SEMICONDUCTOR DETECTORS

- Semiconductor detectors are essentially ionization detectors with solid medium.

- Charged particles or photons produce electron-hole pairs in the semiconducting material; an electric field applied across allows the charges to be collected.

For Si, $W(e^-, \text{hole}) = 3.6\ eV$
For Ge, $\longrightarrow 2.8\ eV$
} About 30 eV in gases.

$\therefore$ Lot more primary ionization!

- Because of their high density (2.33 gm/cc for Si),

ΔE for MIPs $\sim 390\ eV/\mu m$ or
$\simeq 108\ e\text{-}h/\mu m$

That is $3.8\ MeV/cm$ while for Ar $\Delta E \sim .0025\ MeV/cm$

$\therefore > 10^6/cm$ charge-carriers in Si ; $\sim 100/cm$ in Ar

No charge multiplication mechanism (not necessary!)
Typical thickness $\sim 300\ \mu m \rightarrow 3.2 \times 10^4\ e\text{-}h$

- So thin detectors possible & the rigidity allows self-supporting structures.

- High mobility
  $\mu_e = 1450\ cm^2/Vs$; $\mu_h = 450\ cm^2/Vs$.
- Because of the low W-value, solid-state detectors provide excellent energy resolution.
  ← Large statistics of produced charges
- Small range of δ-electrons ⟹ good position measurement
- Small dimensions → fast charge collection (< 10ns)
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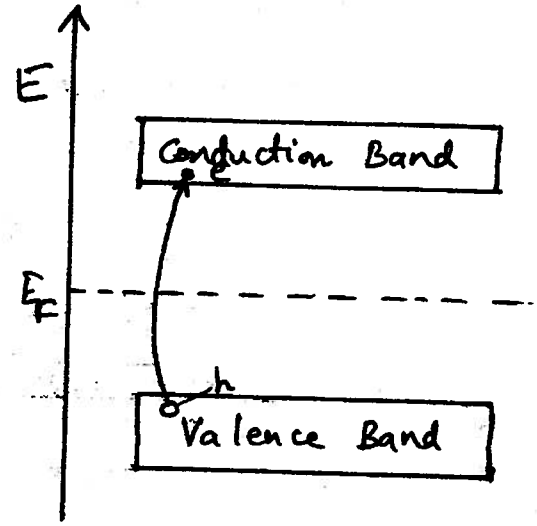
Basic Semi Conductor Physics



$E_F = \frac{E_c + E_v}{2}$
for intrinsic semiconductor

For single atoms in semi-conductors only discrete energy levels are available for electrons.

But, when they condense in crystalline form and a solid body, the discrete energy levels merge to form conduction and valence bands, with an energy gap between them.

Si : Band gap $\simeq$ 1.1 eV
Ge : Band gap = 0.67 eV
} at RT

(Ge detectors are cooled to reduce thermal noise)

→ Pure Silicon is an "intrinsic" semiconductor.

At $T = 0°K$, the valence band is completely full
The conduction band is completely empty

No conduction. → Perfect Insulator

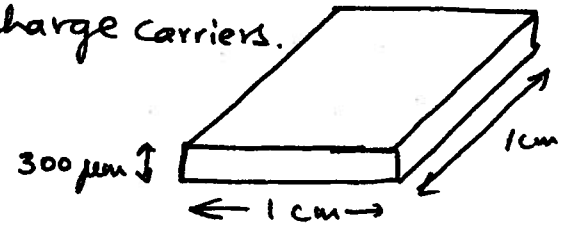
At elevated temperatures, thermal excitation of electrons from VB to CB.

Charge carrier density at RT $\simeq 1.45 \times 10^{10}$ /cc
# of Si atoms $\simeq 5 \times 10^{22}$ /cc

$n_i = 1.45 \times 10^{10}/cc$

So, in a strip 300 μm thick

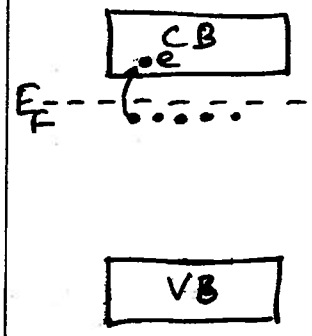
$n_i = 4.5 \times 10^{8}$ free charge carriers.

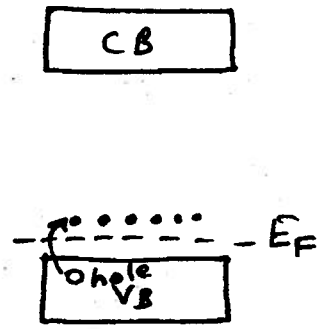


But, only 3.2×10^{4} e-h pairs are produced by a MIP.

∴ Reduce the number of free charge carriers, i.e., deplete the detector

Doping:



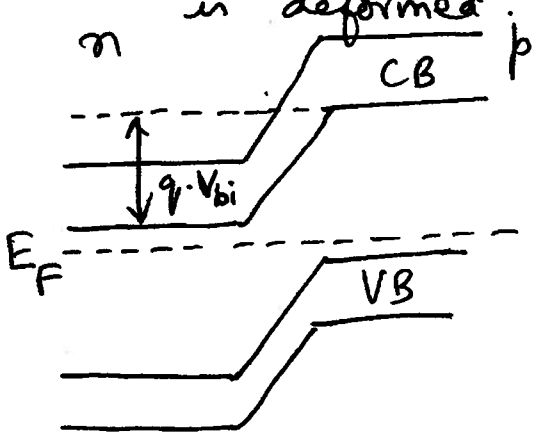


n-type:
Add elements from the V group of periodic table
Donors → donate electrons that move to the CB
e^- majority carriers
E.g., Phosphorous
Arsenic

p-type:
Add elements from III group
Acceptors → accept electrons creating holes.
h: majority carriers
Eg: Boron

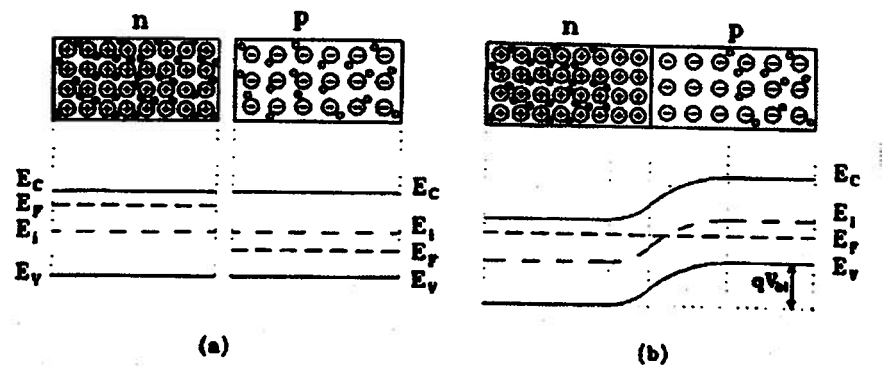
Typical doping levels: $10^{12}/cc - 10^{15}/cc$ for detector Silicon

When the two types are joined, the band structure is deformed.



pn junction

A built-in voltage V_{bi} generated by electron and hole diffusion.



From the requirement that the Fermi levels have to match up in thermal equilibrium, the width of the space charge region becomes,

$$d = \sqrt{\frac{2\epsilon\epsilon_0}{e}\left[\frac{N_A + N_D}{N_A N_D}\right] \cdot V_{bi}}$$

N_A, N_D $\equiv$ Acceptor, donor doping concentrations

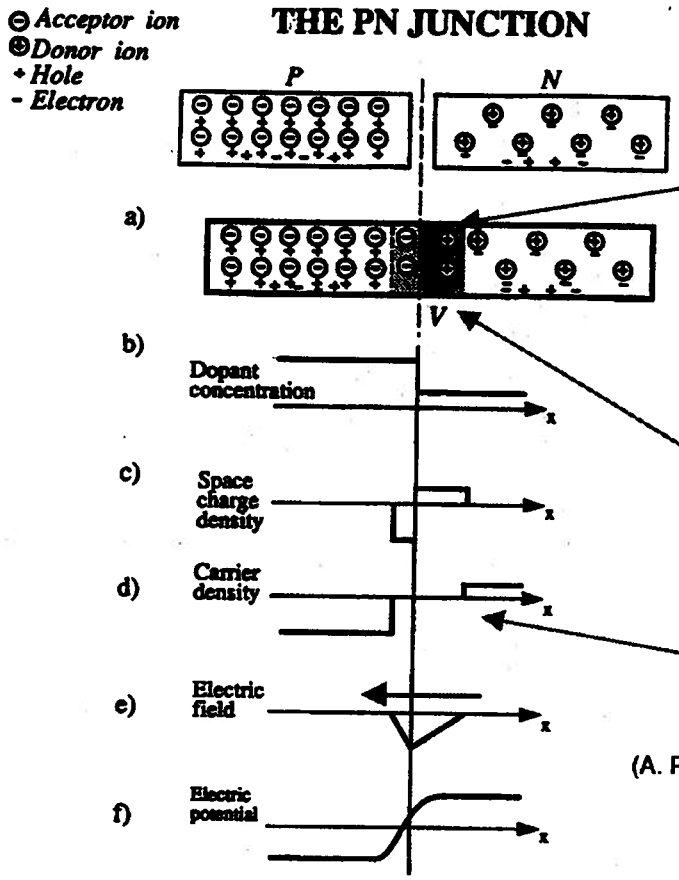
If $N_A >> N_D$ (p^+n junction)

$$d \approx \sqrt{\frac{2\epsilon\epsilon_0}{e N_D} \cdot V_{bi}}$$

For $N_A = 10^{16}/cc$, $N_D = 10^{12}/cc$, $V_{bi} \approx 0.46V$

and $d \simeq 25\,\mu m$.

THE PN JUNCTION

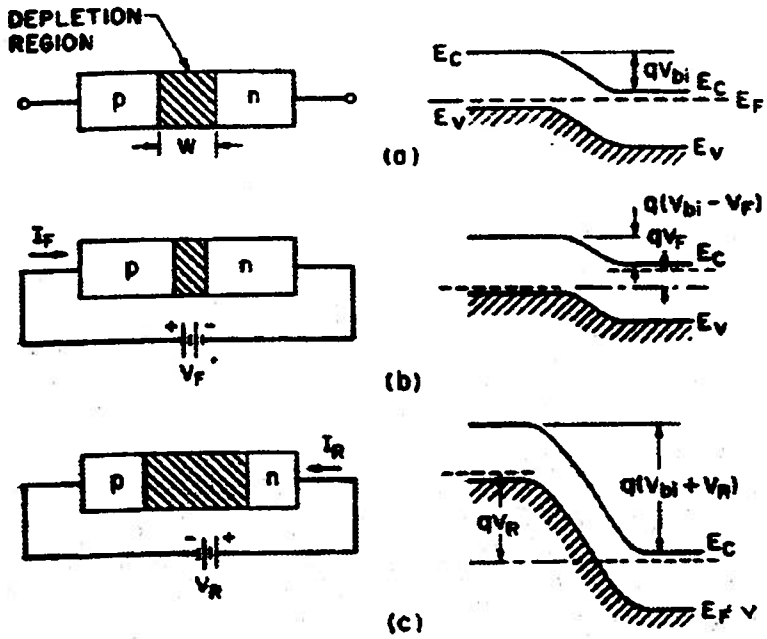


diffusion of e^- into p-zone, h^+ into n-zone → potential difference stopping diffusion

thin depletion zone

no free charge carriers in depletion zone

(A. Peisert, Instrumentation In High Energy Physics, World Scientific)



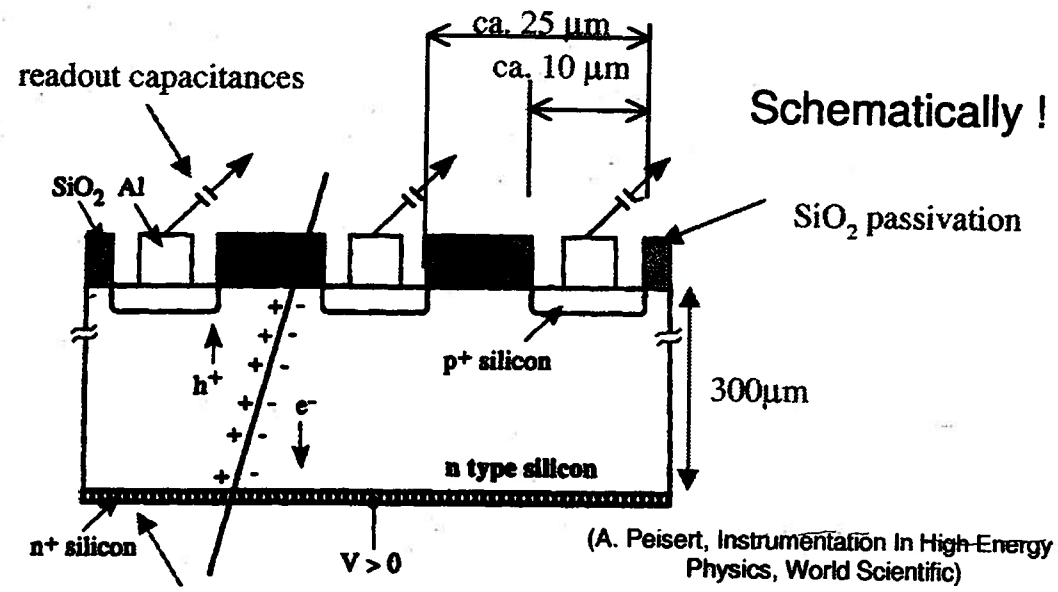
- In the reverse-bias mode, (~ 100 V) the depletion zone can extend over the full junction $\rightarrow$ fully depleted.

$$d = \sqrt{\frac{2\epsilon\epsilon_0}{eN_D}(V_{bi} - V_R)} = \sqrt{2\epsilon\epsilon_0 \mu_e \rho_n (V_{bi} - V_R)}$$

μ_e = mobility of e

ρ_n = resistivity of n-type silicon

Conductivity $\sigma = e\mu_e N_D = \frac{1}{\rho}$



(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

Single-sided microstrip detector

Spatial information obtained by segmenting the p-doped layer

Double-sided microstrip detectors are made by segmenting also the n-doped layer.

Resolution σ depends on the pitch p (distance from strip to strip)

$$\sigma = p/\sqrt{12}$$

Typical pitch ~ 20 µm – 150 µm

50 µm pitch ⟹ 14.4 µm resolution