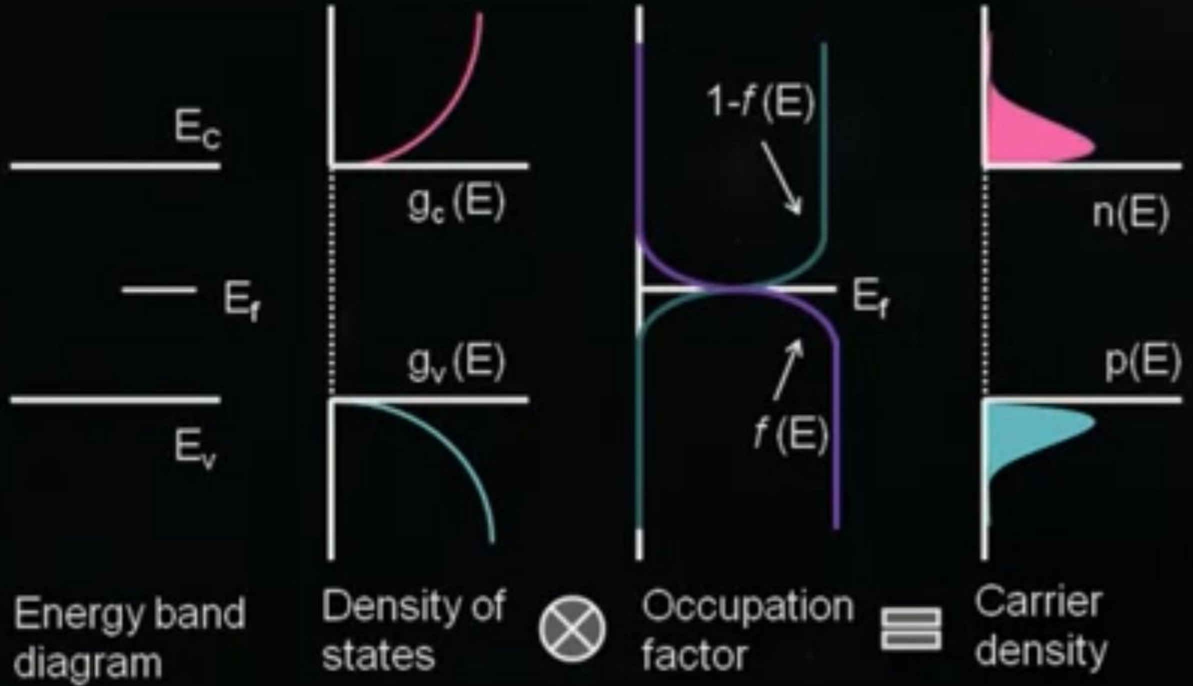
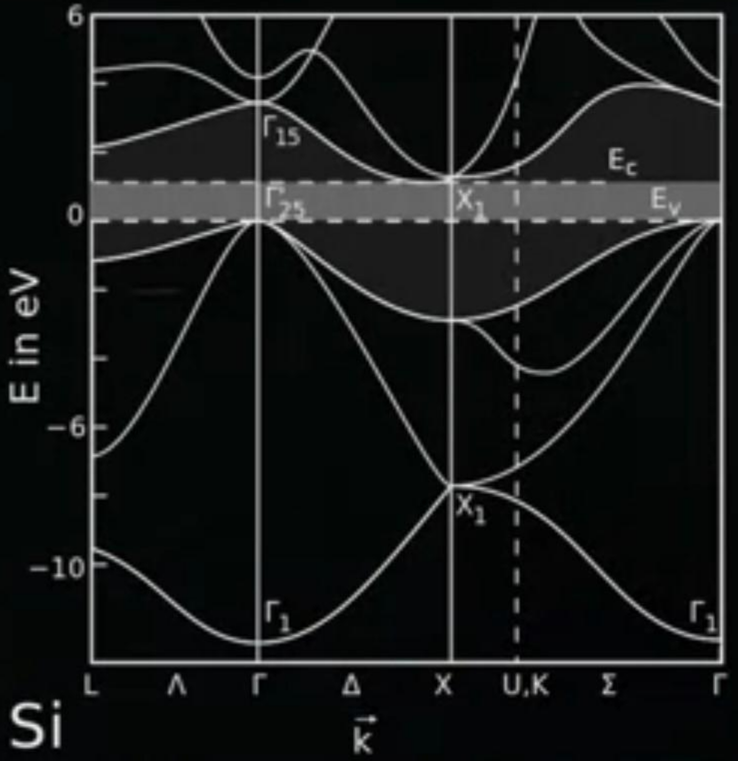
Density of states and carrier density



https://nanohub.org/wiki/CarrierStatisticsPage/Image:Image.png

Intrinsic and extrinsic semiconductors

Energy Band Structure



https://upload.wikimedia.org/wikipedia/commons/thumb/0/04/Band_structure_Si_schematic.svg/580px-Band_structure_Si_schematic.svg.png

Intrinsic semiconductors

$$n(T) = p(T) = n_i(T)$$

$$n_i(T) = \sqrt{N_c(T)N_v(T)}\,\exp\left(-\frac{E_g(T)}{2k_BT}\right)$$

$$E_F = E_v + \frac{1}{2}E_g + \frac{1}{2}k_BT\ln\left(N_v/N_c\right)$$

$$= E_v + \frac{1}{2}E_g + \frac{3}{4}k_BT\ln\left(\frac{m_v^*}{m_c^*}\right)$$

1. $T \to 0K$ $\quad E_F \to$ midgap
2. $\ln\left(\frac{m_v^*}{m_c^*}\right) \to 1$ $\quad E_F$ within $+/- k_BT$ of midgap
3. $k_BT \ll E_F$ $\quad E_F \to$ midgap

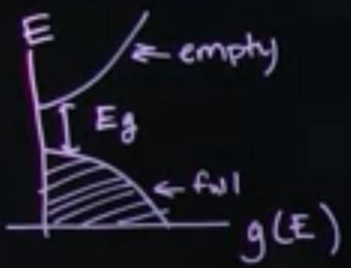
Extrinsic semiconductors

Treat impurities as an additional charge

$+e$ = donor

$-e$ = acceptor

Insulator

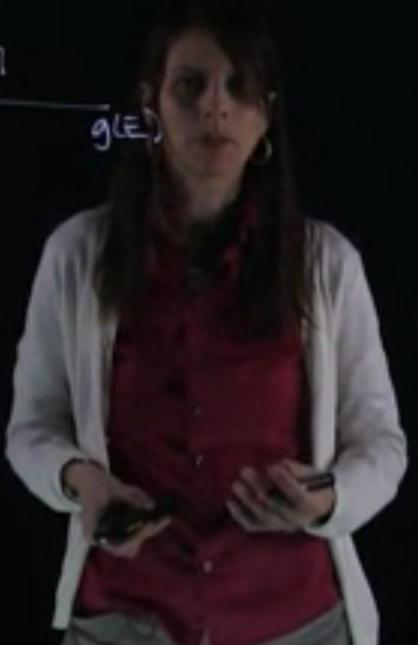


Metal

$T > 0\,K, \propto e^{-E_g/k_BT}$

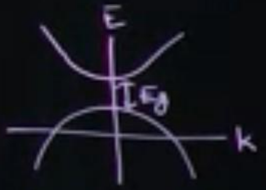
ex) $\begin{cases} T = 300K \\ E_g = 4eV \end{cases}$ prob = 10^{-55}

$E_g = 0.25eV$ " " $= 10^{-2}$
$T = 300K$



So, you can really see from this example

Metals, Insulators & Semiconductors



Semiconductors:

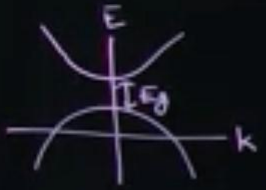
- Special kind of insulators whose band gap is small enough
- How small is small enough?
  - Enough to thermally excite electrons across band gap
  - < 2~3 eV.
- Energy bandgaps of semiconductors (room temp.):

InSb: 0.16 eV	Ge: 0.67 eV
Si: 1.12 eV	GaAs: 1.42 eV
GaP: 2.2 eV	GaN: 3.5 eV
ZnS: 3.68 eV	

So now, let's talk about the rigorous definition of a semiconductor.

1:36 / 2:11

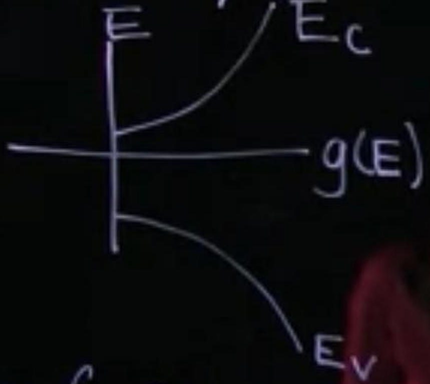
Rigorous definition of semiconductor



The solids that are insulators at T = 0 K but whose energy bandgap is of such a size that thermal excitation leads to observable conductivity at temperatures below its melting point are called the semiconductors.

Carrier Density

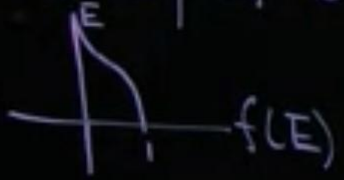
Density of states



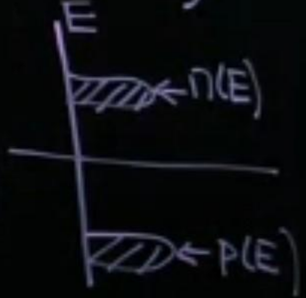
$$n(T) = \int_{E_c}^{\infty} dE\, g_c(E) f(E)$$

$$p(T) = \int_{-\infty}^{E_v} dE\, g_v(E)\left(1 - f(E)\right)$$

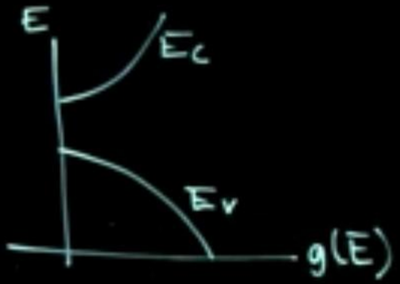
Probability of occupation



$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)}$$



Density of states



$g(E) \sim$ # states/Volume/Energy

$g(E)dE \sim$ # states/volume

$$E = \frac{\hbar^2 k^2}{2m^*} = \frac{\hbar^2}{2m^*}\left(k_x^2 + k_y^2 + k_z^2\right)$$

Ground state of N electron system

$E < E_F$

$$E_F = \frac{\hbar^2 k_F^2}{2m^*}$$

$$V_F = \frac{4}{3}\pi k_F^3 = \frac{4}{3}\pi\left(\frac{2m^* E_F}{\hbar^2}\right)^{3/2}$$

1 allowed state per $(2\pi)^3/V$ ← volume of crystal

$$N = \frac{V_F}{(2\pi)^3/V} = \frac{2V}{6\pi^2}\left(\frac{2m^* E_F}{\hbar^2}\right)^{3/2}$$

$$g(E) = \frac{1}{V}\frac{dN(E)}{dE} = \frac{1}{2\pi^2}\left(\frac{2m^*}{\hbar^2}\right)^{3/2} E^{1/2}$$

halves times E to the one half.

Press Esc to exit full screen

Nondegeneracy

$E_c - E_F \gg k_B T$

$E_F - E_v \gg k_B T$

$\Rightarrow$ Fermi Dirac statistics

$\approx$ Boltzman (classical) statistics

$$f(E) = \frac{1}{1 + e^{\left(\frac{E-E_F}{k_B T}\right)}} \approx \exp\left(-\frac{(E-E_F)}{k_B T}\right)$$

for $E > E_c$

$$1 - f(E) = \frac{1}{\exp\left(\frac{E_F - E}{k_B T}\right) + 1} \approx \exp\left(\frac{-(E_F - E)}{k_B T}\right)$$

$E < E_v$

us to come up with analytic expressions for our integrals.

5:59 / 6:05

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$$n(T) = \int_{E_c}^{\infty} dE\, g_c(E) \exp\left(-\frac{(E-E_F)}{k_B T}\right)$$

$$p(T) = \int_{-\infty}^{E_v} dE\, g_v(E) \exp\left(-\frac{(E_F-E)}{k_B T}\right)$$

$$n(T) = N_c(T) \exp\left(-\frac{(E_c-E_F)}{k_B T}\right)$$

$$p(T) = N_v(T) \exp\left(-\frac{(E_F-E_v)}{k_B T}\right)$$

$$N_c(T) = \int_{E_c}^{\infty} dE\, g_c(E) \exp\left(-\frac{(E-E_c)}{k_B T}\right)$$

$$N_v(T) = \int_{-\infty}^{E_v} dE\, g_v(E) \exp\left(-\frac{(E_v-E)}{k_B T}\right)$$

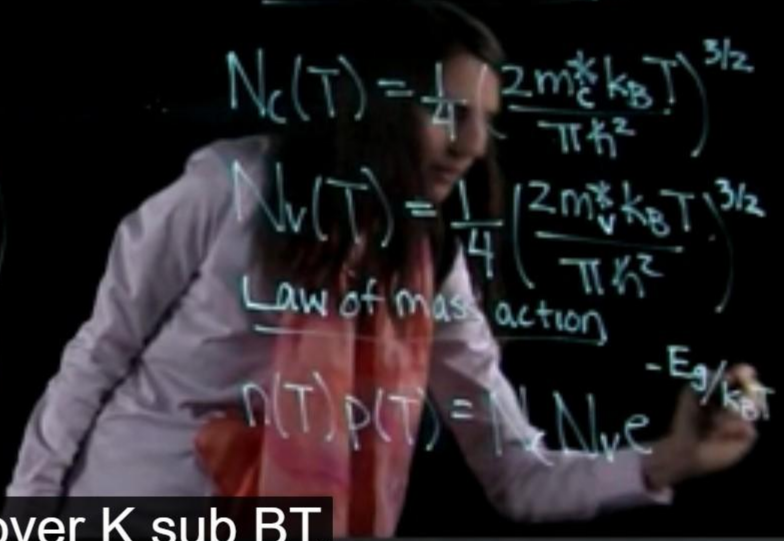
Parabolic bands

$$N_c(T) = \frac{1}{4}\left(\frac{2m_c^* k_B T}{\pi \hbar^2}\right)^{3/2}$$

$$N_v(T) = \frac{1}{4}\left(\frac{2m_v^* k_B T}{\pi \hbar^2}\right)^{3/2}$$

Law of mass action

$$n(T)p(T) = N_c N_v e^{-E_g/k_B T}$$



Eg over K sub BT.

5:51 / 5:56

Fermi levels

Intrinsic semiconductor

$$E_F = E_i = E_v + \frac{1}{2}E_g + \frac{3}{4}k_B T ln\left(\frac{m_v^*}{m_c^*}\right)$$

Extrinsic semiconductor, p doped with $p = N_A$

$$E_F = E_i - k_B T ln\left(\frac{N_A}{n_i}\right) \text{ or } E_F - E_v = k_B T ln\left(\frac{N_v}{N_A}\right)$$

So now, let's look at the case

Fermi levels

Intrinsic semiconductor

$$E_F = E_i = E_v + \frac{1}{2}E_g + \frac{3}{4}k_B T ln\left(\frac{m_v^*}{m_c^*}\right)$$

Extrinsic semiconductor, p doped with $p = N_A$

$$E_F = E_i - k_B T ln\left(\frac{N_A}{n_i}\right) \text{ or } E_F - E_v = k_B T ln\left(\frac{N_v}{N_A}\right)$$

So E_F is now equal
to E_i minus k_B T,

Donor Energy Level

Donor E

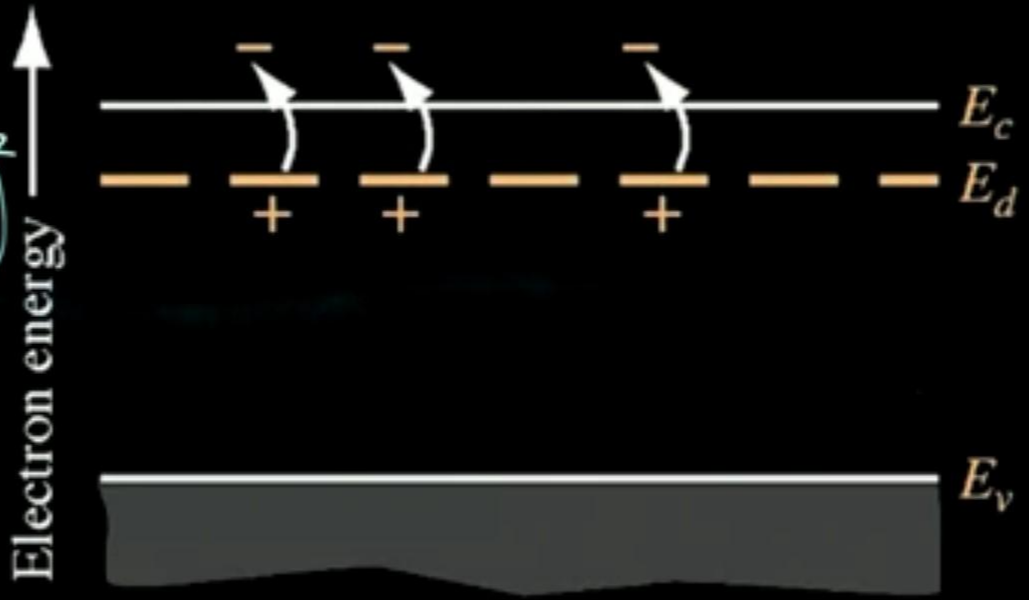
$$E_d = \left\{ \left(\frac{m_c^*}{m_0} \right) \left(\frac{\epsilon_0}{\epsilon_s} \right)^2 \cdot 13.6\,\text{eV} \right\}$$

will change the energy level that appears.

Donor Energy Level

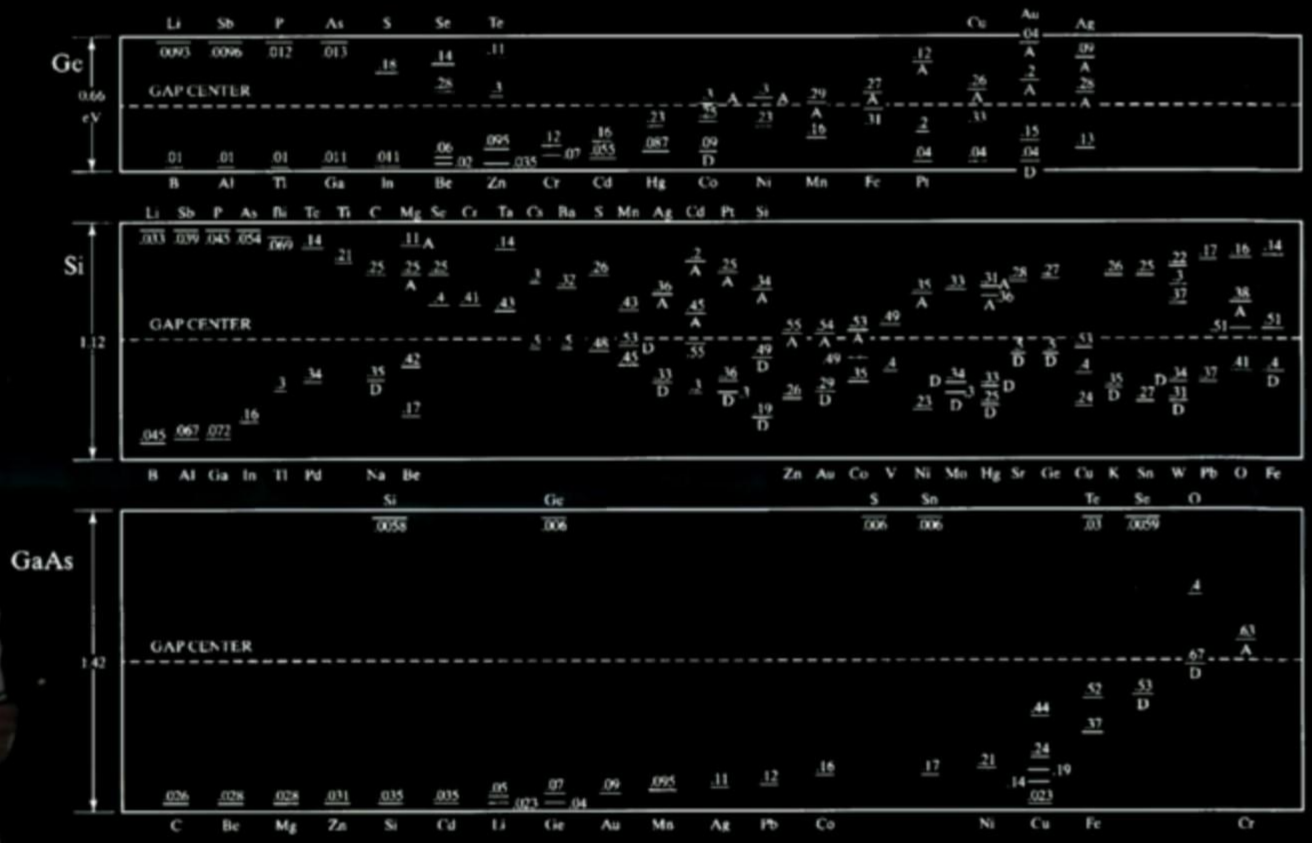
Donor E

$$E_d = \left\{ \left(\frac{m_c^*}{m_0}\right)\left(\frac{\epsilon_0}{\epsilon_s}\right)^2 \cdot 13.6\,\text{eV} \right\}$$



from being essentially an insulator to a good conductor.

Impurity Energy Levels

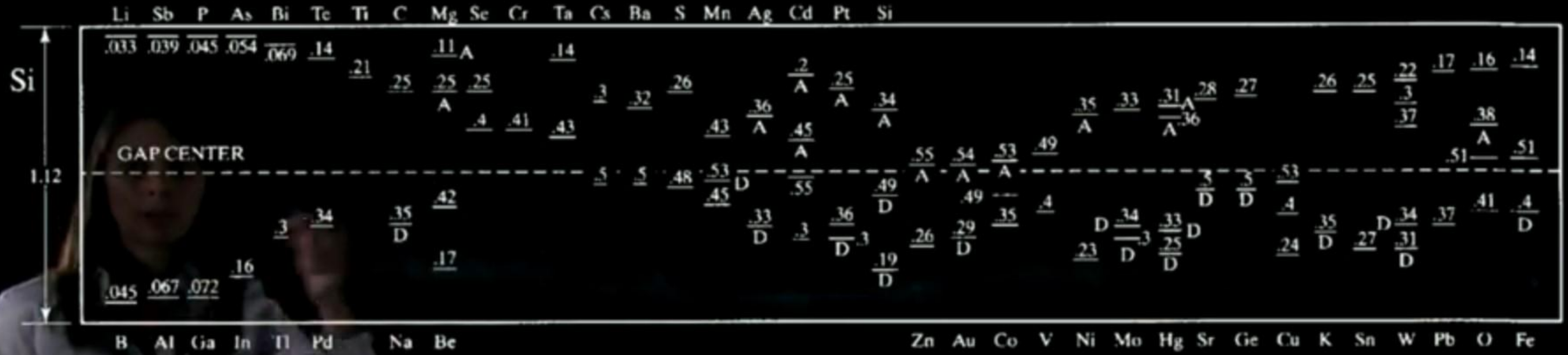


Pierret, Advanced Semiconductor Fundamentals, 2003

This is just showing you the flexibility that you now have in engineering,

0:37 / 1:08

Impurity Energy Levels



Pierret, Advanced Semiconductor Fundamentals, 2003

the conduction band and then also acceptors that are close to the valence band.

1:00 / 1:08

Charge neutrality

$$n_c + n_d + N_A = N_D + p_v + p_A$$

Fully ionized impurities

$$n_d = p_A = 0$$

$$n_c + N_A = N_D + p_v$$

$$\left.\begin{array}{l} N_D > N_A \\ \text{fully ionized} \end{array}\right\} \Delta n = n_c - p_v = N_D - N_A$$

$$n_i^2 = n_c p_v$$

$$n_c, p_v = \frac{1}{2}\left[\Delta n^2 + 4n_i^2\right]^{1/2} \pm \frac{1}{2}\Delta n$$

$$= \frac{1}{2}\left[(N_D - N_A)^2 + 4n_i^2\right]^{1/2} \pm \frac{1}{2}(N_D - N_A)$$

the one half plus or minus one half N_D minus N_A.

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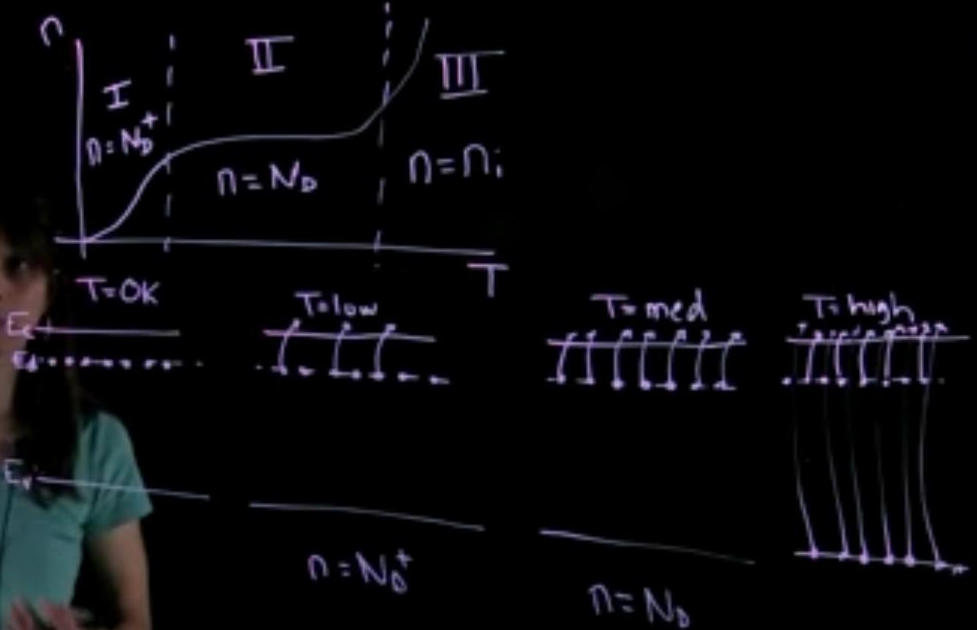
Low impurity concentration

$$\left.\begin{matrix} n \\ p \end{matrix}\right\} = n_i \pm \frac{1}{2}(N_D - N_A)$$

High impurity concentration

$$\left.\begin{matrix} n \\ p \end{matrix}\right\} \quad N_D >> N_A \quad n = N_D - N_A$$

$$p = \frac{n_i^2}{N_D - N_A}$$



to the knobs that we have from doping and also from temperature.

5:11 / 5:20

Recommended References

The references below are the go-to references for semiconductor physics. These texts are completely optional, but note that the last text is freely available.

S. M. Sze, Physics of Semiconductor Devices, Wiley, 2007.

G. Streetman and S. Banerjee, Solid State Electronic Devices, Prentice Hall, 2000

K. F. Brennan, The Physics of Semiconductors, Cambridge, 1999

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