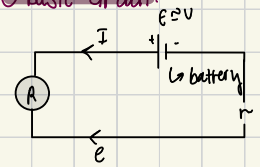
electronics

lecture one: classic electricity

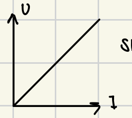
① basic circuit:



(current) $I = \frac{dq}{dt} = \frac{\Delta q}{\Delta t}$ $\Delta q = ne \rightarrow 1.6 \times 10^{-19} C$

num. of electrons

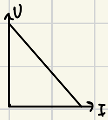
② Ohm's law: $U_R = RI$



slope = resistance (constant)

$U_{battery} = E - I_r$

constant



③ diode:

(based on junction: 2 materials together)

④ all electronic devices are based on semiconductors

semiconductors: transfers electricity

- Insulators → low density of free electrons
- Conductors → high density of free electrons
- Semiconductors → medium density " " " with respect to the density of the atoms

in general, we compare the denisty of free electrons to the density of atoms (the concept of conductivity). when the rate is relatively high → its a conductors, relatively low → insulator, and in the middle → semi-conductor

note: electrons are actually like waves in a cloud in the outher layer of an atom

⑤ electric field: difference in potential; effects the charges

relation that gives the density of free electrons in any material:

Intrinsic: pure materials without modification

$$n_i \equiv n_i(T) = 5.2 \times 10^{15}\, T^{3/2} \exp\left(\frac{-E_g}{2KT}\right)$$

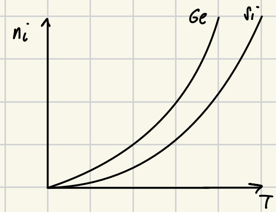
n_i: density of free electrons per cm3

T: temperature

E_g: gap energy depends on the material itself (usually given in joules)

K: Boltzman's constant $= 1.38 \times 10^{-23}$ J/kelvin

convert from celsius to kelvin: $T_{C°} + 273 = T_{K°}$



note: the material that has the bigger gap comes 1st

example: at 300K°

$$n_i\ (Si \text{ at } 300\,K°) = 5.2 \times 10^{15} (300)^{3/2}\, e^{\left(\frac{-1.12 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300}\right)}$$

$E_g(Si) = 1.12\ ev$

$1ev = 1.6 \times 10^{-19} J$

→ $n_i\ (Si \text{ at } 300\,K°) \simeq 10^{10}$ e/cm3

compared to 10^{20} atom/cm3

note: in every atom → so they are neutral

- e electrons (-)
- O Holes (+) } the hole that's left behind when the e^- jumps

$n = p$ → density of holes } in internsic materials

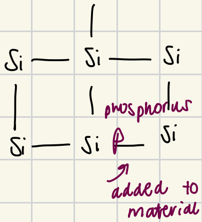
n: density of free electrons

$$\boxed{n_i \times p = n_i^2}$$

o doping:

we need to increase the density of free electrons or holes. by inserting an amount of other materials to the atoms, we drastically increase the density of charge carriers (either electrons or holes)

for Si or Ge (4^{th} IV):



each Si atom bonds with the 1^{st} 4 neighbors by 4 covalent bonds.

1) first type: n-type

n referring to electrons. we need to add atoms (ex: of group 5, phosphorus P)

n_d: density of added phosphorus or donor of electrons

→ n becomes $\cancel{n_i}$ + n_d (becomes the ni)

↳ this is neglected $<$ $(10^{10} + 10^{15})$

in consequence, the density of holes decreases drastically. according to the law $n \times p = n_i^2$

$$p(\text{minority}) = \frac{n_i^2}{n_d}$$

by symmetry or analogy: we can use the p-type dopage

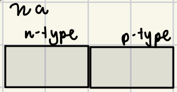
2) 2^{nd} type: p-type:

p refers to holes. this is by adding an acceptor element (such as of group 3: B boron), we increase the density of holes.

n_a: density of added acceptors

$n_a \approx p$ (majority carriers) → n drastically decreases.

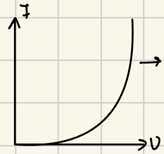
$$n = \frac{n_i^2}{n_a}$$



o junction:

a junction is made by adding 2 doped semi-conductors of, respectively, n-type and p-type. this new device is the basic element diode

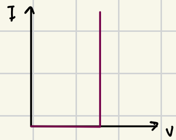
- the idea of the junction is to have a new (I,U) characteristic which is completely different from the resistor behaviour



→ $I_D = I_S \exp\left(\frac{V_D}{V_T} - 1\right)$

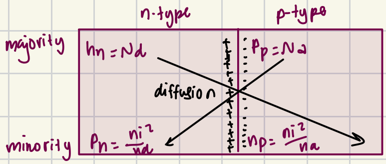
I_S and V_T = cst (depends on the material and its temperature) → they are the parameters

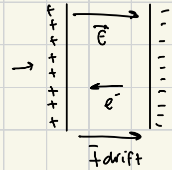
often, we will use a simplified version:



constant voltage model (acting like an open switch)

$|I_{drift}| = |I_{diffusion}|$





two type of currents:

1 drift current:

when a potential difference or electric field is created in a conductor. electrons are flowing and a current is drifting (it is generated)

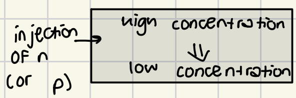
$$J = \frac{I_{drift}}{S} = |\mu_n n + \mu_p p| \times \mathcal{E} \times q$$

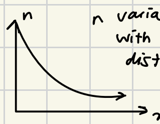
current; known density; electric field; electric charge (1.6×10^{-19} C)

section = surface of side

mobility of electrons and holes

2 diffusion current:





n variable with distance

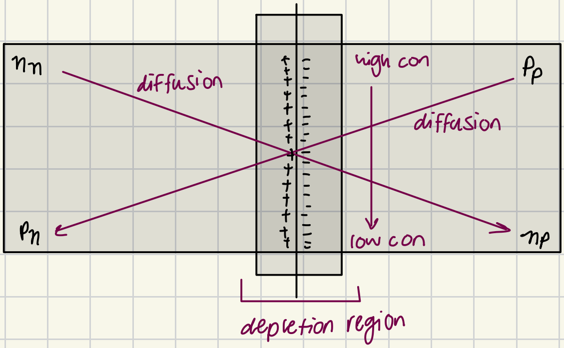
diffusion of n (electrons) from high to low concentration levels → diffusion current is generated (without applying an electric field)

$$J_{diffusion} = \frac{I_{diffusion}}{S} = \left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right) \times q$$

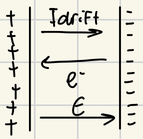
variation of n

diffusivity of n(electrons) and p(holes)

p moves opposite to n



in depletion region (zoomed):



so $I_{drift} \rightarrow$ $\quad \leftarrow I_{diffusion}$

→ drift is opposing to diffusion

→ potential difference / electric field region

At equilibrium:

$$I_{drift} = I_{diffusion}$$

$$\mu_p P q E = D_p \frac{dp}{dx} q$$

$$\frac{dp}{p} = \frac{\mu_p}{D_p} E \, dx$$

$P_p = N_A$

$P_n = \frac{n_i^2}{N_D}$

$$\ln p \Big|_{P_n}^{P_p} = \frac{\mu_p}{D_p} \int_{n_i}^{n_i^2} E \, dx$$

$$= V_2 - V_1 = V_0$$

$$\frac{\mu_p}{D_p} = q/KT$$

$$\boxed{V_0 = \frac{KT}{q} \ln\left(\frac{N_A \times N_D}{n_i^2}\right)}$$

(just know what the formula means)

at equilibrium:

$$V_{thermal} = \frac{KT}{q} \ln\left(\frac{N_a \times N_D}{n_i^2}\right)$$

at $T = 300K \rightarrow \frac{KT}{q} = 26$ mV

for silicon (Si): $n_i = 10^{10}$

$\rightarrow N_a = N_a \approx 10^{16}$

$$\rightarrow 26 \times \ln\left(\frac{10^{16} \times 10^{16}}{10^{10}}\right) = 26 \times \ln(10^{12})$$

$= 718.4 \approx 720$ mV

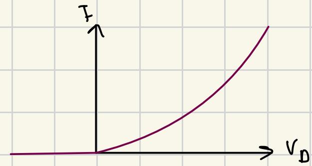
$V_{thermal} \approx 720$ mV

battery in intrinsic has voltage → logically

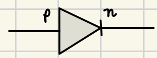
$$\boxed{I_D = I_S \exp\left(\frac{V_D}{V_{thermal}} - 1\right)}$$

diode

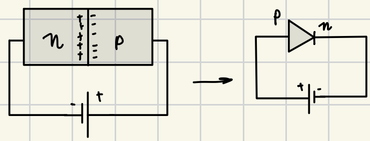
constant given in question



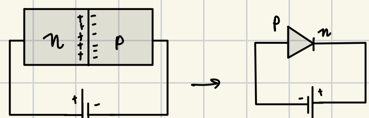
diode:



forward bias:

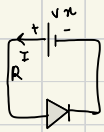


reverse bias:



→ junction doesn't work but acts as an open switch (diode)

week 8:

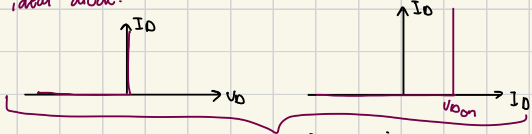


circuit's law: the summation of all the voltages equals to zero

$$-V_x + IR + V_D \overset{?}{=} 0$$

$$-V_x + IR + \ln\left(\frac{I}{I_S}\right) \times V_T = 0$$

ideal diode:



both are simplified versions of constant voltage model

objective: we will try to familiarize using a diode in simple circuits in order to:

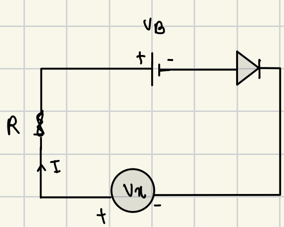
1. find at which critical (point) voltage of the source (V_x ?) the diode will be in the "on mode"
2. we have to draw the characteristics (I, V_x) ; (V_D, V_x); ...

I vs V_x

important V_D vs V_x

* In a general way, to find the critical point (V_{x_1}) we consider the case where the current is flowing, we write its expression of I in terms of V_x (we consider I to be positive), then we find V_{x_1}.

example one:



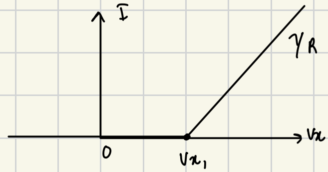
using the constant voltage model where the diode has V_{Don} (V_B and V_{diode} are not variables but we don't know their values)

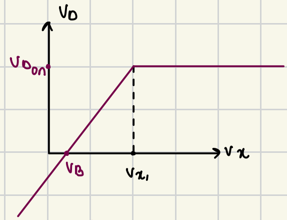
① assume that the current is flowing

$V_x - V_{Don} - V_B - IR = 0$ (we decided to read it counter clockwise)

$$I = \frac{+V_x - V_{Don} - V_B}{R}$$

for $V_x > \underset{V_{x_1} =}{\boxed{(V_{Don} + V_B)}}$, I exists, the diode is on





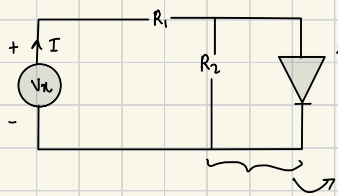
to find how V_D varies with V_x before V_{x_1}:

for $V_x < V_{x_1}$

$V_x = V_B + V_D$

$\longrightarrow V_D = V_x - V_B$ so its a straight line

example two: ideal diode ($V_{Don} = 0$)



$R = 0$

$^1/_{Req} = {^1/_0} + {^1/_{R_2}}$

$^1/_{Req} = \infty$

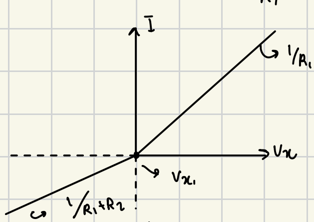
$\rightarrow Req = 0.$

assumption 1: the diode is in the "on mode"

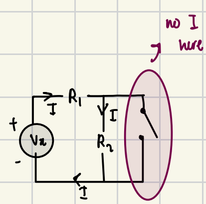
the diode acts as a conducting wire

$\longrightarrow V_x = IR_1 \quad (-V_x + IR)$

$$I = \frac{V_x}{R_1}$$



no I here

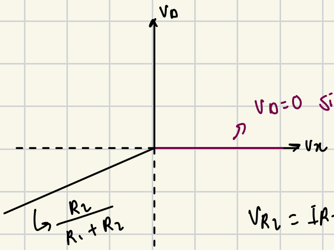


for $V_x < 0 \longrightarrow$ the diode has no current (open switch), but the rest has current passing through them

$$-V_x + IR_1 + IR_2 = 0$$

$$-V_x + I(R_1 + R_2) = 0$$

$$\longrightarrow I = \frac{V_x}{(R_1 + R_2)}$$



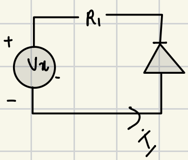
$V_D = 0$ since it's ideal

for $V_x < 0$

$\rightarrow V_D = V_{R_2}$

$$V_{R_2} = I R_2 = \frac{V_x R_2}{(R_1 + R_2)}$$

example 3:



1. find V_{x_1}
2. find (I, V_x)
3. find (V_D, V_x)

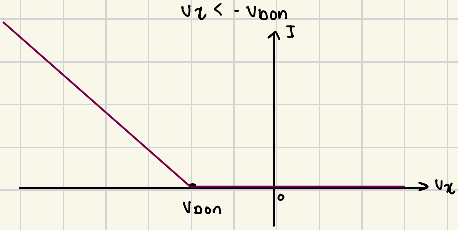
$$V_x + V_{Don} + RI = 0$$

$$I = \frac{-V_x - V_{Don}}{R}$$

$$-V_x - V_{Don} > 0$$

$$-V_x > V_{Don}$$

$$V_x < -V_{Don}$$



if there's no current:

$$V_D = V_x$$