CONDUCTION MECHANISMS

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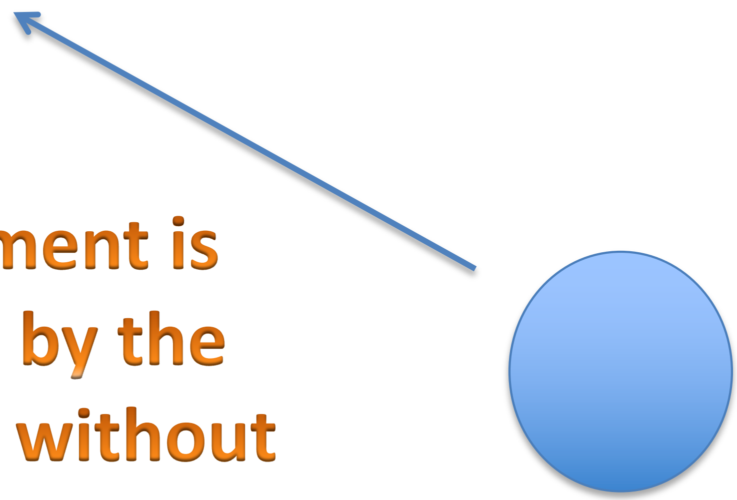


This advertisement is brought to you by the happy electron : without whom, we would not have much of a major!

Equilibrium: No energy exchange with external world; no current flow!

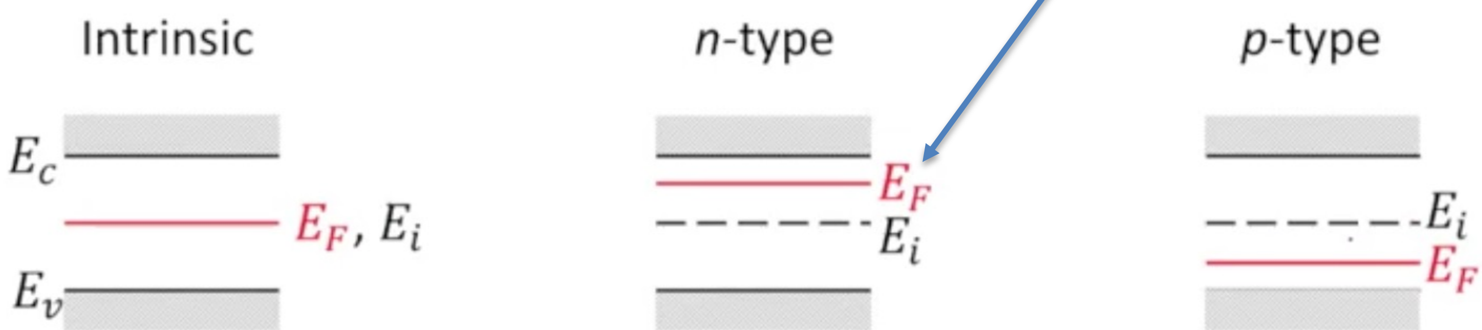
Review of Basic Concepts

- Intrinsic = no dopants
- Extrinsic = dopants

page 8-9 (text)

HW eq at PG 4

Fermi level depends on doping!



$q \cdot \phi_F < 0$

$q \cdot \phi_F > 0$

$$n_i^2 \begin{cases} p_0 = n_i \cdot e^{(E_i - E_F)/k \cdot T} \\ n_0 = n_i \cdot e^{(E_F - E_i)/k \cdot T} = n_i \cdot e^{-\phi_F/\phi_t} \end{cases}$$

$$\phi_F \equiv (E_i - E_F)/q$$

Fermi potential

$$\phi_t \equiv k \cdot \mathrm{T}/q$$

Simplified from Fermi-Dirac statistics to Maxwell-Boltzmann statistics

Non-equilibrium : energy exchange with external world: current flow

- Things have changed that energy is now in the system!

$$p = n_i \cdot e^{\left[\frac{E_i - E_{F_p}}{k \cdot T}\right]}$$

$$n = n_i \cdot e^{\left[\frac{E_{F_n} - E_i}{k \cdot T}\right]}$$

Imrefs (imagination reference) or quasi Fermi levels

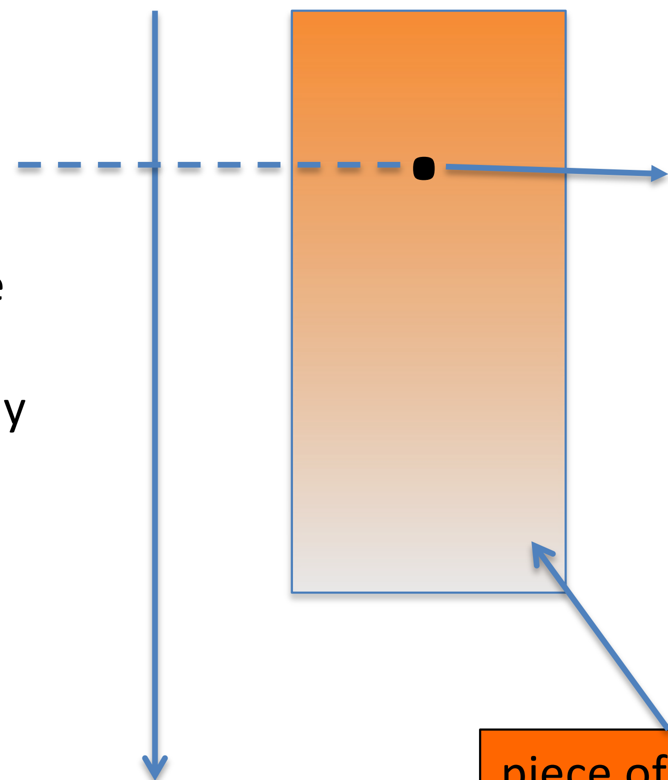
$$\left.\begin{array}{c} E_{F_p} \neq E_{F_n} \\ n \cdot p \neq n_i^2 \end{array}\right\} \text{In general}$$

Charge, Density, Electric Field, and Potential in 1D

one dimensional charge

More info in Appendix A

y



Charge
varies
vertically

$$\rho(y), \varepsilon(y), \psi(y)$$

charge density, electric field, potential

$$\rho = q \cdot (p - n + N_D - N_A)$$

<u>Total</u> charge density assumes all are present more or less at same time!

piece of
semiconductor

Poisson’s Equation

Energy cannot be created or destroyed; overall charge must be maintained. Therefore, the structure must remain electrically neutral overall which is called the *principle of charge neutrality*.

- Poisson’s equation is the basis for most charge that is computed within a given piece of material.

More info in Appendix A

$$\rho = q \cdot (p - n + N_D - N_A)$$

$$\frac{d\varepsilon}{dy} = \frac{\rho(y)}{\epsilon_S}$$

Electric Field vs. Charge Density

becomes

second derivative

$$\varepsilon(y) = -\frac{d\psi}{dy}$$

Electric Field vs. Potential

deriv

$$\boxed{\frac{d^2\psi}{dy^2} = -\frac{\rho(y)}{\epsilon_S}}$$

Poisson’s Equation

ϵ_S is a proportional constant called permittivity

$$\epsilon_S = k_S \cdot \epsilon_0$$

$\varepsilon_0 = 8.854\times10^{-14}$ F/cm

$k_s = 11.9$ silicon

perm of free space

Integrate over a 1D line

- If we take the previous equations and integrate them from point y_0 to point y, we can get equations for Electrical field and Potential at point y

Equivalent Integral Forms

$$\varepsilon(y) = \varepsilon(y_0) + \frac{1}{\varepsilon_s} \cdot \int_{y_0}^{y} \rho(y) \cdot dy$$

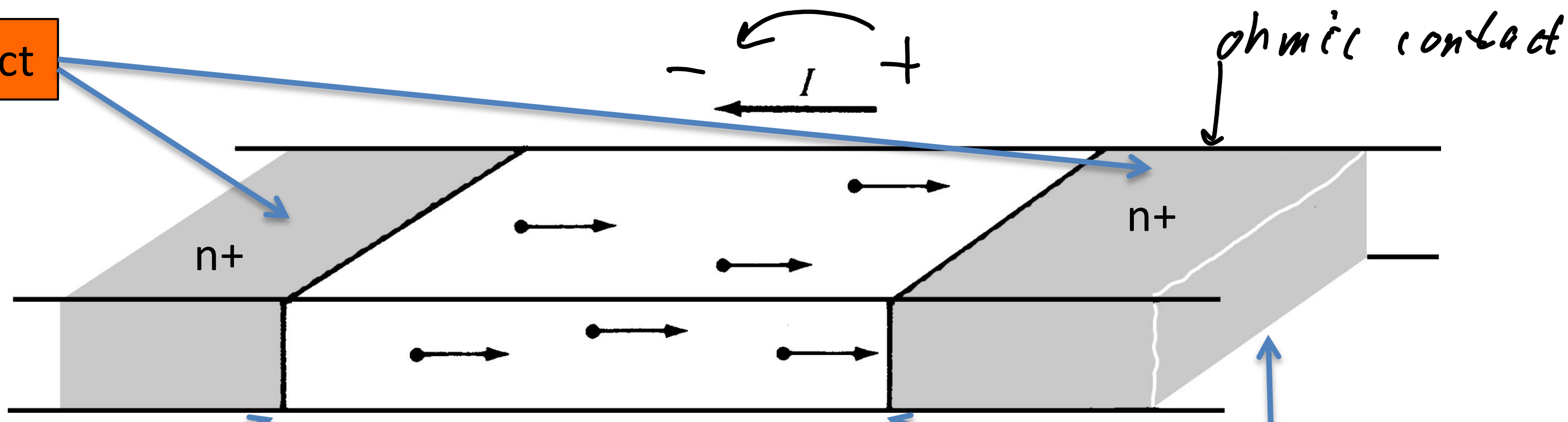
$$\psi(y) = \psi(y_0) - \int_{y_0}^{y} \varepsilon(y) \cdot dy$$

Now, let's move towards conduction mechanisms in a semiconductor – that is, the mechanism responsible for electric current.

Simple Conduction Mechanism

(mechanism responsible for electrical current)

Contact



Point A

Total charge: Q

Point B

FIGURE 1.10 A piece of material with electrons flowing toward the right.

how long it takes

Assume uniform motion with transit time τ (from beginning until end of semiconductor) : flow

Sometimes called ohmic contact – we'll see this more of this later!

Transit Time

- Let's use this transit time to break the conduction or total charge Q across the block from point A to point B.

$$I = \frac{|Q|}{\tau} \qquad \tau = \frac{|Q|}{I}$$

Sometimes this is used as the definition of transit time.

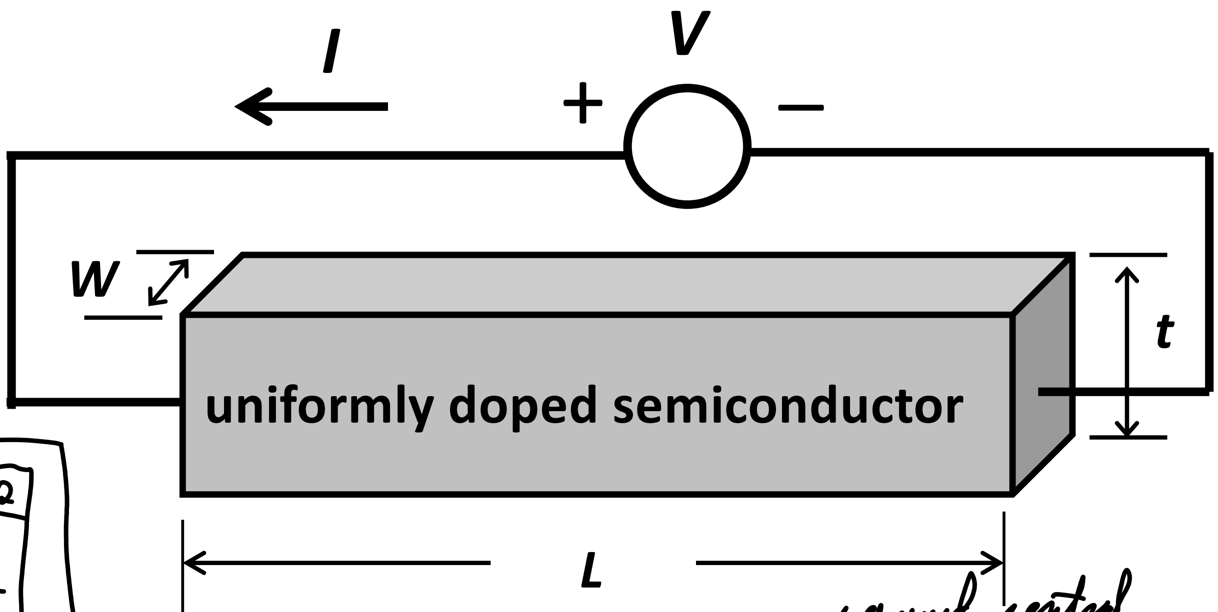
Two main mechanisms for carrier transport in semiconductors:

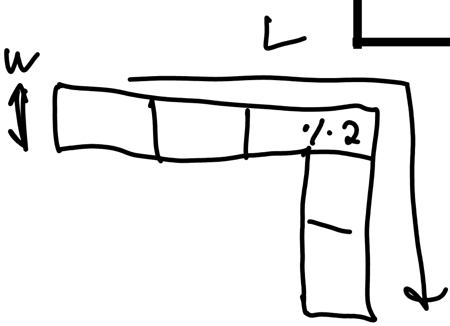
1. Drift (due to electric field)
2. Diffusion (due to thermal energy/random = concentration gradients)

To get conduction, we have to displace the energy by placing a power source across the device. This will infer electron movement by thermal agitation of the crystal lattice, which is a complicated type of motion, if the temperature is above absolute 0.

https://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity

Electrical Resistance





$$\sigma = \frac{1}{\rho} = \frac{J}{E}$$

cannot control

R_s

Resistance

$$R \equiv \frac{V}{I} = \rho \cdot \frac{L}{A} = \rho \cdot \frac{L}{W \cdot t} = \boxed{\frac{\rho}{t}} \cdot \frac{L}{W}$$

[Unit: ohms]

can control

where ρ is the resistivity ← what is this? on a atomic basis?

Drift: Current's 1st Contribution

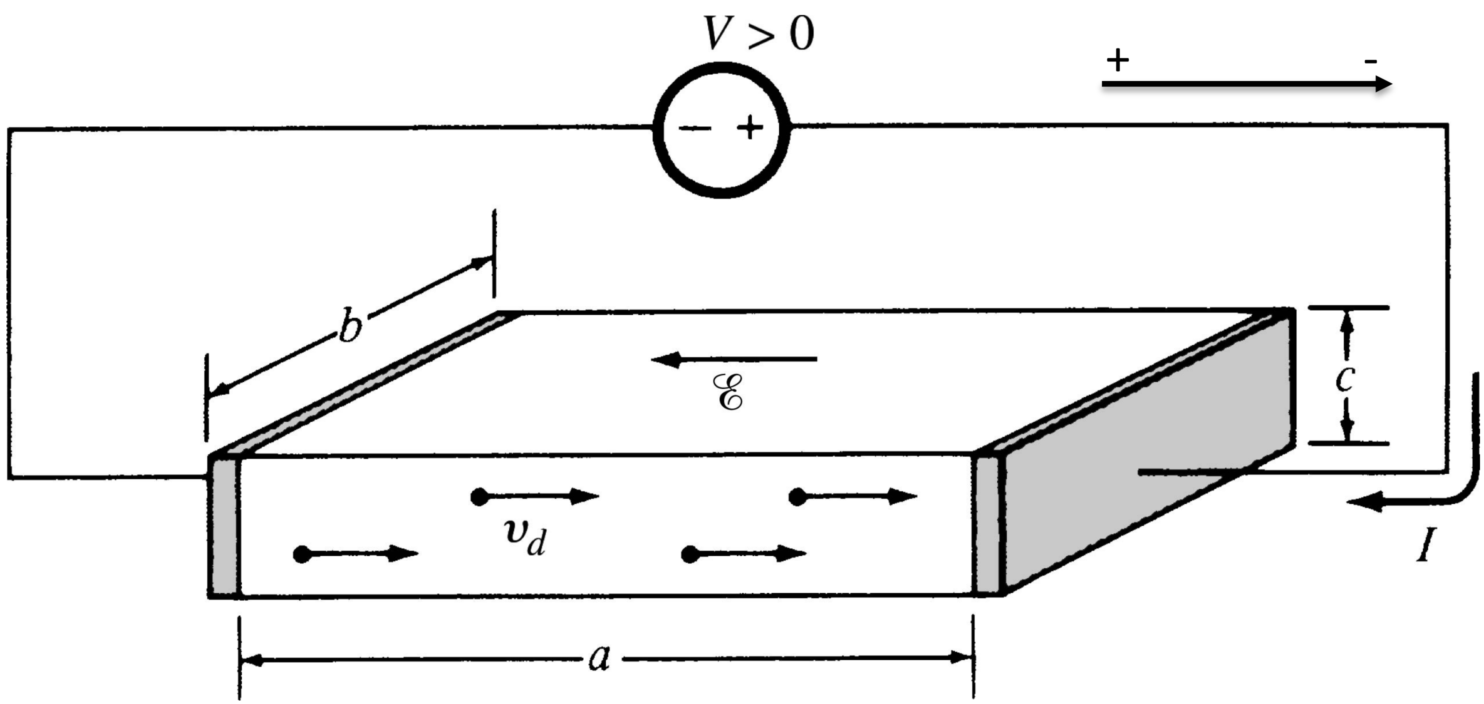


FIGURE 1.12 An n-type semiconductor bar with uniform electron concentration under external bias.

Although drift is not always the same, we can say the average v_d or drift velocity is constant and is proportional to the Electric Field.

Velocity Saturation

Drift velocity depends on Electric Field

bulk mobility

$\mu_B \cdot |\varepsilon|$ ← electric field

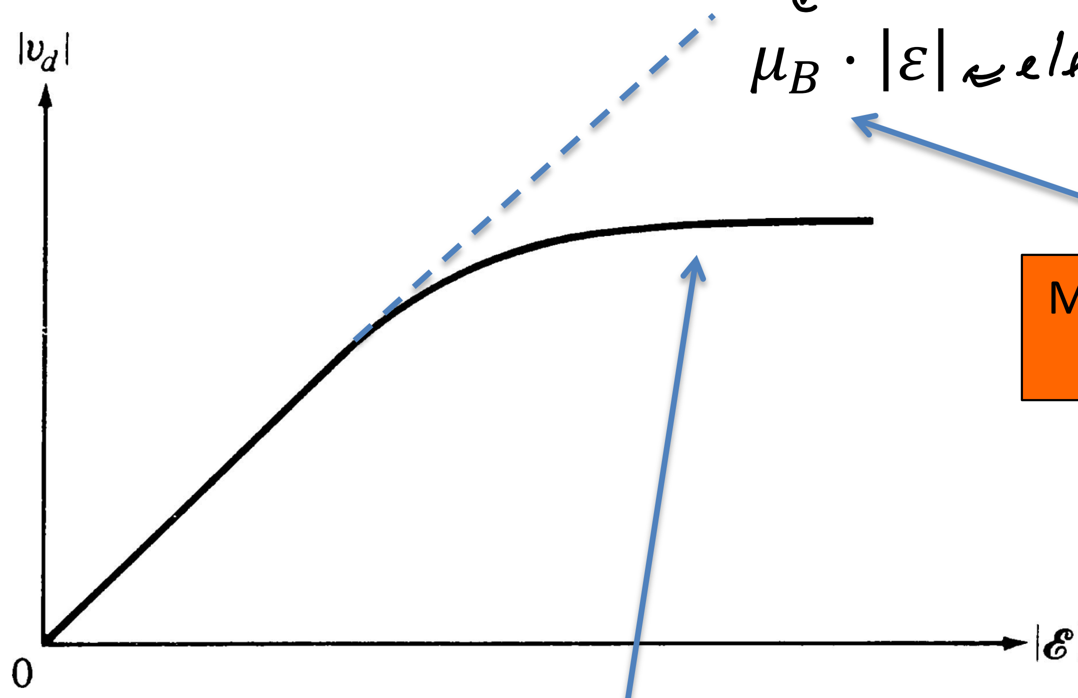


FIGURE 1.11 Magnitude of drift velocity versus magnitude of electric field.

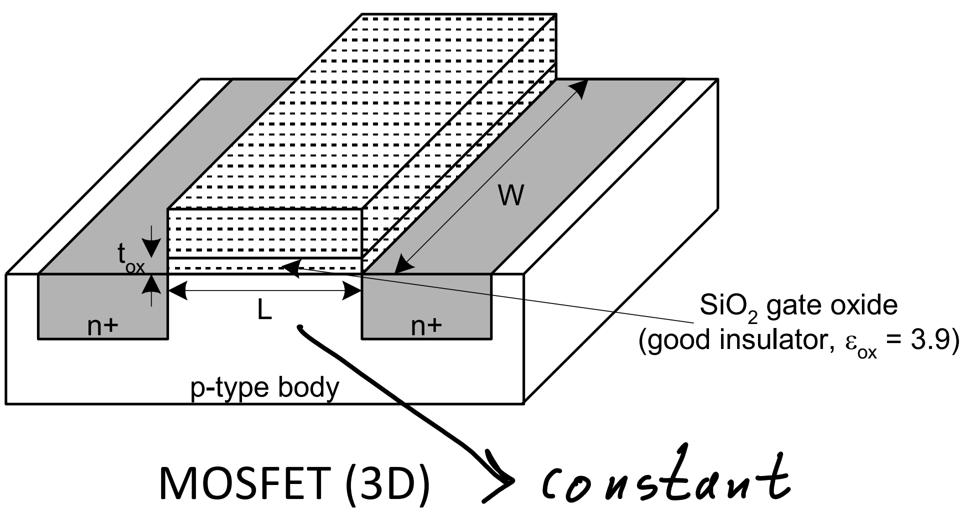
Mobility of the Bulk semiconductor

High electric field causes saturation which occurs because atoms collide and hit each other at these high velocities, and they lose and gain energy and momentum until they reach a balance.

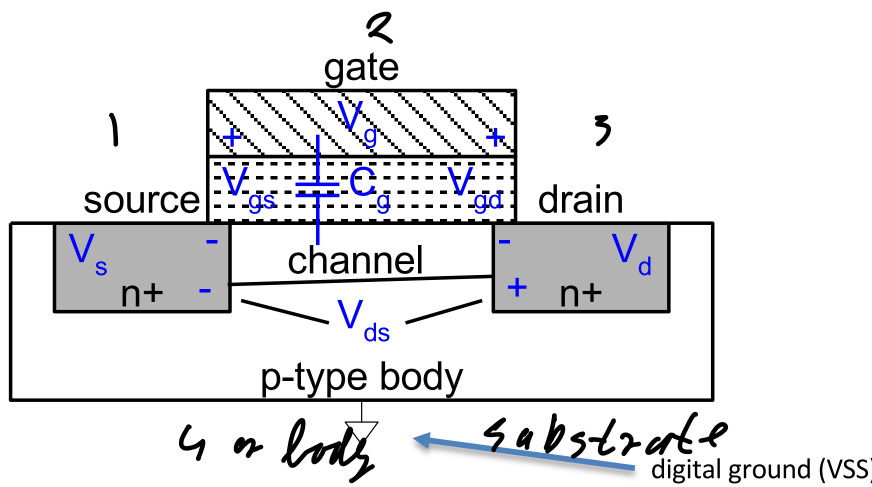
MOSFET Commercial

- MOS structure looks like parallel plate capacitor while operating in something called inversion (ignore for now – really trying to just introduce you to structure).
  - Gate – oxide – channel
- $Q_{channel} = C \cdot V$
- $C = C_g = \varepsilon_{ox} \cdot W \cdot L / t_{ox} = C_{ox} \cdot W \cdot L$

$C_{ox} = \varepsilon_{ox} / t_{ox}$

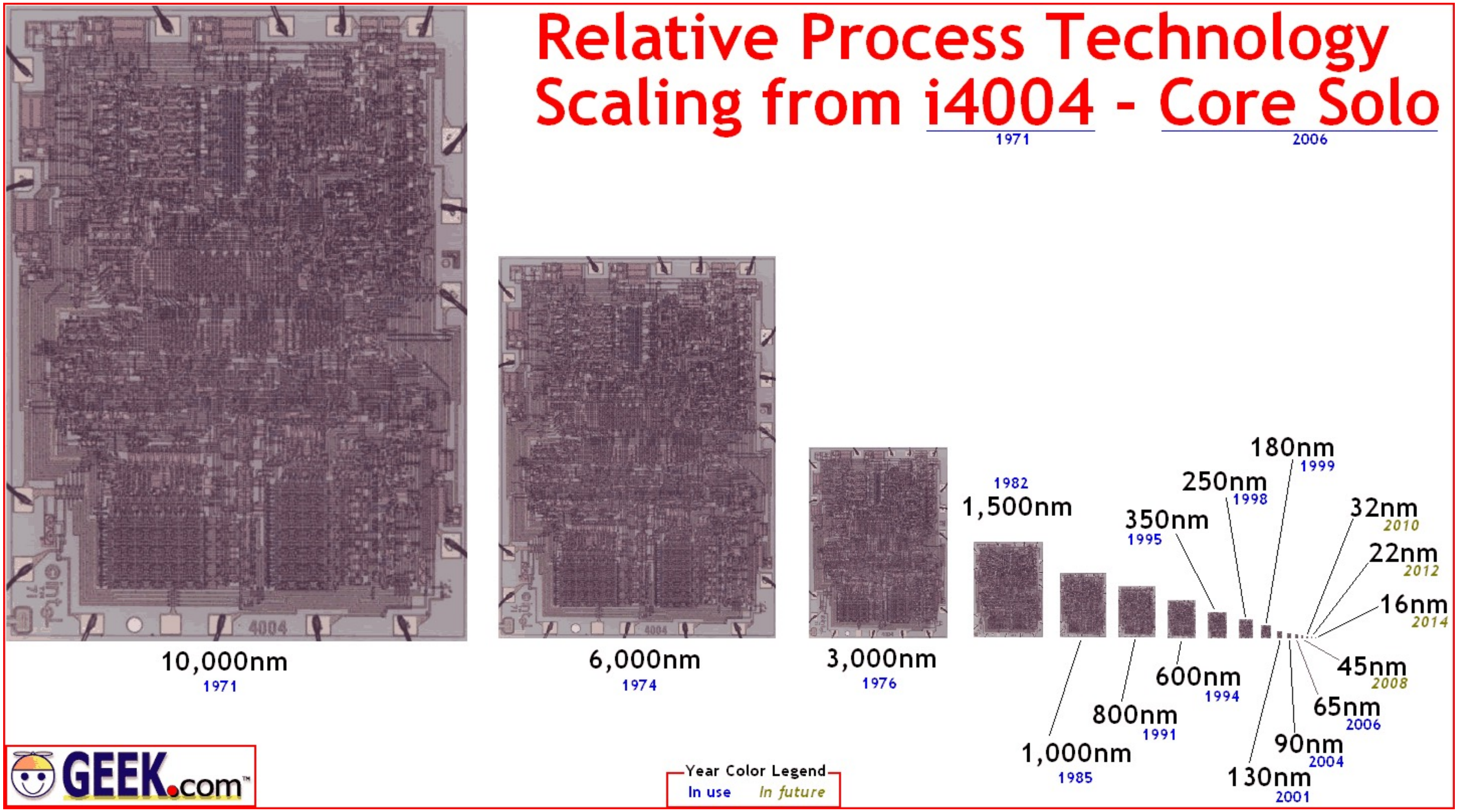


MOSFET (3D)



MOSFET (2D)

Length = Feature Size

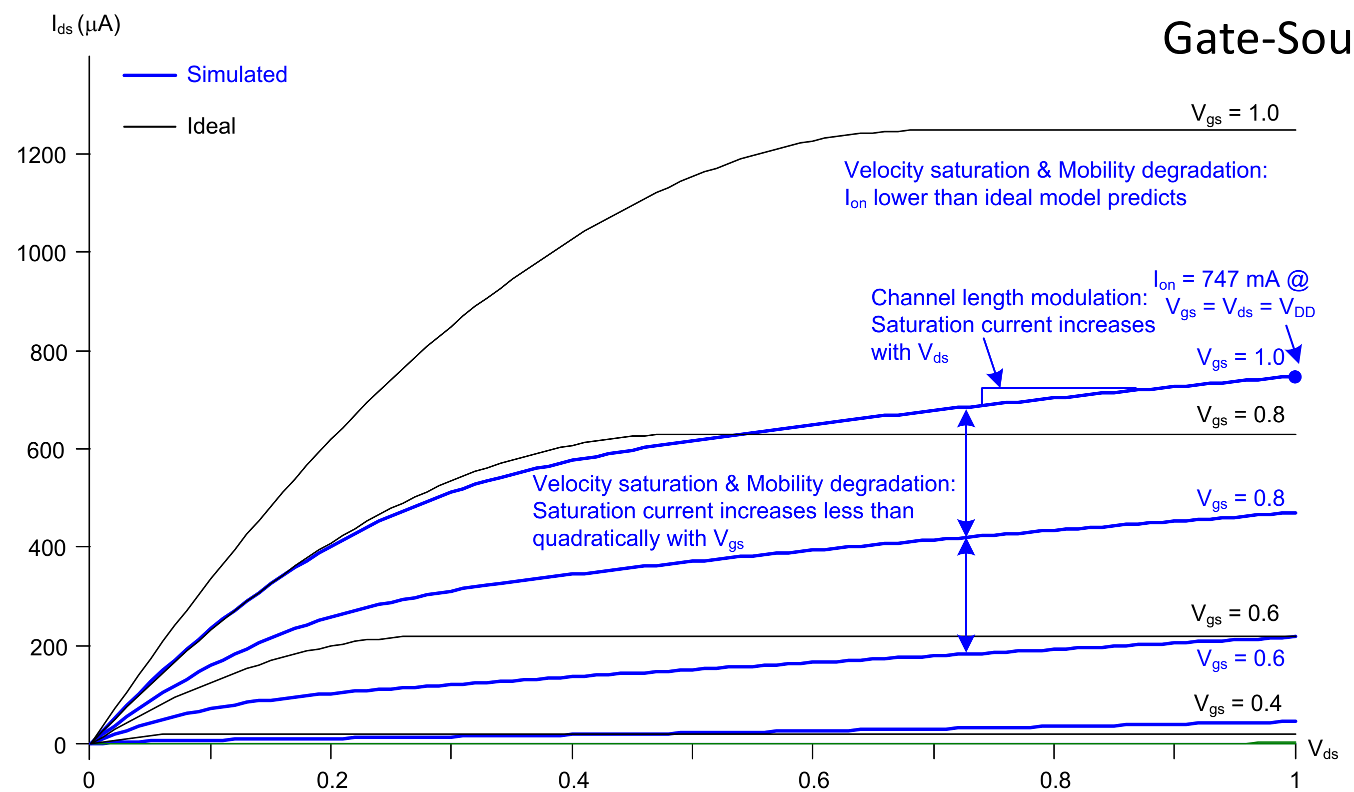


Ideal vs. Simulated nMOS I-V Plot

65 nm IBM (now Global Foundries or GF) process, V_{DD} = 1.0 V

Drain-Source Current

Gate-Source Voltage



[Weste, Harris]

Drain-Source Voltage

Notice that we give voltages referenced to two ports!!!

Drift Current

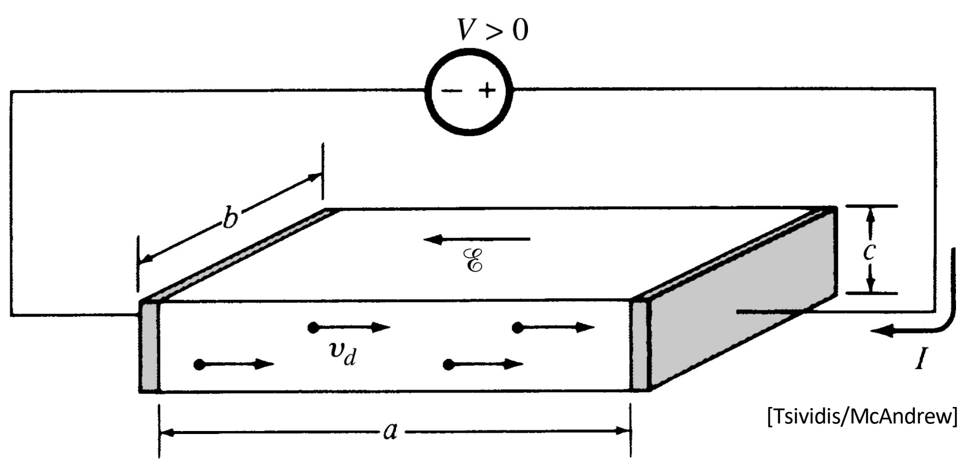
$V > 0$

$$I = \frac{|Q|}{\tau} = b \cdot \frac{|Q|}{b \cdot a} \cdot v_d = b \cdot |Q'| \cdot v_d$$

$$\frac{a}{v_d}$$

Area

Charge per unit area (i.e., $^{|Q|}/_{A}$)



[Tsividis/McAndrew]

Low Electric Field Quantity

$v_d = \mu_B \cdot \varepsilon$

$< 6x10^3\ {}^{V}/_{cm}$

Low electric fields

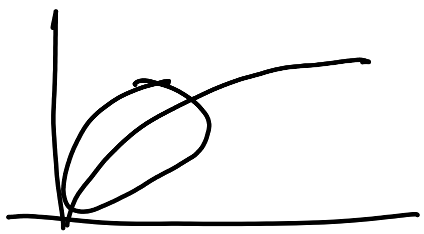
W

$$I = b \cdot |Q'| \cdot v_d = \left(\mu_B \cdot |Q'| \cdot \frac{b}{a}\right) \cdot V = G \cdot V$$

L

ohms Law

$\boxed{\varepsilon = \frac{V}{a}}$ $\left[\frac{V}{m}\right]$



L

$$\tau = \frac{a}{v_d} \Longrightarrow \tau = \frac{a^2}{\mu_B \cdot V}$$

The key is that the current is a function of the geometry b and a. For most modern MOS circuits, we substitute b=Width and a=Length of the transistor.

Increasing the bar's length increases the transit time for two reasons:

1. Distance the electrons must travel becomes larger.
2. The magnitude of the electric field becomes smaller, which slows electrons down.

Conductivity

- Preceding results connect to conductance and conductivity:

$$I = \mu_B \cdot n \cdot q \cdot \frac{b \cdot c}{a} \cdot V$$

(1.3.12), page 21

conductance

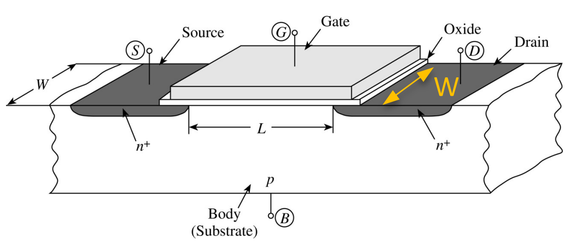
$$I = G \cdot V \quad \left\{ \begin{array}{l} G = \sigma \cdot \dfrac{b \cdot c}{a} \\ \boxed{\sigma = \mu_B \cdot n \cdot q} \rightarrow \text{for HW} \end{array} \right.$$

G = conductance
σ = conductivity

L

W

$\Omega/\square \rightarrow$ unitless



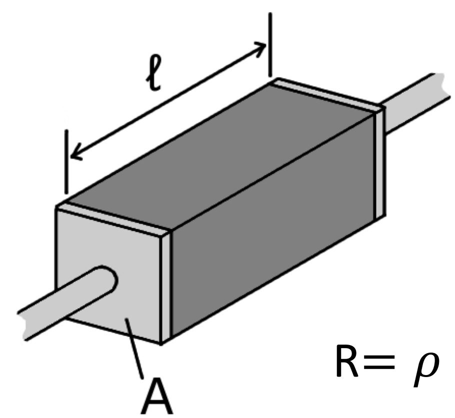
$$G = \mu_B \cdot |Q'| \cdot \frac{b}{a}$$

$$R_S = \frac{1}{G} = (\mu_B \cdot |Q'|)^{-1}$$

$$R = R_S \cdot \frac{a}{b}$$

Sheet Resistance

$[\Omega/\blacksquare]$



$$R = \rho \cdot \frac{l}{A}$$

Current flows from one side to another but its thickness is set at certain level because of its growth

Interpretation

- Larger mobility, smaller transit time
  - For a given field, electrons move faster
- Larger Voltage, smaller transit time
  - For a larger Voltage, given a specific horizontal direction, larger the Electric Field.
- Double length
  - Go twice the distance and takes longer
  - However Electric Field [V/a] half as much
    1. Transit time is larger
    2. Device is larger!!!

$$I = \mu_B \cdot |Q'| \cdot \frac{b}{a} \cdot V$$

W

L

Mobility

- Characterizes how quickly an electron can move through a metal or semiconductor, when pulled by an Electric Field.
  - Also, analogous to holes!
  - Conductivity is also proportional to the product of mobility and carrier concentration.
  - Also dependent on impurity concentrations (including donor and acceptor concentrations), defect concentration, temperature, and electron and hole concentrations.
  - Also, depends on Electric Field, as we saw on the previous page.
    - Can be measured using the Hall effect (specific way to measure Electric Field in the presence of a magnet).
    - U.S. Patent 1,778,796 [1930]
    - https://en.wikipedia.org/wiki/Hall_effect_sensor (see Muller&Kamins, Chapter 1)

$$I_D = I_0 \cdot \left(e^{V_D/\eta \cdot \phi_t} - 1\right)$$

Mobility vs. Dopant

$\boxed{p}$ ~ 2X

because mobility difference

$\boxed{n}$

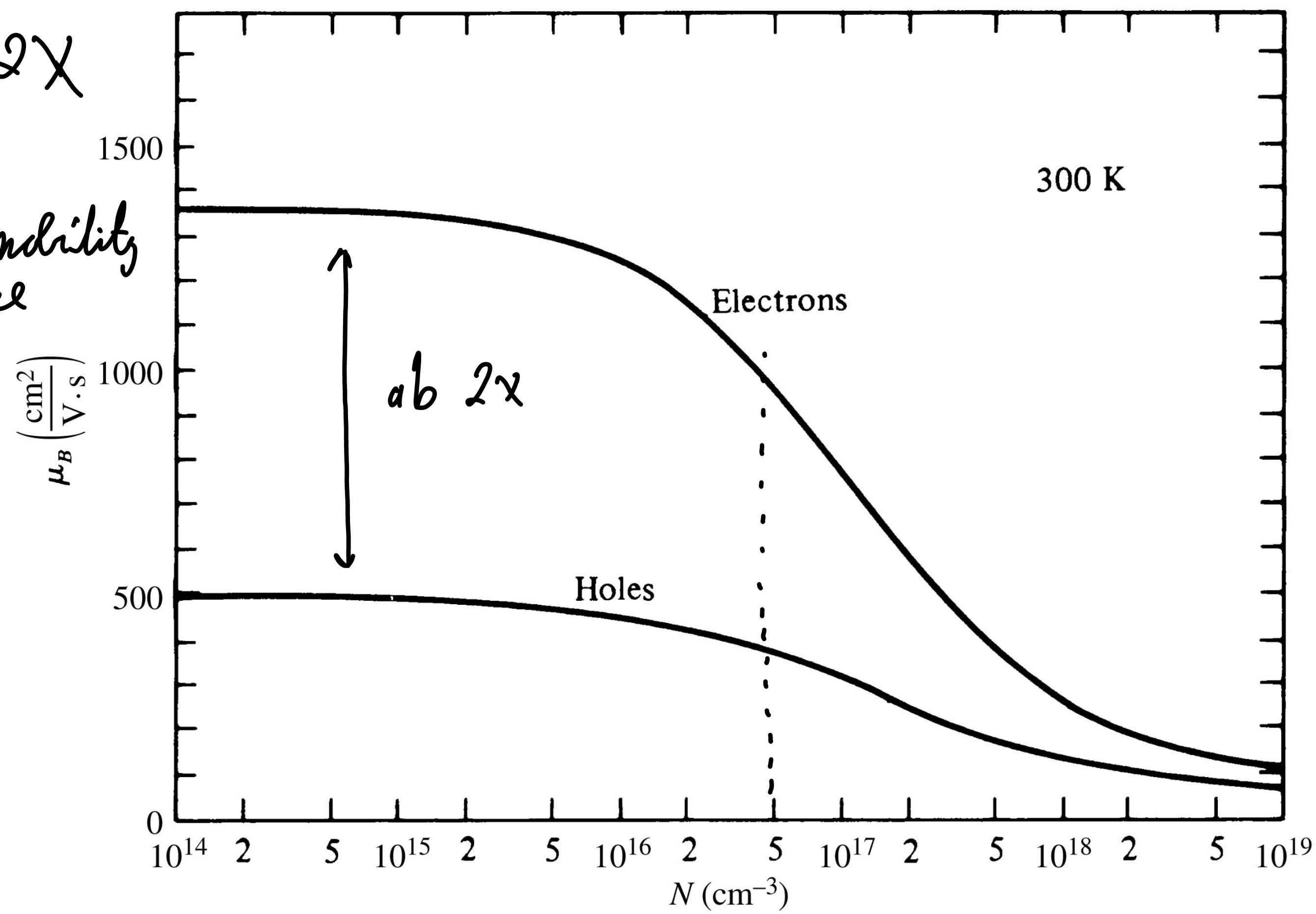


FIGURE 1.13 Electron and hole bulk mobility in silicon at 300 K vs. doping concentration.

Hint: you might need this for HW to find mobility based on doping.

https://www.khanacademy.org/science/health-and-medicine/respiratory-system/gas-exchange-jv/v/fick-s-law-of-diffusion

Diffusion : Current’s 2nd Contribution

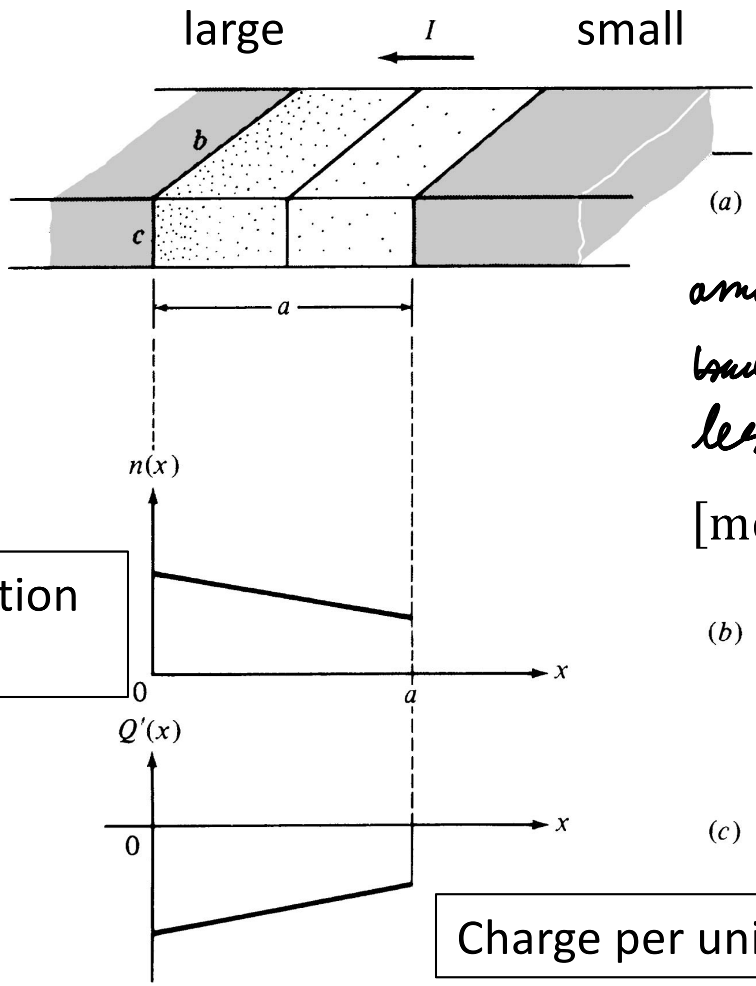


FIGURE 1.15 (a) A semiconductor bar with nonuniform electron concentration along its length; (b) the electron concentration in (a) for a special case of interest; (c) charge per unit area corresponding to (b).

concentration gradient

Charge per unit Area

Electrons tend to diffuse from high concentrations to low concentrations : statistic phenomena

amount of particles travel from more to less

$$\text{flux} = \frac{\#\ \text{particles}}{\text{area} \cdot \text{time}}$$

$$[\text{mol}/(\text{sec} \cdot cm^2)] \qquad J_{A_z} = -D_{AB} \cdot \frac{\Delta \text{c}}{\Delta \text{z}}$$

Diffusion constant => speed

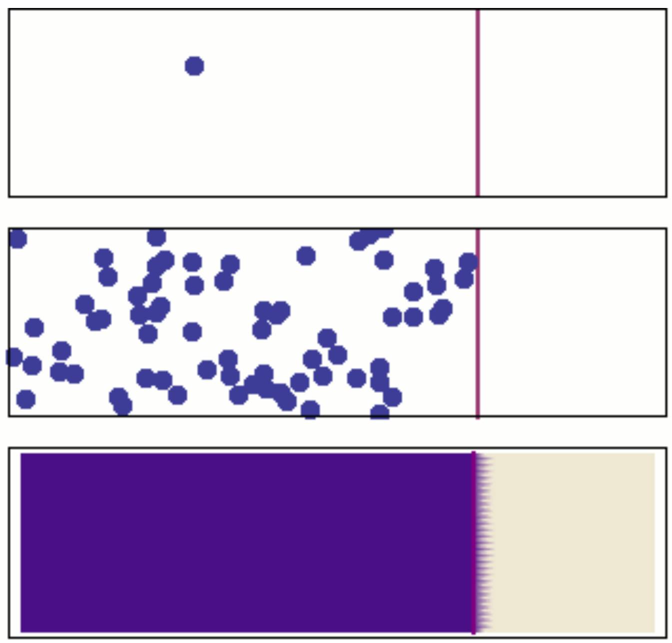
$$\frac{\text{mol}}{\text{sec}} = J_A \cdot \text{Area}$$

Adolf Fick : 1st Law of Diffusion

https://en.wikipedia.org/wiki/Fick's_laws_of_diffusion

Fick’s Law

- Fick’s Law is extremely useful in detailing the 2nd fundamental property of current in a semiconductor.
- This is called diffusion current.
- Fick’s Law is also important in areas of metabolism and other important engineering applications.



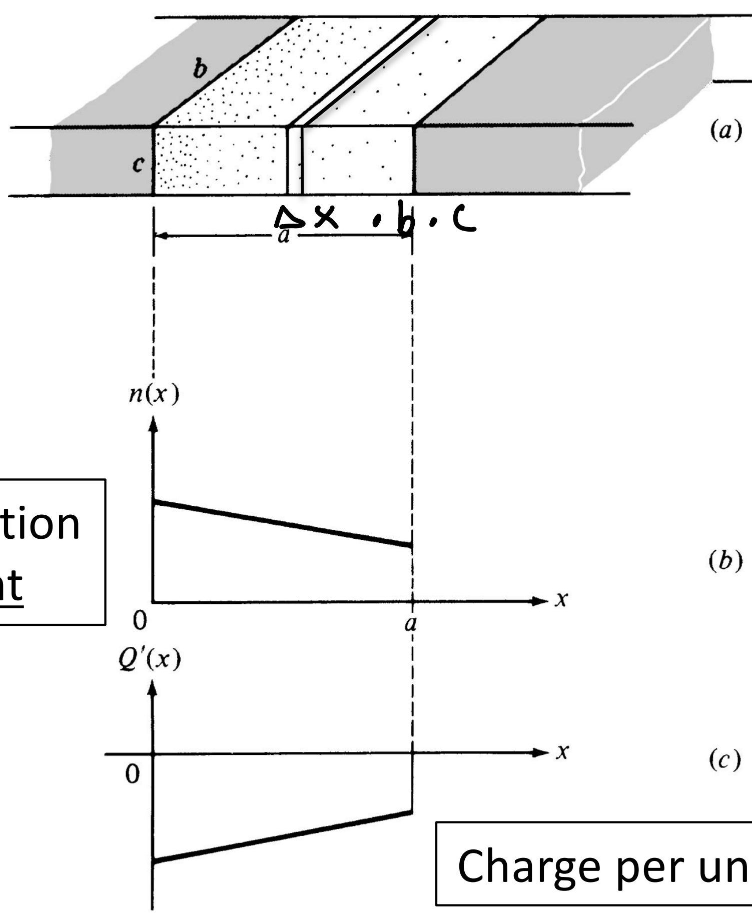
[Wikipedia]

https://youtu.be/j4m0Ye5Qgcg?si=HervtILuP5zkGphL

Diffusion : Current's 2nd Contribution

Thin Slab!

Δx



concentration gradient

Charge per unit Area

FIGURE 1.15 (a) A semiconductor bar with nonuniform electron concentration along its length; (b) the electron concentration in (a) for a special case of interest; (c) charge per unit area corresponding to (b).

constant

Δx

$$I = D \cdot q \cdot (b \cdot c) \cdot \left(-\frac{dn}{dx}\right)$$

why (−)?

Cross sectional area of which charge flows

$$\phi_t = \frac{k \cdot T}{q}$$

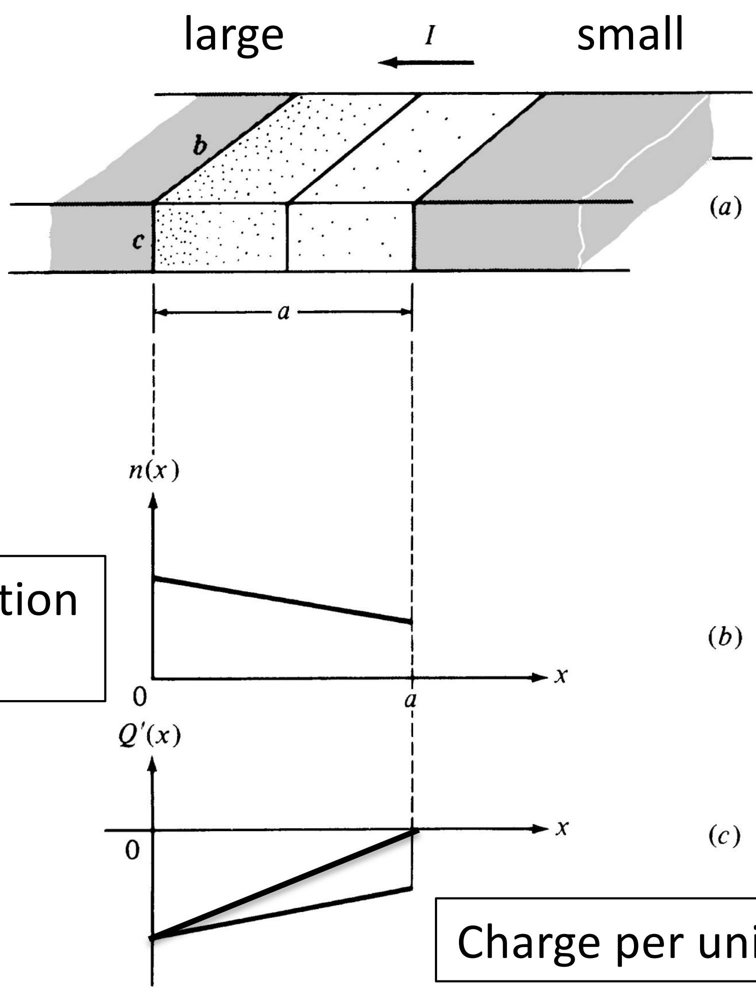
$$D = \mu_B \cdot \phi_t$$

Einstein Relation

$$Q'(x) = -\frac{q \cdot (b \cdot c \cdot \Delta x) \cdot n(x)}{b \cdot \Delta x}$$

$$= -q \cdot c \cdot n(x)$$

Diffusion : Current's 2nd Contribution



concentration gradient

Charge per unit Area

FIGURE 1.15 (a) A semiconductor bar with nonuniform electron concentration along its length; (b) the electron concentration in (a) for a special case of interest; (c) charge per unit area corresponding to (b).

$$I = D \cdot q \cdot (b \cdot c) \cdot \left(-\frac{dn}{dx}\right)$$

$$I = \mu_B \cdot \phi_t \cdot b \cdot \frac{dQ'(x)}{dx} \qquad (1.3.20)$$

$$Q'(a) = 0 \quad \tau = \frac{a^2}{\mu_B \cdot (2 \cdot \phi_t)} \qquad (1.3.26)$$

special case

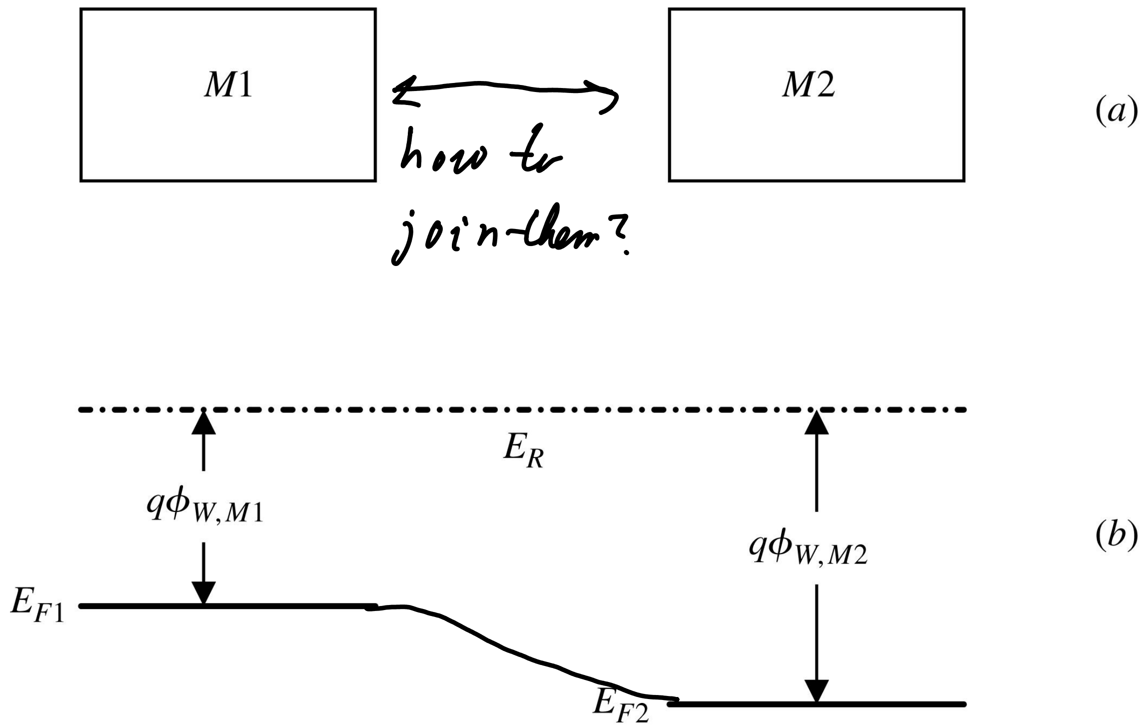
Total Current

- There will be a similar result for hole current

$$I_{total} = I_n + I_p$$
$$= \left(I_{n,\,\mathrm{drift}} + I_{n,\,\mathrm{diffusion}}\right) + \left(I_{p,\,\mathrm{drift}} + I_{p,\,\mathrm{diffusion}}\right)$$

- Usually two or more of these equations is typically negligible.
- The total electron and hole currents can be expressed in terms of quasi-Fermi levels (Appendix B).

Two Materials (separated)



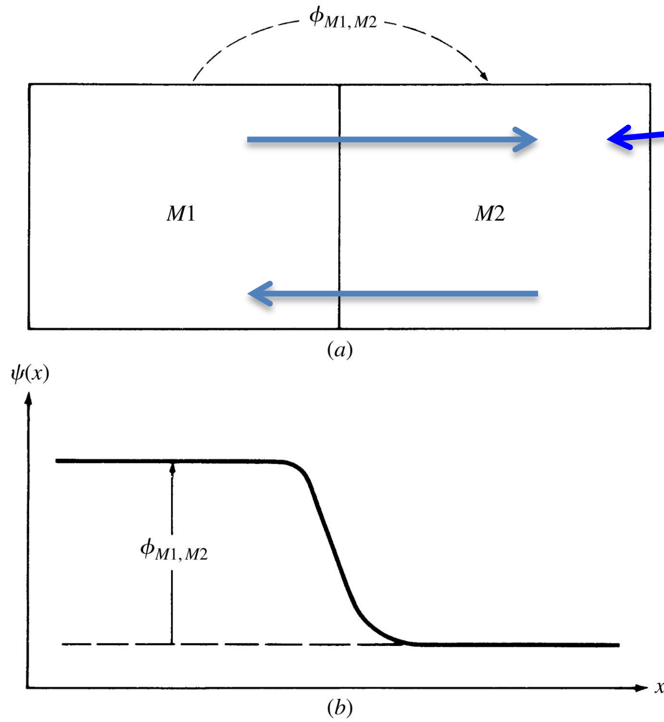
Work function of 2nd material is larger than 1st material.

Objective: what happens when two materials are joined together?

- $q \cdot \phi_{W,\,M_i}$: Work function of Material M_i ← diff between the two fermi levels!
- Work function of a material = Energy takes to go from the Fermi energy level to the Vacuum energy level, which corresponds to the energy level of electron removed far away from the material so that it is not influenced by it.
- Fermi Levels = A measure of how heavily populated with electrons or holes!

Combining of Semiconductors

- Assumption: plenty of electrons in M1
- Tend to Diffuse from M1 to M2



Electron and hole movement

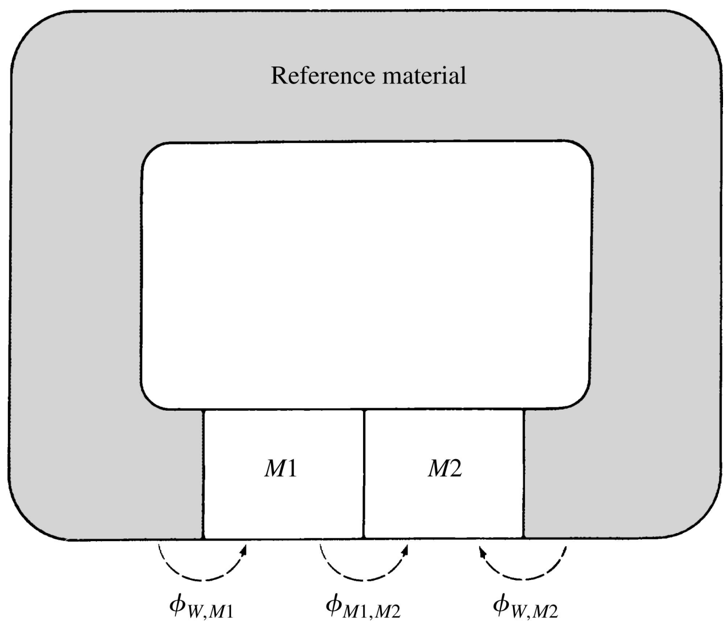
- Equilibrium will be eventually reached where certain number of positive charges will be revealed in M1 and is such to just counteract the farther diffusion of electrons of M1 to M2
  - I_{drift} cancels $I_{diffusion}$
- Again, the Fermi energy, loosely speaking, is a definition of how energetic the electrons are in the corresponding material (or measure how heavily populated the materials are with electrons or holes).

In equilibrium, you must have a single Fermi energy level!

$$\phi_{M1,M2} = \phi_{W,M2} - \phi_{W,M1}$$

Unique thought experiment

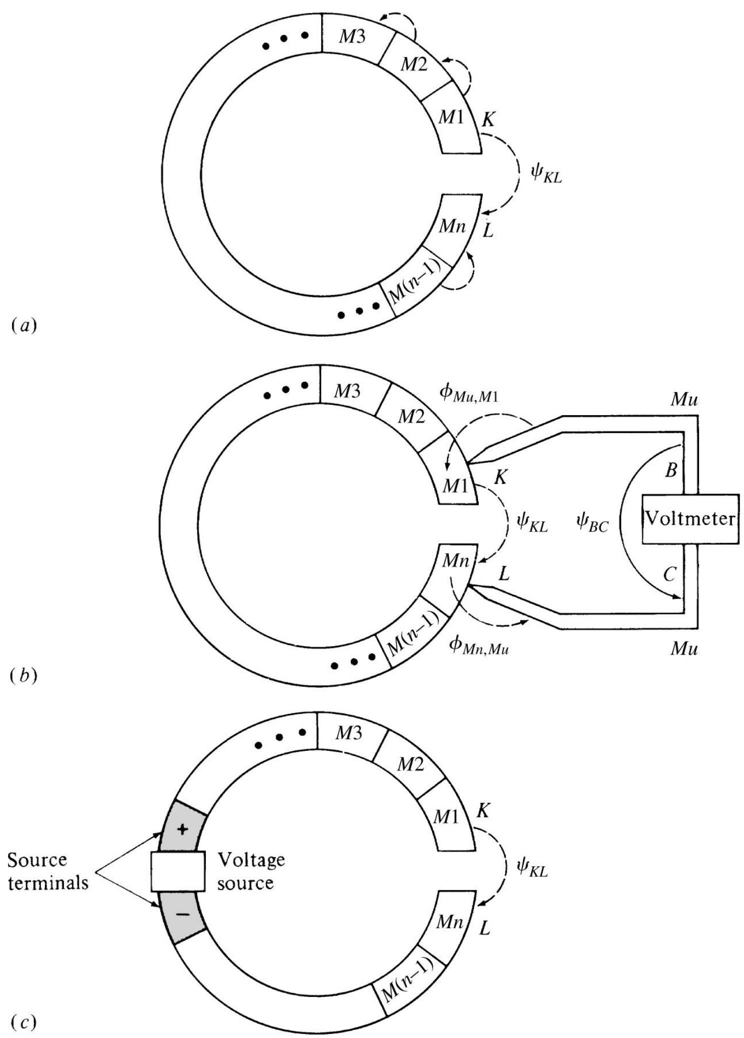
- Now, let's assume we can divide the materials up into two semiconductors that form a loop.
  - This should be viewed similar to as a circuit.
  - Sum up all the contact potentials together.



Contact potentials are defined as the electric potential that develops when you join two dissimilar materials together.

$$\phi_{M1,\,M2} = \phi_{W,\,M2} - \phi_{W,\,M1}$$

Divide many times…



- Now, taking the previous circuit and dividing many times, we come up with a unique way that the textbook views this item.
  - I think its thought-provoking in how materials act together.
  - Look at potential between points K and L cancels

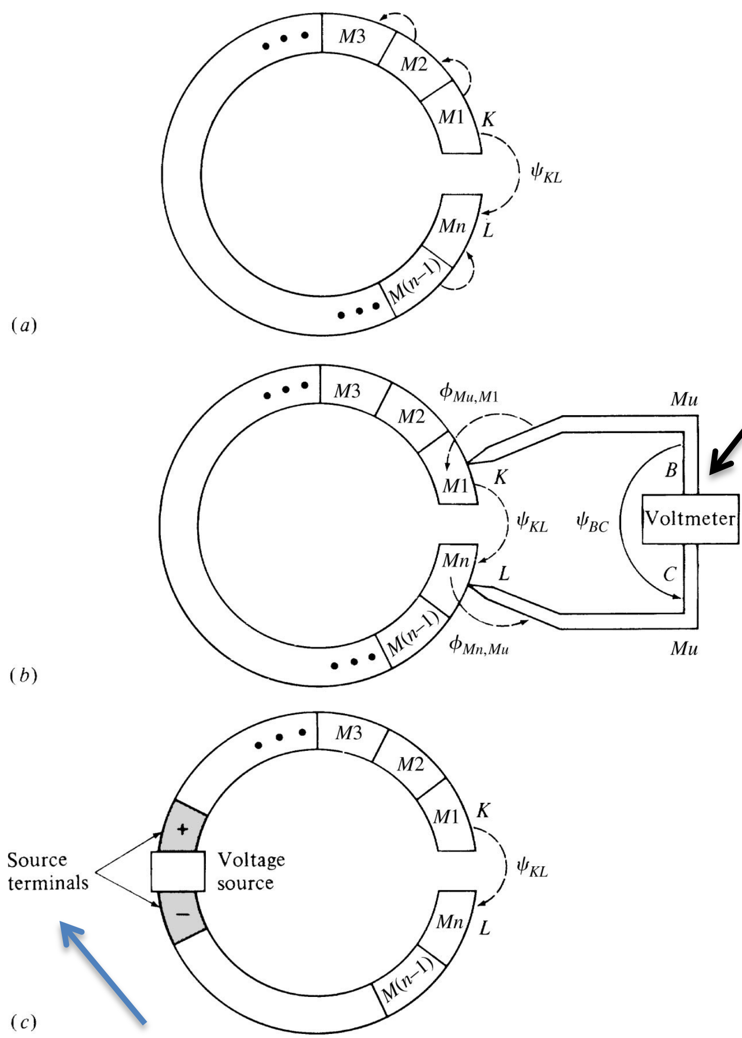
$$\psi_{KL} = (\cancel{\phi_{W,M2}} - \phi_{W,M1}) + (\phi_{W,M3} - \cancel{\phi_{W,M2}}) + \cdots$$

last one – first one

$$\psi_{KL} = \phi_{W,Mn} - \phi_{W,M1}$$

Resulting potential of two ending materials!

Divide many times…



Insert battery!

- Q: Can the potential we just calculated be measured?
  - Let's try to measure this with a Voltmeter!
  - Hard to actually measure contact potentials!
- Assume Voltmeter has some material to measure the material, Mu (e.g., aluminum, copper, …)

$$\psi_{BC} = \phi_{W,Mu} - \phi_{W,Mu} = 0$$

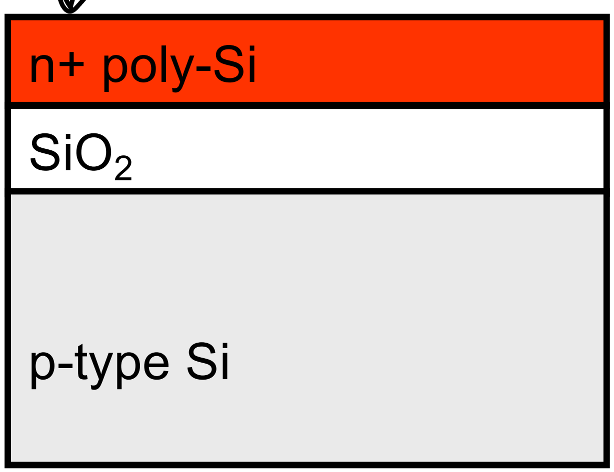
$$\phi_{KL} = V_{source} + \left(\phi_{W,Mn} - \phi_{W,M1}\right)$$

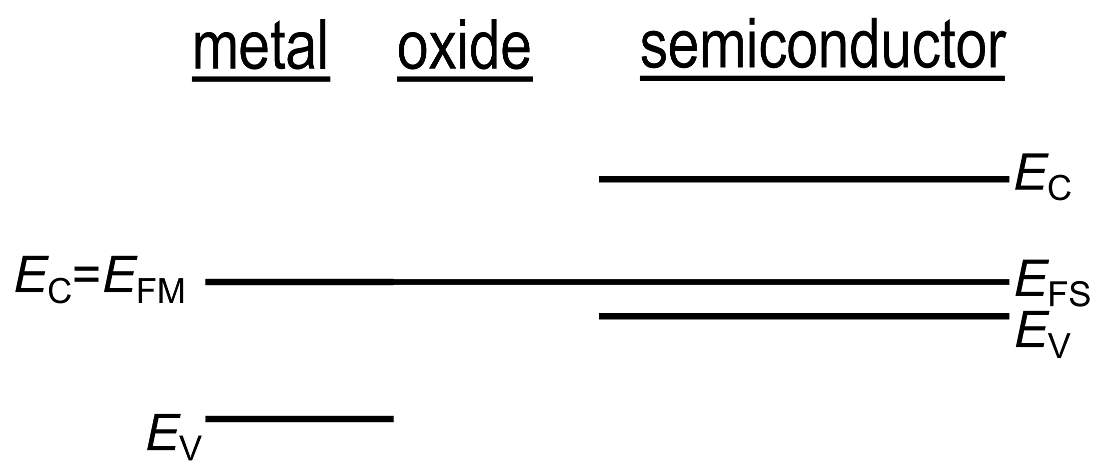
Voltmeter would measure: $\psi_{BC} = V_{source}$

MOS Equilibrium Energy-Band Diagram

concentration $> 10^{14}$ cm^{3} electrons degenerate semiconductor

M
O
S





MOS Band-Diagram Guidelines (cont.)

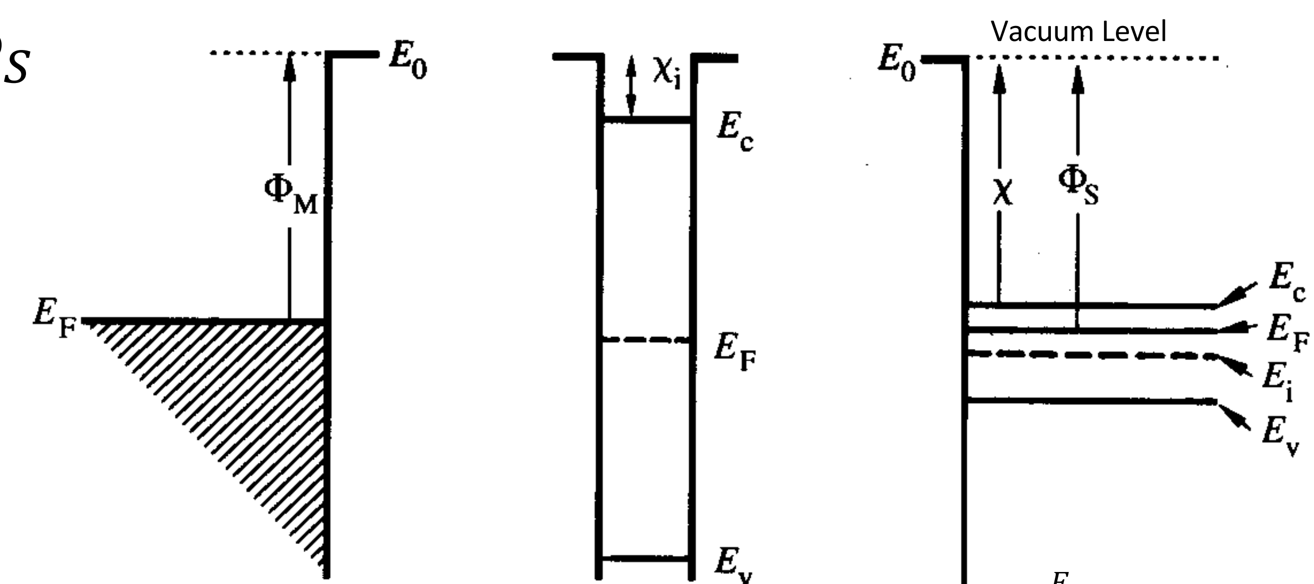
- The barrier height for conduction-band electron flow from the Si into SiO_2 is 4.1 eV
  - This is equal to the electron-affinity difference (χ_{Si} and χ_{SiO2})
- The barrier height for valence-band hole flow from the Si into SiO_2 is 4.8 eV
- The vertical distance between the Fermi level in the metal, E_{FM}, and the Fermi level in the Si, E_{FS}, is equal to the applied gate voltage:

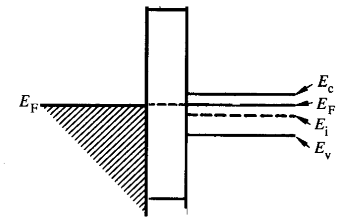
$$q \cdot V_G = E_{FS} - E_{FM}$$

http://ecee.colorado.edu/~bart/book/book/title.htm

Special Case: Equal Work Functions

$$\Phi_M = \Phi_S$$





$$\chi_{Si} = 4.05\ V$$

$$\frac{E_g}{q}_{si,\,\text{non-degenerate}} = 1.12\ eV \quad T = 300\ K$$

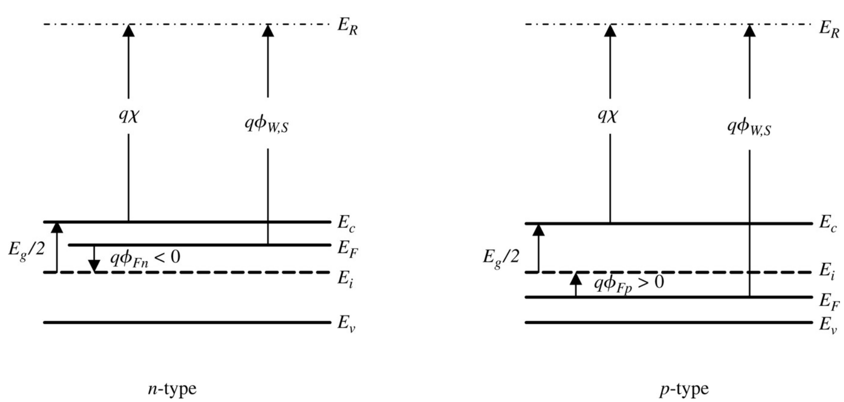


FIGURE 1.19 Semiconductor work function $q \cdot \phi_{W,S}$ and its components.

$$\phi_{W,S} = \chi + \frac{E_G}{2 \cdot q} + \phi_F$$

The Fermi Potential is a quantity that characterizes a semiconductor material at a given temperature.

Summary

- We can understand basic process of conduction in devices and how to form equations from its theory.
- Potential comes from differences in conduction called Contact Potentials.
- There are two forms of conduction in MOSFET devices:
  - Drift current
  - Diffusion current
- Transistors are nothing more than conduction items that switch on and off.
  - The question is how do we make something meaningful out of these switches?