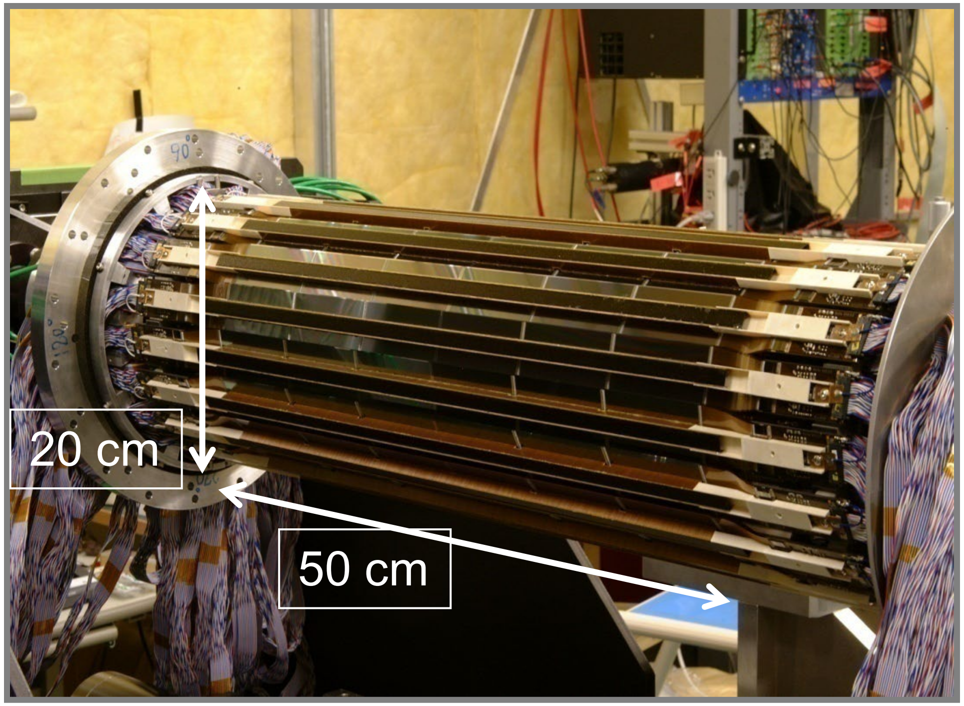
Semiconductor detectors

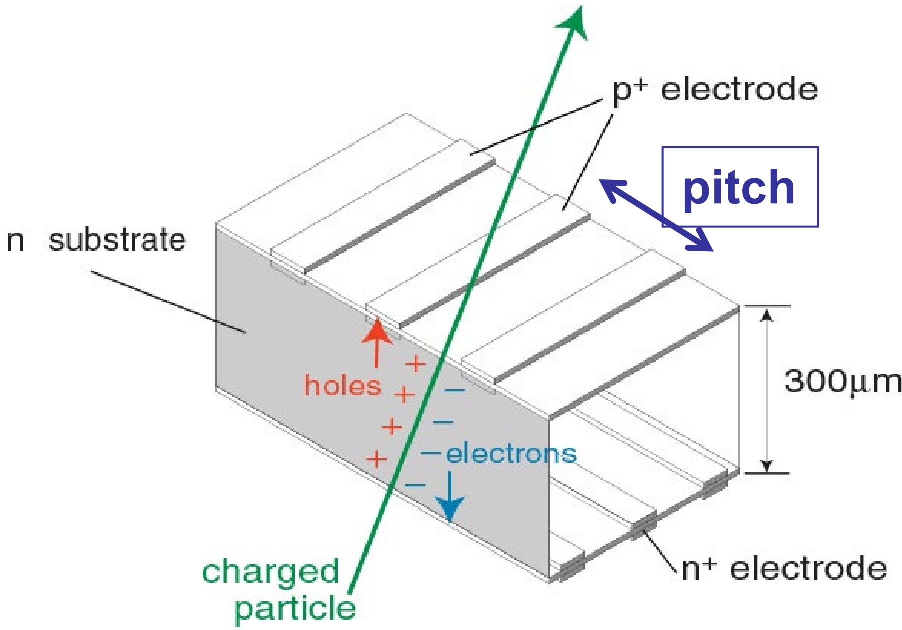
- properties of semiconductors
- p-i-n diode
- interface metal-semiconductor
- measurements of energy
- space sensitive detectors
- radiation damage in detectors

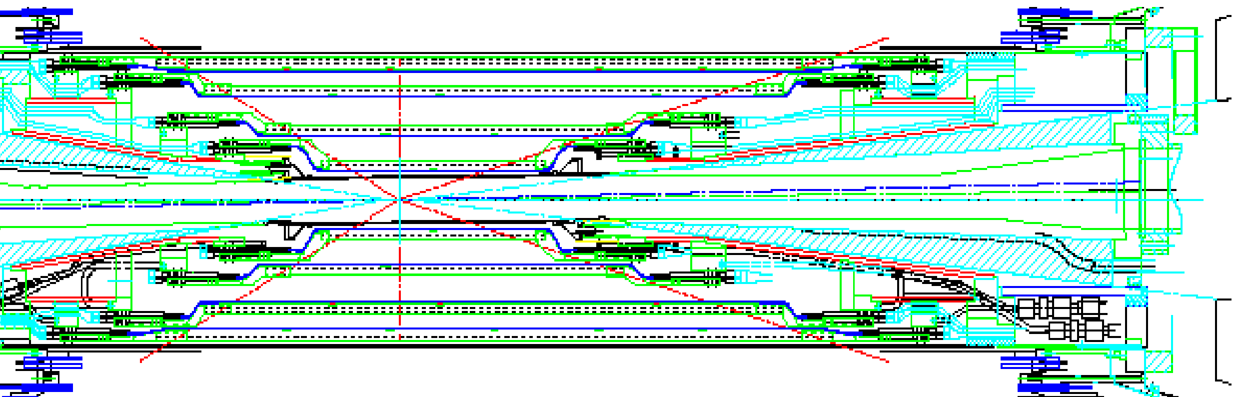
Literatura:

W.R.Leo: Techniques for Nucear and Particle Physics Experiments
H. Spieler: Semiconductor Detector Systems
G. Lutz: Semiconductor Radiation Detectors
S.M. Sze: Physics of Semiconductor Devices
Glenn F. Knoll: Radiation Detection and Measurement

Typical tracking device in particle physics: silicon strip detector







Two coordinates measured at the same time

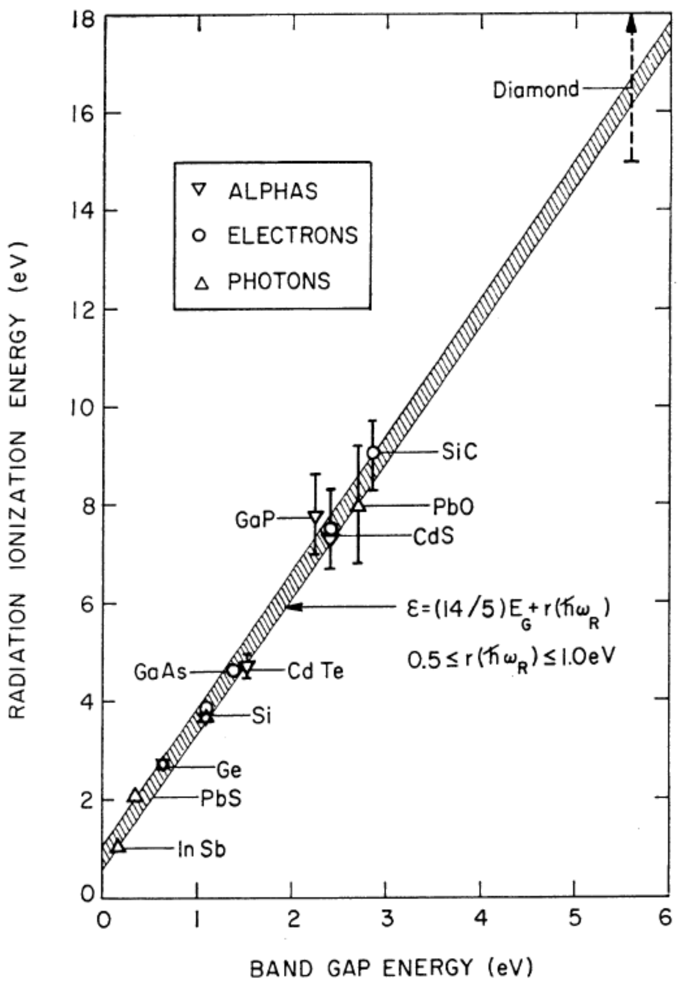
Typical strip pitch ~50μm, resolution about ~15 μm

Why semiconductors?

- Energy resolution of a detector depends on statistical fluctuation in the number of free charge carriers that are generated during particle interaction with the detector material

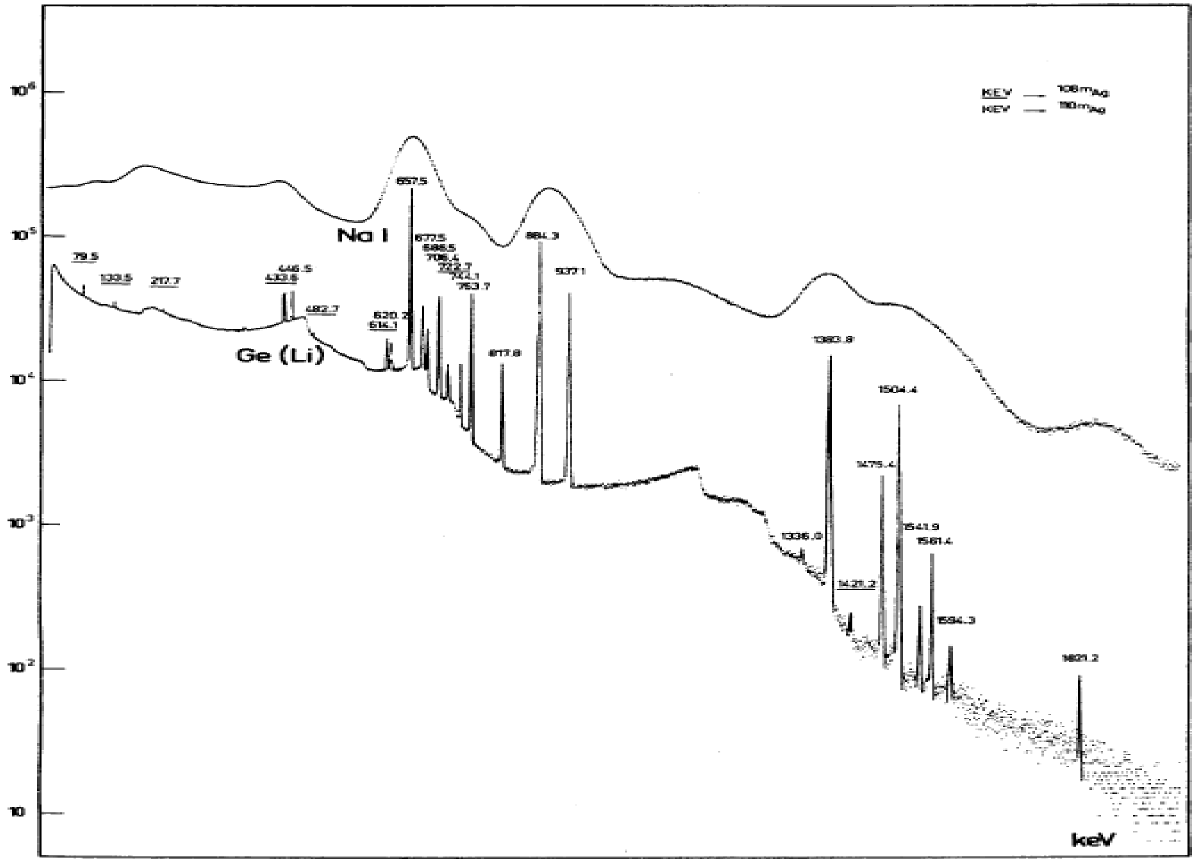
- Low energy needed for generation of free charge carriers → good resolution

- Gas based detectors: a few 10eV
- Semiconductors: a few eV!



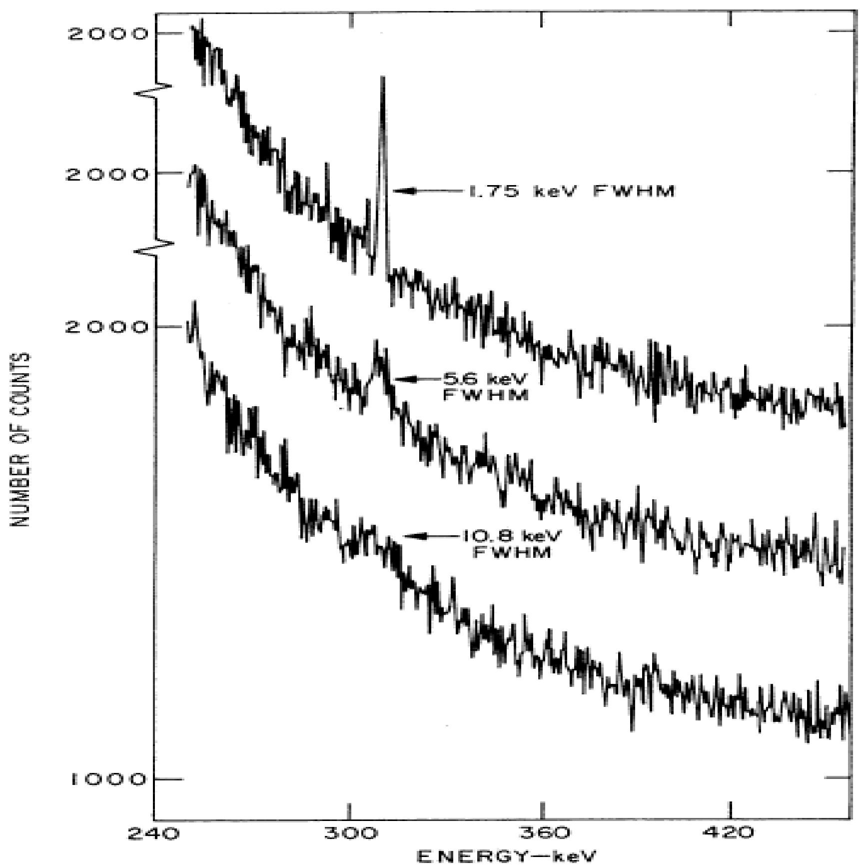
C.A. Klein, J. Applied Physics **39** (1968) 2029

Comparison: radiation spectrum as measured with a Ge (semiconductor) in NaI (scintillation) detector



(J.Cl. Philippot, IEEE Trans. Nucl. Sci. NS-17/3 (1970) 446)

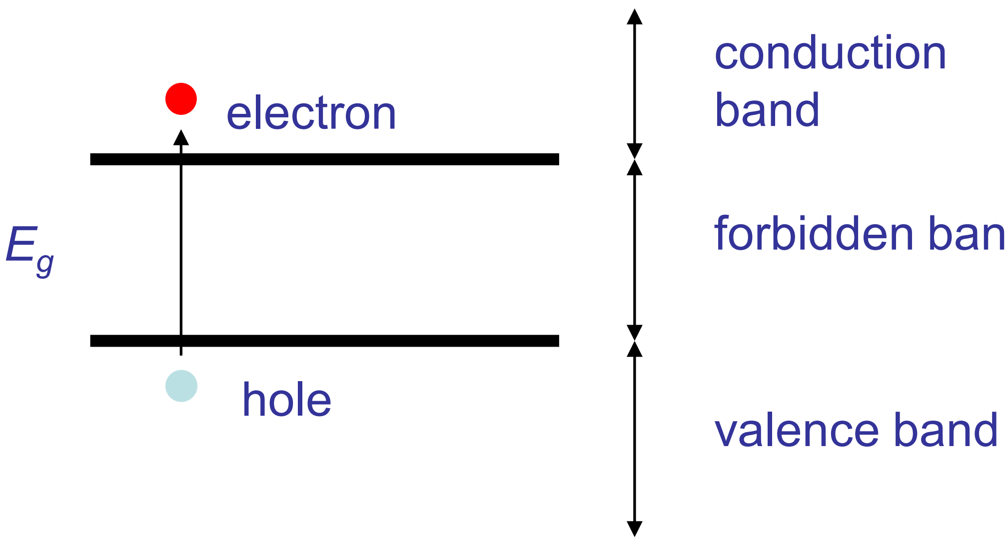
good energy resolution → easier signal/background separation



G.A. Armantrout *et al.*, IEEE Trans. Nucl. Sci. NS-19/1 (1972) 107

Principle of operation:

Semiconductor detector operates just like an ionisation chamber: a particle, which we want to detect, produces a free electron – hole pair by exciting an electron from the valence band:



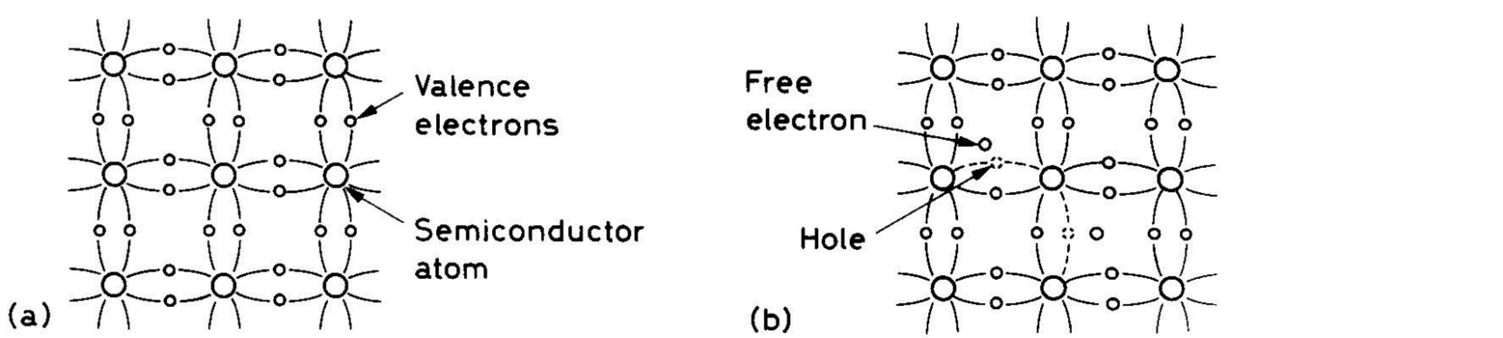


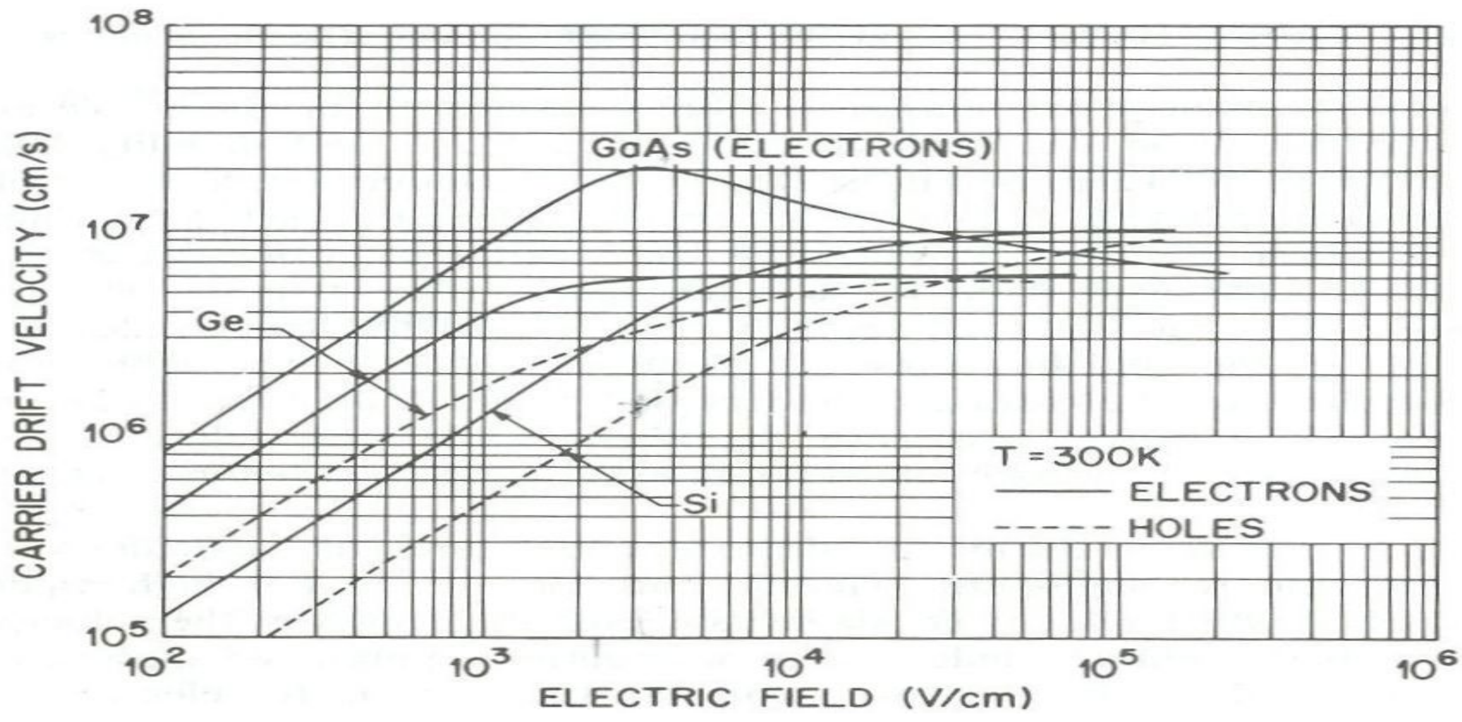
Fig. 10.2. Covalent bonding of silicon: **(a)** at 0 K, all electrons participate in bonding, **(b)** at higher temperatures some bonds are broken by thermal energy leaving a *hole* in the valence band

Drift velocity in electric field:

$$v_d = \mu \cdot E$$

μ mobility

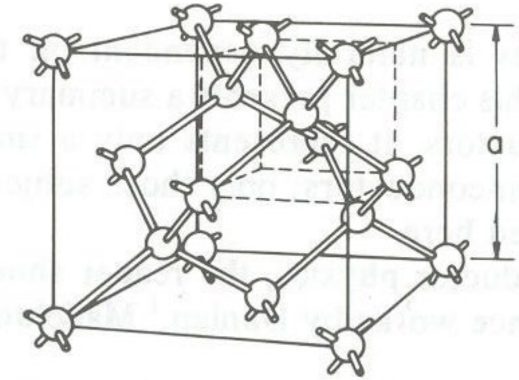
different for electrons and for holes!



properties of semiconductors

	ρ [kg dm^{-3}]	ε	E_g [eV]	μ_e [cm^{2}V^{-1}s^{-1}]	μ_h [cm^{2}V^{-1}s^{-1}]
Si	2.33	11.9	1.12	1500	450
Ge	5.32	16	0.66	3900	1900
C	3.51	5.7	5.47	4500	3800
GaAs	5.32	13.1	1.42	8500	400
SiC	3.1	9.7	3.26	700	
GaN	6.1	9.0	3.49	2000	
CdTe	6.06		1.7	1200	50

Intrinsic (pure) semiconductor (no impurities)



DIAMOND
(C, Ge, Si, etc)

n - concentration of conduction electrons

p - concentration of holes

$$n = \int_{E_c}^{E_t} N(E)F(E)dE$$

N(E) density of states

$$F(E) = \frac{1}{1 + \exp(\frac{E - E_F}{kT})}$$

E_F Fermi energy level

Fermi-Dirac distribution

See Modern Physics 2 for a detailed discussion

Pure semiconductor
Neutrality: ⇨ n=p

$$E_F = \frac{E_c + E_v}{2} + \frac{3kT}{4}\ln(\frac{m_h}{m_e})$$

⟶ ratio of effective masses of holes and electrons

$$n = N_c \times \exp\left(-\frac{(E_c - E_F)}{kT}\right)$$

$$p = N_v \times \exp\left(-\frac{(E_F - E_v)}{kT}\right)$$

$$n \times p = n_i^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$$

$$n_i = \sqrt{N_e N_v}\,\exp\left(-\frac{E_g}{2kT}\right)$$

E_c energy of the bottom of conduction band
E_v energy of the top of the valence band
$E_g = E_c - E_v$ width of the forbidden band

N_c, N_v: effective density of states in the conduction and valence bands

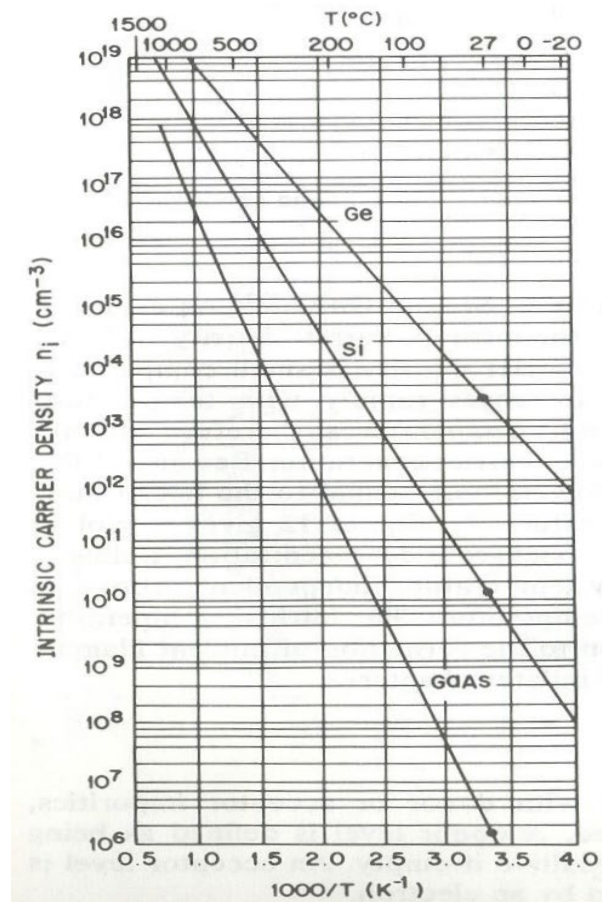


Fig. 11 Intrinsic carrier densities of Ge, Si, and GaAs as a function of reciprocal temperature. (After Thurmond, Ref. 20.)

n_i number density of free charge carriers in an intrinsic semiconductor (only for electrons and holes)

At room themperature:

$$n_i = 1.4 \times 10^{10}\, cm^{-3} [Si]$$

$$n_i = 2.4 \times 10^{13}\, cm^{-3} [Ge]$$

$$\text{out of } 10^{22} \text{ atoms } cm^{-3}$$

Signal vs background

Assume a gamma ray of E=370 keV is absorbed through photo-effect in a detector, a Si cube with 1cm sides.

The number of electron-hole pairs is 370keV / 3.7eV = 10^5

Number of electrons in the conduction band is $1.4\ 10^{10}$

→ Need a material free of charge carriers

→ Combination of the differently doped Si crystals (p-n junction) with a bias voltage

Properties of semiconductors are modified if we add impurities

- **Donor levels** → neutral, if occupied
  charged +, if not occupied
- **Acceptor levels** → neutral, if not occupied
  charged -, if occupied

shallow acceptors – close to the valence band (e.g. three-valent atoms in Si – examples B, Al)

shallow donors – close to the conduction band (e.g. five-valent atoms in Si – examples P, As)

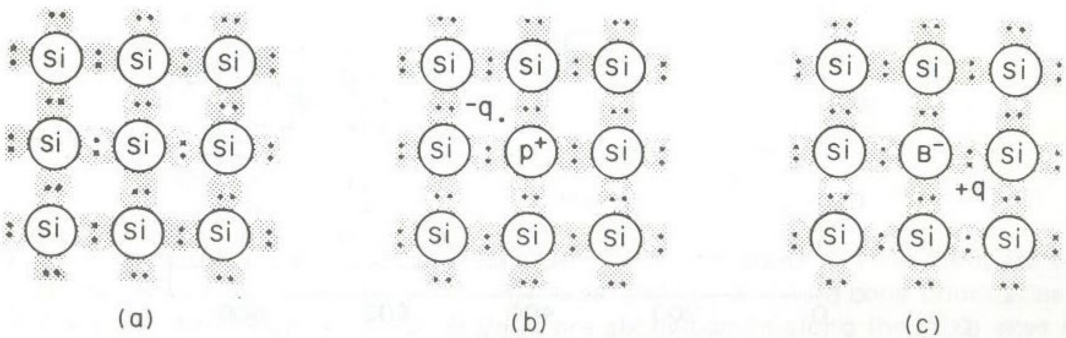


Fig. 9 Three basic bond pictures of a semiconductor. (*a*) Intrinsic Si with negligible impurities. (*b*) *n*-type Si with donor (phosphorus). (*c*) *p*-type Si with acceptor (boron).

n-type semiconductor, with added donors

p-type semiconductor, with added acceptors

Binding energy of a shallow donor state is smaller because of a smaller effective mass and because of the diectric constant (11.9 for Si)

for Si $$\frac{13.6eV \cdot \frac{m_{eff}}{m_0}}{\varepsilon^2} \approx 0.05eV$$

In most cases it can be assumed that all shallow donors (acceptors) are ionized since they are far from the Fermi level.

Neutrality:

$$n + N_A = p + N_D$$

As a result, the Fermi level gets shifted:

$$E_F - E_i = kT \ln(\frac{N_D}{n_i})$$ if N_D » N_A , *n type semiconductor*

$$E_i - E_F = kT \ln(\frac{N_A}{n_i})$$ if N_A » N_D , *p type semiconductor*

Properties of semiconductors with imputies (doped semiconductors)

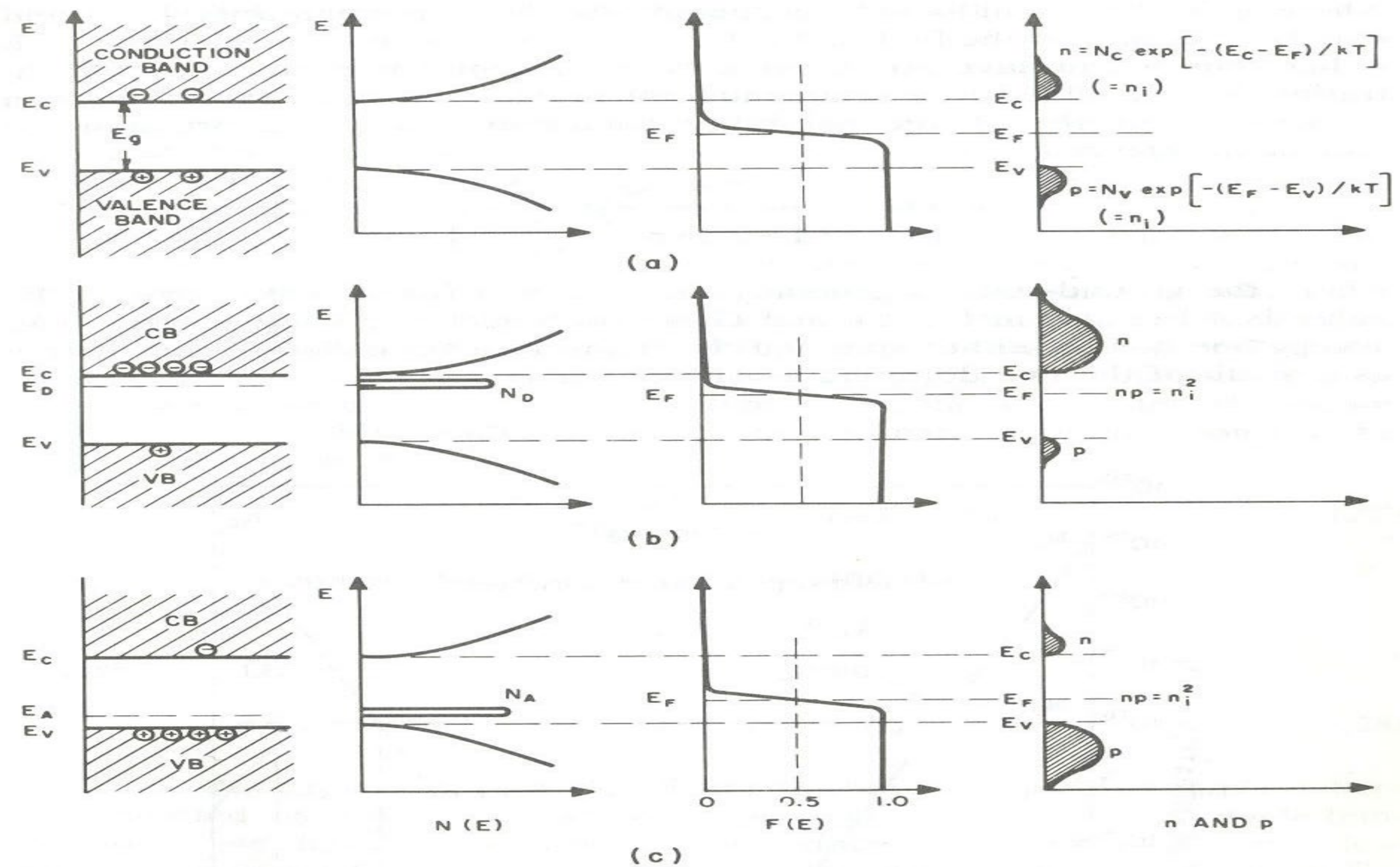


Fig. 14 Schematic band diagram, density of states, Fermi–Dirac distribution, and the carrier concentrations for (*a*) intrinsic, (*b*) *n*-type, and (*c*) *p*-type semiconductors at thermal equilibrium. Note that $pn = n_i^2$ for all three cases.

Resistivity of semiconductors

$$v_d = \mu \cdot E$$ Charge drift in electric fieldu *E*, *μ* mobility

$$j = \sigma \cdot E = \frac{E}{\rho} = e_0 \cdot v_{d_e} \cdot n + e_0 \cdot v_{d_h} \cdot p$$

$$\rho = \frac{1}{e_0(\mu_e n + \mu_h p)}$$ specific resistivity

at room temperature,

intrinsic semiconductor :

$$\rho_{Si} = 230\text{k}\Omega\text{cm}$$

$$\rho_{Ge} = 47\Omega\text{cm}$$

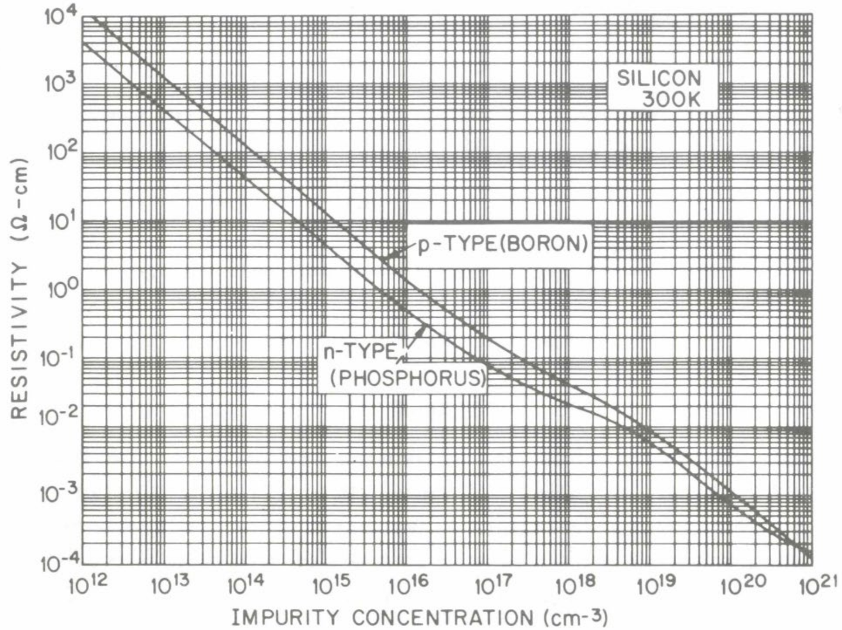
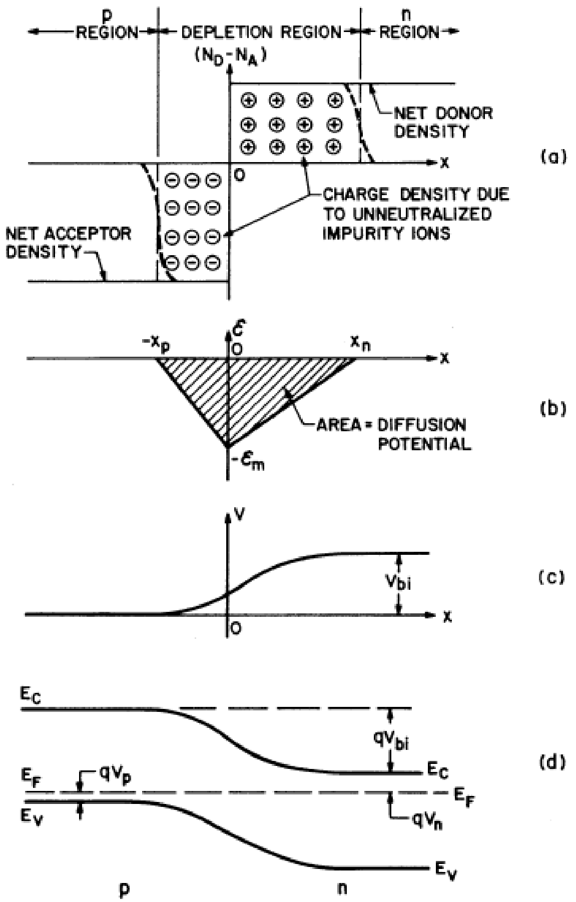


Fig. 21 Resistivity versus impurity concentration for silicon at 300 K. (After Beadle, Plummer, and Tsai, Ref. 38.)

p-n structure



(from Sze, *Physics of Semiconductor Devices*)

At the p-n interface we have an inhomogenous concentration of electrons and holes → difussion of electrons in the p direction, and of holes into the n direction

At the interface we get an electric field (Gauss law)

Potential difference

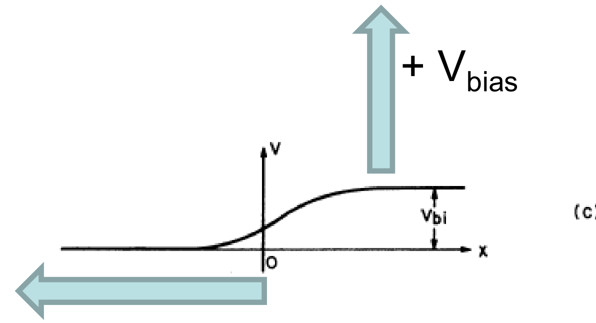
$$V_{bi} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

V_{bi} = built-in voltage difference, order of magnitude 0.6V

To the signal only those charges can contribute that were produced in the depleted region with a non-zero electric field →
The depleted region should cover most of the detector volume!

How to excrease the size of the depleted region: apply external voltage V_{bias}

- if the potencial barrier is increased, the depleted regic increases → larger active volume of the detector – voltage in the **reverse direction**
- if the potencial barrier decreases, the active volume is reduced, we get a larger current, voltage is in the conduction direction.



The height of the potential barrier: $V_B = V_{bias} + V_{bi}$

How large is the depleted region (x_p+x_n)?

Neutrality:

$N_a\, x_p = N_d\, x_n$

For the electric field we have the Poisson equation:

$$\frac{d^2V}{dx^2} = -\frac{\rho_e}{\varepsilon\varepsilon_0} = \frac{e_0 N_{a,d}}{\varepsilon\varepsilon_0}$$

$$\frac{dV}{dx} = \begin{cases} -\dfrac{e_0 N_d}{\varepsilon\varepsilon_0}(x - x_n) & 0 \le x \le x_n \\ \dfrac{e_0 N_a}{\varepsilon\varepsilon_0}(x + x_p) & -x_p \le x \le 0 \end{cases}$$

The electric field varies linearly as a function of the coordinate, potential quadratically

$$x_n = \left(\frac{2\varepsilon\varepsilon_0 V_{bias}}{e_0 N_d (1 + N_d / N_a)}\right)^{1/2}$$

$$x_p = \left(\frac{2\varepsilon\varepsilon_0 V_{bias}}{e_0 N_a (1 + N_a / N_d)}\right)^{1/2}$$

$$d = x_n + x_p = \left(\frac{2\varepsilon\varepsilon_0 V_{bias}}{e_0} \frac{(N_a + N_d)}{N_a N_d}\right)^{1/2}$$

$$\text{example}: N_a >> N_d \;\Rightarrow d \approx x_n \approx \left(\frac{2\varepsilon\varepsilon_0 V_{bias}}{e_0 N_d}\right)^{1/2}$$

increases as $V_{bias}^{1/2}$

in terms of the spec. resistivity ρ:

$$d \approx \left(2\varepsilon\varepsilon_0 \rho_n \mu_e V_{bias}\right)^{1/2}$$

example: silicon $d = \begin{cases} 0.53(\rho_n V_{bias})^{1/2} \mu\text{m} \;\; \text{n-type} \\ 0.32(\rho_\text{p} V_{bias})^{1/2} \mu\text{m} \;\; \text{p-type} \end{cases}$

if ρ=20000kΩcm and V_{bias}=1 V → d~75μm

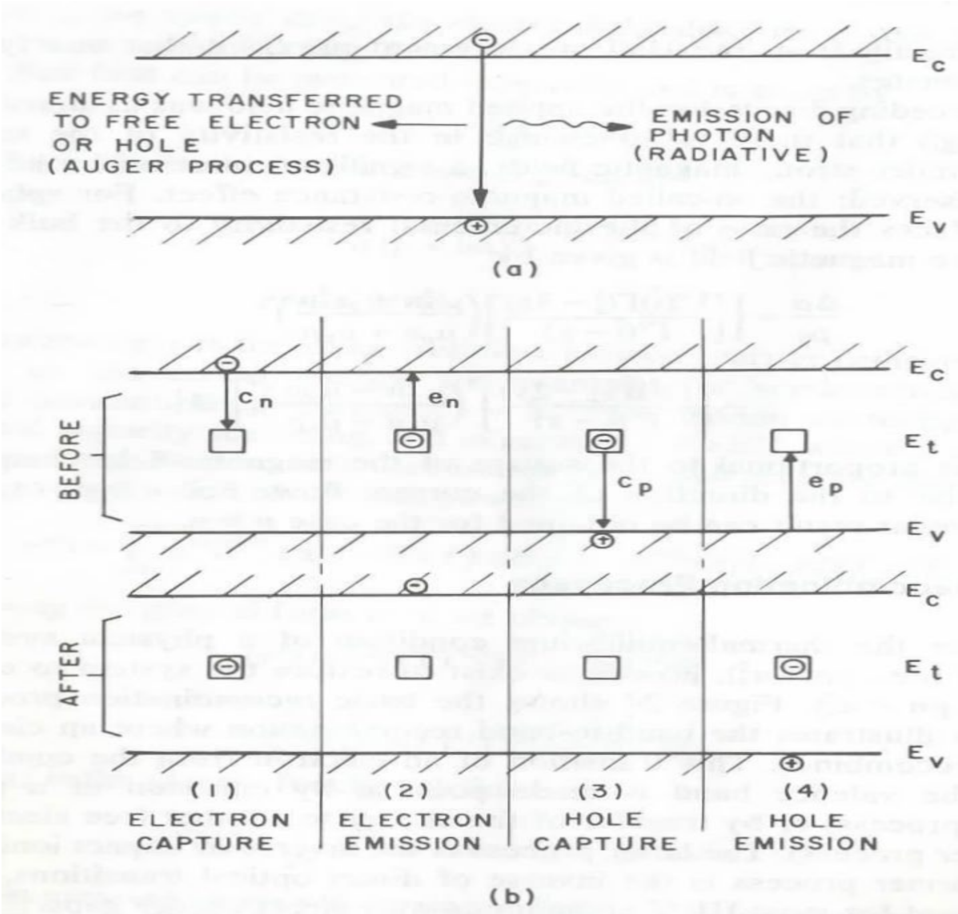
Leakage current

= current in the reverse direction

difussion current:

- difussion of minority carriers into the region with electric field
- current of majority carriers with large enough thermic energy, such that they overcome the potencial barrier

generation current: generation of free carriers with the thermal excitation in the depleted layer



The probability of excitation is dramatically increased in the presence of intermediate levels.

generation current:

$$j_{gen} \propto N_t T^2 \exp\left(-\frac{E_g}{2kT}\right) \qquad N_t \text{ concentration of traps}$$

→ high T – high generation current
→ wider forbidden band E_g, lower generation current

Consequence: some detectors have to be cooled (Ge based, radiation damaged silicon detectors)

metal-semiconductor interface (Schottky barrier)

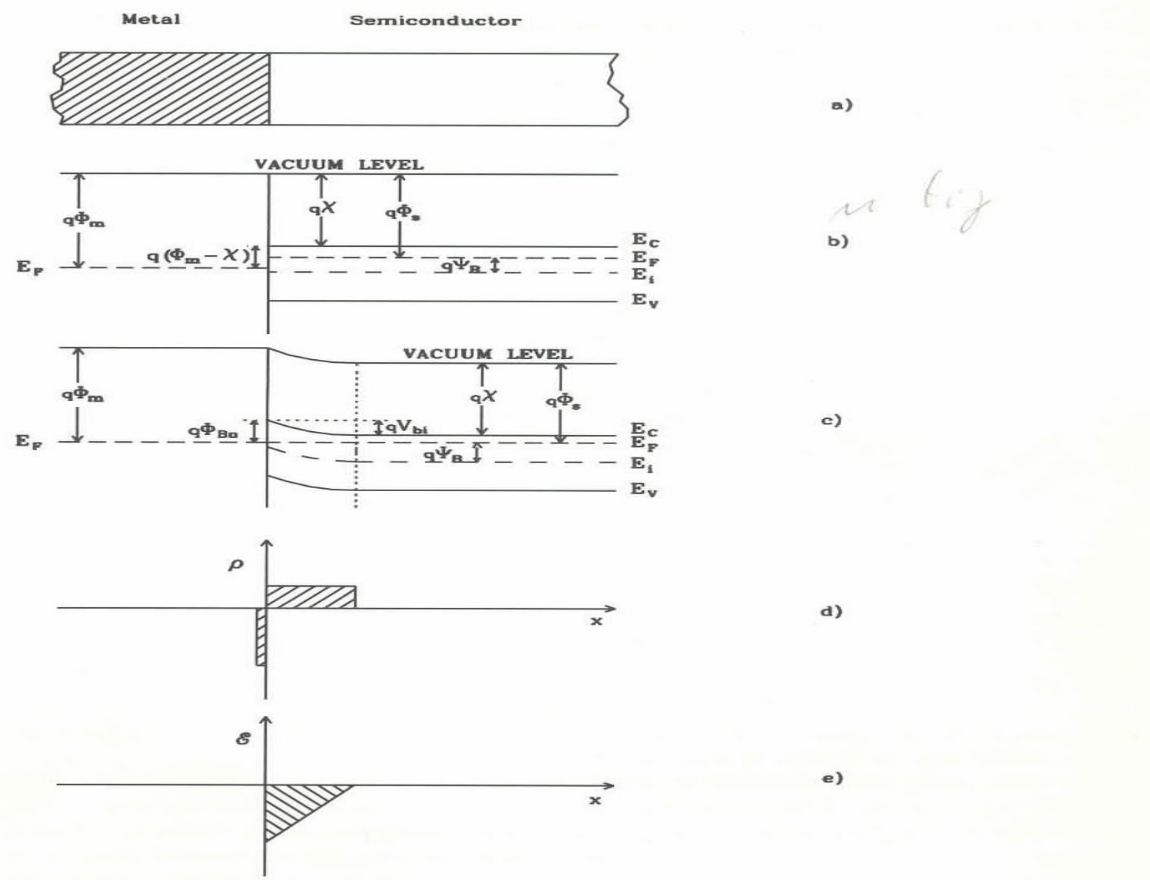


Fig. 3.9a–e. Metal–semiconductor contact (a). Description in the band model: metal and *n*-type semiconductor separately in thermal equilibrium (b); metal and semiconductor joined together (c); charge density (d); electric field (e)

X electron affinity

Φ work function

Assumption $\Phi_m > \Phi_s$

$V_{bi} = \Phi_m - \Phi_s$

58 3 Basic Semiconductor Structures

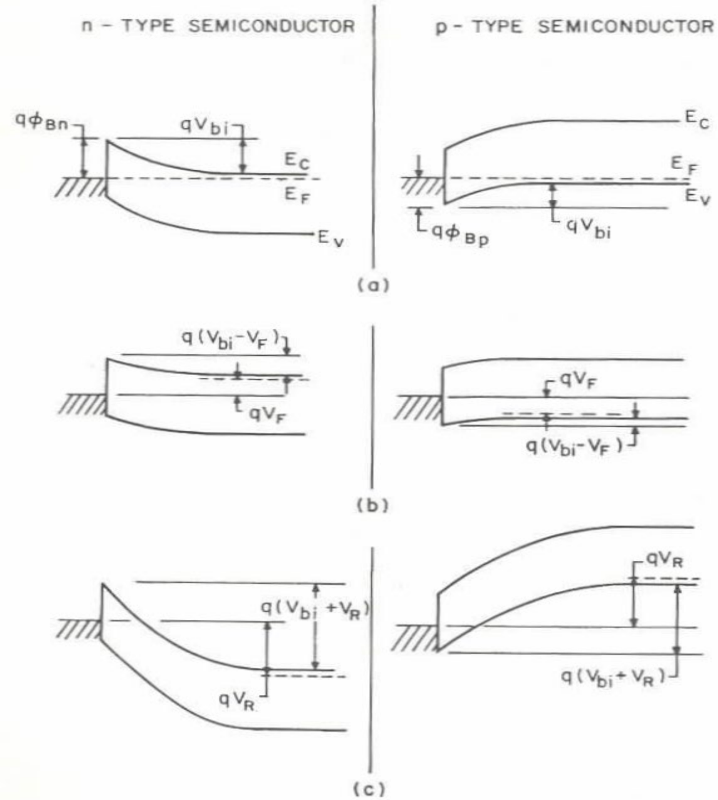


Fig. 3.10a–c. Energy band diagram for metal–n-type and p-type semiconductor junction: in thermal equilibrium (a); with forward bias (b); with reverse bias (c). (After Sze 1985, p. 164 Fig. 4)

No external voltage

voltage in the conduction direction

voltage in the reverse direction

Ohmic contact: high concentration of impurities → thin barrier → tuneling

Manufacturing of semiconductor detectorjev

1. manufacturing of monocrystals in form of a cylinder:

- Czochralski (Cz) method

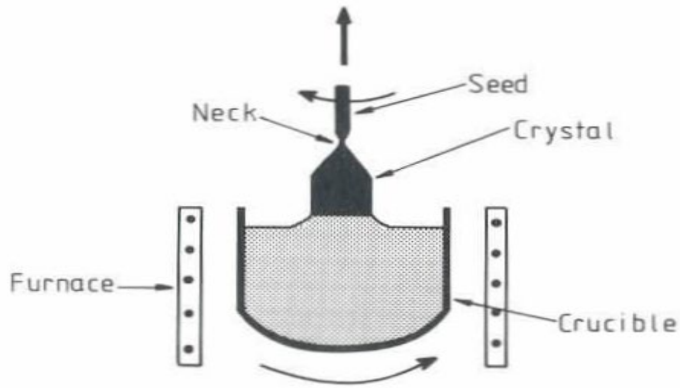


Figure 3.4 A schematic illustration of the basic features of a Czochralski crystal growth process.

Liquid silicon is in contact with the vessel – higher concentration of (unwanted) impurities

Float zone method:

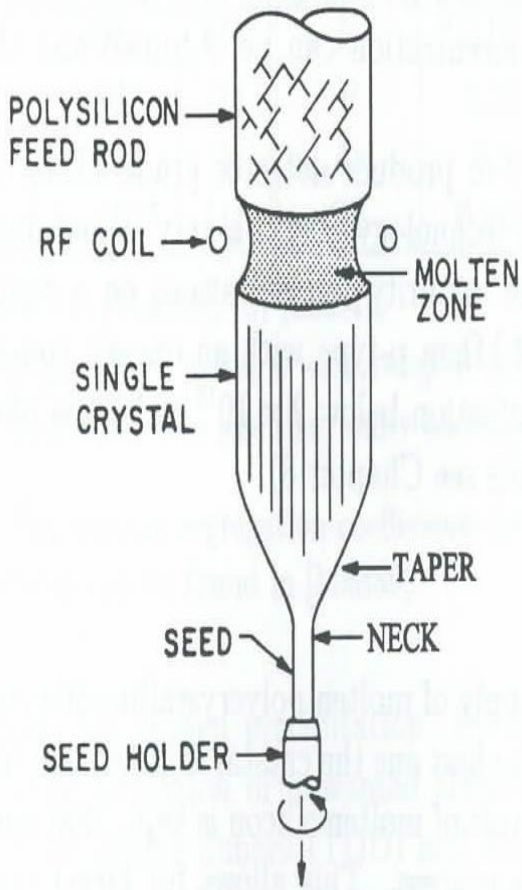


Figure 2.2: Schematic setup for the Float zone (FZ) process (after [Sze85]).

No contact of the liquid semiconductor with the walls – higher purity of the material.

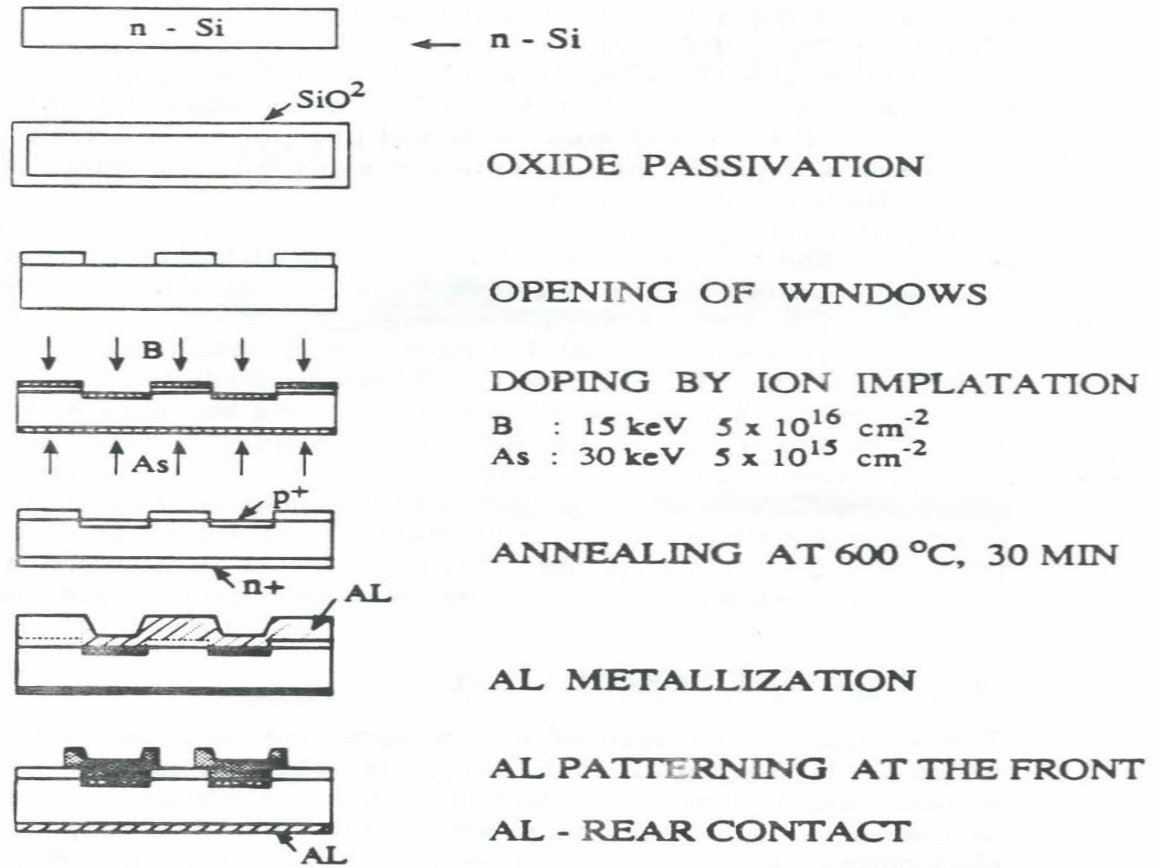
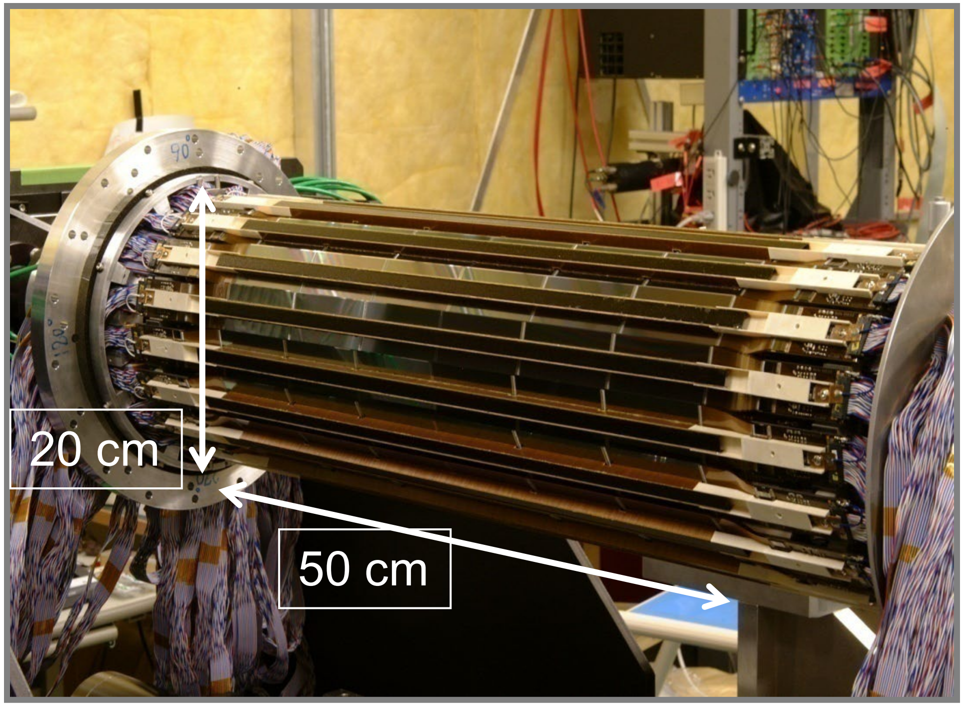
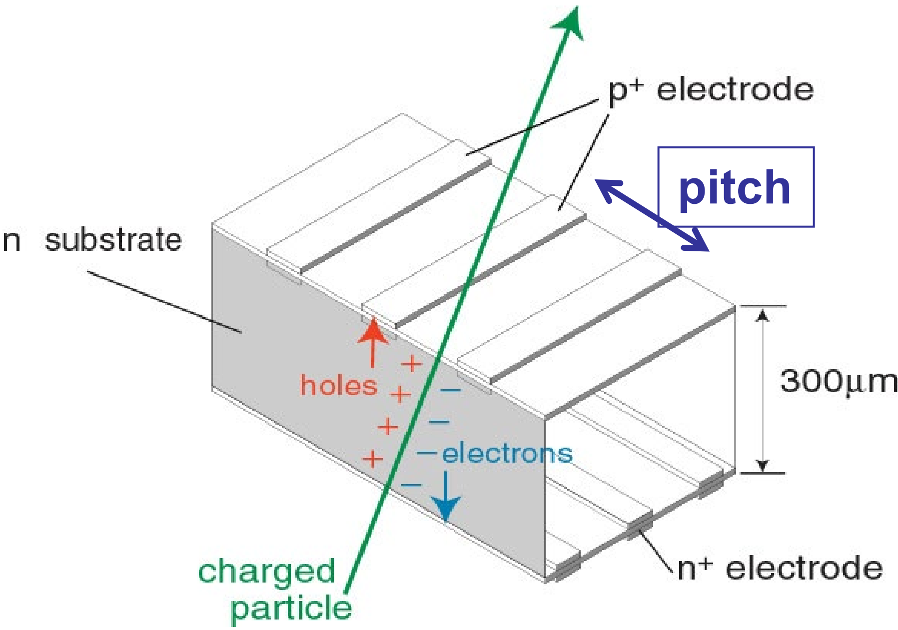


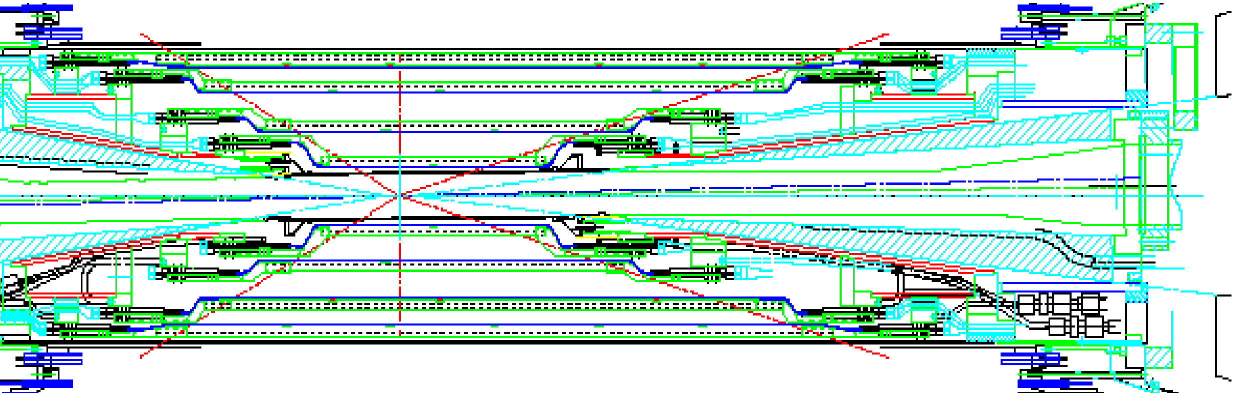
Figure 7: The planar process for detector fabrication (from reference [24]).

Photolitography for pattern fabrication

Typical tracking device in particle physics: silicon strip detector







Two coordinates measured at the same time

Typical strip pitch ~50μm, resolution about ~15 μm

Signal development in a semiconductor detector

1. interaction of particles with matter (generation of electron – hole pairs)

$$\left(\frac{dE}{dx}\right)_{ion} \propto \rho \frac{Z}{A} \text{ for M.I.P. (minimum ionizing particle, } Z=1)$$

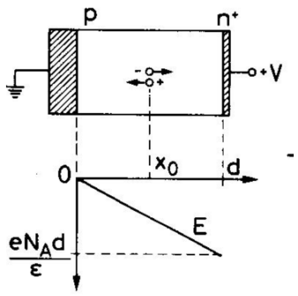
$$\frac{1}{\rho}\frac{dE}{dx} \approx 1.6 \frac{MeV}{gcm^{-2}} \qquad \beta = \frac{v}{c} \approx 0.96$$

2. drift of charges in electric field causes an induced current on the electrodes (signal) – similar as in the ionisation detector

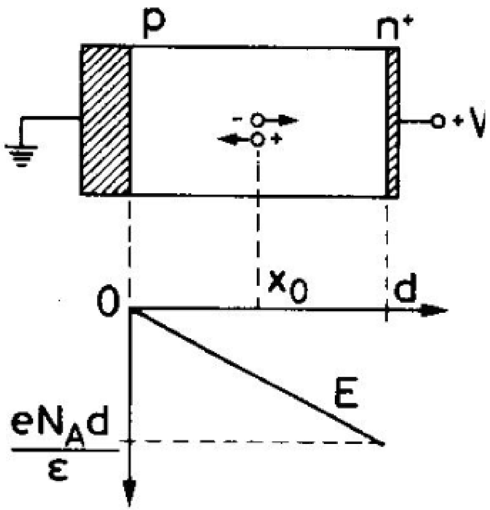
3. Electric field in a uniformly charged volume

$$\frac{d^2V}{dx^2} = -\frac{\rho_e}{\varepsilon\varepsilon_0} = \frac{e_0 N_{a,d}}{\varepsilon\varepsilon_0}$$

→ $E \propto -x$ for a negatively charged volume (depleted p doped region)



Signal development 2



Relation between charge carrier propagation and induced current:

detector volume V=S*d
n = concentration of carriers

I=j*S   current through surface S
$I=e_0*v*n*S$

For a single drifting electron:
n*V=n*S*d=1
n*S=1/d

and therefore for a single drifting electron we get:
$I=e_0*v/d$
and
$dQ*d = e_0*dx$

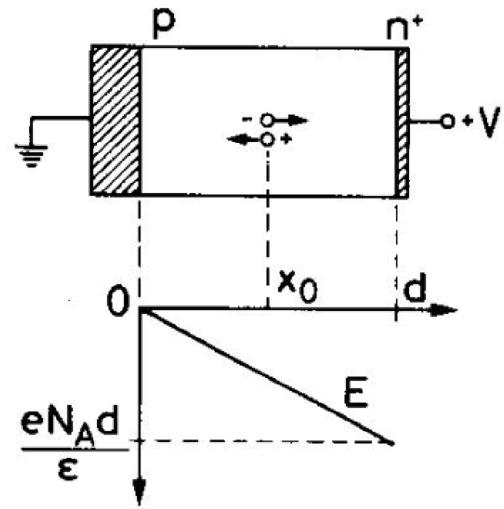
Signal development

For an electron-hole pair created at x_0 in p-n detector, p-doped and higly n doped (n+)

$$dQd = qdx$$

$$E = -\frac{1}{\varepsilon\varepsilon_0} eN_A x$$

$$E = -\frac{x}{\mu_h \tau}, \quad \text{with} \quad \tau = \rho\varepsilon\varepsilon_0 \quad \text{and} \quad \frac{1}{\rho} = eN_A\mu_h$$



electrons: $\frac{dx}{dt} = v = -\mu_e E = \frac{\mu_e}{\mu_h}\frac{x}{\tau}$

$$x(t) = x_0 \exp\left(\frac{\mu_e}{\mu_h}\frac{t}{\tau}\right)$$

$$Q_e(t) = -\frac{e}{d}(x(t) - x_0) = -\frac{e}{d}x_0\left(\exp\left(\frac{\mu_e}{\mu_h}\frac{t}{\tau}\right) - 1\right) \quad \text{for } t < \tau\frac{\mu_h}{\mu_e}\ln\frac{d}{x_0}$$

holes: $\frac{dx}{dt} = v = \mu_h E = -\frac{x}{\tau}$

$$x(t) = x_0 \exp\left(-\frac{t}{\tau}\right)$$

$$Q_h(t) = \frac{e}{d}(x(t) - x_0) = -\frac{e}{d}x_0\left(1 - \exp\left(-\frac{t}{\tau}\right)\right)$$

Signal development 3

For an electron-hole pair created at x_0

electrons:

$$Q_e(t) = -\frac{e}{d}(x(t)-x_0) = -\frac{e}{d}x_0\left(\exp\left(\frac{\mu_e}{\mu_h}\frac{t}{\tau}\right)-1\right) \quad \text{for } t < \tau\frac{\mu_h}{\mu_e}\ln\frac{d}{x_0}$$

holes:

$$Q_e(t) = \frac{e}{d}(x(t)-x_0) = -\frac{e}{d}x_0\left(1-\exp\left(-\frac{t}{\tau}\right)\right)$$

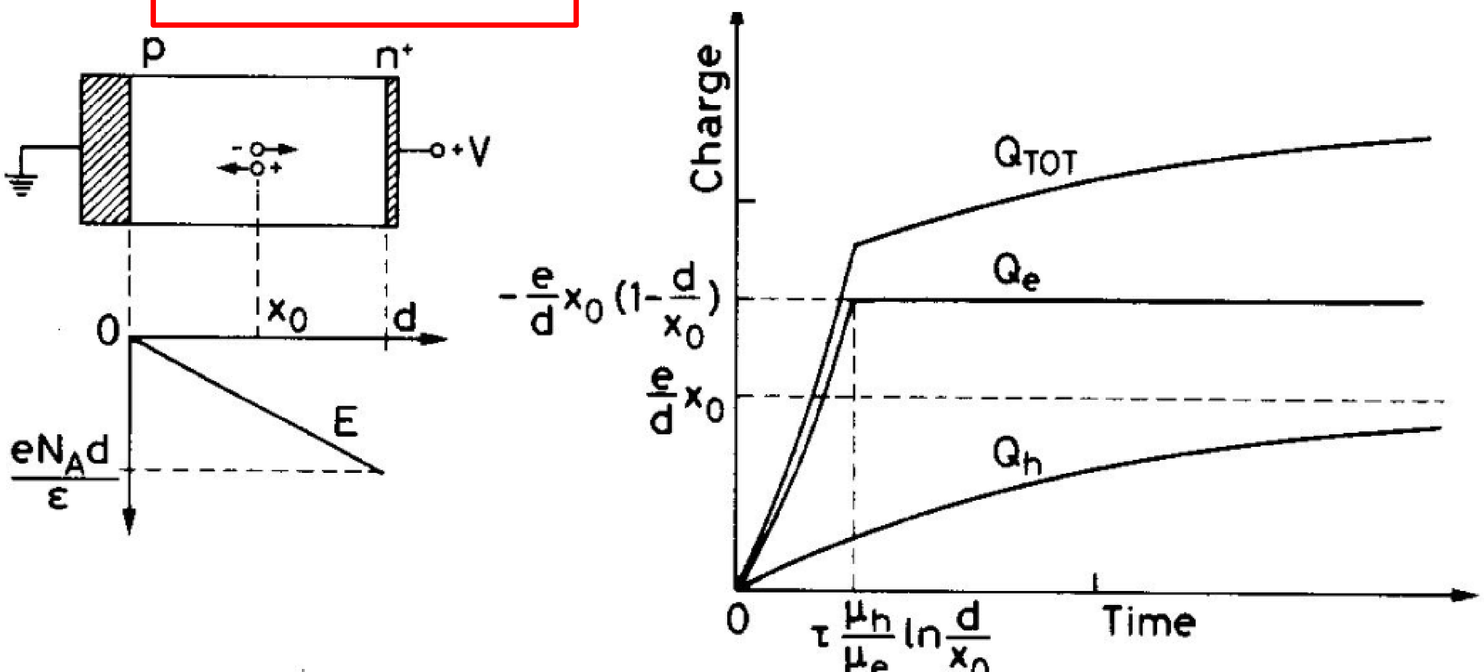


Fig. 10.10. Signal pulse shape due to a single electron-hole pair in an np junction

	dE/dx $[MeV/cm]$	Number of pairs/cm	ε (eV)
Si	3.87	$1.07\ 10^6$	3.61
Ge	7.26	$2.44\ 10^6$	2.98
C	3.95	$0.246\ 10^6$	16
gas	~keV/cm	a few 100	~30
Scint.			~300-1000/ph.e.

Si on average ~100 electron-hole pairs /μm

Radiation damage

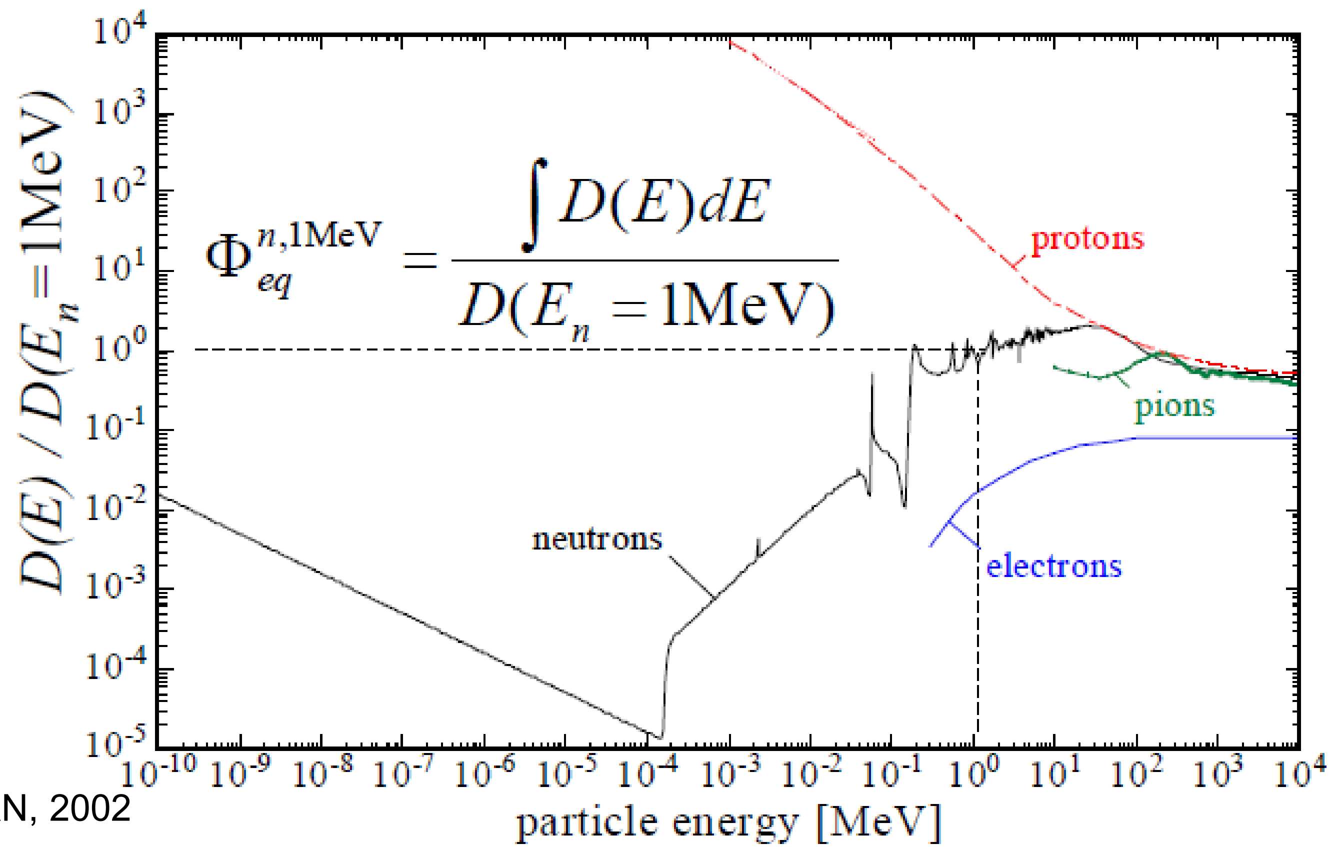
Damage caused by:

- Bulk effect: lattice damage, vacancies and interstitials
- Surface effects: Oxide trap charges, interface traps.

NIEL hypothesis (not fully valid !):

damage $\propto$ energy deposition in displacing collisions

Rel. damage function (normalized to neutrons of 1 MeV)

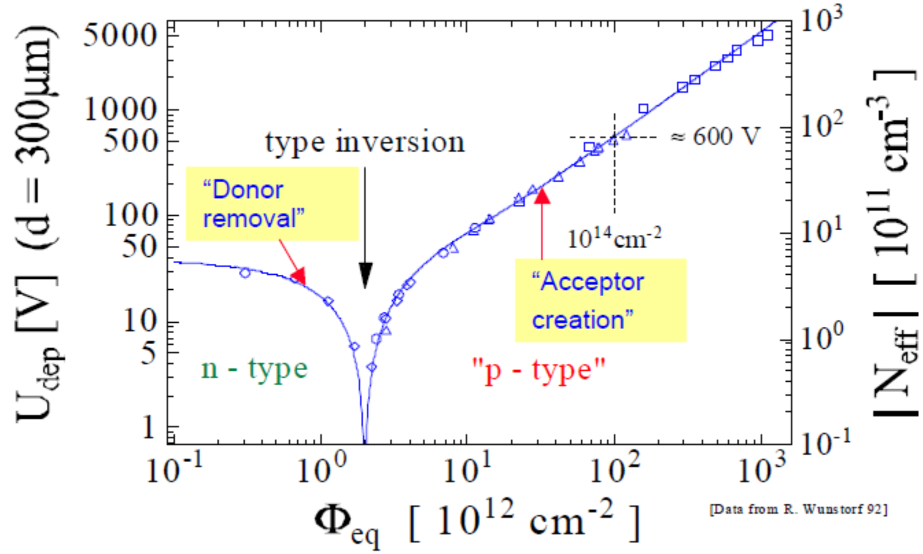


$$\Phi_{eq}^{n,1\mathrm{MeV}} = \frac{\int D(E)\,dE}{D(E_n = 1\mathrm{MeV})}$$

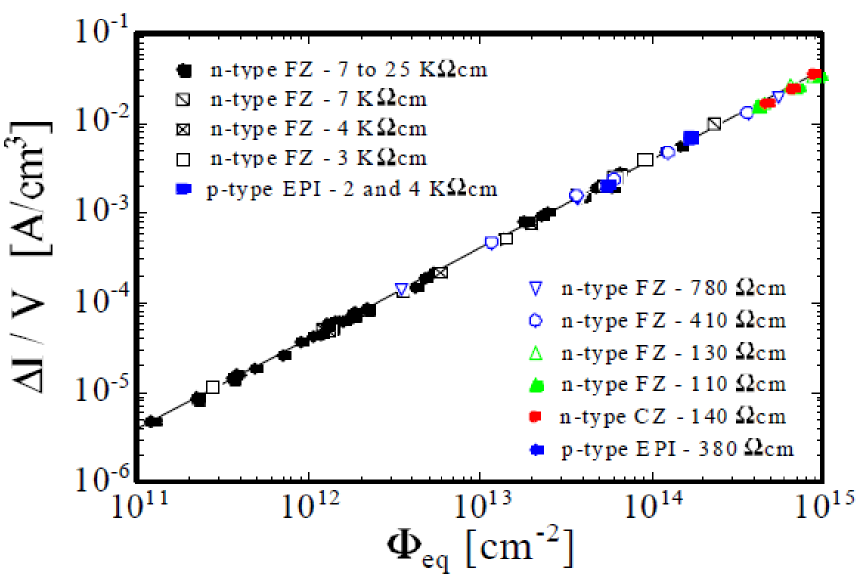
C. Joram, Academic training, CERN, 2002

Main radiation induced macroscopic changes

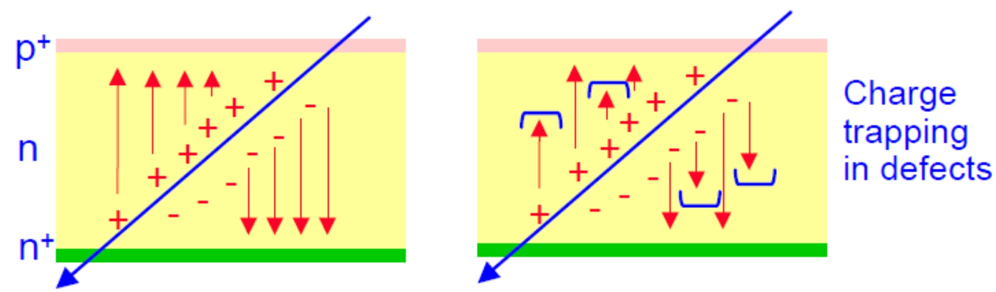
2. Change of depletion voltage. Very problematic.



1. Increase of sensor leakage current



3. Decrease of the charge collection efficiency



How to mitigate these effects?

- Geometry: build sensors such that they stand high depletion voltage (500V)
- Environment: keep sensors at low temperature (< -10ºC) → Slower reverse annealing. Lower leakage current.

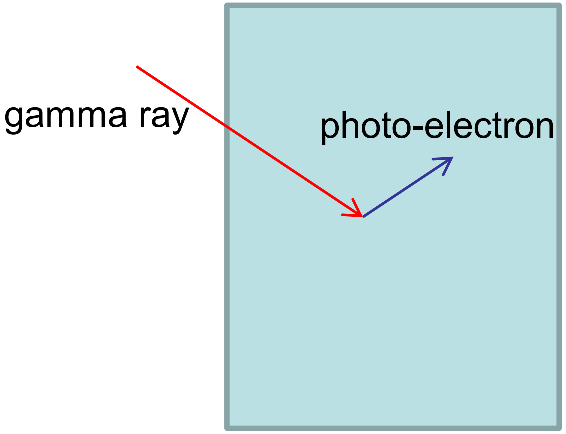
C. Joram, Academic training, CERN, 2002

Absorption of gamma rays

- Photoeffect

$$\sigma_{ph} \propto Z^5 \frac{1}{E_\gamma^{7/2}} \quad (E_K < E_\gamma < m_e c^2)$$

$$\sigma_{ph} \propto Z^5 \frac{1}{E_\gamma} \quad (E_\gamma >> m_e c^2)$$



- Compton scattering

$$\sigma \propto Z$$

- Pair production

$$\sigma \propto Z^2$$

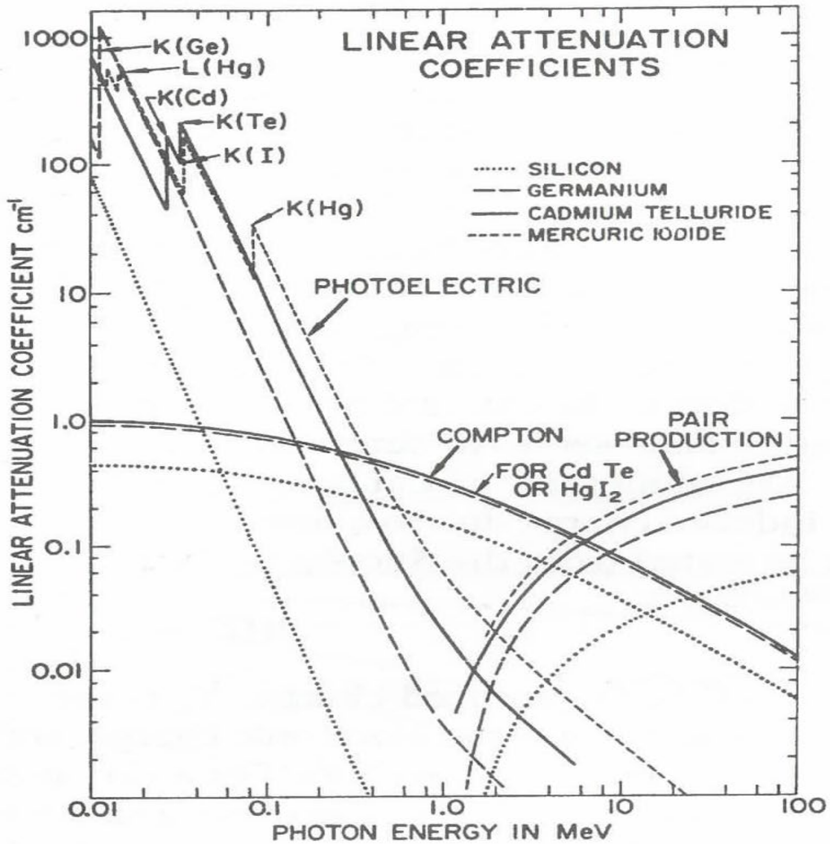


Figure 13.22 Photoelectric, Compton, and pair production linear attenuation coefficients for Si, Ge, CdTe, and HgI_2. *K*-shell absorption edges are shown. (From Malm.[46])

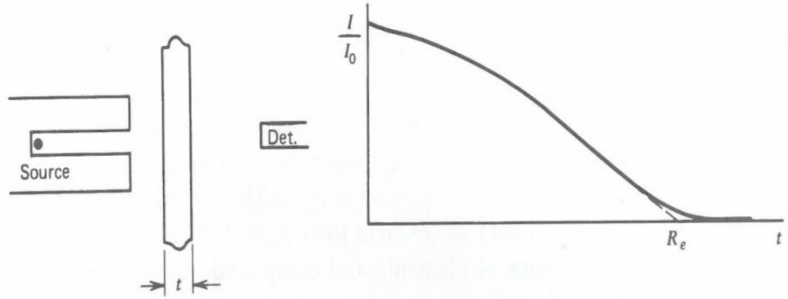
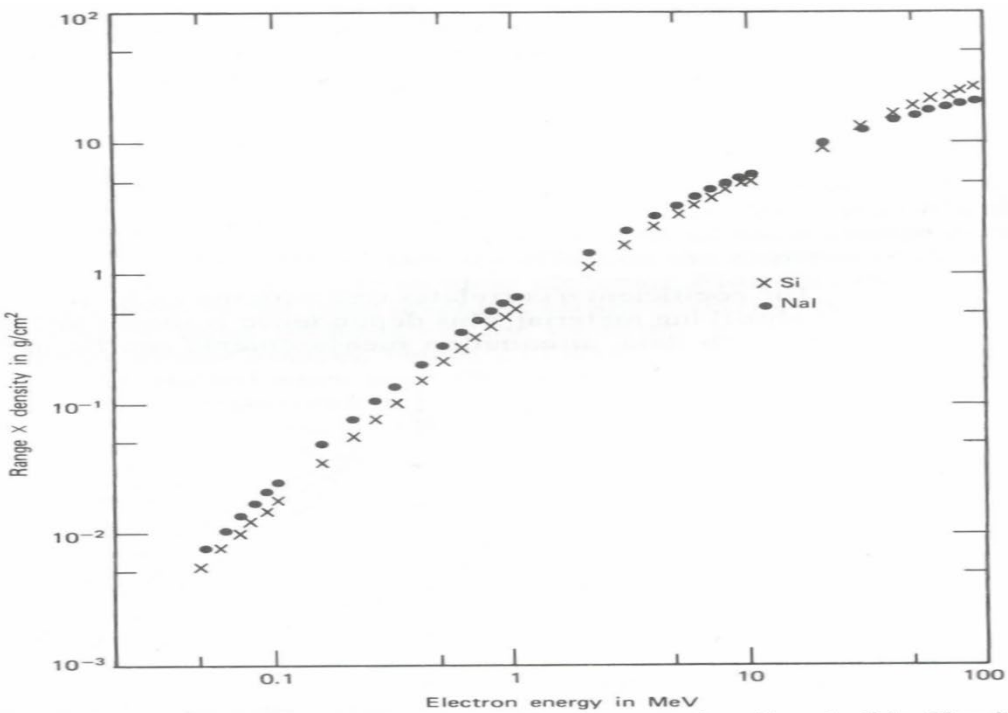


Figure 2.13 Transmission curve for monoenergetic electrons. R_e is the extrapolated range.



~0.4mm

Range in cm: divide by the density of Si, 2.3 g/cm^3

Figure 2.14 Range–energy plots for electrons in silicon and sodium iodide. If units of ma thickness (distance × density) are used for the range as shown, values at the same electro energy are similar even for materials with widely different physical properties or atom number. (Data from Mukoyama.[24])

(b)

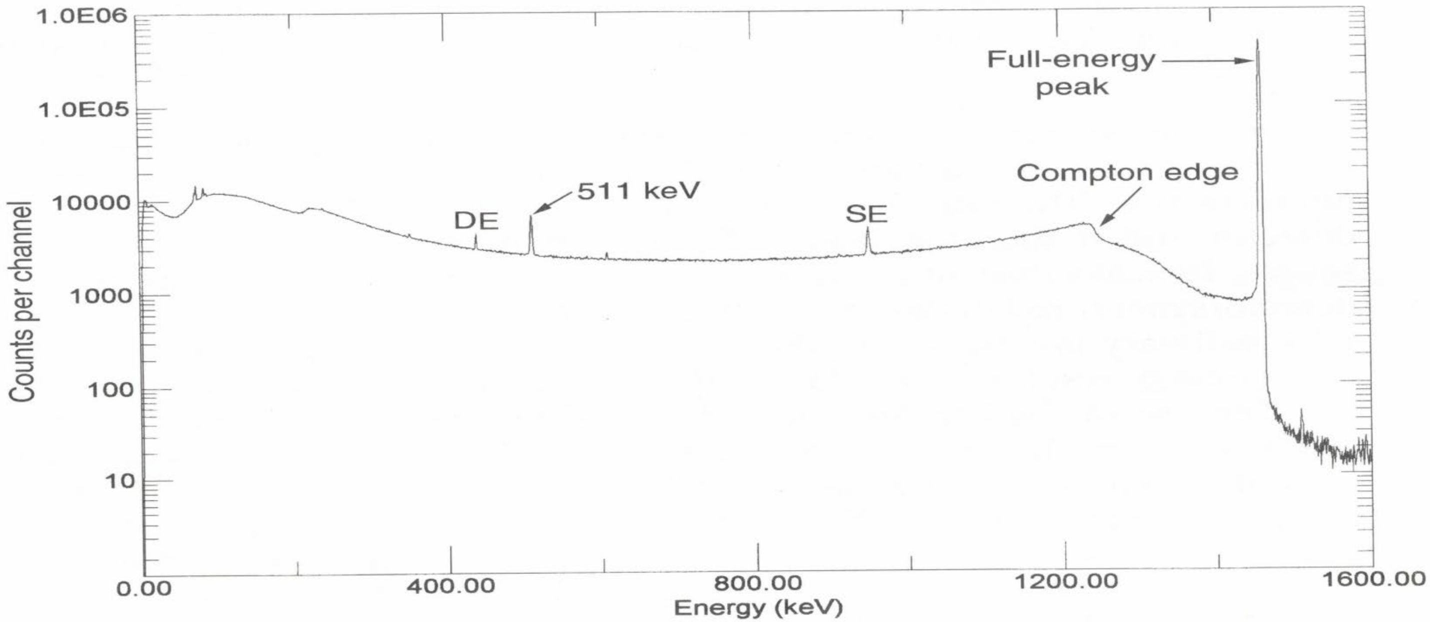


Figure 12.15 Pulse height spectra taken with a *p*-type HPGe detector with 110% relative efficiency, defined on p. 450. (Spectra courtesy R. Keyser, EG&G ORTEC, Oak Ridge, Tennessee.) (*a*) Spectrum recorded from 662 keV gamma rays emitted by a ^{137}Cs source showing the effects of photoelectric absorption and Compton scattering in the detector. In addition to the backscatter peak, Compton continuum, and full energy peak features, a small sum peak is evident from pulse pile-up (see Ch. 17), as well as a small peak from 1460 keV background gamma rays from ^{40}K. (*b*) Spectrum from 1460 keV gamma rays emitted by ^{40}K that now shows the additional effects of pair production taking place in the detector and surrounding materials. Both single escape (SE) and double escape (DE) peaks can be seen, along with the peak at 511 keV due to annihilation radiation produced by pair production interactions in surrounding materials.

Germanium detectors

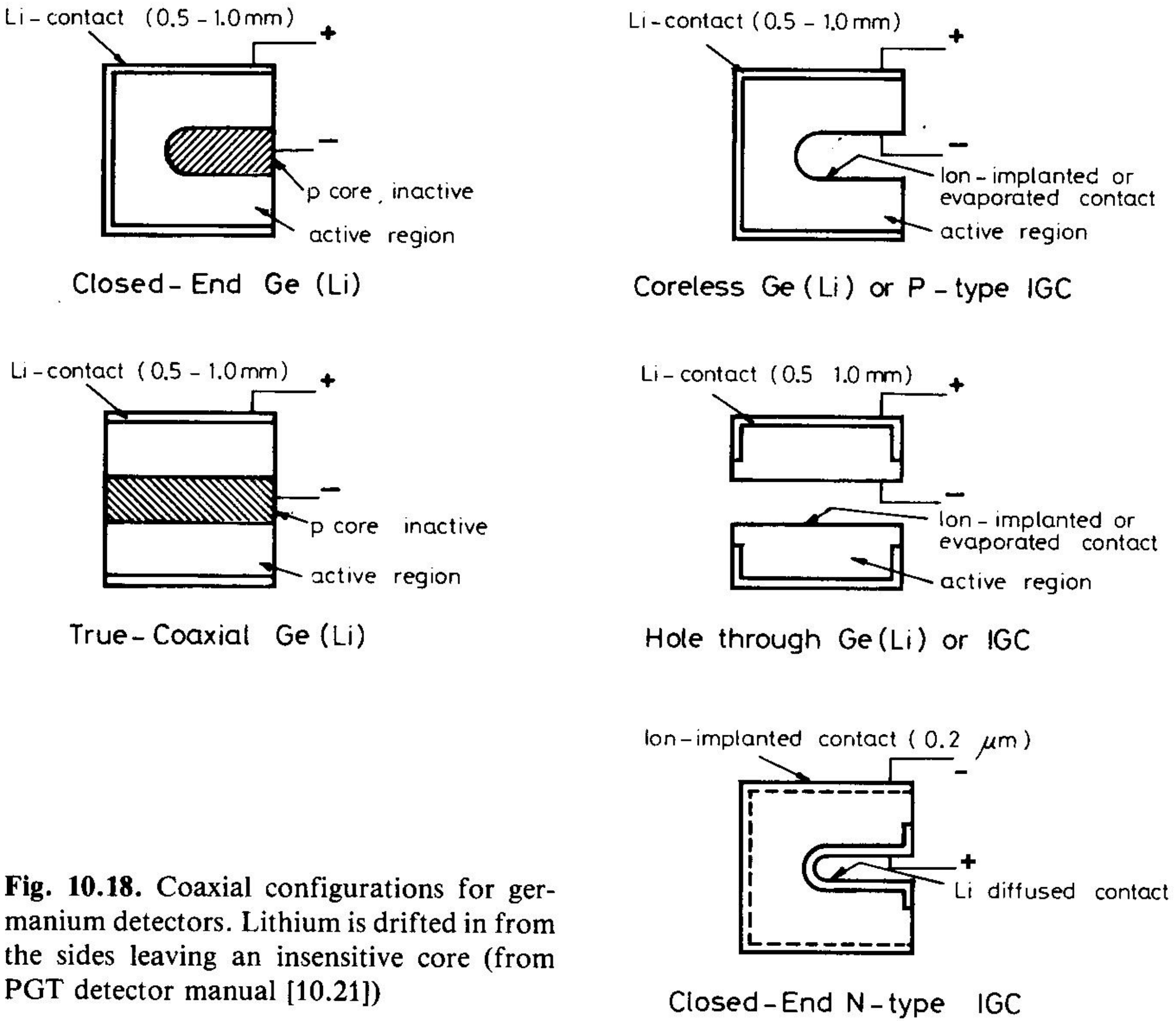


Fig. 10.18. Coaxial configurations for germanium detectors. Lithium is drifted in from the sides leaving an insensitive core (from PGT detector manual [10.21])

Energy resolution of gamma detectors

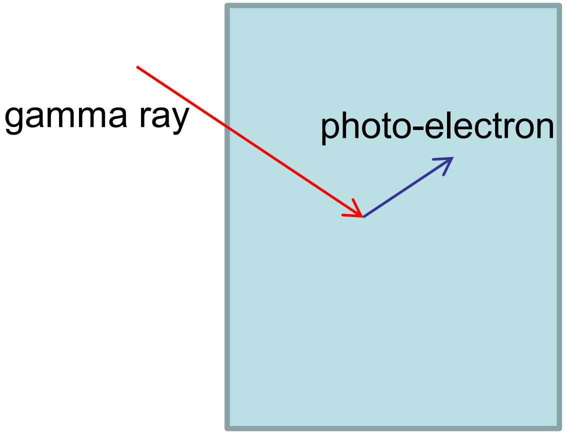
Depends on the statistical fluctuation in the number of generated electron-hole pairs.

If all energy of the particle gets absorbed in the detector – E_0 (e.g. gamma ray gets absorbed via photoeffect, and the photoelectron is stopped):

on average we get

$$\bar{N}_i = \frac{E_0}{\varepsilon_i}$$

generated pairs



$\varepsilon_i \sim$ 3.6eV for Si
~ 2.98 eV for Ge
Average energy needed to create an e-h pair

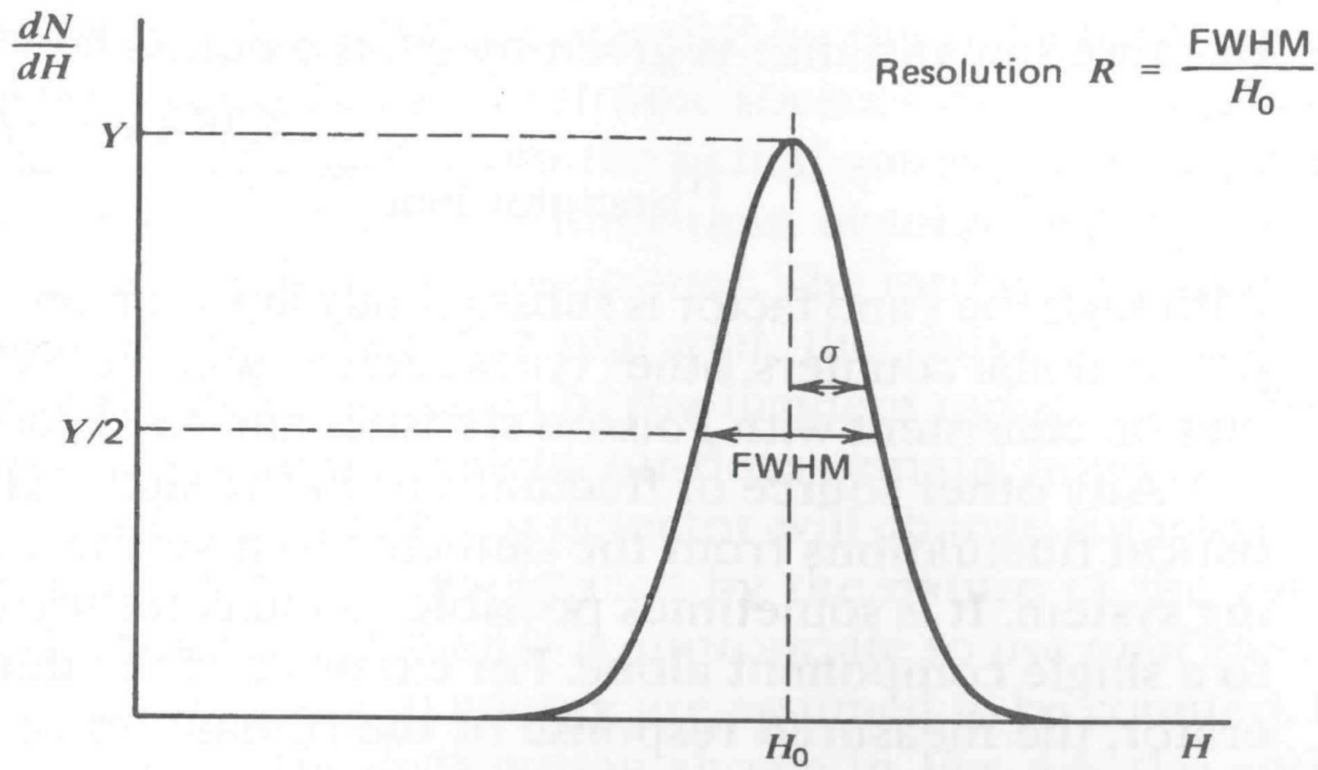


Figure 4.5 Definition of detector resolution. For peaks whose shape is Gaussian with standard deviation σ, the FWHM is given by 2.35σ.

If we have a large number of **independent** events with a small probability (generation of electron-hole pairs) → binominal distribution → Poisson

Standard deviation – r.m.s. (root mean square):

$$\sigma = \sqrt{\bar{N}_i}$$

The measured resolution is actually better than predicted by Poisson statistics

- Reason: the generated pairs e-h are not really independent since there is only a fixed amount of energy available (photoelectron looses all energy).
- Photoelectron looses energy in two ways:

- pair generation (E_i ~ 1.2 eV per pair in Si)
- excitation of the crystal (phonons) E_x ~0.04 eV for Si

$\bar{N}_x$ Average number of crystal excitations

$\bar{N}_i$ Average number of generated pairs

$$\sigma_x = \sqrt{\bar{N}_x} \quad \text{standard deviation}$$

$$\sigma_i = \sqrt{\bar{N}_i}$$

Since the available energy is fixed (monoenergetic photoelectrons):

$$E_i \Delta N_i = -E_x \Delta N_x \Rightarrow E_i \sigma_i = E_x \sigma_x$$

E_i = energy needed to excite an electron to the valence band *(=E_g)*

$$\Rightarrow \sigma_i = \frac{E_x}{E_i}\sqrt{\bar{N}_x}$$

Width of the energy loss distribution

$$E_i \bar{N}_i + E_x \bar{N}_x = E_0 \Rightarrow \bar{N}_x = \frac{E_0 - E_i \bar{N}_i}{E_x}$$

$$\sigma_i = \frac{E_x}{E_i}\sqrt{\frac{E_0 - E_i \bar{N}_i}{E_x}} \qquad \text{make use of } \bar{N}_i = \frac{E_0}{\varepsilon_i}$$

$$\Rightarrow \sigma_i = \sqrt{\bar{N}_i}\sqrt{\frac{E_x}{E_i}\left(\frac{\varepsilon_i}{E_i} - 1\right)} = \sqrt{F \bar{N}_i}$$

F Fano factor – improvement in resolution

F ~ 0.1 for silicon

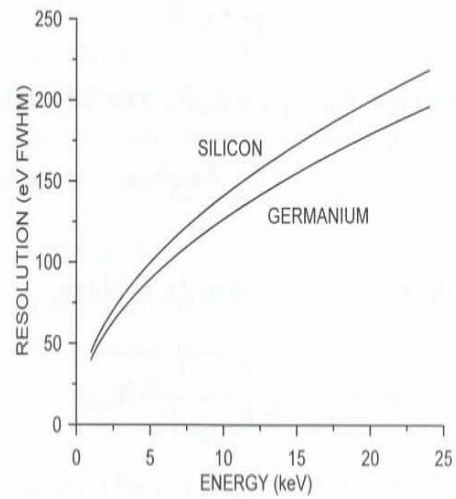


FIG. 2.12. Intrinsic resolution of silicon and germanium detectors *vs.* energy.