Thursday, 1/15/26

Review of Solid State Physics, Continued

1. Background

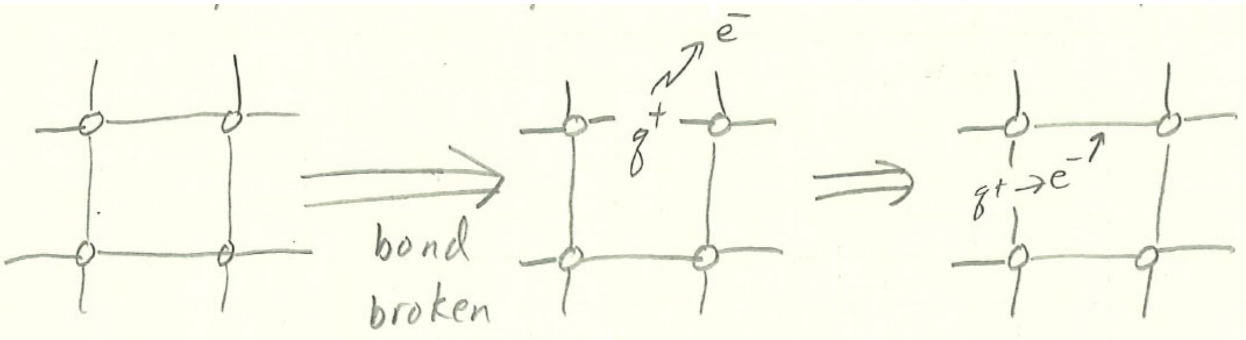
Let “n” be the density of conduction (or free) electrons.

$[n] = e^-/cm^3$

For intrinsic Si: $n_i = n$

Remember from last time that n_i is the intrinsic carrier density and $n_i^2 = BT^3 e^{-E_G/KT}$.

For single crystal (monocrystalline) Si: there are 4 covalently bonded Si atoms:



When energy, E, is applied such that $E \geq E_G$, this results in the creation of an electron-hole pair:

→ electrons can move anywhere

→ holes can only move about the crystal lattice

Electrons (-q) and holes (q) are charge carriers where $q = 1.62x10^{-19}$ C.

Define “p” as the “hole density.” $[p] = holes/cm^3$

For intrinsic Si: $n_i = n = p$.

Also, $n_i^2 = pn$ → whenever there is thermal equilibrium without external stimulus (voltage, current, light, etc.).

"ρ" is the electrical resistivity.

$\rho = \frac{1}{\sigma}$ where σ is the electrical conductivity

2. Drift Currents

Charged particles move (or drift) in response to an applied electric field. This results in a drift current, j, where:

j = Qv, [j] = A/cm^2

Q is charge density, [Q] = C/cm^3

v is charge velocity in the electric field, and is also called "carrier drift velocity."

[v] = cm/s

Positive charges move in the direction of the electric field, and negative charges flow in the opposite direction of the electric field.

For low electric fields (of interest to this class): v is proportional to E, leading to:

$$\vec{v}_n = -\mu_n \vec{E}$$

$$\vec{v}_p = \mu_p \vec{E}$$

Where $\vec{v}_n$ is the velocity vector for electrons

$\vec{v}_p$ is the velocity vector for holes

μ_n is the electron mobility: 1350 cm^2/V for intrinsic Si

μ_p is the hole mobility, 500 cm^2/V for intrinsic Si

Notice that $\mu_n > \mu_p$. This is because electrons can move freely though the crystal while holes can only move about the crystal through the covalent bond structure.

Let's define electron and hole drift current densities: j_n^{drift} and j_p^{drift}, respectively.

$[j_n^{drift}, j_p^{drift}]$ = A/cm^2

Let's consider simplified 1-D vectorless equations for j_n^{drift} and j_p^{drift}:

$$j_n^{drift} = Q_n v_n = (-qn)(-\mu_n E) = qn\mu_n E$$

$$j_p^{drift} = Q_p v_p = (qp)(\mu_p E) = qp\mu_p E$$

Then we can define the total drift current density: j_T^{drift}:

$$j_T^{drift} = j_n^{drift} + j_p^{drift} = q(n\mu_n + p\mu_p)E = \sigma E$$

"σ": is the electrical conductivity, where:

$$\sigma = q(n\mu_n + p\mu_p)$$

$[\sigma] = (\Omega\cdot\text{cm})^{-1}$

"ρ" is electrical resistivity: $\rho = \frac{1}{\sigma}$

Note: $\rho = \frac{E}{j_T^{drift}}$: $\Omega \cdot cm = \frac{V/_{cm}}{A/_{cm^2}} \rightarrow \Omega = \frac{V}{A}$ → Ohm's law…

3. Doping

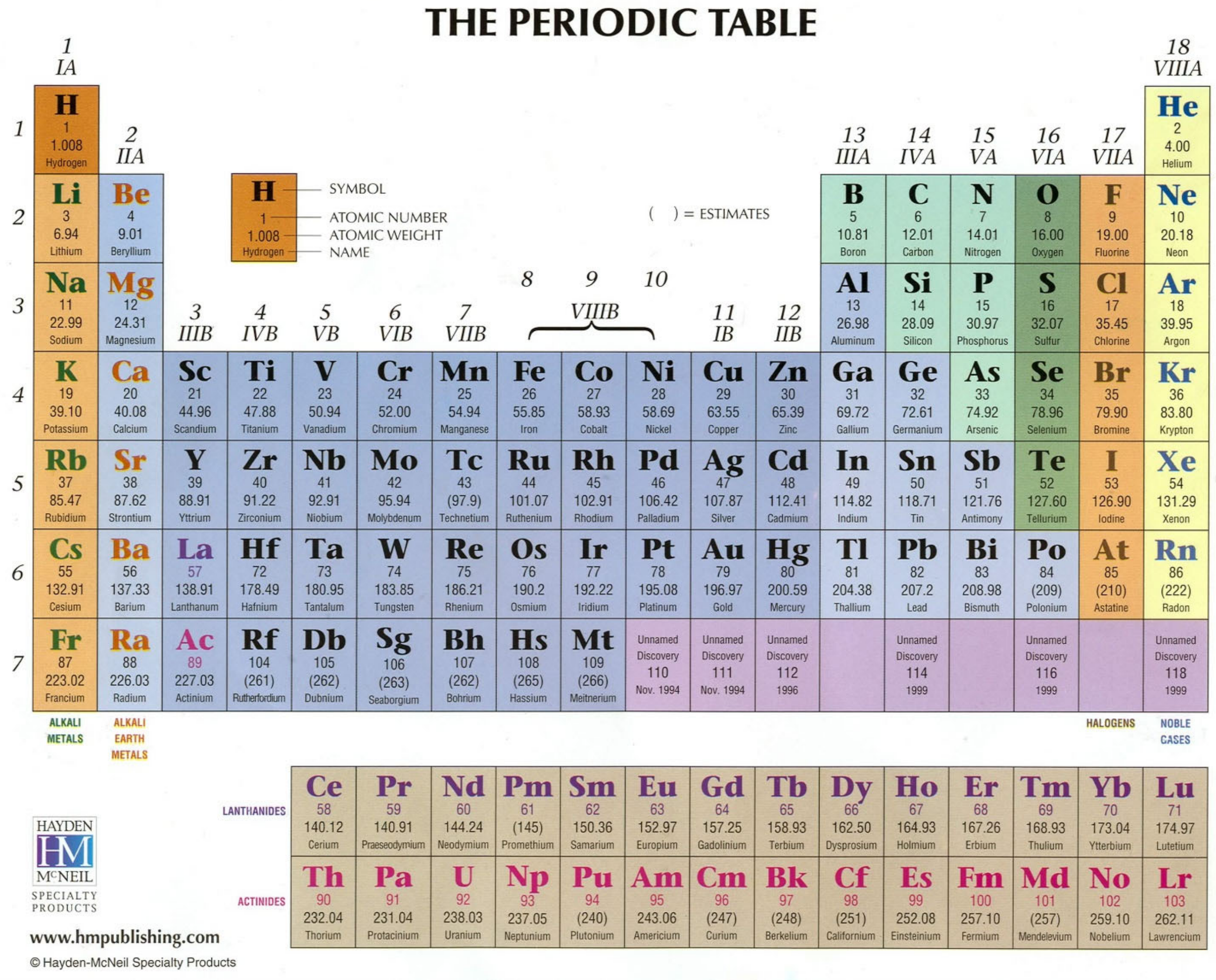
Doping is the process of adding impurities to the intrinsic semiconductor material.

Donor impurities: elements with one extra electron in their outer shell compared to the intrinsic semiconductor material. They will donate electrons.

Acceptor impurities: elements with one less electron in their outer shell compared to the intrinsic semiconductor material. They will donate holes.

Silicon is a Column IV element: it has 4 valence electrons in its outer shell.

Consider the periodic table below:



THE PERIODIC TABLE

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	**H** 1 1.008 Hydrogen																	**He** 2 4.00 Helium
2	**Li** 3 6.94 Lithium	**Be** 4 9.01 Beryllium											**B** 5 10.81 Boron	**C** 6 12.01 Carbon	**N** 7 14.01 Nitrogen	**O** 8 16.00 Oxygen	**F** 9 19.00 Fluorine	**Ne** 10 20.18 Neon
3	**Na** 11 22.99 Sodium	**Mg** 12 24.31 Magnesium											**Al** 13 26.98 Aluminum	**Si** 14 28.09 Silicon	**P** 15 30.97 Phosphorus	**S** 16 32.07 Sulfur	**Cl** 17 35.45 Chlorine	**Ar** 18 39.95 Argon
4	**K** 19 39.10 Potassium	**Ca** 20 40.08 Calcium	**Sc** 21 44.96 Scandium	**Ti** 22 47.88 Titanium	**V** 23 50.94 Vanadium	**Cr** 24 52.00 Chromium	**Mn** 25 54.94 Manganese	**Fe** 26 55.85 Iron	**Co** 27 58.93 Cobalt	**Ni** 28 58.69 Nickel	**Cu** 29 63.55 Copper	**Zn** 30 65.39 Zinc	**Ga** 31 69.72 Gallium	**Ge** 32 72.61 Germanium	**As** 33 74.92 Arsenic	**Se** 34 78.96 Selenium	**Br** 35 79.90 Bromine	**Kr** 36 83.80 Krypton
5	**Rb** 37 85.47 Rubidium	**Sr** 38 87.62 Strontium	**Y** 39 88.91 Yttrium	**Zr** 40 91.22 Zirconium	**Nb** 41 92.91 Niobium	**Mo** 42 95.94 Molybdenum	**Tc** 43 (97.9) Technetium	**Ru** 44 101.07 Ruthenium	**Rh** 45 102.91 Rhodium	**Pd** 46 106.42 Palladium	**Ag** 47 107.87 Silver	**Cd** 48 112.41 Cadmium	**In** 49 114.82 Indium	**Sn** 50 118.71 Tin	**Sb** 51 121.76 Antimony	**Te** 52 127.60 Tellurium	**I** 53 126.90 Iodine	**Xe** 54 131.29 Xenon
6	**Cs** 55 132.91 Cesium	**Ba** 56 137.33 Barium	**La** 57 138.91 Lanthanum	**Hf** 72 178.49 Hafnium	**Ta** 73 180.95 Tantalum	**W** 74 183.85 Tungsten	**Re** 75 186.21 Rhenium	**Os** 76 190.2 Osmium	**Ir** 77 192.22 Iridium	**Pt** 78 195.08 Platinum	**Au** 79 196.97 Gold	**Hg** 80 200.59 Mercury	**Tl** 81 204.38 Thallium	**Pb** 82 207.2 Lead	**Bi** 83 208.98 Bismuth	**Po** 84 (209) Polonium	**At** 85 (210) Astatine	**Rn** 86 (222) Radon
7	**Fr** 87 223.02 Francium	**Ra** 88 226.03 Radium	**Ac** 89 227.03 Actinium	**Rf** 104 (261) Rutherfordium	**Db** 105 (262) Dubnium	**Sg** 106 (263) Seaborgium	**Bh** 107 (262) Bohrium	**Hs** 108 (265) Hassium	**Mt** 109 (266) Meitnerium	Unnamed Discovery 110 Nov. 1994	Unnamed Discovery 111 Nov. 1994	Unnamed Discovery 112 1996		Unnamed Discovery 114 1999		Unnamed Discovery 116 1999		Unnamed Discovery 118 1999
	ALKALI METALS	ALKALI EARTH METALS															HALOGENS	NOBLE GASES

LANTHANIDES	**Ce** 58 140.12 Cerium	**Pr** 59 140.91 Praseodymium	**Nd** 60 144.24 Neodymium	**Pm** 61 (145) Promethium	**Sm** 62 150.36 Samarium	**Eu** 63 152.97 Europium	**Gd** 64 157.25 Gadolinium	**Tb** 65 158.93 Terbium	**Dy** 66 162.50 Dysprosium	**Ho** 67 164.93 Holmium	**Er** 68 167.26 Erbium	**Tm** 69 168.93 Thulium	**Yb** 70 173.04 Ytterbium	**Lu** 71 174.97 Lutetium
ACTINIDES	**Th** 90 232.04 Thorium	**Pa** 91 231.04 Protacinium	**U** 92 238.03 Uranium	**Np** 93 237.05 Neptunium	**Pu** 94 (240) Plutonium	**Am** 95 243.06 Americium	**Cm** 96 (247) Curium	**Bk** 97 (248) Berkelium	**Cf** 98 (251) Californium	**Es** 99 252.08 Einsteinium	**Fm** 100 257.10 Fermium	**Md** 101 (257) Mendelevium	**No** 102 259.10 Nobelium	**Lr** 103 262.11 Lawrencium

H — SYMBOL
1 — ATOMIC NUMBER
1.008 — ATOMIC WEIGHT
Hydrogen — NAME

( ) = ESTIMATES

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Observe that while Si is a class IV material, class V materials (such as P, As, and Sb) have 5 electrons in their outer shell, and are therefore <u>Donor Materials</u>.

Likewise, class III materials (such as B and Al) have 3 electrons in their outer shell, and are therefore <u>Acceptor Materials</u>.

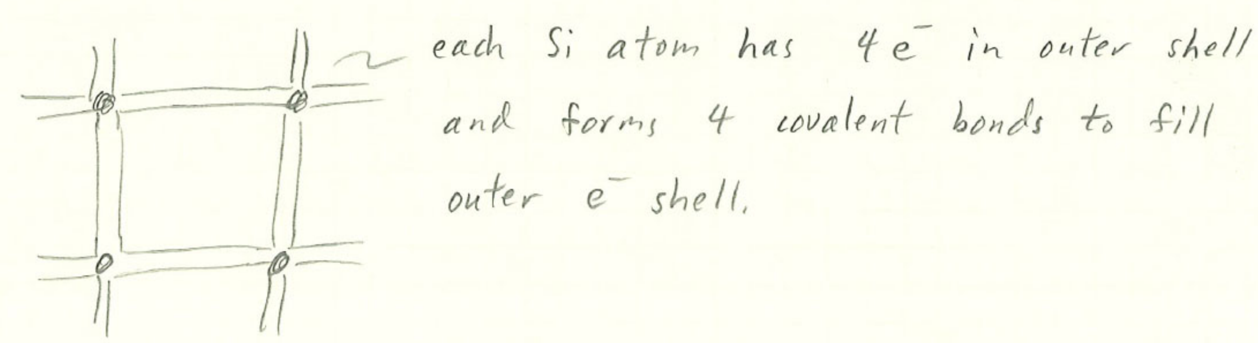
After an intrinsic semiconductor material has had a <u>donor impurity</u> added to it, it then requires very little thermal energy for a donor atom to give up its “extra” electron for conduction.

> This, however, results in a fixed +q charge which stays fixed in the crystal lattice.

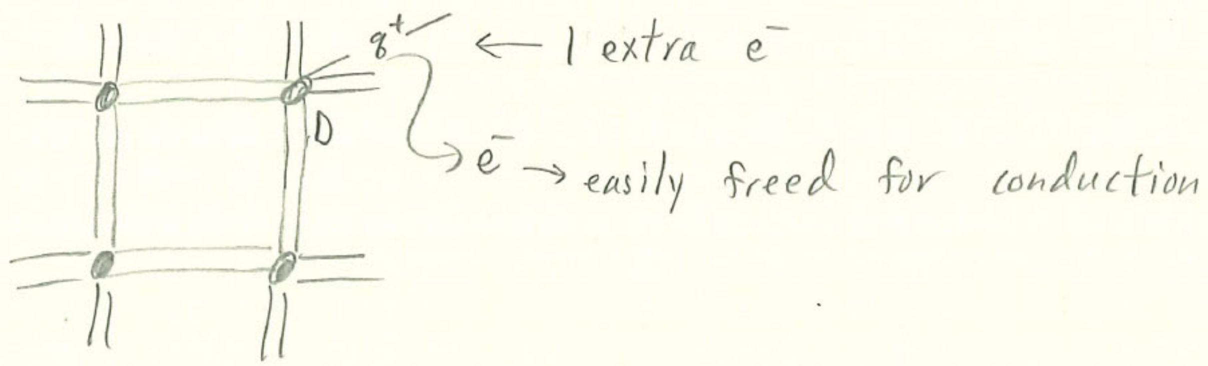
Similarly, after an intrinsic semiconductor material has had an <u>acceptor impurity</u> added to it, it is very easy for a nearby electron to move into this vacancy, creating a hole (i.e. vacancy) where the electron moved from in the covalent bond structure. The hole then can move through the crystal lattice: when an electron moves out and a hole moves to that atom, it has a +q charge. Each acceptor atom that accepts an electron has a –q <u>immobile charge</u> in the crystal lattice at that location.

This is illustrated pictorially below:

Intrinsic Si


each Si atom has 4 e^- in outer shell and forms 4 covalent bonds to fill outer e^- shell.

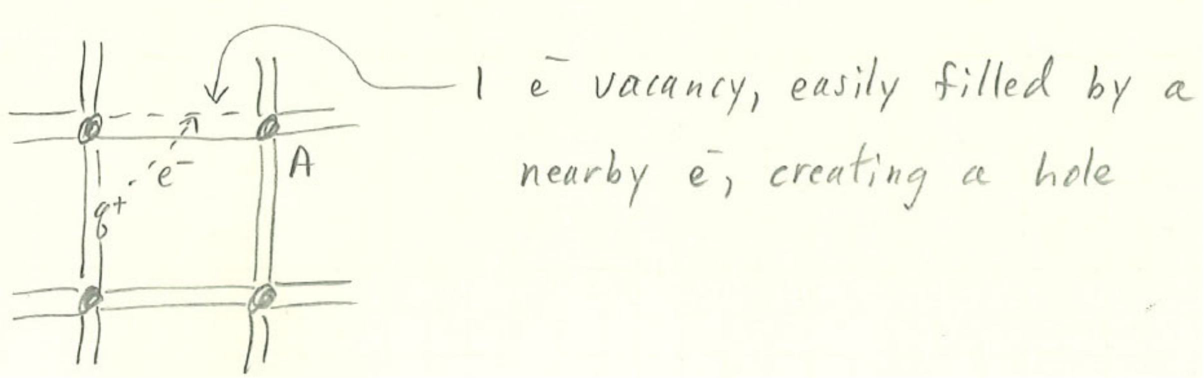
Donor atom in Si



← 1 extra e^-

e^- → easily freed for conduction

Acceptor atom in Si



1 e^- vacancy, easily filled by a nearby e^-, creating a hole

Due to doping impurities: if n > p: the material is called "n-type."

If p > n: the material is called "p-type."

The carrier with the larger population is called the "majority carrier."

The carrier with the smaller population is called the "minority carrier."

Define "N_D" as the donor impurity concentration: $[N_D]$ = atoms/cm^3.

Define "N_A" as the acceptor impurity concentration: $[N_A]$ = atoms/cm^3.

Note: after doping, the semiconductor material is still <u>charge neutral</u>.

Therefore: $q(N_D + p - N_A - n) = 0$.

Also: $pn = n_i^2$ still.

Electrical conductivity for a doped semiconductor:

For an n-type material: $\sigma \cong q\mu_n n \cong q\mu_n(N_D - N_A)$.

For an p-type material: $\sigma \cong q\mu_p p \cong q\mu_p(N_A - N_D)$.

Observe that increasing the dopant also increases the electrical conductivity.

4. Non-uniform Doping

When the doping is non-uniform, a gradient in the electron and hole concentration results.

This causes diffusion currents in the semiconductor.

Define: D_n as the electron diffusivity: $[D_n]$ = cm^2/s.

D_p as the hole diffusivity: $[D_p]$ = cm^2/s.

Now consider Einstein's relationship:

$$\frac{D_n}{\mu_n} = \frac{KT}{q} = \frac{D_p}{\mu_p}$$

You should recognize $\frac{KT}{q}$ as the thermal voltage, which is approximately 25 mV at room temperature.

Define j_n^{diff} and j_p^{diff} as the n and p diffusion current densities:

$$j_n^{diff} = (-q)D_n\left(-\frac{\partial n}{\partial x}\right) = +qD_n\frac{\partial n}{\partial x}, \quad \left[j_n^{diff}\right] = \text{A/cm}^2$$

$$j_p^{diff} = (+q)D_p\left(-\frac{\partial p}{\partial x}\right) = -qD_p\frac{\partial p}{\partial x}, \quad \left[j_n^{diff}\right] = \text{A/cm}^2$$

5. Total Current Density

The total current density in the semiconductor material is equal to the sum of the drift current density and the diffusion current density:

$$j_n^T = q\mu_n nE + qD_n\frac{\partial n}{\partial x} = q\mu_n n\left(E + V_T\frac{1}{n}\frac{\partial n}{\partial x}\right)$$

$$j_p^T = q\mu_p pE - qD_p\frac{\partial p}{\partial x} = q\mu_p p\left(E + V_T\frac{1}{p}\frac{\partial p}{\partial x}\right)$$

6. Energy Band Model (for a semiconductor)

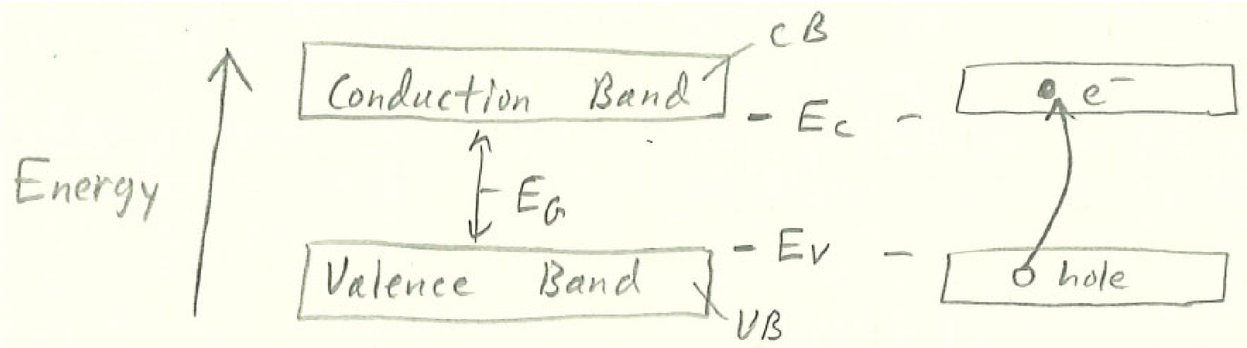
Define these terms:

"E_c" = Conduction Band: the lowest energy level in the conduction band.

"E_v" = Valence Band: the highest energy level in the valence band.

"E_G" = Bandgap Energy: $E_G = E_c - E_v$

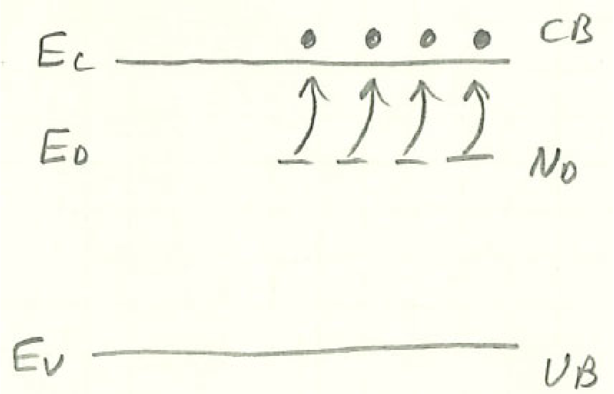
The creation of an electron-hole pair can be represented pictorially:



In the drawing above, an electron-hole pair is created when an electron moves from the valance band to the conduction band. For example, due to thermal energy. The electron cannot have an energy level between E_c and E_v.

a. For n-type Semiconductor

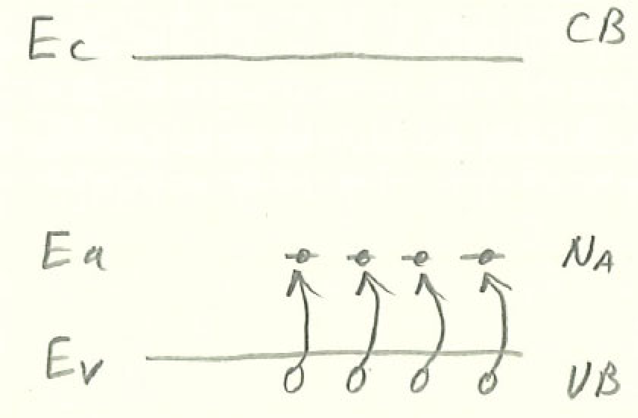
Let E_D be the donor energy level (near the conduction band edge).



E_D is so close the E_C that almost all electrons at E_D have moved to the CB and are available for conduction.

b. For a p-type Semiconductor

Let E_a be the acceptor energy level, which is near the valence band edge.



E_v is so close to E_a that almost all acceptor sites are filled, leaving holes in the valence band for conduction.

c. Compensated semiconductors

Compensated semiconductors have both donor and acceptor impurities.

Electrons seek the lowest energy state, and fill all available acceptor sites.

The remaining free electron population is n: $n = N_D - N_A$.