm = zone in which the particle has to deposit its energy
- Suitable for β and (weak energy) X-ray detection



Lithium-Drifted Silicon Diode – Si(Li) – p-i-n Diode (3)

- We consider p-type Si
- Diffusion of lithium (donor) that compensates acceptors → Si(Li) detector
- Li is used because of its high diffusion coefficient → it does not move until lattice sites but slides up to interstices and forms a pair with p type impurities of the medium
- Problem: at room temperature → Li continue to diffuse → it overcomes all crystal → necessity of cooling the detector (even in no-use periods) → use of liquid nitrogen

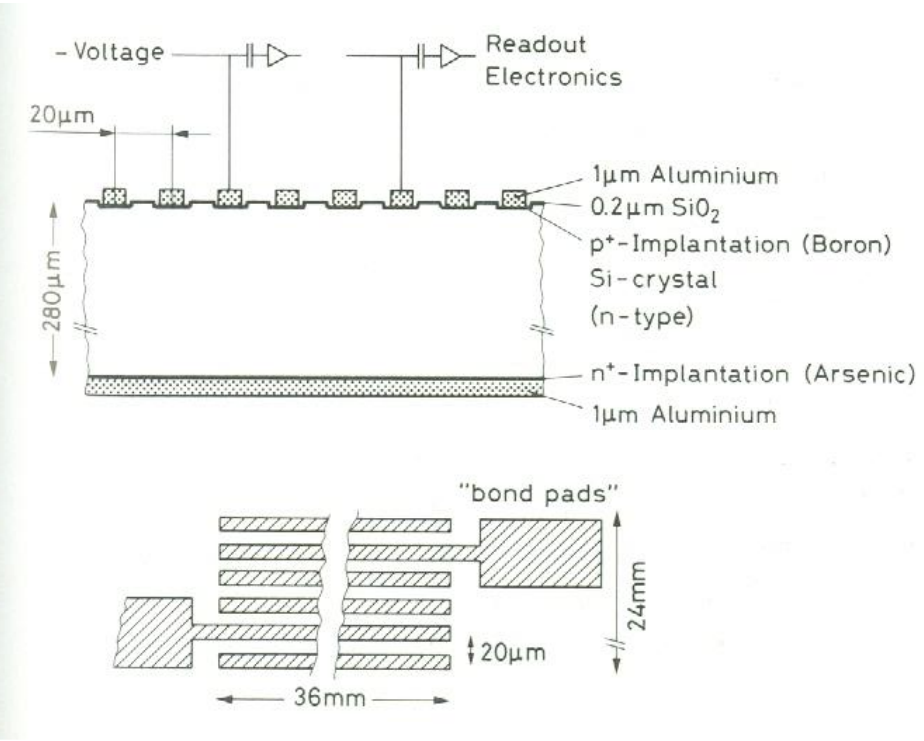
Micro-Strip detector (1)

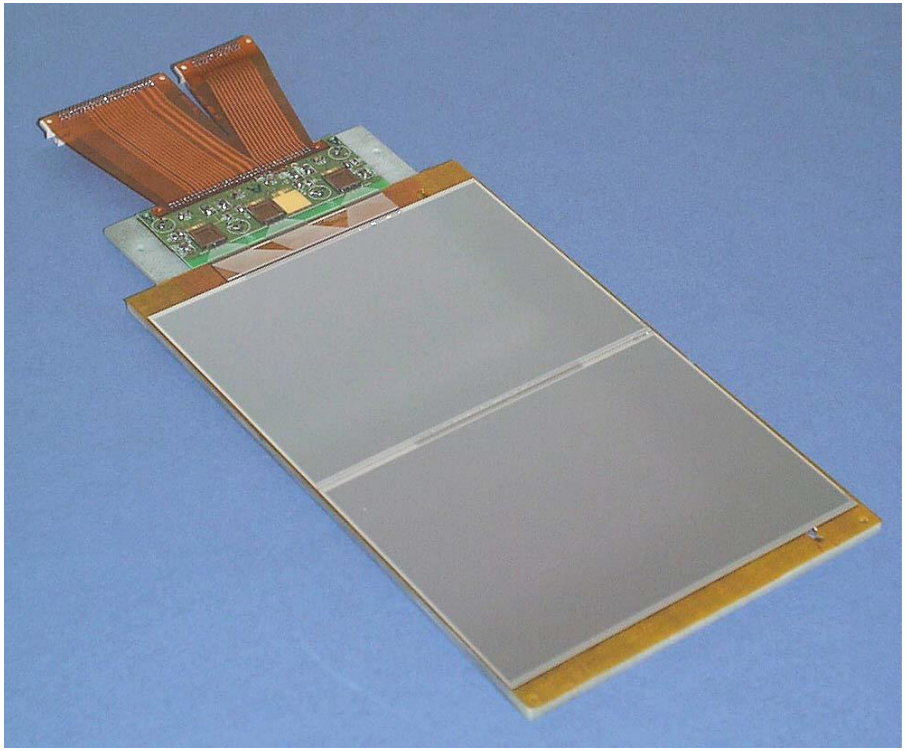
- Detector constituted of a substrate of n type Si on which a series of micro-strips of p type Si are implanted at 20 μm intervals and linked to aluminium contacts

- The number of collected charges at a given contact is dependent on the trajectory of the incident particle

- Space resolution ≈ 5 μm

Micro-Strip detector (2)





Charged particle tracking detector used in the CMS (Compact Muon Solenoid) experiment

Germanium detectors

- Due to its small band gap (≈ 0.7 eV) → operation must be at low temperatures to prevent leakage current from thermally generated e^--h^+ pairs in the depletion zone
- At 77 K (temperature of liquid nitrogen) → average energy for e^--h^+ pair creation: 2.96 eV
- Large atomic number (Z_{Ge}=32 while Z_{Si}=14) → large photoelectric cross section (60 times greater in Ge than in Si) → mainly used for γ-ray detection
- Not often used for charged particles detection because no advantage over Si and Ge needs cooling
- Typical resolution for 1.33 MeV γ: 1.7 keV (or 0.13%) with $F < 0.13$
- **Expensive**

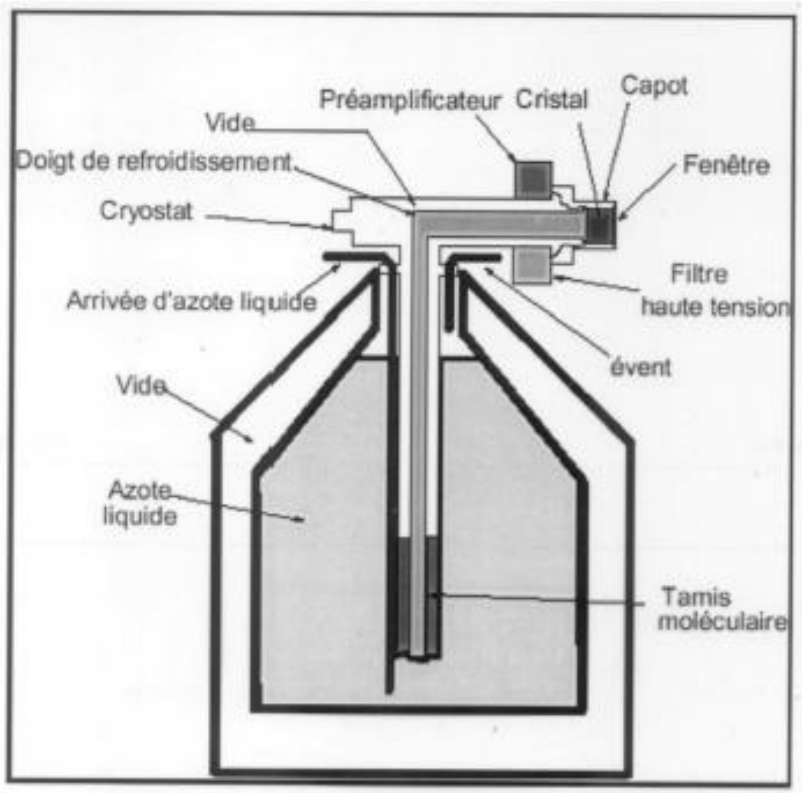
Lithium-Drifted Germanium Diodes - Ge(Li)

- Diffusion of lithium inside p type Ge → Ge(Li) detector
- In practice thickness of the compensated zone: ≈ 15-20 mm
- Due to the diffusion of Li at room temperature → necessity of continuously cooling (not only during use)
- No more used actually

Intrinsic Germanium (High Purity Germanium: HPGe)

- Actually → possibility to obtain high purity Ge crystals (< 10^{10} impurity atoms/cm^3) → quasi-intrinsic Ge → development of HPGe detector (« High Purity Germanium »)
- The crystals can be p or n type according to the nature of residual impurity traces
- The junctions are carried out by doping with ion-implantation one of the faces of the quasi-intrinsic crystal which can be a very large volume
- Colling necessary only during use for radiation detection to reduce the thermal background noise and not during storage
- Frequently use for γ spectroscopy

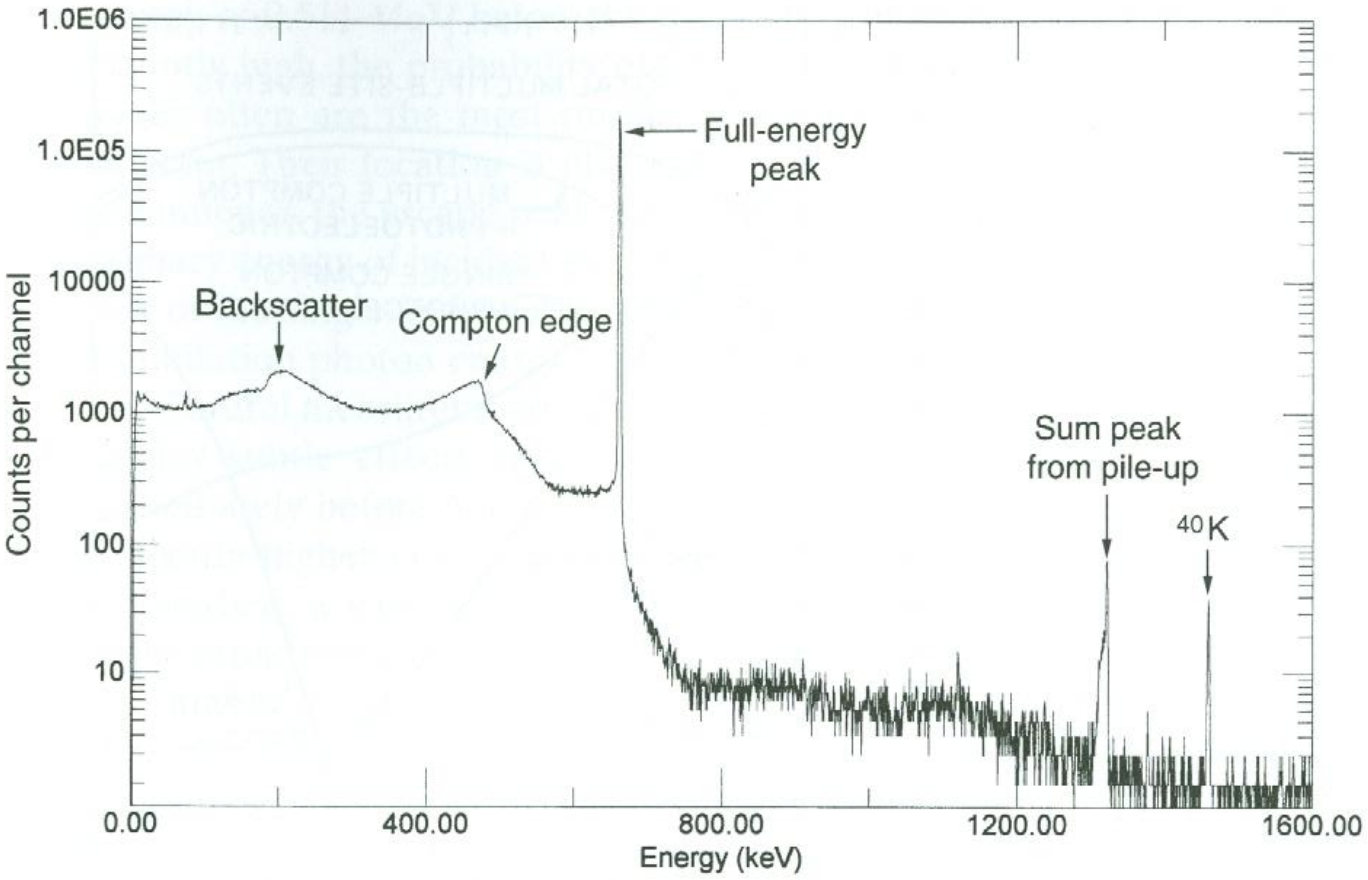
Photo et scheme of HPGe detector with liquid nitrogen



Example of HPGe detector with electrical cooling

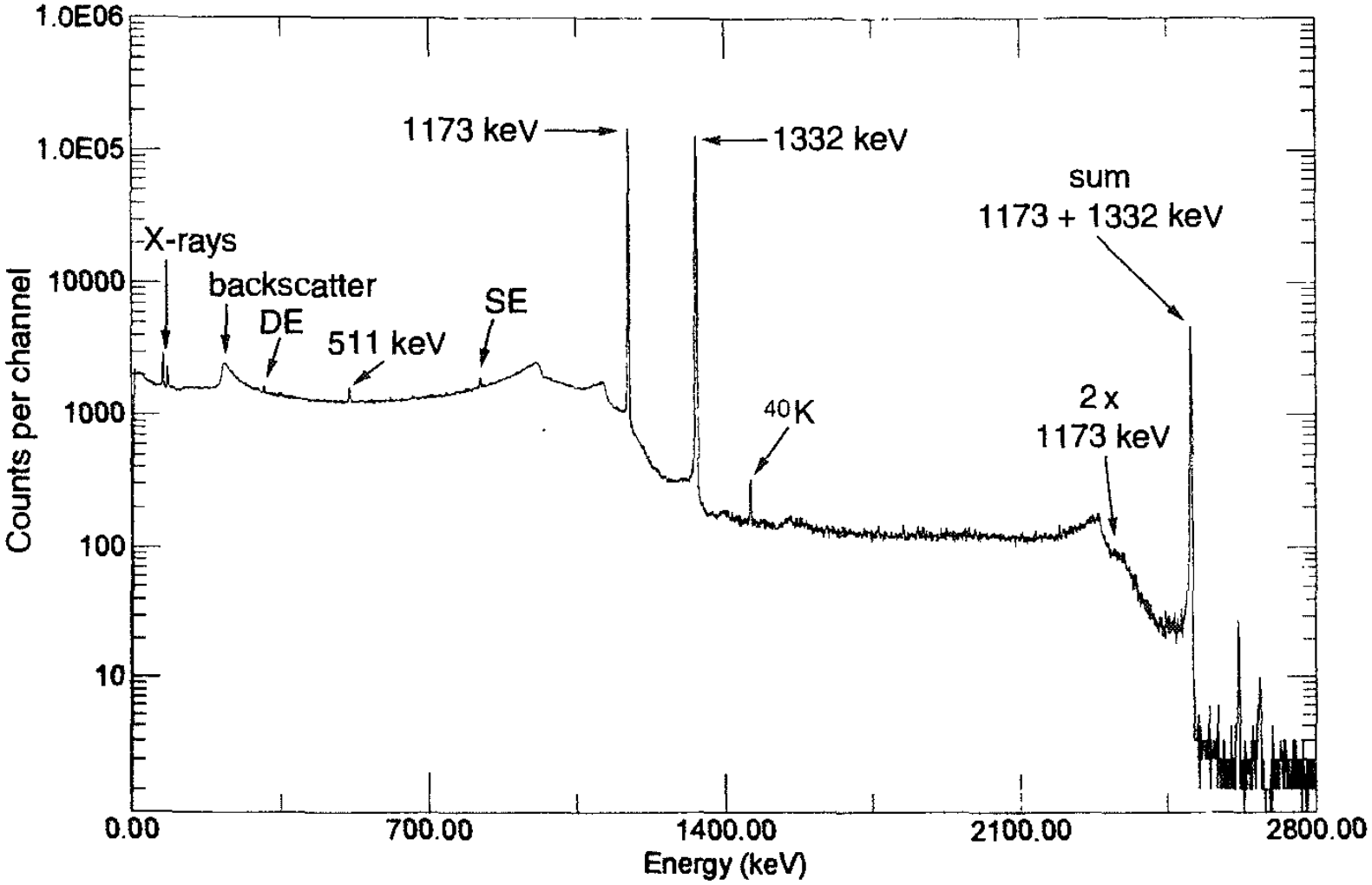
Detector HPGe *Falcon 5000* from Canberra with pulsed gas tube cooling (refrigeration machine operating in closed cycle → allow to obtain permanent cooling sources (≈ 3-120 K) by using the thermodynamic cycles of compression/relaxation of gaseous He)

Example of γ spectroscopy with HPGe (1)



Spectrum of γ rays emitted by ^{137}Cs source

Example of γ spectroscopy with HPGe (2)



Spectrum of γ rays emitted by ^{60}Co source

Other semiconductor materials

- Wish to use high performance detectors but without cooling → use at room temperature → low thermal background noise → E_g large « enough »

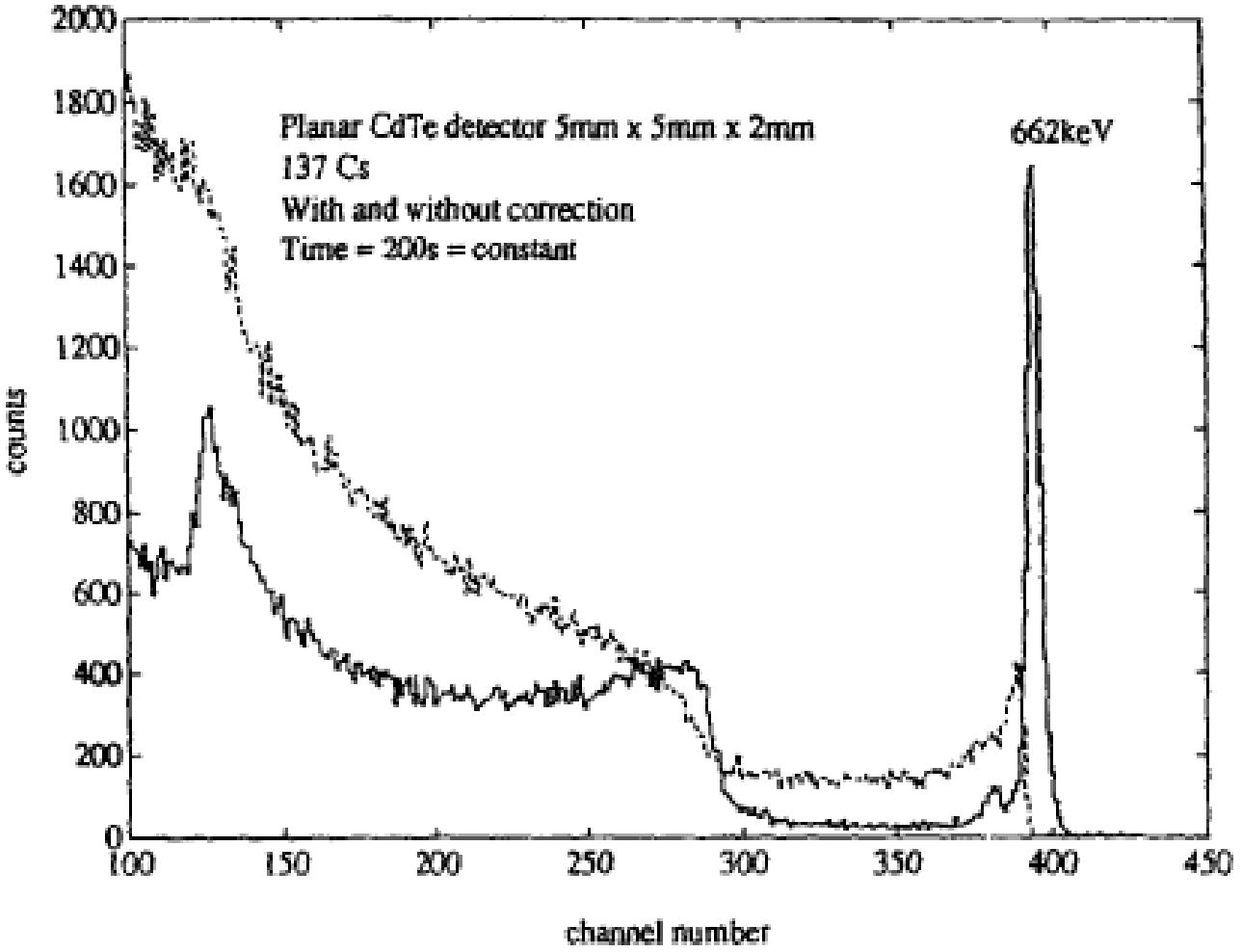
- Use of materials with high Z to maximize photoelectric effect for the detection of γ

- CdTe, HgI_2, GaAs, GaSb, InSb,…

Cadmium telluride detectors (CdTe)

- High Z (Z_{Cd} = 48 and Z_{Te} = 52) → cross section for photoelectric effect 5 $\times$ larger than for Ge
- Energy band gap large enough (E_g = 1.52 eV) → use at room temperature
- Poor collection efficiency of h^+ ↔ capture by traps → energy resolution less good than for Si or Ge
- Trapping of e^- by deep acceptor levels → accumulation of the charges → polarization variable in time → ↘ of the charge collection and ↘ of the thickness of the depletion region → efficiency ↘
- Difficult transport of charges → limited volume
- Commercially available but expensive
- Used when the detection efficiency of high energy γ isessential

Example of γ spectroscopy with a CdTe



γ spectrum from ^{137}Cs source

Possibility to electronically compensate the h^+ trapping

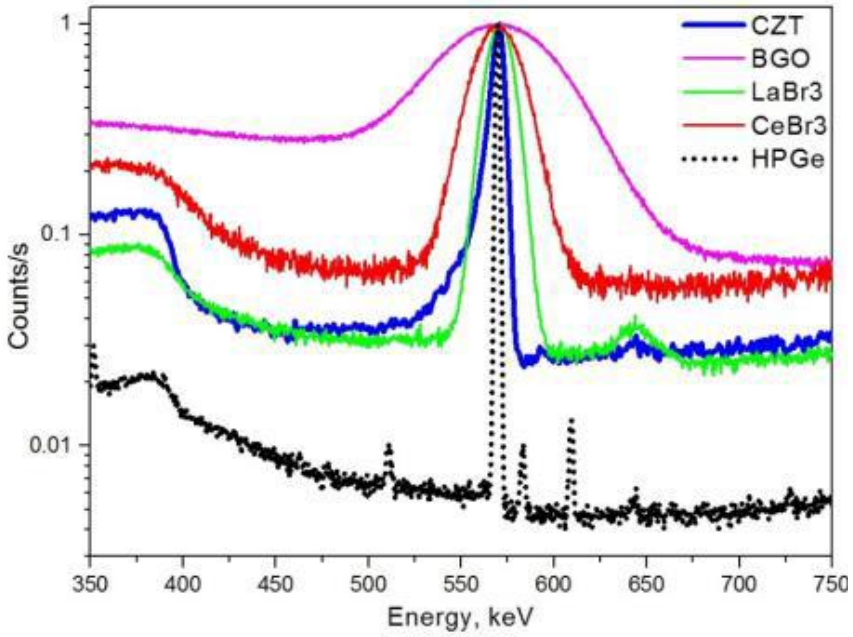
Mercuric iodide Detectors (HgI_2)

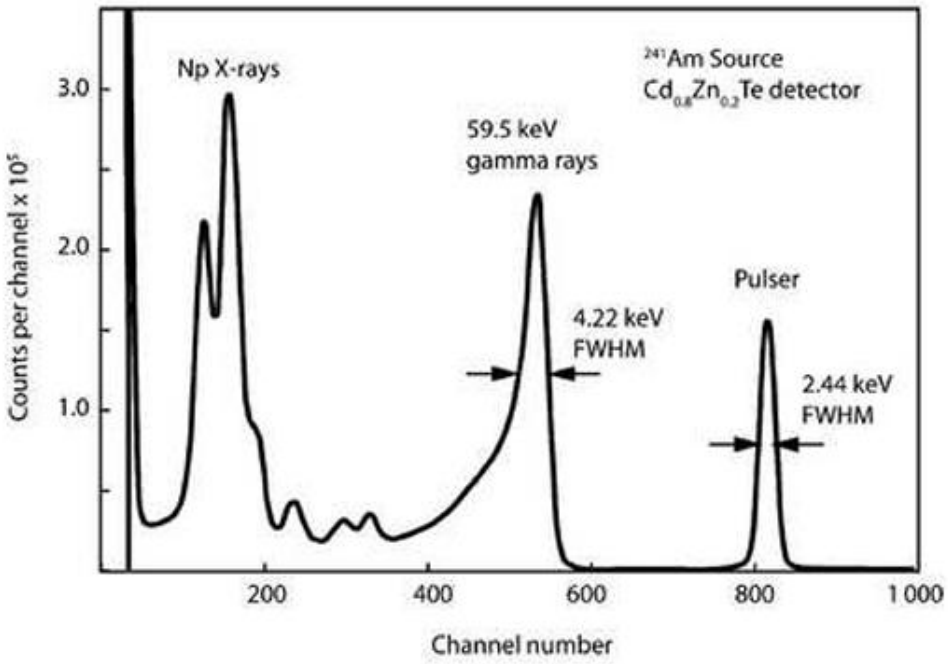
- High Z (Z_{Hg} = 80 and Z_I = 53) → cross section for photoelectric effect 50 × larger than for Ge → 85% of a 100 keV photons beam is absorbed in 1 mm thick HgI_2 (for a equivalent percentage → 10 mm Ge or 2.6 mm CdTe are needed)
- Large energy band gap (E_g = 2.13 eV) → use at room temperature with a very small thermal background noise
- Problems: weak h^+ mobility, incomplete charge collection caused by h^+ trapping, polarization, deterioration of the surface with time → limited resolution, limited volume, efficiency ↘ with time
- High price

CZT detector (1)

- Use of ternary compound $Cd_{1-x}Zn_xTe$ (CZT) with $0.04 < x < 0.2$
- Energy band gap varying between 1.53 and 1.64 respectively
- At room temperature → very good energy resolution and large volume possible
- **BUT** 10 years ago →
  - no polarization effect but trapping of holes at short term → asymmetry of the peaks
  - Difficulties to obtain a crystal without defect (such as metallic inclusions, grains boundary,…) → complex reproducibility

CZT detector (2)





CZT detector (3)

- Now → solution for asymmetry → use of coplanar anodes → the signal depends only on the movement of the electrons

- The flat anode electrode is replaced by a set of thin parallel strips connected alternately to two different amplifiers → two independent reading electrodes

- One set of strips (A) is brought to a slightly higher positive potential than the other set of strips (B) → 2 effects

CZT detector (4)

- Effect 1 : electrons only gather on anode A → movement of electrons near the strips induces most of the signal on anode A only
- Effect 2 : movement of charges (holes in particular) at large distance from the plane of the strips induces the same signal on anodes A and B

- The difference between the signals on the two anodes (A-B) depends only on the movement of the electrons → signal due to holes disappears → asymmetry disappears for (A-B)
- Then → technological development → reproducibility ↗ → crystals between 1 and 8 cm^3 → very compact
- CZT detector will be the dominant gamma detector in the next few years

Summary of applications of semiconductor detector

- Silicon detectors (generally SSB or implantation) → principal use in spectroscopy (or detection) of charged particles (proton, α,…) and for the determination of the trajectories of charged particles

- Germanium detectors (generally HPGe) → principal use for detection and spectroscopy of γ rays

- CZT detector → detection and spectroscopy of γ rays for nuclear medicine