Week 8: Ch. 11 Semiconductor diodes

Principles of Scintillation Counters

Semiconductor Diodes

-- basics of semiconductors

--- pure elements & dopants

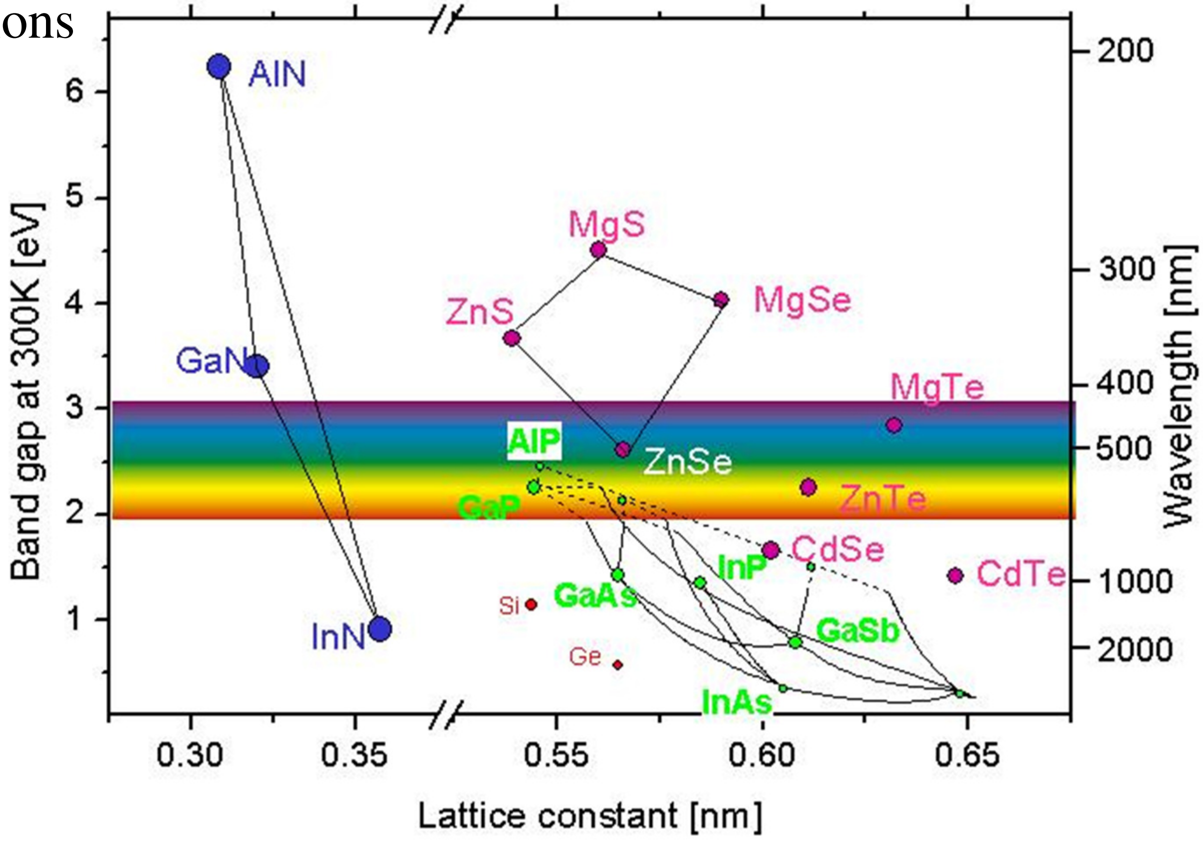
--- 5-3 Materials

-- ion collection, leakage current

--- diode structure, pn, np junctions

--- depletion region

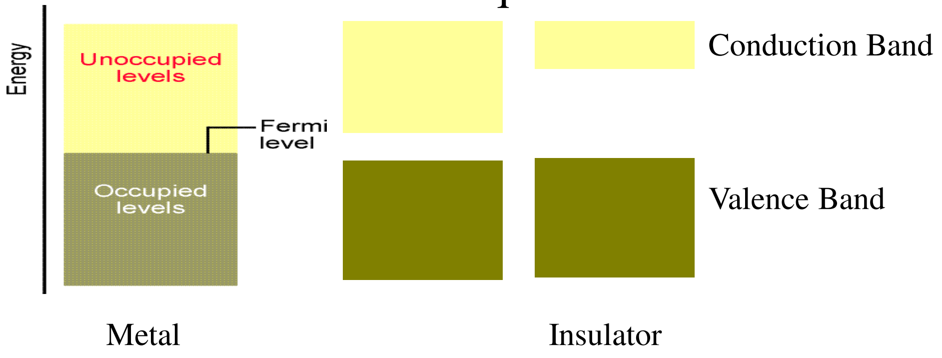
Germanium Diodes



Chap. 11 – Semiconductor Diodes

Semiconductor diodes provide the best resolution for energy measurements, silicon based devices are generally used for charged-particles, germanium for photons.

- Scintillators require ~ 100 eV / “information carrier” .. Photoelectrons in this case
- Gas counters require ~ 35 eV / “information carrier” .. Ion-pairs or Electrons
- Solid-state devices require ~ 3 eV / “information carrier” .. Electron/hole pairs



Conduction Band

Valence Band

Metal

Insulator

A semiconductor is an insulator with a small band gap, ~1.2eV for silicon. Generally want smallest band gap ***but*** thermal excitation across the gap provides a leakage current. N.B. the actual band gap depends on the direction relative to the lattice (Si and Ge do not crystallize in cubic lattices) and the gap decreases slowly with temperature.

The ratio of ‘w’ to band gap is approximately constant for a wide range of materials – division of excitation energy between e/h pair and phonons, etc. is ~ constant.

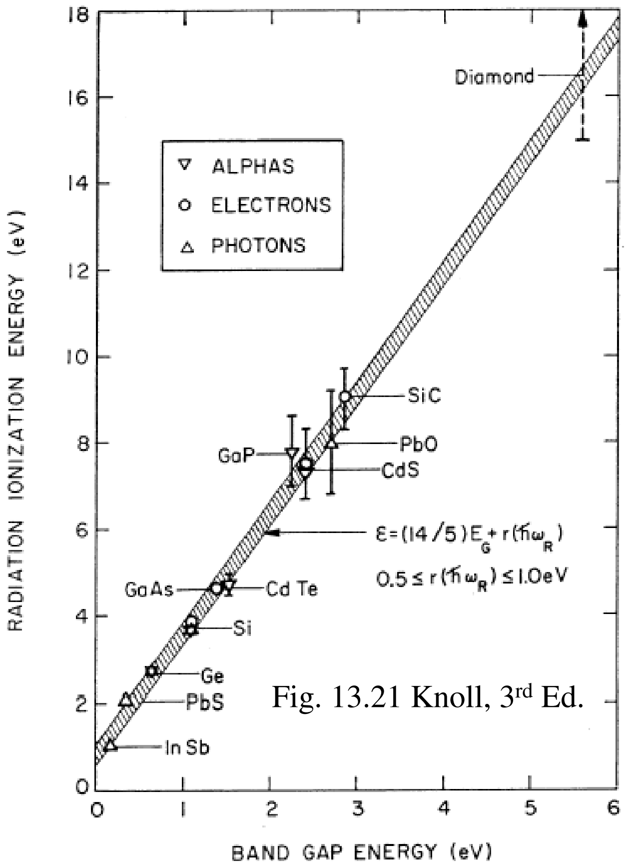


Fig. 13.21 Knoll, 3rd Ed.

C.A.Klein, J.App. Phys. 39 (1968) 2029

Semiconductors – Charge carriers

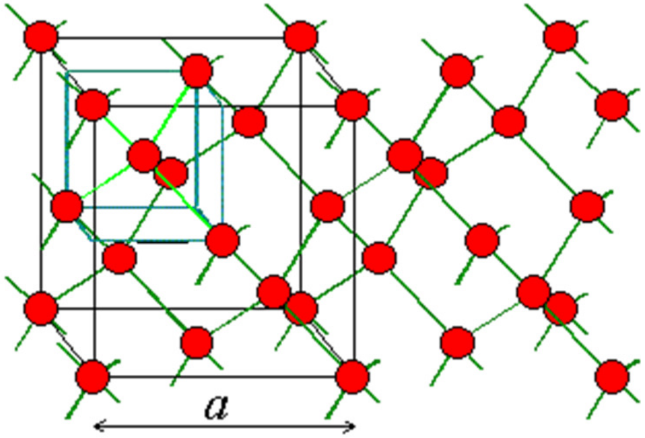
"pure" material, no dopants is called "intrinsic"

The intrinsic carrier density in a semiconductor is low:

$$\rho_e \sim \sqrt{N_V N_C}\, e^{-\varepsilon/2k_BT} \qquad k_BT = 0.026\, eV \ @\ 25^\circ C$$

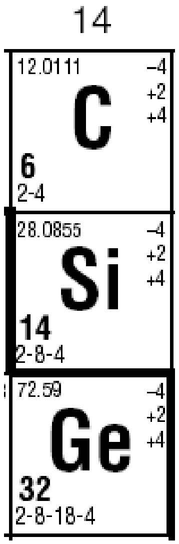
$$\rho_e \sim \sqrt{10^{19}10^{19}}\ e^{-20} \quad \sim 10^9 - 10^{10}\, cm^{-3}$$

N_v and N_c are the densities of states in the valence and conduction bands. (Only rough estimates given here.)

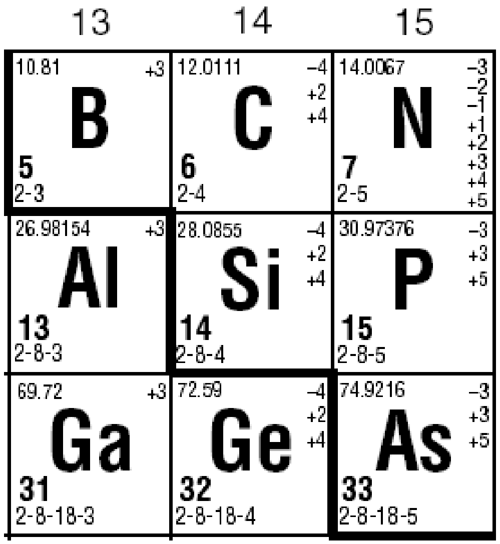


"diamond lattice"

	Lattice Constant
Carbon	0.356 nm
Silicon	0.543 nm
Germanium	0.565 nm



Semiconductors – Dopants



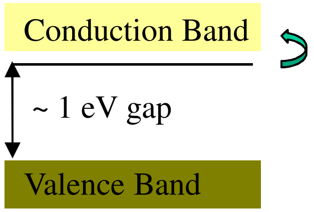
13	14	15
10.81 +3 **B** 5 2-3	12.0111 −4 +2 +4 **C** 6 2-4	14.0067 −3 −2 −1 +1 +2 +3 +4 +5 **N** 7 2-5
26.98154 +3 **Al** 13 2-8-3	28.0855 −4 +2 +4 **Si** 14 2-8-4	30.97376 −3 +3 +5 **P** 15 2-8-5
69.72 +3 **Ga** 31 2-8-18-3	72.59 −4 +2 +4 **Ge** 32 2-8-18-4	74.9216 −3 +3 +5 **As** 33 2-8-18-5

Add atoms from the neighboring groups in the periodic table

- •Group 15, Phosphorous, nearly same size, excess electron
- •Group 13, Boron, nearly same size, electron deficit

Donor level from P atom below conduction band by ~ 0.05 eV ..
Thermally excite from donor, excess electrons→ n-type

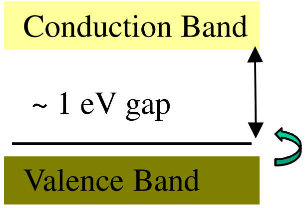
$$e^{-0.05/2kT} \sim e^{-1}$$



Conduction Band

~ 1 eV gap

Valence Band



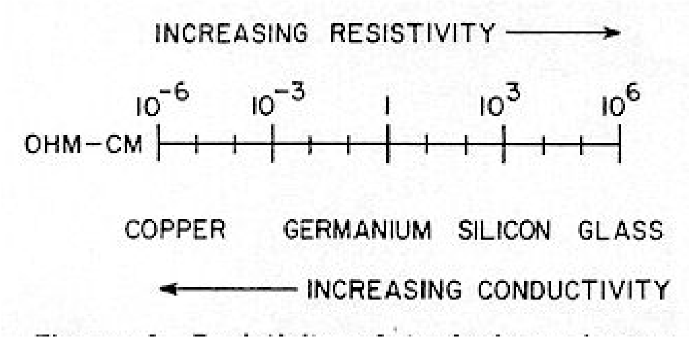
Conduction Band

~ 1 eV gap

Valence Band

Acceptor level from B atom above valence band by ~ 0.05 eV ..
Thermally excited from valence band, excess holes → p-type

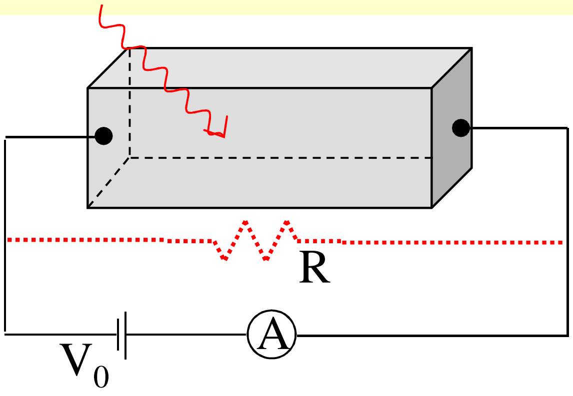
Control the conductivity by controlling the amount of dopants!
N.B. 2 ppb gives $(2\mathrm{x}10^{-9})\ (5\mathrm{x}10^{22}/\mathrm{cm}^3) = 10^{14}\ /\mathrm{cm}^3 >> 10^9$ for Si



For an n-type material, the electrons carry the current so that the resistivity is:

$$\rho = \frac{1}{q_e N_D \mu_e}$$

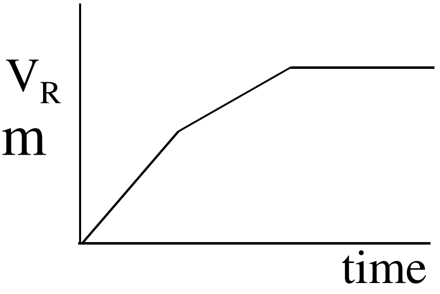
Semiconductor – Ion Chamber?



Imagine constructing a simple block of intrinsic semiconductor and trying to use it as an ion chamber … The block has a length, “L” and a cross sectional area, “A” with a resistivity of ρ = 60k ohm-cm (high quality silicon). Apply nominal V_0 = 60V bias to collect ions.

1 MeV energy into material creates ~ $3x10^5$ e/h in ~50 ns … limiting drift velocity ~ 10^7 cm/s

$$i_{signal} \sim \frac{\Delta q}{\Delta t} = \frac{3x10^5\left(1.6x10^{-19}\right)}{\left(L\ \ cm/10^7 cm/s\right)} = \frac{5}{L}10^{-7}\text{Amps for L in cm}$$

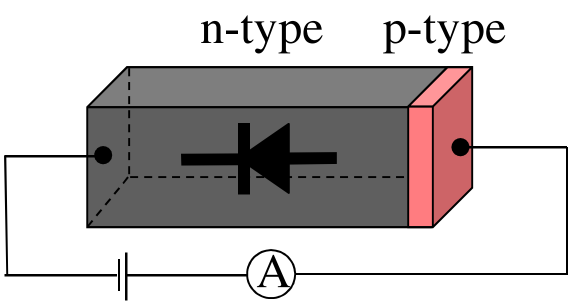


$$I_{Leakage} = \frac{V_0}{R} \quad where \quad R = \rho\frac{L}{A}$$

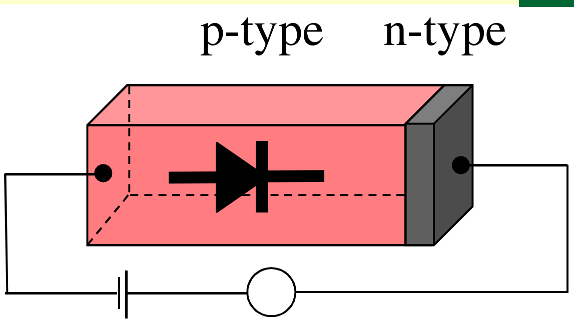
$$I_{Leakage} = \frac{V_0 A}{\rho L} \quad \rightarrow \quad \frac{60A}{60,000L} = \frac{A}{L}10^{-3}\text{Amps for A/L in cm}$$

Thus, I >> i   so we need a trick to kill the leakage current.

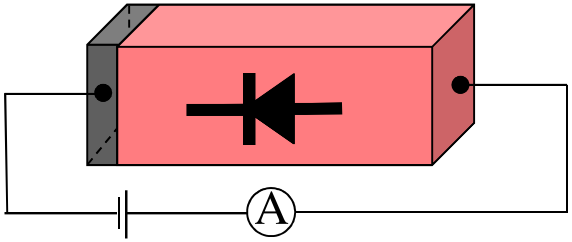
Semiconductor Diodes – 1



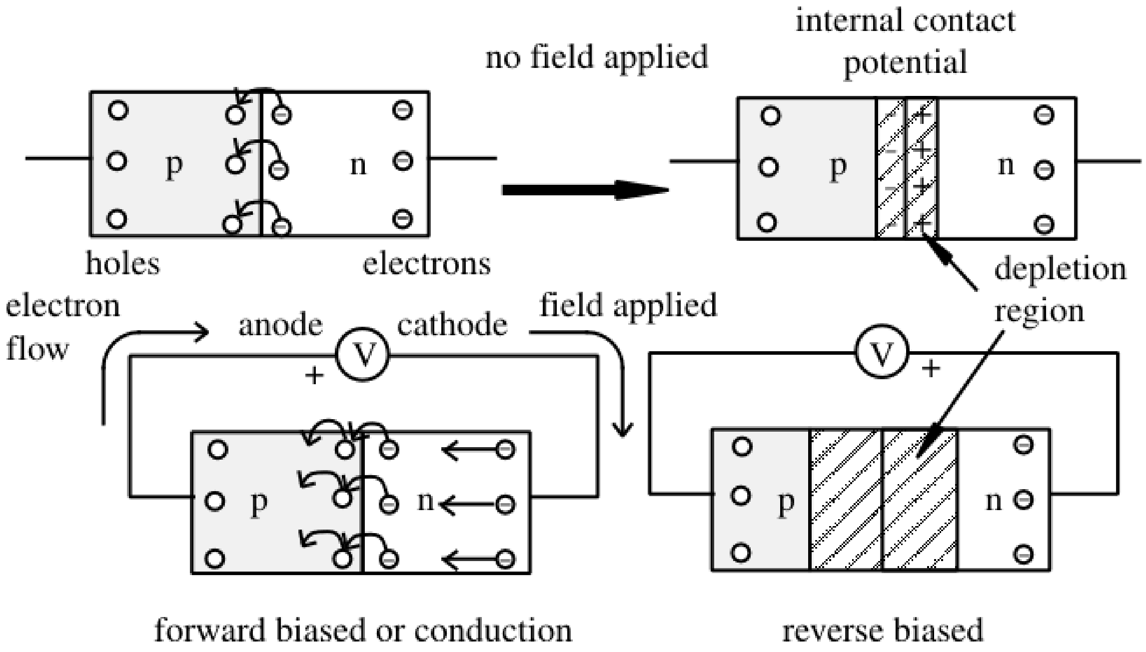
“Forward” bias – normal flow of current



“Reverse” bias – no nominal current



The “type” is determined by the implanted atoms .. Different atoms can be put into a single piece of semiconductor, then an internal field will form due to migration of charges.



Semiconductor Diodes – 2

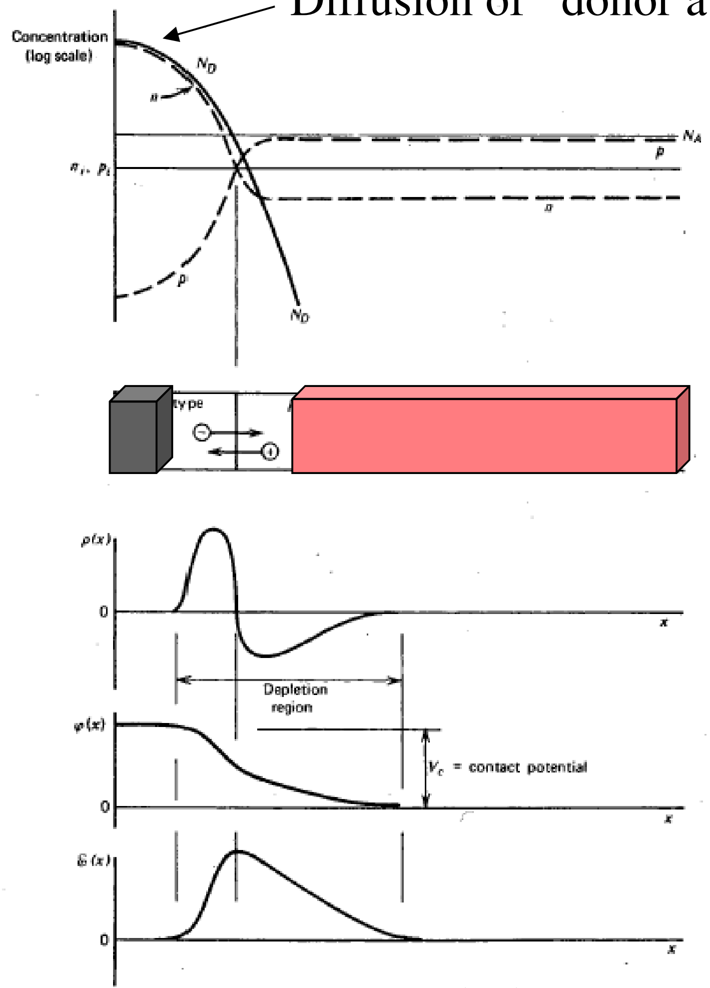


Fig. 11.8 Knoll, 3rd , 4th Eds.

Diffusion of “donor atoms” into bulk p-type material gives concentration profile

bulk p-type dopant concentration is much, much lower than the concentration of donor atoms (figure contains a log scale)

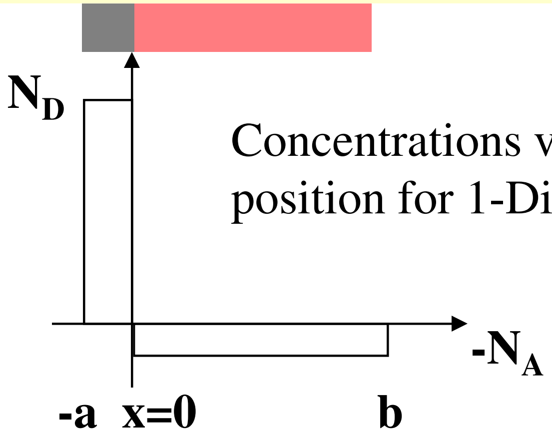
Charge density, ρ(x): Migration of the charge across the boundary causes a charge separation and a “depletion region” … in this case the holes migrate for a longer distance due to imbalance in concentrations in two regions

Which creates an internal electric potential, ϕ(x) with a potential difference of ~ 1V

and an electric field, E(x), where the lines of force originate on positive ions and terminate on the negative ions.

The depleted region has a very low concentration of mobile charge carriers and a very high resistivity – this is a very good region to measure/collect ionization.

Semiconductor Diodes – Model for Depletion Depth



Concentrations versus position for 1-Dimension

Charge neutrality gives: $a*N_D=b*N_A$ (1)

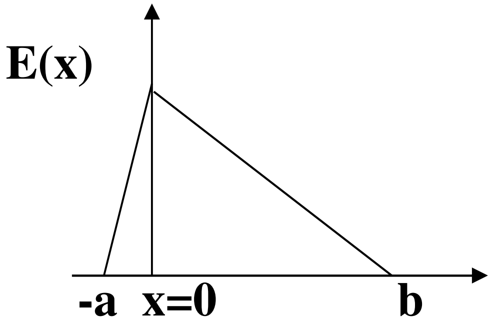
Depletion depth, d = a+b

One Dimensional Poisson Equation in two regions:

$$\frac{d^2\phi}{dx^2} = \frac{-\rho(x)}{\varepsilon} = \begin{cases} \dfrac{-q_e N_D}{\varepsilon} & a < x \le 0 \\ \dfrac{+q_e N_A}{\varepsilon} & 0 < x \le b \end{cases}$$

Boundary Conditions:

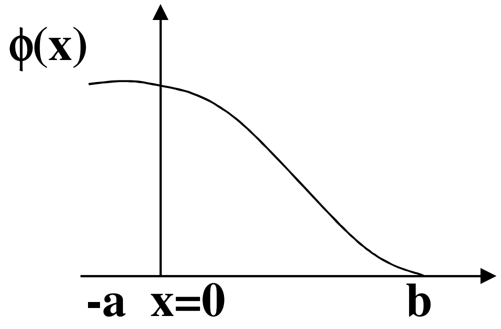
$E(x=-a)=0$ & $E(x=b)=0$



$$-E(x) = \frac{d\phi}{dx} = \begin{cases} \dfrac{-q_e N_D}{\varepsilon}(x+a) & a < x \le 0 \\ \dfrac{+q_e N_A}{\varepsilon}(x-b) & 0 < x \le b \end{cases}$$

Boundary Conditions:

$\phi(x=-a)=V$ & $\phi(x=b)=0$



$$\phi(x) = \begin{cases} \dfrac{-q_e N_D}{2\varepsilon}(x+a)^2 + V & a < x \le 0 \\ \dfrac{+q_e N_A}{2\varepsilon}(x-b)^2 & 0 < x \le b \end{cases}$$

Match at $x=0$:

$$\frac{-q_e N_D}{2\varepsilon}a^2 + V = \frac{+q_e N_A}{2\varepsilon}b^2 \quad (2)$$

Depletion depth: combine (1) & (2) $(a+b)*b = 2\varepsilon V / q_e N_A$

Generally b > a .. $d = b \sim (2\varepsilon V / q_e N_A)^{1/2}$

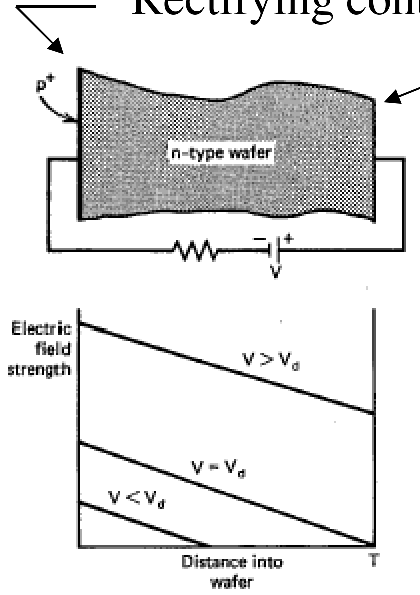
Semiconductor Diodes – 3

Some properties of the junction:

$$d \sim \sqrt{\frac{2\varepsilon V}{q_e N_A}} \qquad \& \qquad \rho = \frac{1}{q_e N_D \mu_e}$$

$$d \sim \sqrt{2\varepsilon V \rho \mu} \qquad \& \qquad C = \frac{\varepsilon A}{d}$$

$$E = \Delta V / \Delta x \quad \rightarrow \quad E_{\max} = \frac{2V}{d}$$



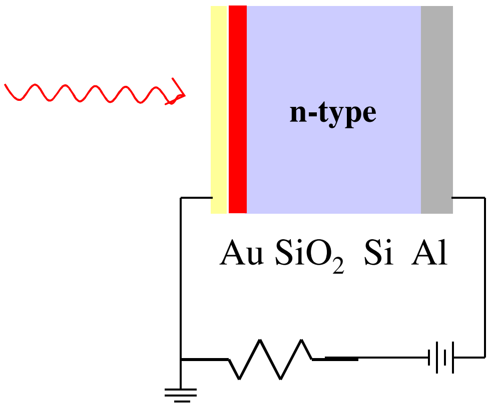
Rectifying contact

ohmic or blocking contact

Fig. 11.12 Knoll, 3rd ,4th Eds.

One can apply an external (reverse) bias voltage such that the depletion layer extends from the junction to the full thickness of the device

Silicon Surface Barrier Device



Au SiO$_2$ Si Al

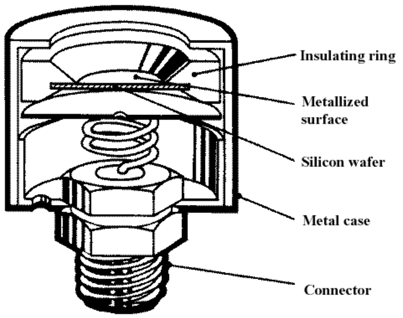


Fig. 11.11 Knoll, 3rd ,4th Eds.
(From EG&G Ortec)

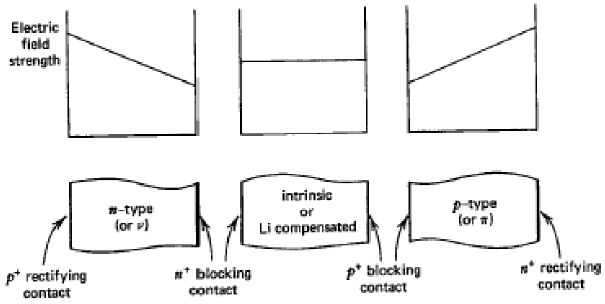
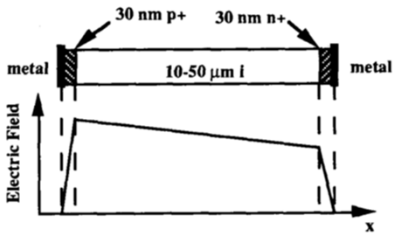
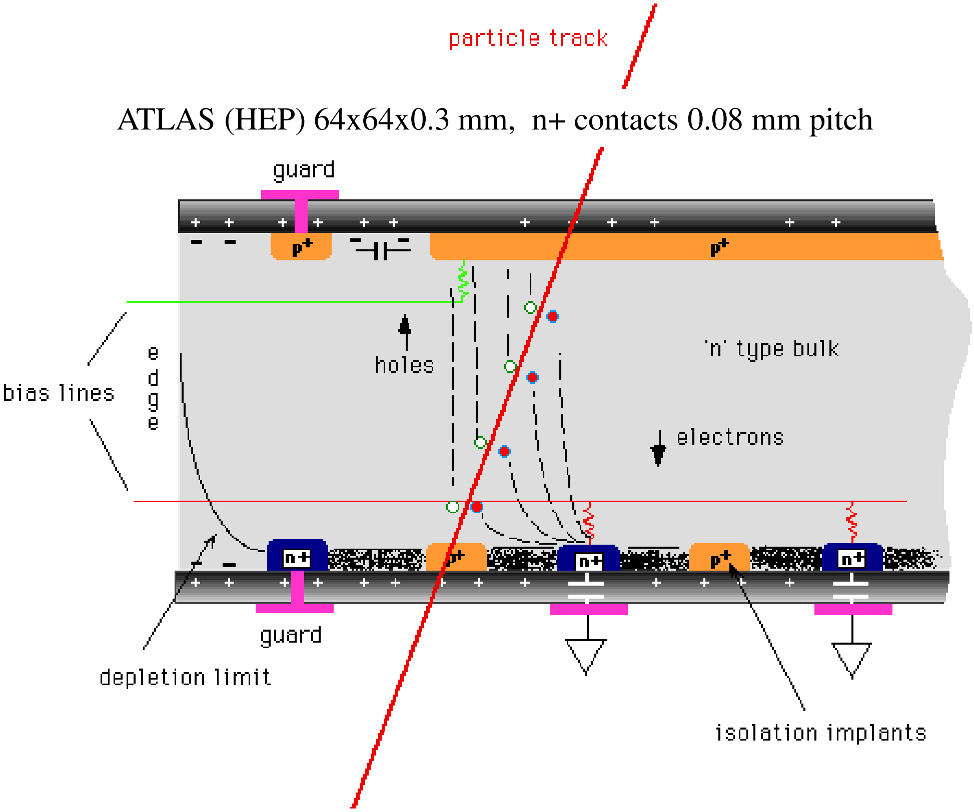


Fig. 11.13 Knoll, 3rd ,4th Eds.

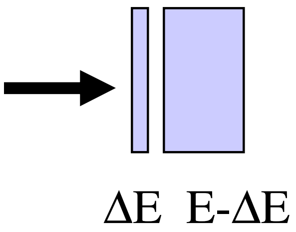


Semiconductor Diodes



ATLAS (HEP) 64x64x0.3 mm, n+ contacts 0.08 mm pitch

Silicon layers are thin, typically 0.3mm but up 5mm are produced. (dictated by the semiconductor chip industry).



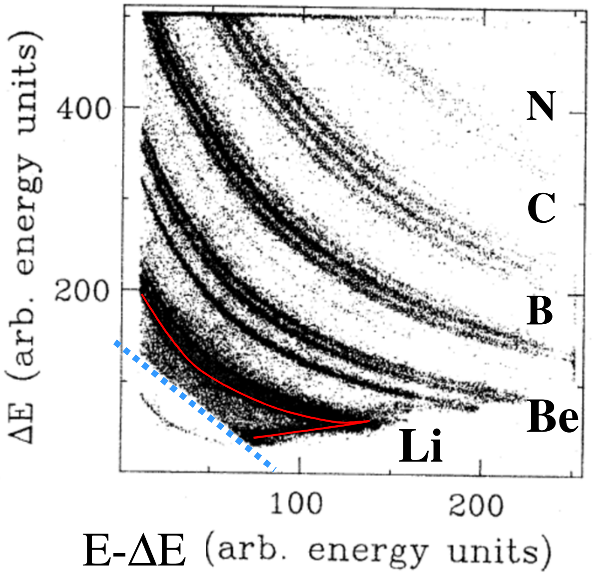
Silicon Detector "telescopes" combine a thin device with a thick device to identify charged particles.

$$\frac{dE}{dx} = C_1 \frac{MZ^2}{E} \ln\left(C_2 \frac{E}{M}\right)$$

$$\Delta E = \Delta x \left(\frac{dE}{dx}\right) \propto \frac{MZ^2}{E} \quad \rightarrow \quad \Delta E \propto \frac{1}{E}$$

Punch-through

Software cut



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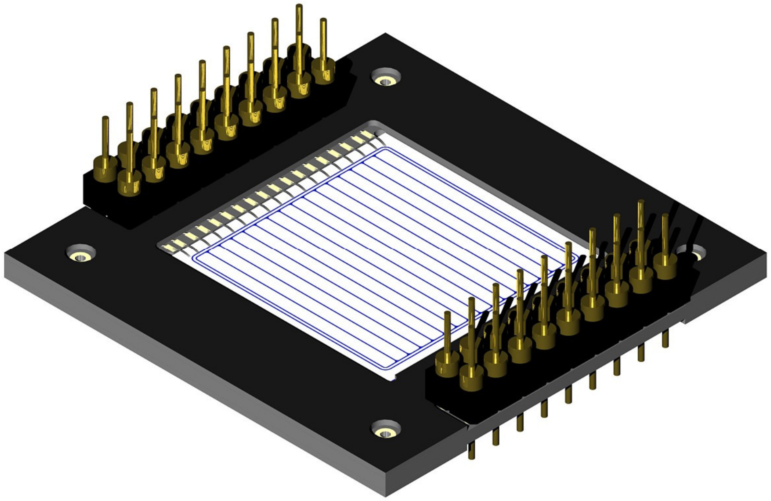
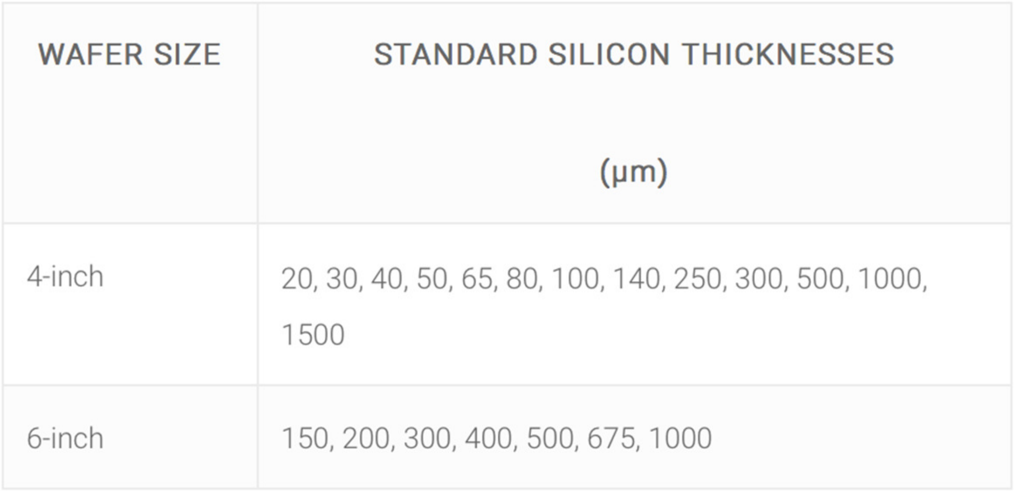
Semiconductor Diodes – Micron Semiconductor

http://www.micronsemiconductor.co.uk





WAFER SIZE	STANDARD SILICON THICKNESSES (µm)
4-inch	20, 30, 40, 50, 65, 80, 100, 140, 250, 300, 500, 1000, 1500
6-inch	150, 200, 300, 400, 500, 675, 1000