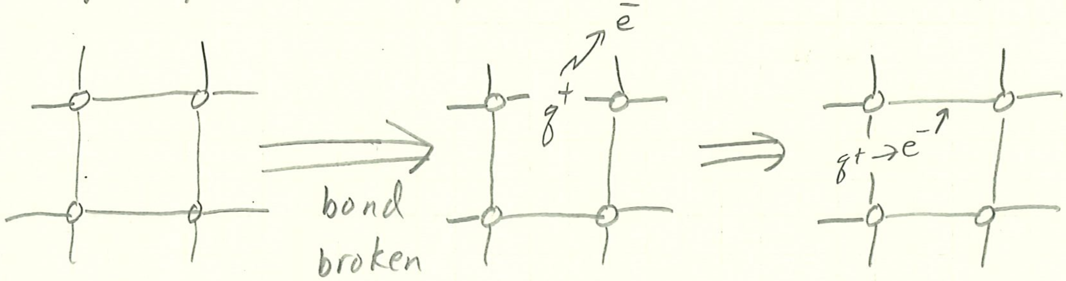
$n \equiv$ density of conduction (or free) electrons

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

For intrinsic Si : $n_i = n$

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



Energy $\geq E_G$ results in the creation of an electron-hole pair

→ electrons can move anywhere

→ holes can only move about the crystal lattice

Electrons and holes are charge carriers

$$\begin{array}{ccc} \downarrow & & \downarrow \\ -q & & +q \end{array} \Rightarrow q = 1.62 \times 10^{-19} C$$

$p \equiv$ hole density , $[p] =$ holes/cm^3

For intrinsic Si : $n_i = n = p$

$n_i^2 = pn$ → whenever there is thermal equilibrium w/o external stimulus (voltage, current, light)

Electrical resistivity $\equiv \rho = 1/\sigma$, $\sigma \equiv$ conductivity

a. Drift Currents

charged particles move (drift) in response to an applied electric field

→ results in a drift current, j

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

$Q \equiv$ charge density, $[Q] = C/cm^3$

v = charge velocity in the electric field

↳ also called "carrier drift velocity"

$[v] = cm/s$

positive charges move in direction of the E field

negative charges move in opposite direction of the E field

For low electric fields : $v \propto E$ → of interest to this class

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

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

where $\vec{v}_n$ = velocity of electrons

$\vec{v}_p$ = velocity of holes

μ_n = electron mobility, 1350 cm^2/V for intrinsic Si

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

Notice $\mu_n > \mu_p$: e^-'s can move freely through crystal while holes can only move about the crystal through the covalent bond structure

Electron and hole drift current densities, j_n^{drift} and j_p^{drift}

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

1-D vectorless equation versions:

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

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

Total drift current density $\equiv j_T^{drift}$

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

σ = electrical conductivity $= q(n\mu_n + p\mu_p)$, $[\sigma] = (\Omega\text{-cm})^{-1}$

$\rho = 1/\sigma \equiv$ resistivity

Note: $\rho = \dfrac{E}{j_T^{drift}}$; $\Omega \cdot cm = \dfrac{V/cm}{A/cm^2}$

$$\Downarrow$$

$$R = \frac{V}{I} \rightarrow \text{Ohm's law}$$

3. Doping

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

Donor Impurities - one extra e^- in outer shell: donate e^-'s

Acceptor Impurities - one less e^- in outer shell: donate holes

Si: a Column IV element: 4 valence e^-'s in outer shell

THE PERIODIC TABLE

Period	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	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 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

Key: H — SYMBOL; 1 — ATOMIC NUMBER; 1.008 — ATOMIC WEIGHT; Hydrogen — NAME

( ) = ESTIMATES

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1. Class V materials (such as P, As, Sb) have 5 valence electrons in outer shell → <u>Donor Materials</u>

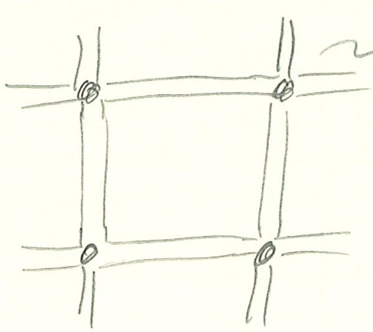
Class III materials (such as B, Al) have 3 valence electrons in outer shell → <u>Acceptor Materials</u>

→ With a <u>donor impurity</u> → it requires very little thermal energy for the donor atom to give up its extra e^- for conduction.

* Results in a fixed $+q$ charge which stays fixed in the crystal lattice

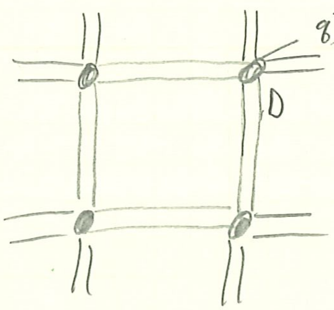
→ With an <u>acceptor impurity</u> → it is easy for a nearby e^- to move into this vacancy, creating another vacancy (hole) in the bond structure. This hole can move through the crystal lattice. When an e^- moves out and the hole moves to that atom, it has a $+q$ charge. Each acceptor atom that accepts an e^- has a $-q$ <u>immobile charge</u> in the crystal lattice.

<u>Intrinsic Si</u>



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

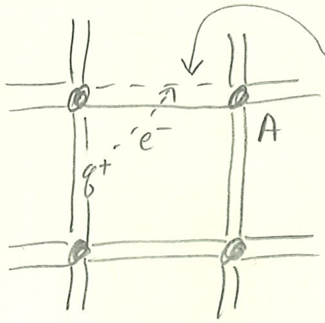
Donor atom in Si



← 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 $n > p$: material is called n-type

if $p > n$: material is called p-type

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

The " " " smaller " " " "minority carrier"

N_D = donar impurity concentration (atoms/cm³)

N_A = acceptor " " (atoms/cm³)

Note: the semiconductor material is still charge neutral

$$\therefore\ q(N_D + p - N_A - n) = 0$$

Also : $pn = n_i^2$ still

$\sigma \cong q\mu_n n \cong q\mu_n(N_D - N_A)$ for n-type material

$\sigma \cong q\mu_p p \cong q\mu_p(N_A - N_D)$ for p-type material

2. Nonuniform Doping

→ results in gradients in the e^- and hole concentrations

∴ resulting in diffusion currents

D_n = electron diffusivity, cm^2/s

D_p = hole diffusivity, cm^2/s

Einstein's relationship : $\frac{D_n}{\mu_n} = \frac{KT}{q} = \frac{D_p}{\mu_p}$

$\frac{KT}{q} = V_T \equiv$ thermal voltage

$V_T \approx 25\,mV$ at room temperature

Diffusion current density : j_p^{diff} and j_n^{diff}

$$j_p^{diff} = (+q)D_p\left(-\frac{\partial p}{\partial x}\right) = -q D_p \frac{\partial p}{\partial x} \qquad (A/cm^2)$$

$$j_n^{diff} = (-q)D_n\left(-\frac{\partial n}{\partial x}\right) = +q D_n \frac{\partial n}{\partial x} \qquad (A/cm^2)$$

3. Total Current = drift current + diffusion current

Total electron current density = j_n^T

Total hole current density = j_p^T

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

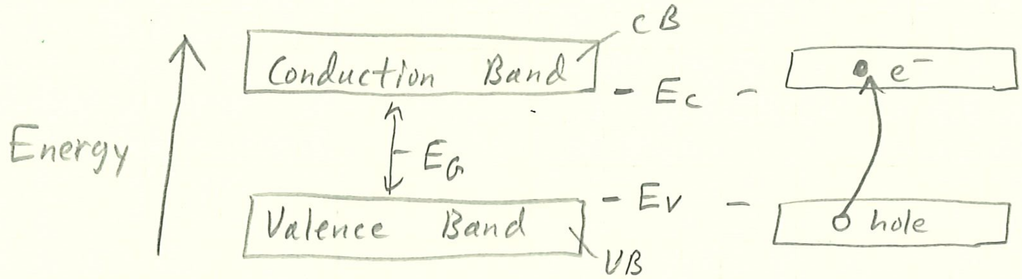
$$j_p^T = q\mu_p p E - q D_p \frac{\partial p}{\partial x} = q\mu_p p \left(E - V_T \frac{1}{p}\frac{\partial p}{\partial x}\right)$$

3. <u>Energy Band Model</u> for a semiconductor

Conduction Band : E_C = lowest energy level in conduction band

Valence Band : E_V = highest energy level in valence band

Energy Bandgap : $E_G = E_C - E_V$

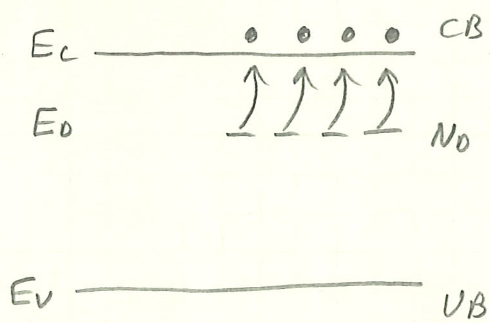


An electron-hole pair is created when an e^- moves from the valence band to the conduction band

→ for example, due to thermal energy

a. <u>For n-type semiconductor</u>

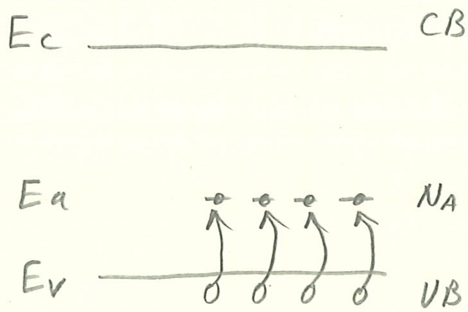
E_D = donor energy level → near conduction band edge



E_D is so close to E_C that almost all e^-'s at E_D have moved to CB and are available for conduction

b. <u>For p-type semiconductors</u>

E_a = acceptor energy level → near valence band edge



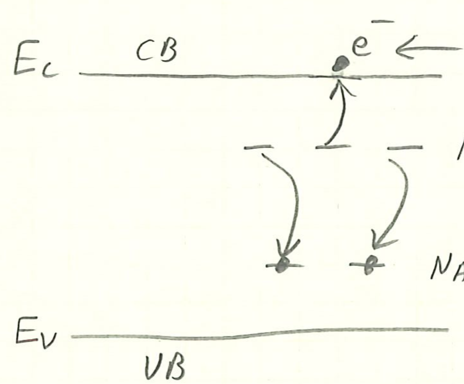
E_v is so close to E_a that almost all acceptor sites are filled, leaving holes in the valence band for conduction.

c. <u>Compensated semiconductors</u> : both donor and aceptor impurities

→ e^-'s seek the lowest energy state, and fill all available aceptor sites.

→ remaining free e^- population $= n = N_D - N_A$

For $N_D > N_A$:



← available for conduction

↓

<u>Note</u> : e^- is above E_c line!