Lecture 20

Monday, March 1, 2021

DOPED SEMICONDUCTORS

$\Delta n = n - p \implies \Delta n \longleftrightarrow \mu$ $\qquad \delta n_i = 0$

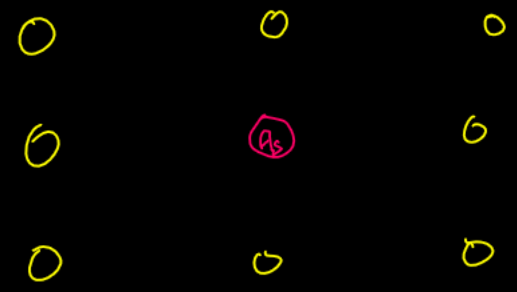
$\Delta n = ?$

TYPES OF IMPURITIES

DONOR IMPURITY – GIVE UP ELECTRONS (DONORS) n-DOPED

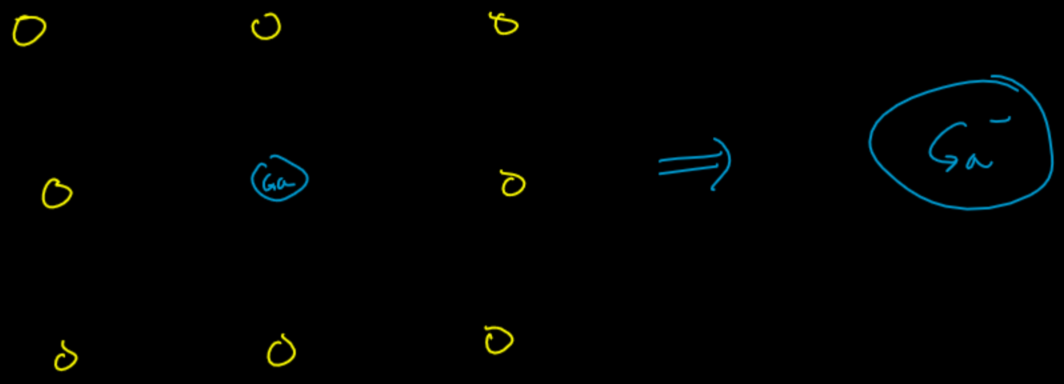
$A_s \rightarrow$ GROUP V

O = Ge



$\implies$ A_s^+ GIVES UP e^-

ACCEPTORS – TAKE ON EXTRA ELECTRON P-DOPED



"ABSORBS" e^- $\Rightarrow$ GIVES UP HOLE

$\# e^-$ $\quad \# e^+$ (HOLES)

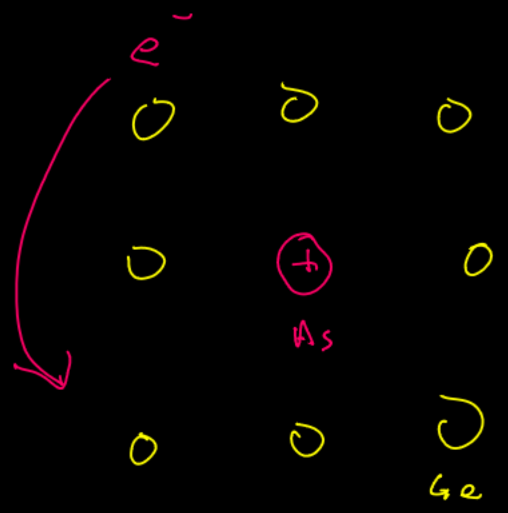
COMPENSATED SEMICONDUCTORS (BOTH n & p DOPANTS)

TO CALCULATE Δn $\Rightarrow$ IMPURITY LEVEL ENERGIES

① SHALLOW LEVEL IMPURITIES (AS OPPOSED TO DEEP LEVELS)

BEHAVE LIKE **HYDROGEN ATOMS**

$R_y = 13.6\ eV$



Ⓐ $m_e^* \rightarrow m_e$ (REPLACE e^- MASS BY m_e^*

($m_h^* \rightarrow$ FOR ACCEPTORS) $m^* \sim 0.1 - 0.01\ m_e$

Ⓑ DIELECTRIC CONSTANT FOR MATERIAL

$\epsilon \approx 10 - 20$ FREE SPACE

TAKE "k" STATES OUT OF BOTTOM CONDUCTION (DONORS)

(TOP VALENCE ACCEPTORS)

BOHR RADIUS

$$\left(\frac{e^2}{r} \rightarrow \frac{e^2}{\epsilon r} \right)$$

⇑ DIELECTRIC MATERIAL

$$\frac{m}{m^*}\epsilon \underbrace{\frac{\hbar^2}{m e^2}}_{a_0 \; = \; 0.53\ \text{Å}} \Rightarrow \epsilon \frac{\hbar^2}{m^* e^2}$$

ϵ = DIELECTRIC FUNCTION

RYDBERG ENERGY

$$\left(\frac{m^*}{m\epsilon^2}\right)\underbrace{\left(\frac{m e^4}{2\hbar}\right)}_{R_y^0 = 13.6\,\text{eV}}$$

GaAs

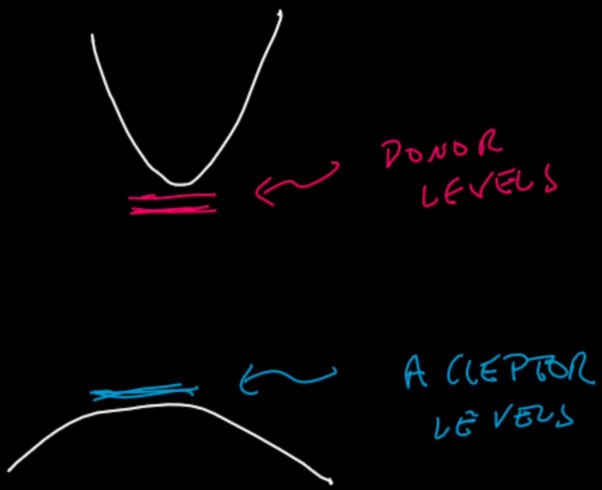
$m^* \simeq 0.067\, m_e$

$\epsilon = 13.6$

$\Rightarrow$

$a = 104\,\text{Å}$ LARGE!

$R_y = 5.3\ \text{meV}$ (SMALL)



SHALLOW LEVELS $\Longleftrightarrow$ HYDROGENIC LEVELS

THERMAL EQUILIBRIUM # DONORS @ A GIVEN SITE

$$\langle n \rangle = \frac{\sum_j N_j e^{-\beta(E_j - \mu N_j)}}{\sum_j e^{-\beta(E_j - \mu N_j)}}$$

↑ AVE # e^- @ DONOR SITE

CAN HAVE 0, ↑, ↓, ↑↓ ← 2 ELECTRONS

NORMALLY IGNORE ↑↓ BECAUSE COULOMB REPULSION IS TOO HIGH!

$$\langle n \rangle = \frac{2 e^{-\beta(\varepsilon_d - \mu)}}{1 + 2 e^{-\beta(\varepsilon_d - \mu)}}$$

|| # e^- ON DONOR SITE

$$\langle n \rangle = \frac{1}{\frac{1}{2} e^{\beta(\varepsilon_d - \mu)} + 1}$$

↑ NOTE $\frac{1}{2}$.

THIS IS NOT FERMI-DIRAC FUNCTION (WITH EXTRA $\frac{1}{2}$)

SYSTEM IS HIGHLY INTERACTING

IN LIMIT $\varepsilon_d - \mu \gg k_B T \Rightarrow \langle n \rangle \sim 2 e^{-\beta(\varepsilon_d - \mu)} \ll 1$)

$\langle n \rangle$ SMALL $\Rightarrow$ DONORS ARE IONIZED!

$\langle p \rangle$ SMALL $\Rightarrow$ ACCEPTORS "IONIZED" $\Rightarrow$ (HOLES)

$$\Delta n = n_c - p_v \approx N_d - N_a$$

$\Updownarrow$

μ

$$R_H \sim \frac{-1}{nec}$$

METALS $\Rightarrow$ CARRIER DENSITY NOT SENSITIVE TO T

$$\sigma = \frac{n e^2 \tau}{m} \qquad \vec{J} = \sigma \vec{E}$$

SEMICONDUCTORS $\rightarrow$ CARRIER DENSITY, STRONGLY T DEP.
(DOPANTS)

$$\mu \equiv \frac{|v|}{E}$$

MOBILITY; $|v|$ ← VELOCITY; E ← ELECTRIC FIELD

$$J = (n e \mu_e + p e \mu_h) E$$

τ = SCATTERING TIME

$$\mu_e = \frac{e \tau_e}{m_e^*} \qquad \mu_h = \frac{e \tau_H}{m_H^*}$$

m_{eh} = EFFECTIVE MASSES

ROOM T MOBILITIES	e	h
GaAs	8000	300
DIAMOND	1800	1200
Si	1350	480
Ge	3600	1800
InAs	30,000	450

WHY $\mu_h < \mu_e$?

$m_h^* > m_e^*$

$\tau_H < \tau_e$