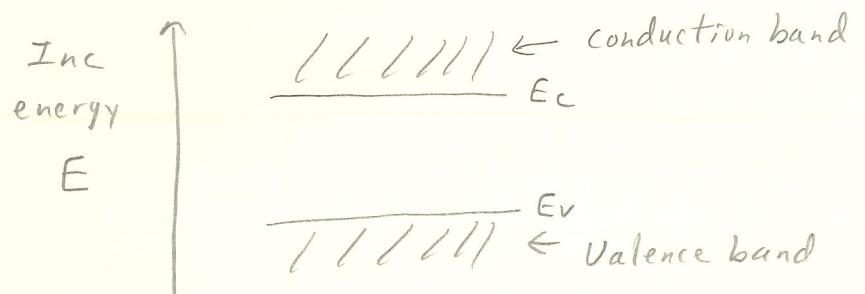


I. Energy Band Model (for an ^{intrinsic} semiconductor)



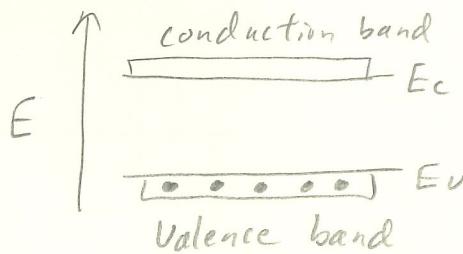
$E \leq E_v \rightarrow$ electron is in the valence band

$E \geq E_c \rightarrow$ electron is a free electron, for conduction

According to Quantum Mechanics, e^- 's cannot have $E_v < E < E_c$

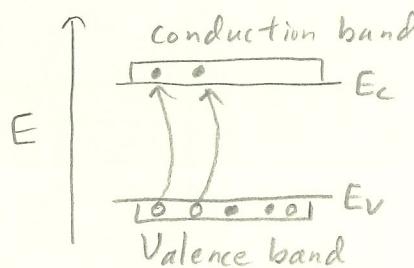
$$E_G = \text{bandgap energy} = E_c - E_v$$

a. At $T = 0\text{K}$ (absolute zero)



All e^- 's are in the valence band : none available for conduction

b. At $T > 0\text{K}$



a few e^- 's acquire enough thermal energy to jump to the conduction band, thus creating an electron-hole pair

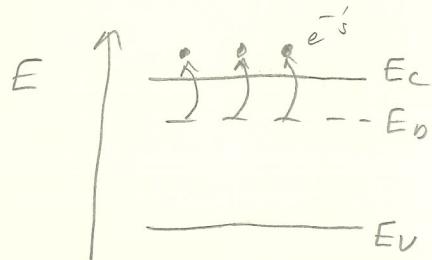
2. Energy Band Model for a Doped Semiconductor

a) concentration N_D of donor atoms

→ introduces new localized energy levels: E_D

$E_D \equiv$ donor energy level

E_D is near the conduction band edge



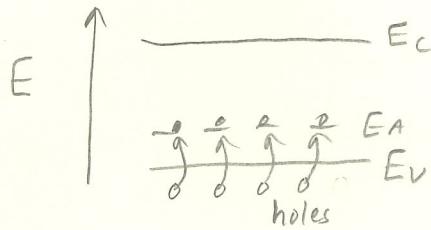
at room temp, $E_C - E_D$ is Very small: so most e's go to the conduction band and are available for conduction

b) concentration N_A of acceptor atoms

→ introduces new localized energy levels: E_A

$E_A \equiv$ acceptor energy level

E_A is near the Valence band edge

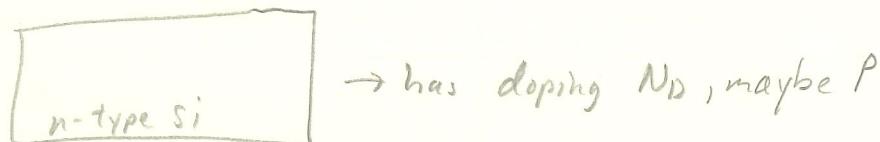


at room temp, $E_A - E_V$ is Very small: so most e's go from the valence band to the E_A level, thus holes in the valence band are created and available for conduction

→ Diodes - Chapter 3 : p. 72

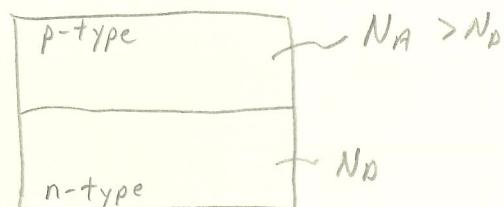
1) pn junction diode → invented by Russel Ohl, 1939

(1) start with n-type Si substrate

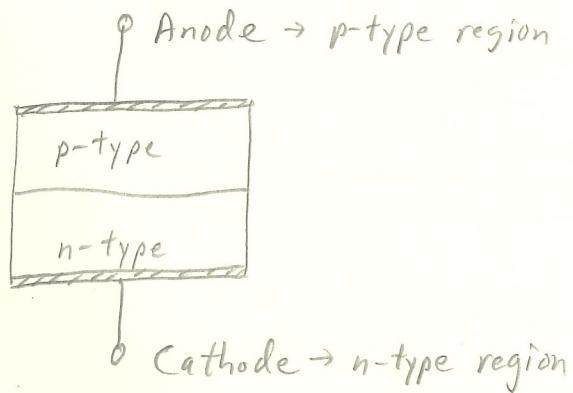


(2) add p-type impurities to part of substrate where $N_A > N_D$

↙
maybe
B

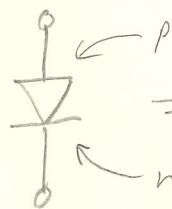


(3) add electrical contacts:



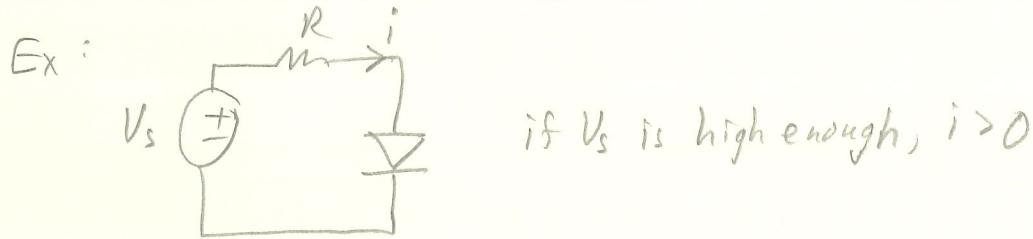
schematic symbol:

Anode

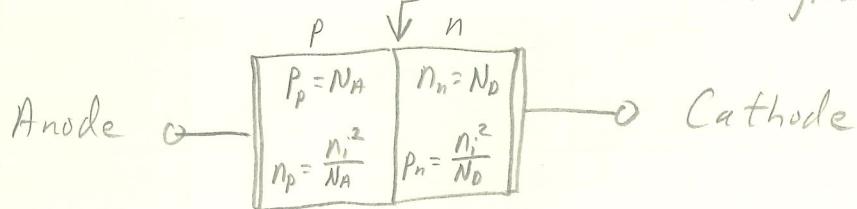


\Rightarrow positive current flows in direction of the arrow

Cathode



a) How the p-n diode works (open circuit case)
metallurgical junction



typical pn diode e^- + hole densities:

p-type side: $p_p = 10^{17}$ holes/cm³, $n_p = 10^3 e^-/\text{cm}^3$: $p_p \gg n_p$

n-type side: $p_n = 10^4$ holes/cm³, $n_n = 10^{16} e^-/\text{cm}^3$: $n_n \gg p_n$

metallurgical
junction

note: e = electron
o = hole

p-type | n-type

e	o	e	e
o	e	o	o
e	b	o	e
b	o	o	e
e	b	o	e
b	o	e	e
e	o	e	e
b	o	e	e
e	o	e	e

← nonuniform doping
across the junction

↑	↑
many holes	many e^-
few e ⁻ s	few holes

Remember: when doping is not uniform, this creates a gradient in the e^- + hole concentration.

→ Free carriers tend to diffuse from regions of high concentration to regions of low concentration

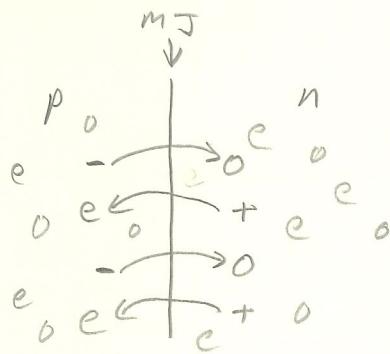
i) mobile holes diffuse from p-side to n-side
 mobile e⁻'s diffuse from n-side to p-side

But: as mobile holes move from p-side to n-side, they leave behind the immobile negatively charged acceptor atoms.

As mobile e⁻'s move from n-side to p-side, they leave behind the immobile positively charged donor atoms

\rightarrow neg. charged acceptor atom

\leftarrow pos. charged donor atom



Result: a region depleted of mobile carriers develops around the metallurgical junction \rightarrow this is a Space Charge Region (SCR), also called a depletion region or depletion layer

The space charge results in an electric field across the MJ

$$\hookrightarrow E(x)$$

$E(x)$ results in a "built-in potential" or "junction potential" across the pn junction SCR

$$\downarrow \phi_j$$

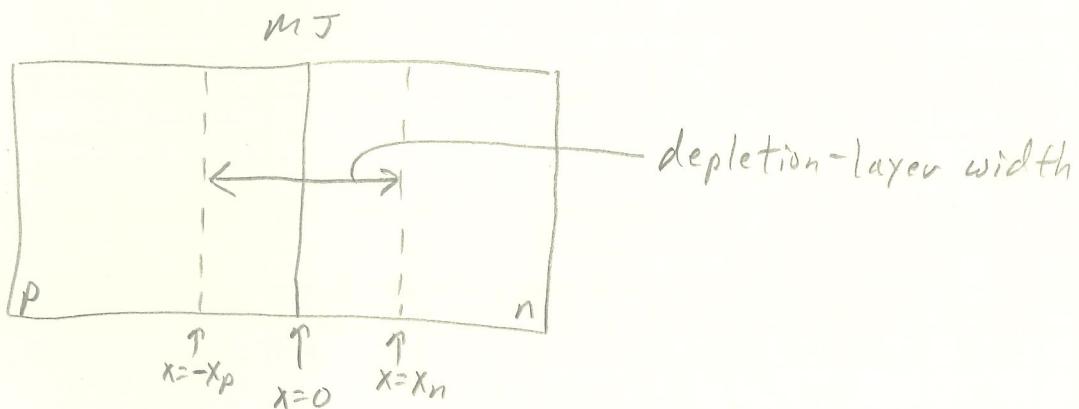
$$\text{where } \phi_j = - \int E(x) dx$$

also: $\phi_j = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$ where $V_T = \frac{kT}{q}$, the thermal voltage

The depletion-layer width is given by:

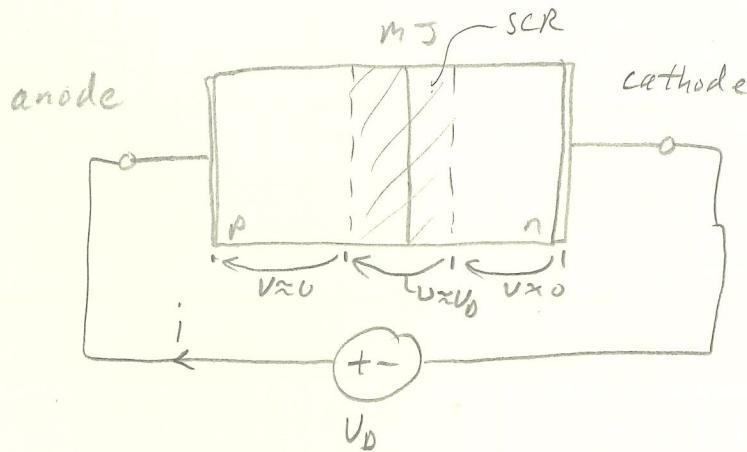
$$W_{d0} = (x_n + x_p) = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j}, [W_{d0}] = m$$

where ϵ_s = semiconductor permittivity, $[\epsilon_s] = F/cm$



$E(x)$ from the immobile charges results in ϕ_j , which is a barrier to further e^-/hole flow across the junction

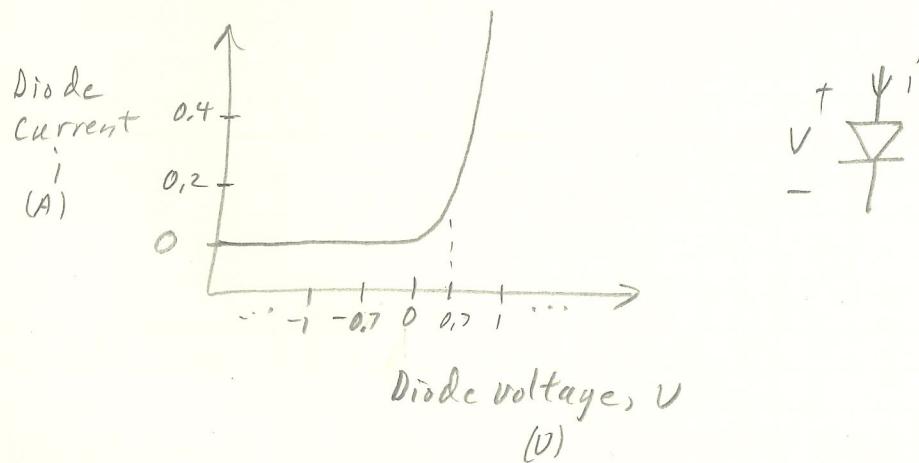
b) Applying an external voltage across the pn diode



the neutral regions in the diode represent low resistance to current

- ii the external voltage is applied directly across the space charge region (SCR)
- ii V_D reduces the potential barrier at the SCR for electrons and holes to flow
 - if $V_D > 0 \rightarrow$ potential barrier is reduced
 - if $V_D < 0 \rightarrow$ potential barrier is increased
- if $V_D > 0$ and $V_D \geq$ "turn-on" or "cut-in" voltage, significant current flows through the diode

Diode i-v characteristic



- ii The diode has a nonlinear response and acts like a one way valve