

Tuesday, 1/21/25

Review of Solid State Physics, Continued

1. Background

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

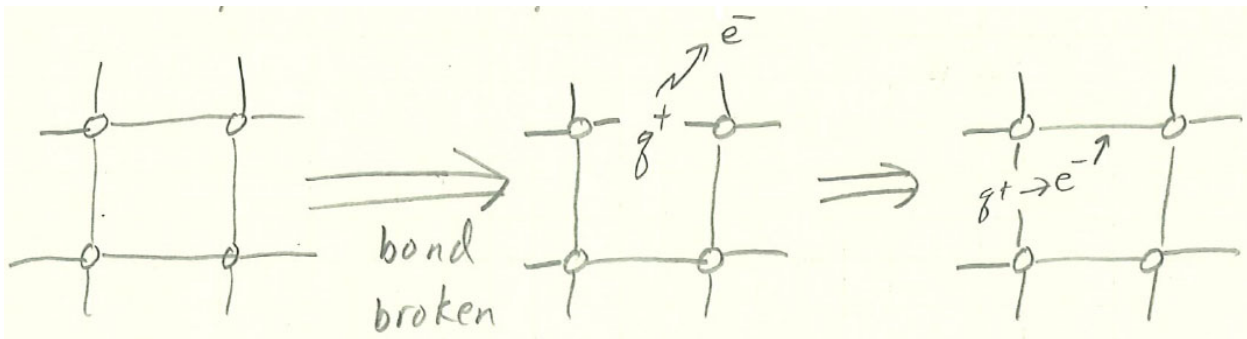
$$[n] = e^-/\text{cm}^3$$

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 $q = 1.62 \times 10^{-19}$ C.

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

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

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

“ ρ ” is the electrical resistivity.

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

2. Drift Currents

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

$$j = Qv, [j] = \text{A/cm}^2$$

Q is charge density, $[Q] = \text{C/cm}^3$

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

$$[v] = \text{cm/s}$$

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: $1350 \text{ cm}^2/\text{V}$ for intrinsic Si

μ_p is the hole mobility, $500 \text{ cm}^2/\text{V}$ for intrinsic Si

Notice that $\mu_n > \mu_p$. This is because electrons can move freely through 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.

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

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

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																	18 VIIIA	
1 H 1 1.008 Hydrogen																	He 2 4.00 Helium	
2 IIA	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	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	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

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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 Protactinium	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

([https://www.ajax4hire.com/Periodic_Table/Periodic_Table_of_Elements\(hmpublishing.com\).jpg](https://www.ajax4hire.com/Periodic_Table/Periodic_Table_of_Elements(hmpublishing.com).jpg))

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 Donor Materials.

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

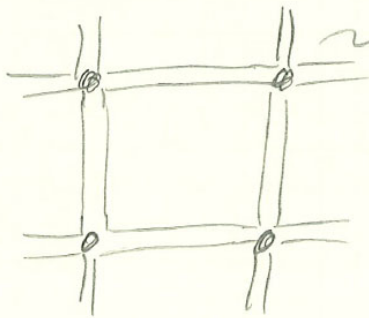
After an intrinsic semiconductor material has had a donor impurity added to it, it then requires very little thermal energy for a donor atom to give up its “extra” electron for conduction.

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

Similarly, after an intrinsic semiconductor material has had an acceptor impurity 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 $-q$ immobile charge in the crystal lattice at that location.

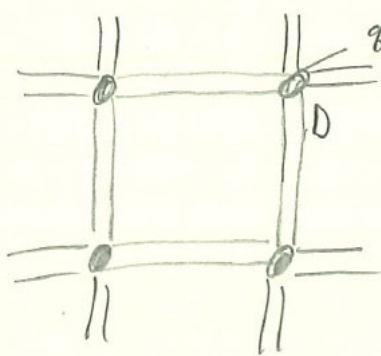
This is illustrated pictorially below:

Intrinsic Si



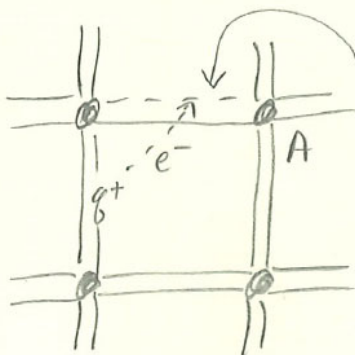
each Si atom has $4e^-$ in outer shell and forms 4 covalent bonds to fill outer e^- shell.

Donor atom in Si



q^+ ← 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: $[N_D] = \text{atoms/cm}^3$.

Define “ N_A ” as the acceptor impurity concentration: $[N_A] = \text{atoms/cm}^3$.

Note: after doping, the semiconductor material is still charge neutral.

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: $[D_n] = \text{cm}^2/\text{s}$.

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

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:

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

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

5. Total Current

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

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

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

6. Energy Band Model (for a semiconductor)

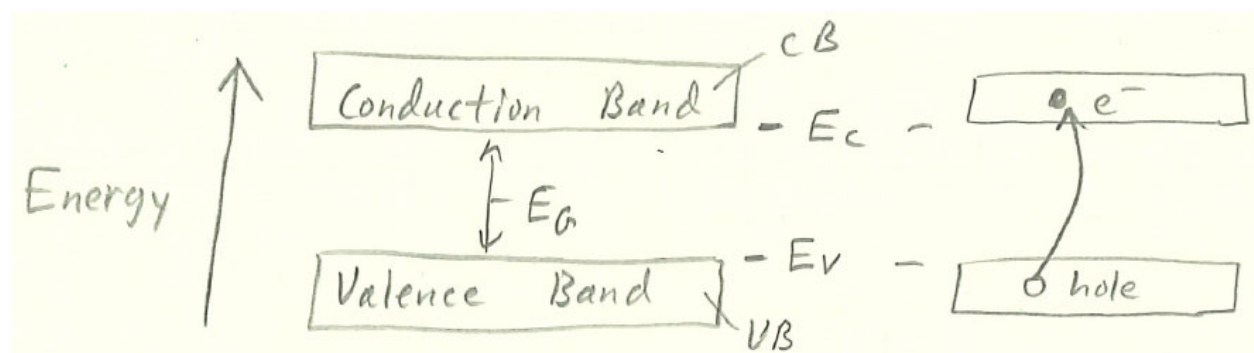
Define these terms:

“ 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: $E_G = E_c - E_v$

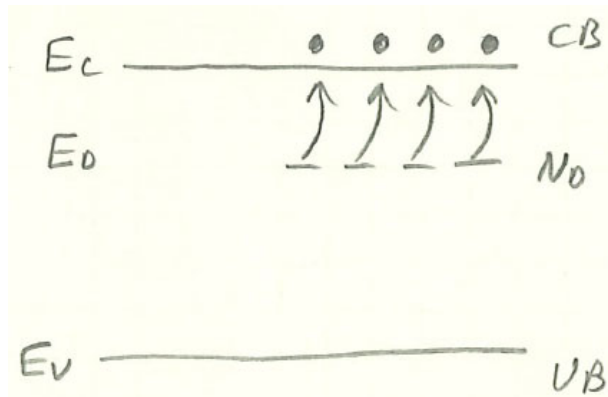
The creation of an electron-hole pair can be represented pictorially:



In the drawing above, an electron-hole pair is created when an electron moves from the valence 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

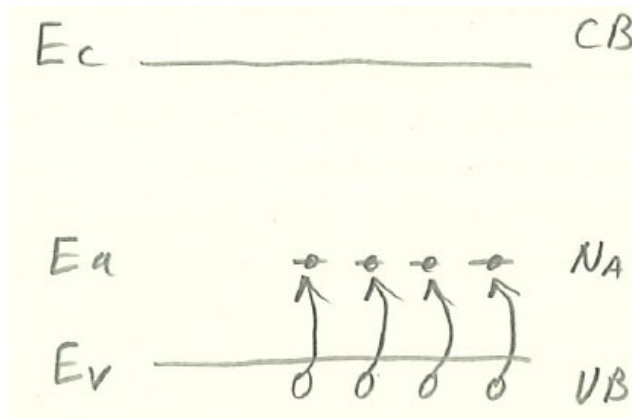
Let E_D be the donor energy level (near the conduction band edge).



E_D is so close to 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 $n: n = N_D - N_A$.

