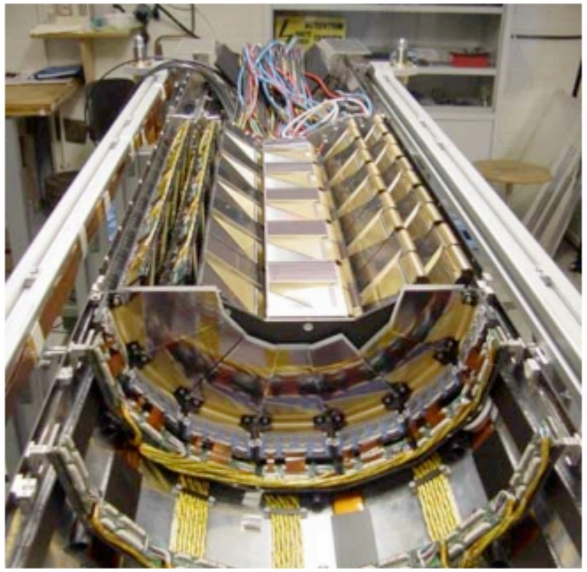
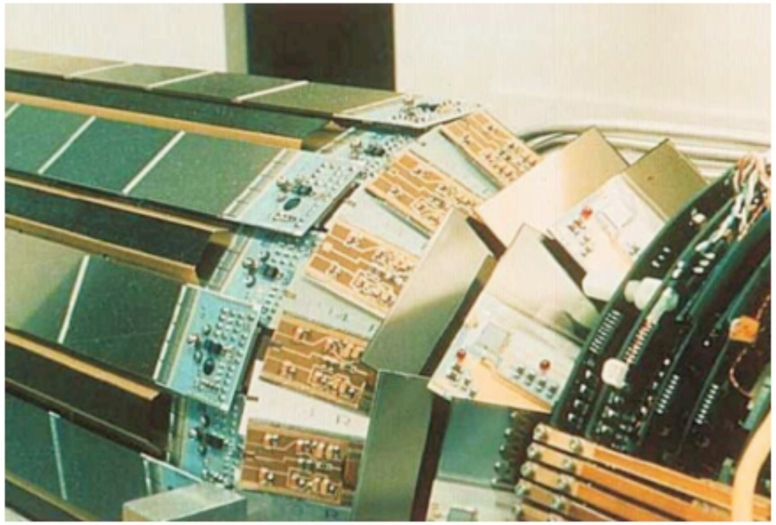
Semiconductor-Detectors

Motivation

- ~ 1950: Discovery that pn-- junctions can be used to detect particles.
- Semiconductor detectors used for energy measurements (Germanium)
- Since ~ 30 years: Semiconductor detectors for precise position measurements.
- precise position measurements possible through fine segmentation (10-- 100µm)
- multiplicities can be kept small (goal:<1%)
- Technological advancements in production technology
- developments for micro electronics



ZEUS MVD 2000

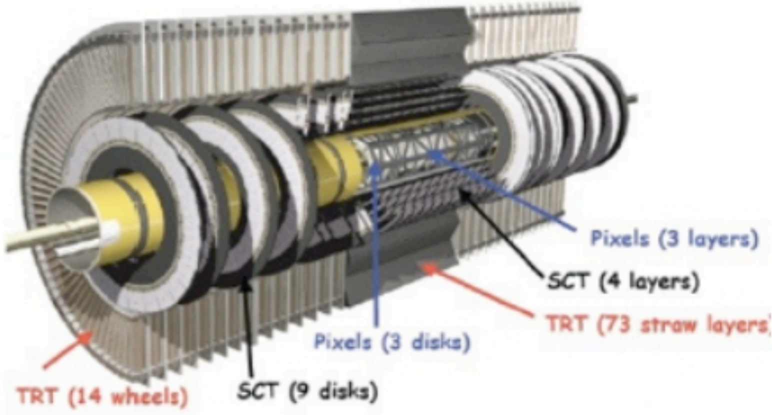


DELPHI VFT 1996

Large Silicon Systems

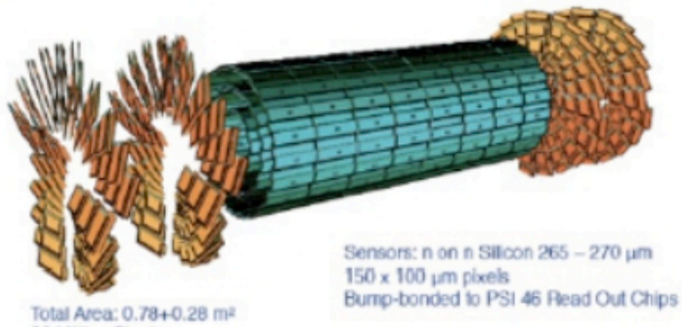
ATLAS
Strips: 61 m^2 of silicon, 4088 modules, $6x10^6$ channels

Pixels: 1744 modules, 80 x 10^6 channels

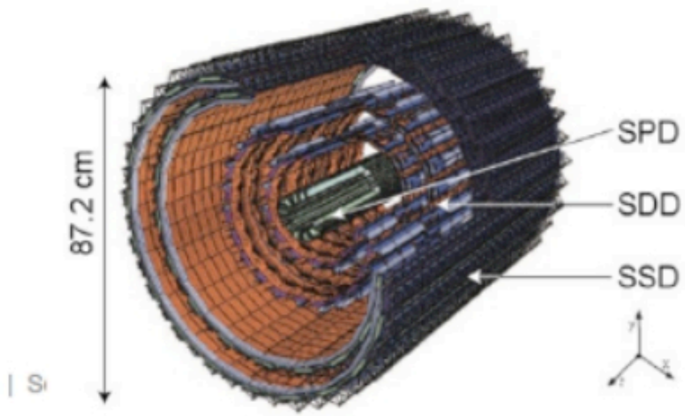


CMS
the world largest silicon tracker
200 m² of strip sensors (single sided)
11 x 10^6 readout channels

~1m² of pixel sensors, $60x10^6$ channels



ALICE
Pixel sensors
Drift detectors
Double sided strip detectors



LHCb
VELO: Si Strips

Pros/Cons of semiconductors as detection material

- Semiconductor detectors have a high density
- Large energy loss over short distance: thin detectors
- Diffusion effect is smaller than in gas detectors resulting in achievable position resolution of less than 10 μm

- Low ionization energy (few eV per e - hole pair) compared to
  gas detectors (20 - 40 eV per e - ion pair) or
  scintillators (400 - 1000 eV to create a photon)

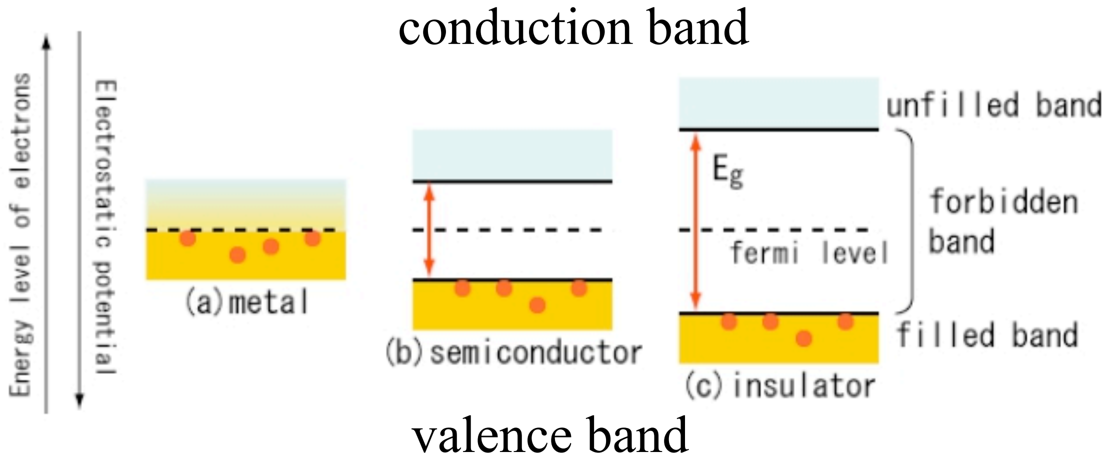
- Typically no internal amplification, i.e. small signal
  with a few exceptions (getting more common)

- High cost per surface unit
  silicon, read out chips, cooling

  High number of readout channels
  Large power consumption ➜ cooling

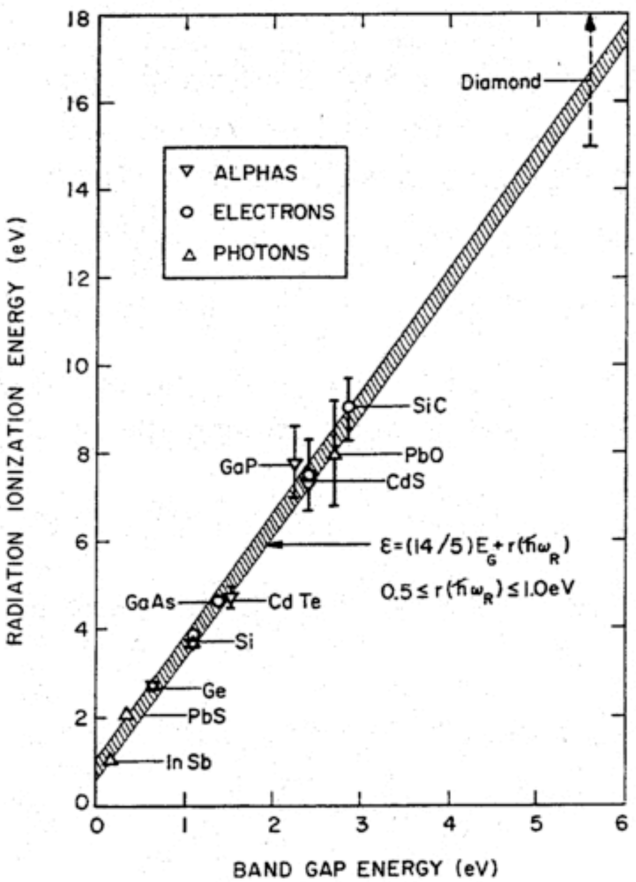
Energy bands

- In free atoms the electron energy levels are discrete.
- In a solid, energy levels split and form nearly - continuous bands



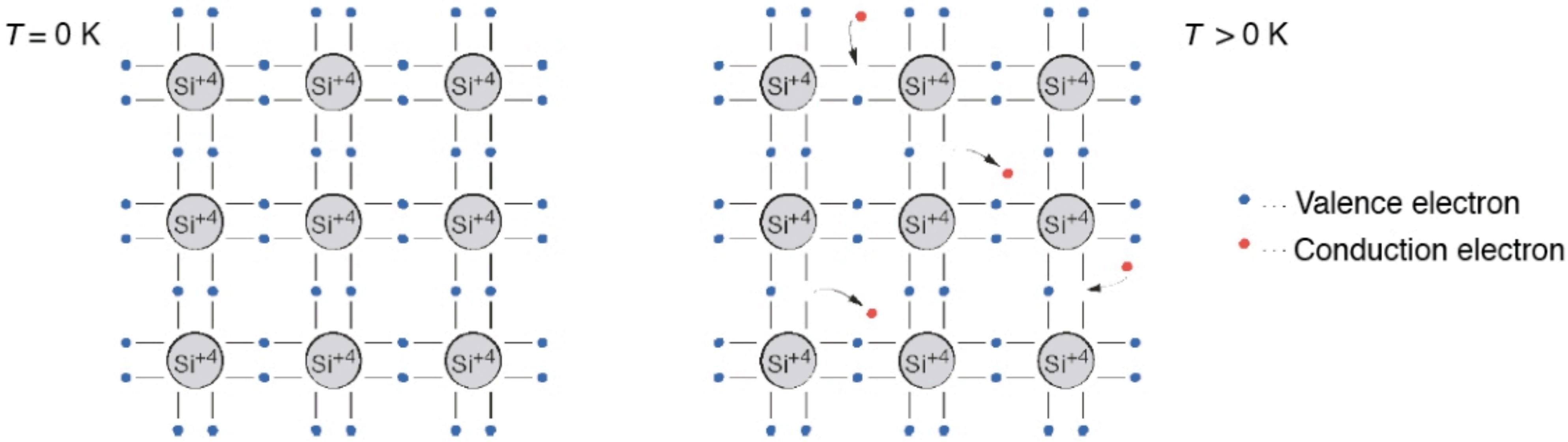
- Large gap: the solid is an insulator
- No gap: it is a conductor
- Small band gap: semiconductor

C.A.Klein,J.AppliedPhysics39(1968)2029



- For silicon, the band gap is 1.12 eV, but it takes 3.6 eV to ionize an atom
  ➔ rest of the energy goes to phonon excitations (heat).

Band Model for Elements IV (Example for Si)



Each atom has 4 closest neighbors, the 4 electrons in the outer shell are shared and form covalent bonds.

- At low temperature all electrons are bound
- At higher temperature, thermal vibrations break some of the bonds
- free e- cause conductivity (electron conduction)
- The remaining open bonds attract other e- ➔ the "holes" change position (hole conduction)

Intrinsic Carrier Concentration

- Due to the small band gap in semiconductors, electrons already occupy the conduction band at room temperature.
- Electrons from the conduction band may recombine with holes.
- A **thermal equilibrium** is reached between **excitation** and **recombination** **:** charge carrier concentration $n_e = n_h = n_i$

intrinsic carrier concentration:

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

factor 2 every $\Delta T = 8^0$ K

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

(Ge: n_i= 2.4 10^{13} cm^{-3} at 300K)

(*) N_C and N_V are the density of states in the valence and conduction band, respectively

Elemental Semiconductors

Germanium: Needs cooling due to small band gap of 0.66 eV (liquid N^2 at 77 K)
mainly used in nuclear physics: Very good energy resolution!

Silicon: Can be operated at room temperature (band gap of 1.12 eV)
Synergies with micro electronics industry
Standard material for detectors in high energy physics

Diamond (CVD * or single crystal): Allotrope of carbon
Large band gap of 5.5 eV (requires no depletion zone)
Very radiation hard
Disadvantages: low signal and high cost

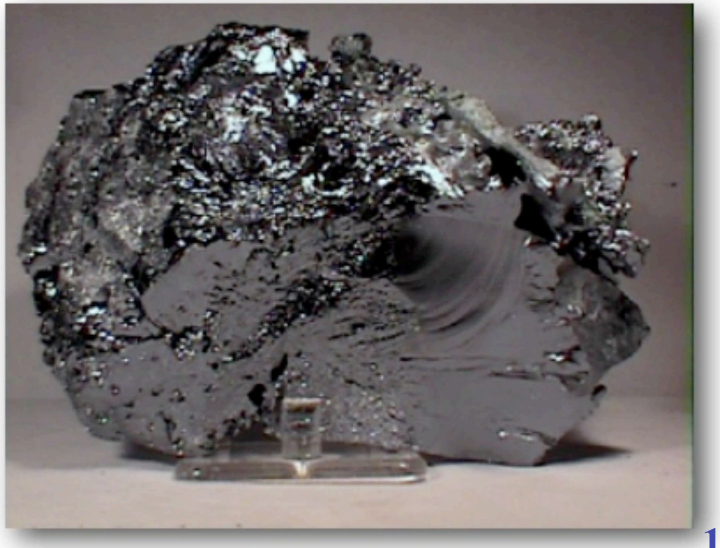
(*) CVD: Chemical Vapor Deposition

Material Properties

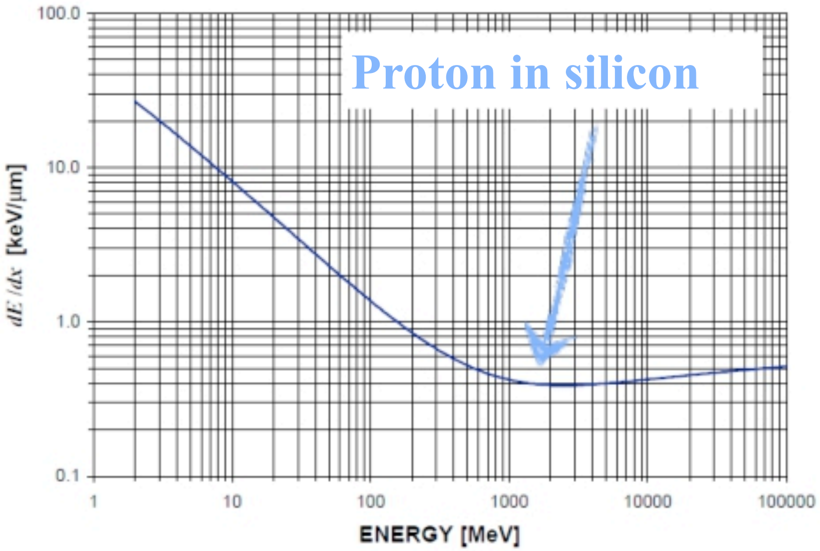
	Si	Ge	GaAs	CdTe	Diamant	SiC
band gap	1.12	0.67	1.42	1.56	5.48	2.99
energy for e - hole pair [eV]	3.6	2.9	4.2	4.7	13.1	6.9
e- for MIP (300µm)	24000	50000	35000	35000	9300	19000
Z	14	32	31+33	48+52	6	14+6

Why is silicon used more often ?

- Silicon is the only material which can be produced in larger areas in high quality
- compare band gap to $kT = 0.026$ eV at room temperature ➔ dark current under control
- high density compared to gases: $\rho=2.33 g/cm^{-3}$
- good mechanical stability
- large charge carrier mobility
- fast charge collection $\delta t \sim 10 ns$
- radiation tolerant

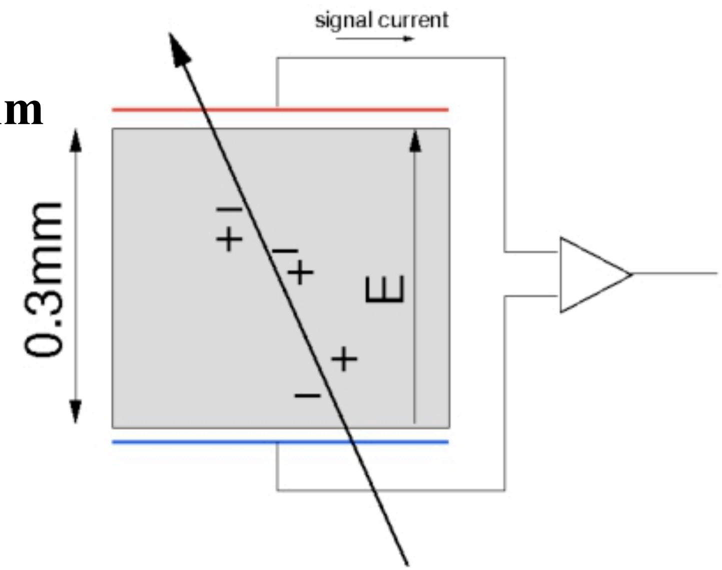


Constructing a Detector



Si detector:

Thickness: 0.3 mm
Area: 1 cm²



· mean ionization energy ***I₀*** **= 3.62 eV**,

· mean energy loss per flight path of a mip ***dE/dx*** **= 3.87 MeV/cm**

Signal of a mip in detector:

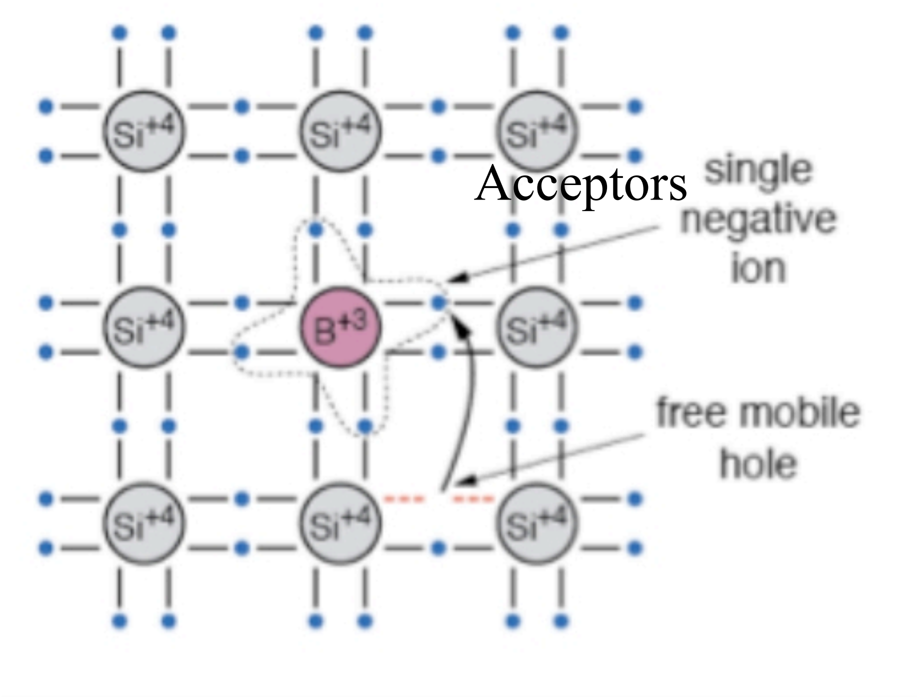
$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6\,\mathrm{eV/cm} \cdot 0.03\,\mathrm{cm}}{3.62\,\mathrm{eV}} \approx 3.2 \cdot 10^4\ e^- h^+ - \text{pairs}$$

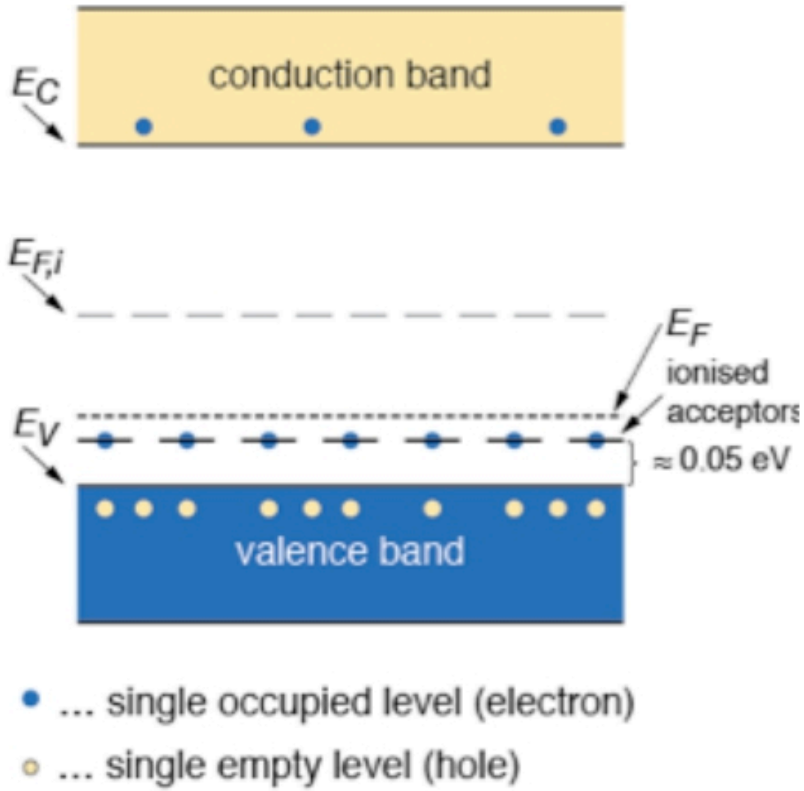
Intrinsic charge carrier in a volume of same thickness and A=1cm² (*T* = 300 K):

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

Result: The number of thermally created e– h+ --pairs (noise) is four orders of magnitude larger than the signal

Doping Silicon



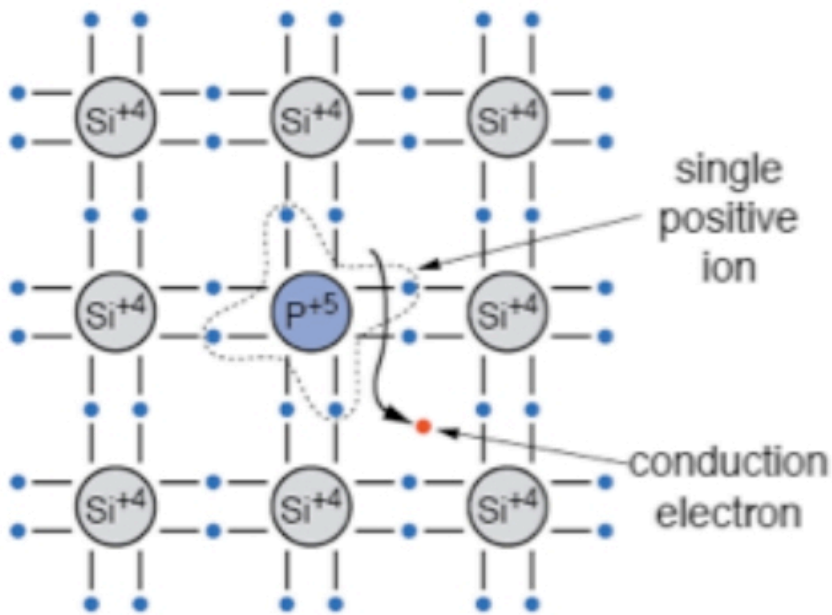


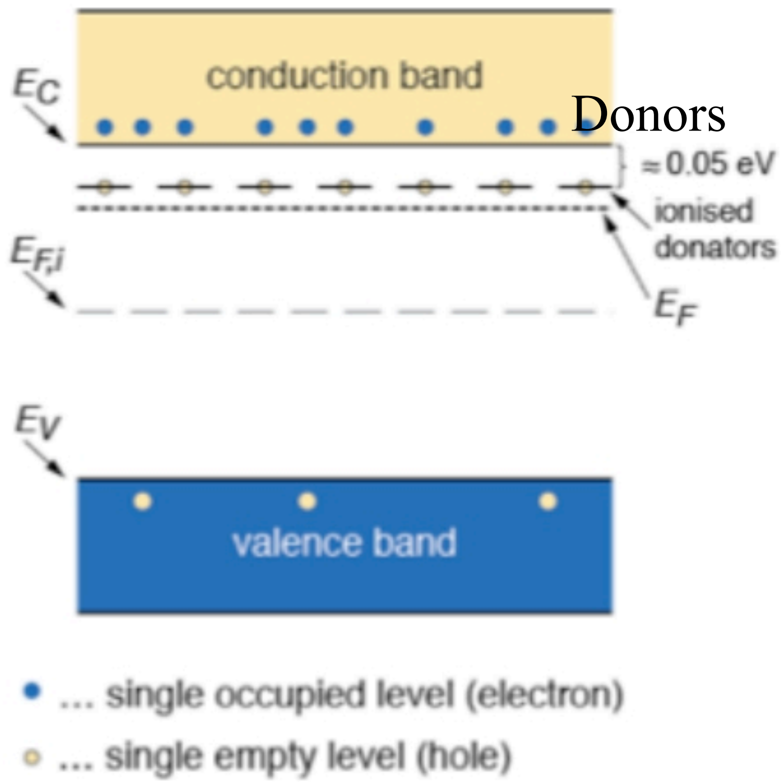
p--type:

- In a p --type semiconductor, positive charge carriers (holes) are obtained by adding impurities of acceptor ions (eg . Boron (type III)).
- Acceptors introduce energy levels close to valence band thus 'absorb' electrons from VB, creating holes (E_F closest to VB)

Holes are the majority carriers.

Doping Silicon





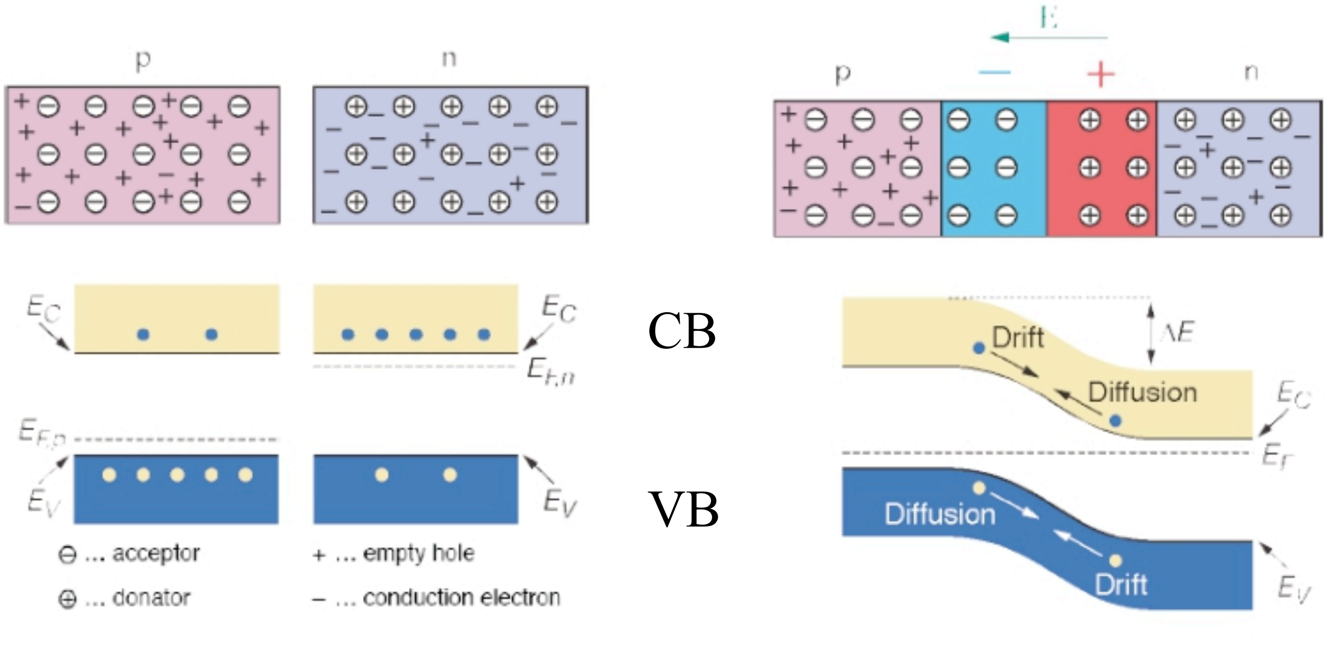
n--type:

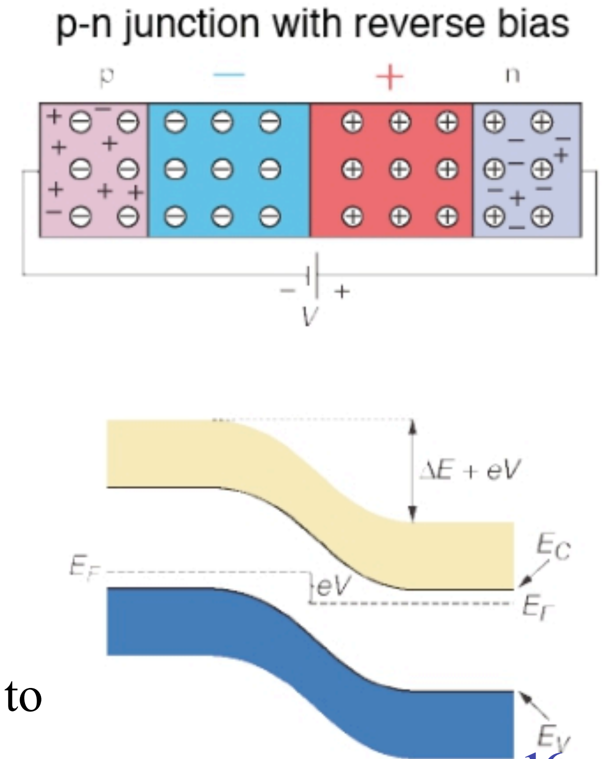
- ➜ In an n --type semiconductor, negative charge carriers (electrons) are obtained by adding impurities of donor ions (eg . Phosphorus (type V))
- ➜ Donors introduce energy levels close to conduction band thus almost fully ionized (E_F closest to CB)

Electrons are the majority carriers.

pn Junction

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





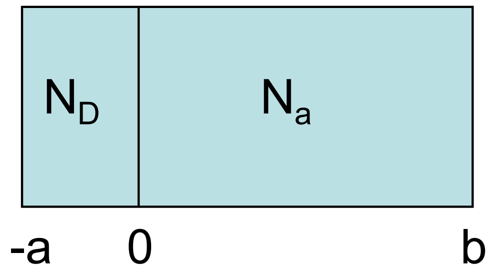
Applying an external voltage V with the cathode to p and the anode to n (reverse biasing), e-h pairs are pulled out of the depletion zone.

➔larger depletion zone ➔ suppress current across the junction

Depth of the Depletion Layer I

Poisson-Equation for the potential U(x) (1-dimensional for simplicity):

$$\frac{d^2U(x)}{dx^2} = \frac{-\rho(x)}{\varepsilon\varepsilon_0}$$



with $E_x = -dU/dx \rightarrow \frac{dEx(x)}{dx} = \frac{\rho(x)}{\varepsilon\varepsilon_0}$

$$\rho(x) = \begin{cases} eN_D & für\ -a < x \le 0 \\ -eN_A & für\ 0 < x \le b \end{cases}$$

Asymmetric double layer with N_D, N_A density of donor- and acceptor impurities.

Assumption: $N_D >> N_A$ and a<b
Boundary conditions for electric field:

$$E_x(-a) = 0 = E_x(b)$$

1. Integration of Poisson equation with above boundary conditions

$$\Rightarrow dU/dx = \begin{cases} -\frac{eN_D}{\varepsilon\varepsilon_0}(x+a) & für\ -a < x \le 0 \\ +\frac{eN_A}{\varepsilon\varepsilon_0}(x-b) & für\ 0 < x \le b \end{cases}$$

Depth of the Depletion Layer II

Boundary condition for the potential:

$$U(-a) = 0 \quad und \quad U(b) = -U_0$$ ←applied voltage

2. Integration:

$$U(x) = \begin{cases} -\dfrac{eN_D}{2\varepsilon\varepsilon_0}(x+a)^2 & für\ -a < x \leq 0 \\ +\dfrac{eN_A}{2\varepsilon\varepsilon_0}(x-b)^2 - U_0 & für\ 0 < x \leq b \end{cases}$$

Use $N_D a = N_A b$ and continuity at x=0:

$$b(a+b) = \frac{2\varepsilon\varepsilon_0 U_0}{eN_A}$$

For the strongly asymmetric case ($N_D >> N_A$) b>>a (b: thickness of p-doped layer)

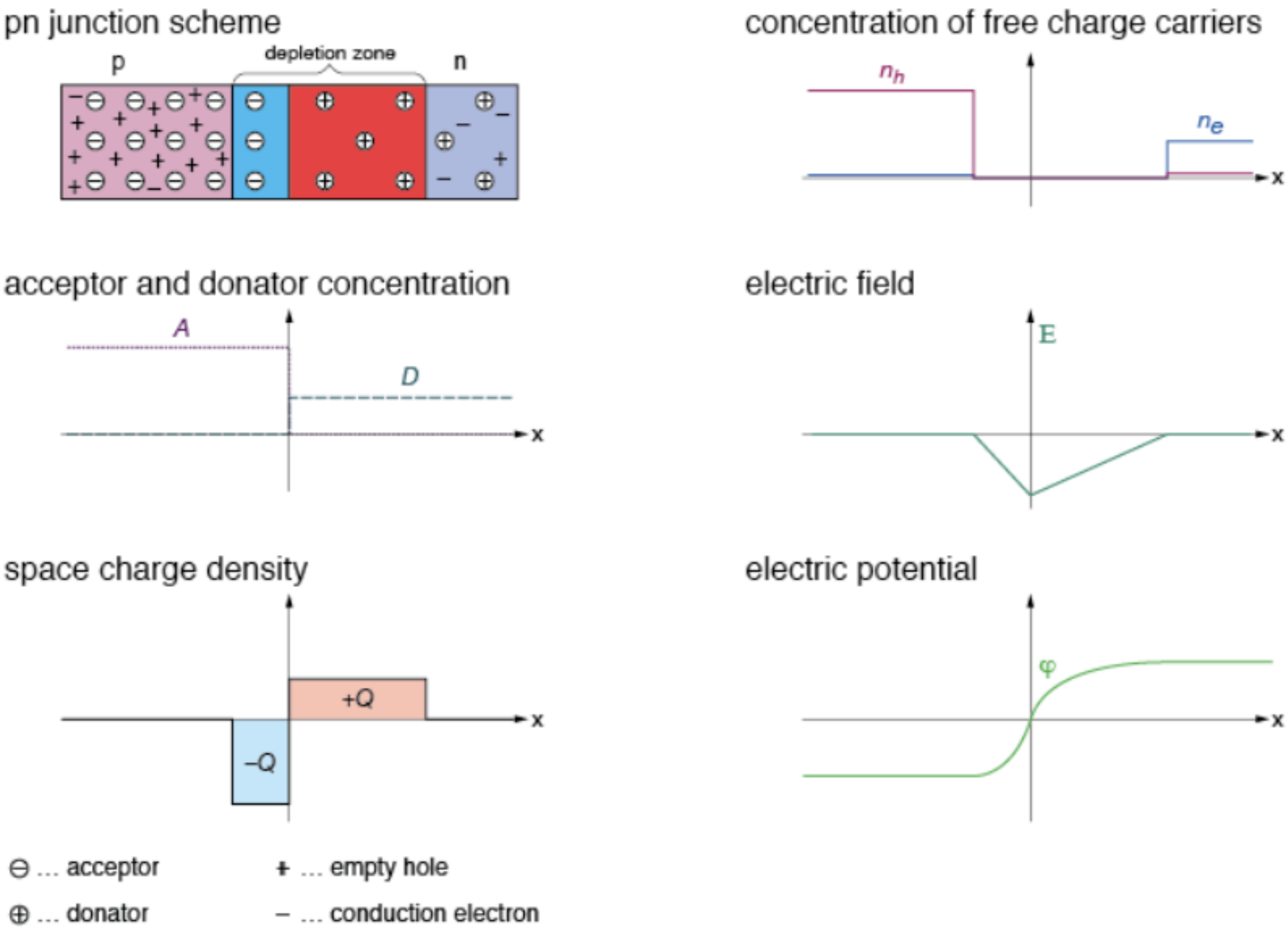
→d=a+b~b →

$$d = \sqrt{\frac{2\varepsilon\varepsilon_0 U_0}{eN_A}}$$

The pn-Junction: Electric Field

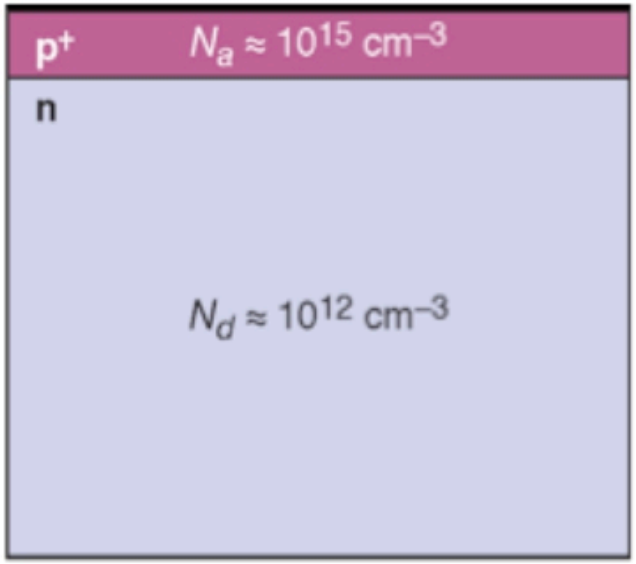
The highest field strength is then at x=0:

$$E_x(0) = \sqrt{\frac{2eN_A U_0}{\varepsilon_0 \varepsilon}} = \frac{2U_0}{d}$$



Width of the depletion zone: Example

- Effective doping concentration in typical silicon detector with p+-n junction
  - $N_a = 10^{15}$ cm^{-3} in p+ region
  - $N_d = 10^{12}$ 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:**

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

with

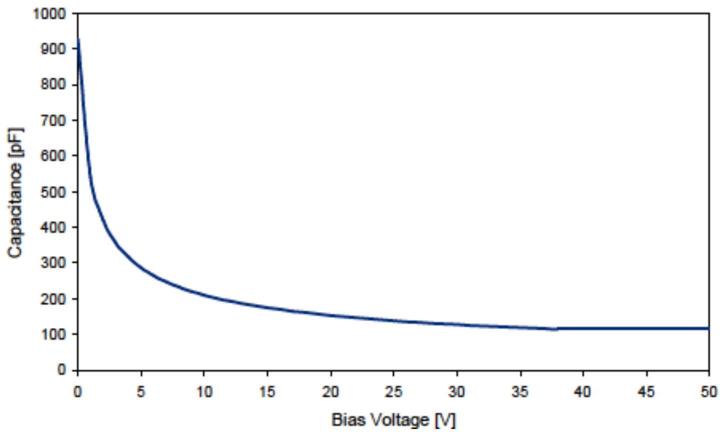
$$\rho = \frac{1}{e \mu N_{eff}}$$

V ... External voltage
ρ ... specific resistivity
µ ... mobility of majority charge carriers
N_{eff} ... effective doping concentration

Derived by solving Poisson equation, $N_a >> N_d$

Full Depletion Voltage and Doping Concentration

The capacitance vs. voltage characteristic of a diode can be used to determine the doping concentration of the detector material

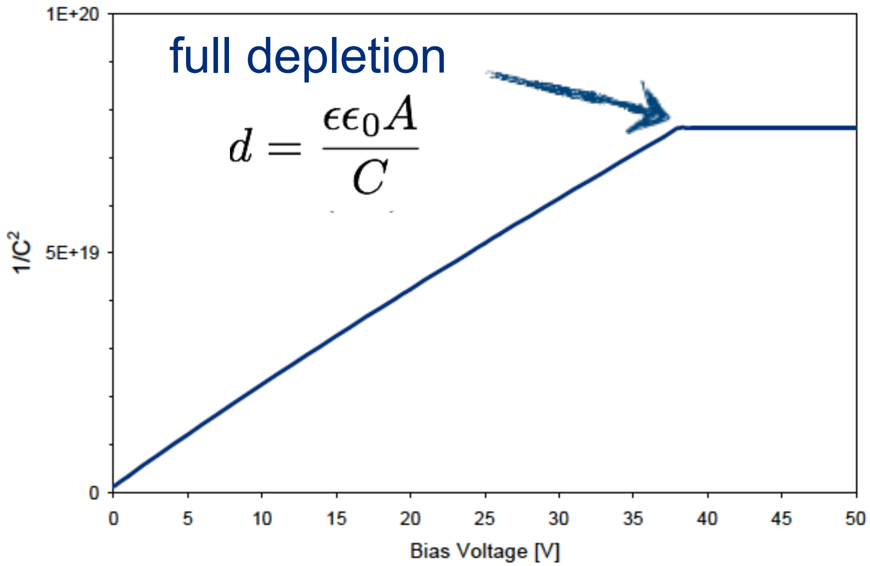


$$C = A\sqrt{\frac{\epsilon q_e N}{2(V_b + V_{bi})}}$$

A = area
N = dopant concentration
V_b = bias voltage
V_{bi} = built-in voltage

from this measurement the dopant concentration as a function of the diode depth is determined

$$N(x) = \frac{2}{\varepsilon\varepsilon_0 q_e A^2}\left(\frac{d\left(1/C^2\right)}{dV}\right)^{-1}$$



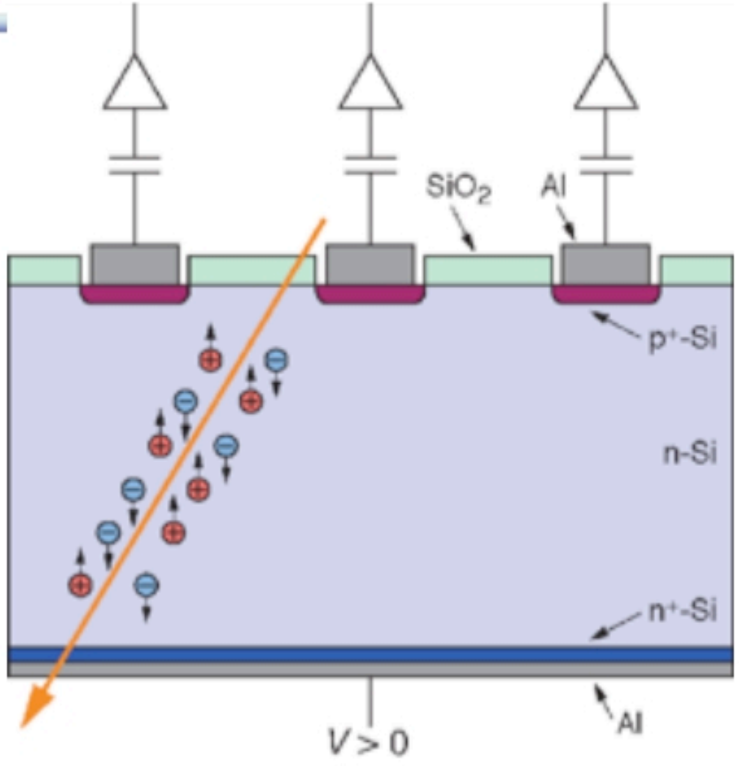
$$d = \frac{\epsilon\epsilon_0 A}{C}$$

the dopant concentration defines the electric field in the diode

$$E(x) = \frac{q_0}{\epsilon \cdot \varepsilon_0} \cdot \int N(x) \cdot dx$$

Position Resolution -- Strip Detector

- Charge carrier drift to electrodes and induce signal
- By segmenting the implant we can reconstruct the position of the traversing particle in one dimension



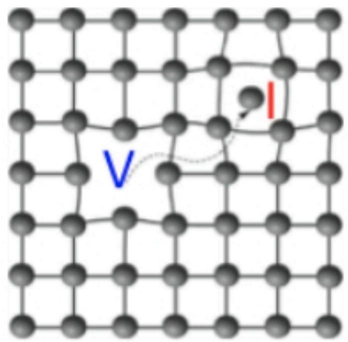
Example : p+ --in--n strip sensor:

- Strips are (f.e.) Boron implants (p-- type)
- Substrate is Phosphorous doped (~2-- 10 kΩcm) and ~300μm thick, V_{dep}< 200V
- Backside Phosphorous implant to establish ohmic contact and to prevent early breakdown
- Highest field close to the collecting electrodes where most of the signal is induced
- Deposition of SiO2 with a thickness of 100–200 nm between p+ and aluminum strip
- AC coupling blocks leakage current from the amplifier

Problem: Radiation Damage

- Radiation damage the silicon on atomic level significantly leading to macroscopic effect.

- **Bulk effects:** displacement damage and built up of crystal defects due to Non Ionizing Energy Loss (NIEL) **(main problem for sensors).**
  unit : 1MeV equivalent neutron/cm^2 (up to 10^{15} n_{eq}/cm^2)

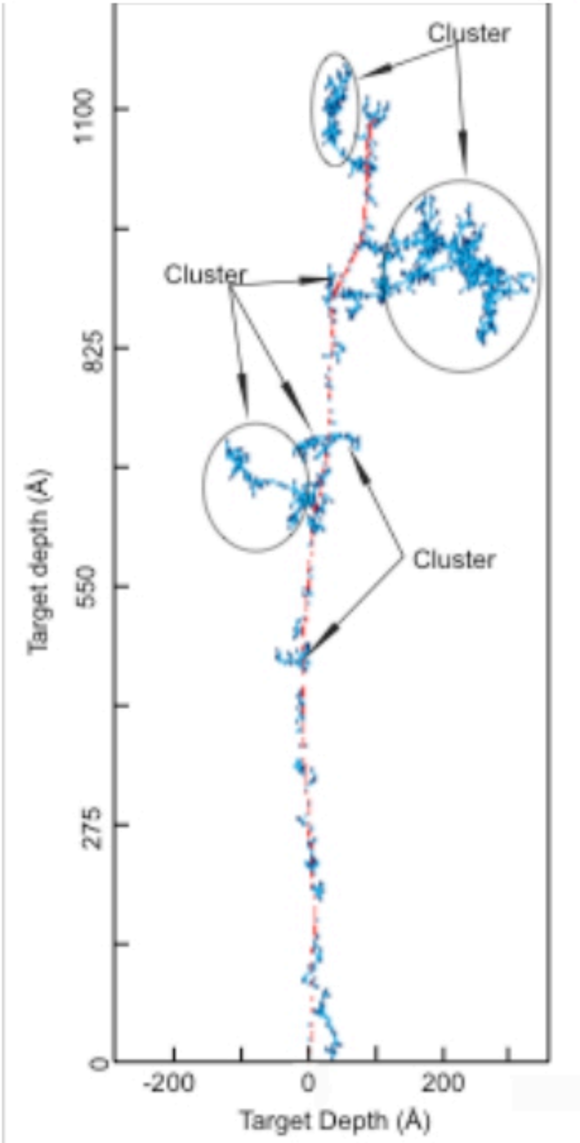


Defects composed of:
Vacancies and **I**nterstitials

Compound defects with impurities possible!

- **Surface effects:** Generation of charge traps due to ionizing energy loss (Total ionizing dose, TID) **(main problem for electronics).**
  unit : Rad (up to 100 MRad)

very complex topic ….



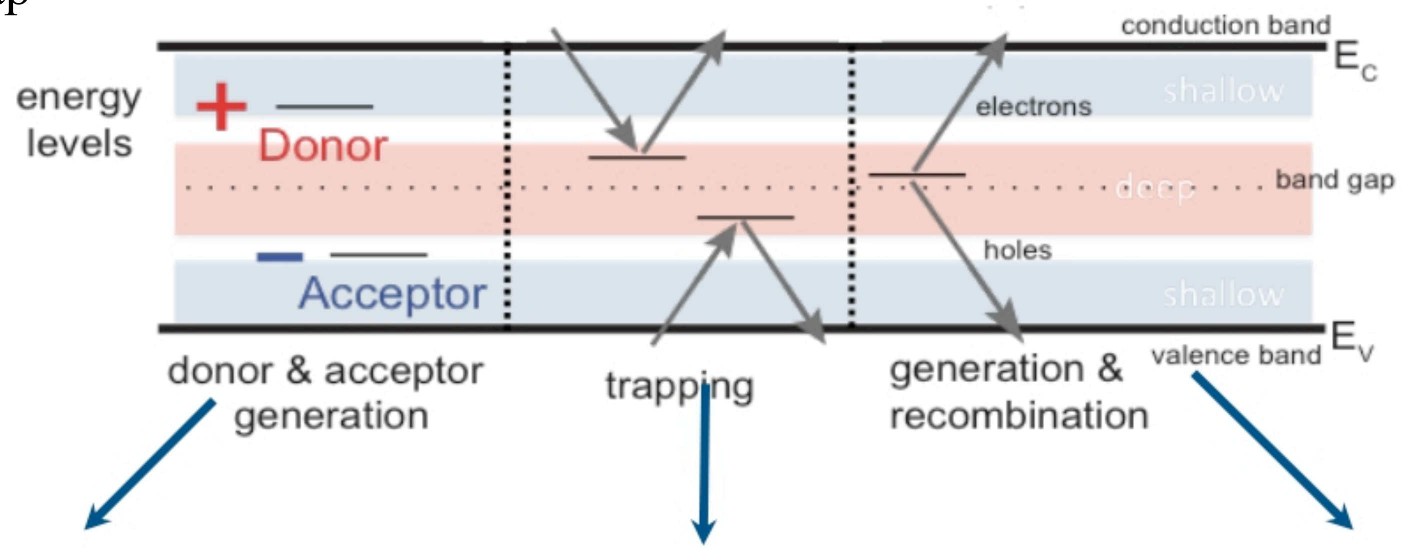
A.Junkes,PhDthesis,UniHamburg2011

Simulation of 50 keV PKA damage cascade (1

n)

Radiation Damage: Bulk Defects

- Impact of defects on detector properties depends on defect level in band gap



Change of effective doping concentration (N_{eff})

Increase of depletion voltage
or Underdepleted operation

Increased charge trapping

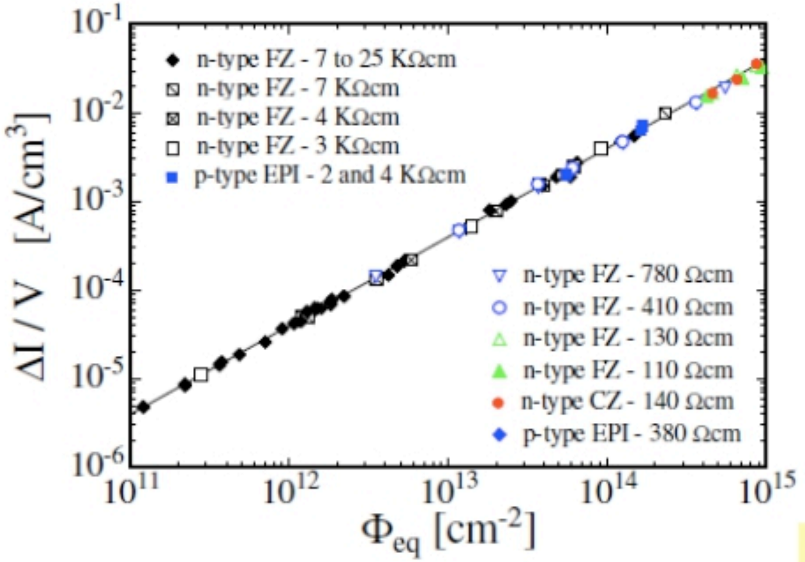
Loss of signal (reduced charge collection efficiency)

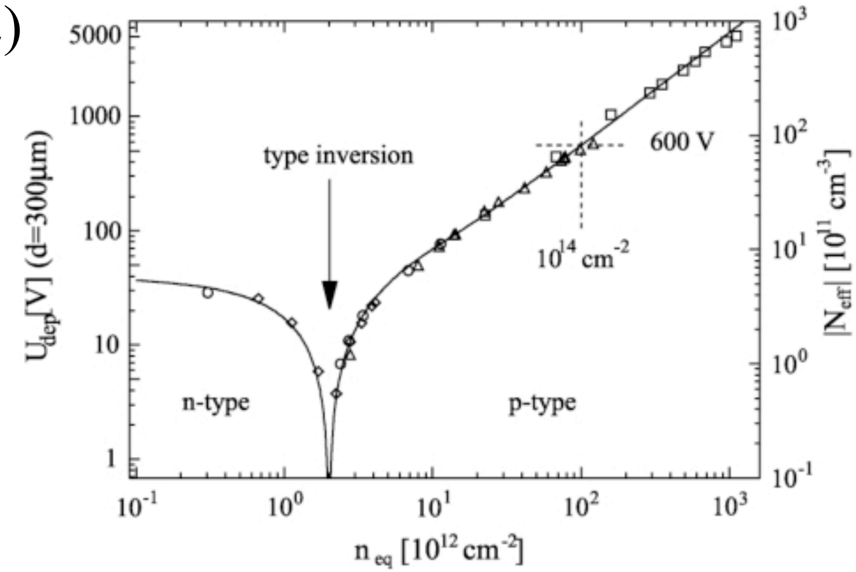
Increase of leakage current
higher shot noise
thermal runaway

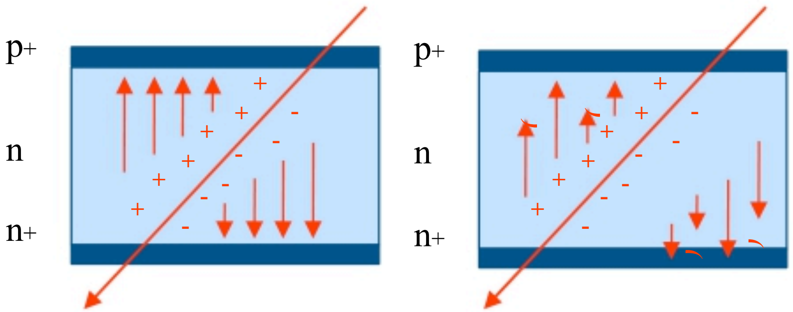
→ Cooling during operation helps!

Consequences of Radiation Damage

1) direct excitation now possible ➪ higher leakage current ➪ more noise
2) can also contribute to space charge ➪ higher V_{bias} necessary for full depletion
3) "charge trapping", causing lower charge collection efficiency ➪ lower signal

1) 

2) 

3) 

Charge trapping in defects

Counter measures

- Geometrical: develop sensors that can withstand higher depletion voltages
- Thinner sensors (but FE electronics with higher sensitivity needed)
- Environment: sensor cooling (-10 .. -20⁰ C)
- Oxigen-- rich Si can help: depletion voltage