ELEC 315: PN Junctions and Devices

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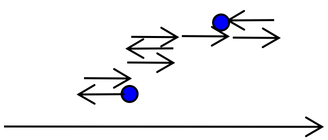
Outline

- Diffusion and drift of carriers
- Current continuity equation
- PN Junctions
- Devices: Diodes, photodetectors, solar cells, MOSFETs

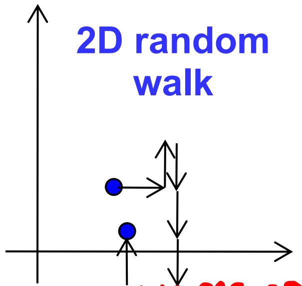
Diffusion of Carriers

Movement of electrons and holes (charge carriers) results in effective charge movement and current in materials.
Electrons and holes move based on Brownian motion (random walk).
In this random movement, electrons effectively move from a location where the concentration of electrons is higher to where this concentration is lower.

1D random walk

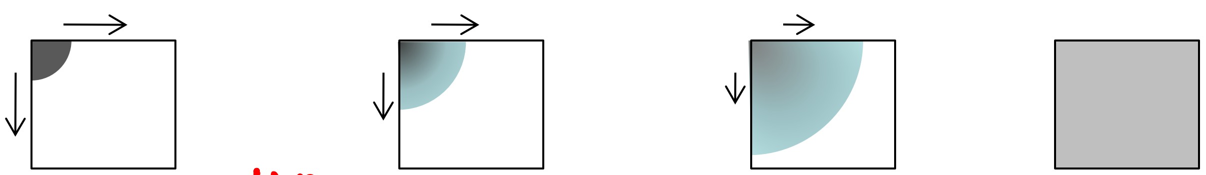


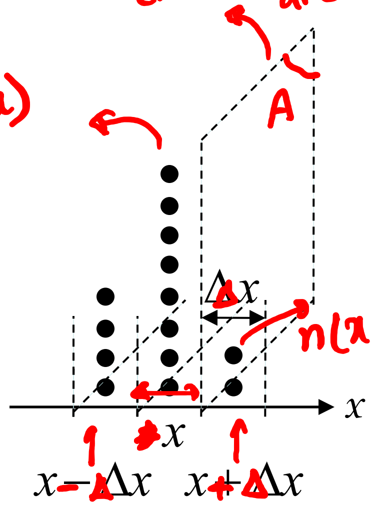
2D random walk



average speed

$\Delta x = v_{avg} \cdot \Delta\tau$





First law of diffusion

$\Delta\tau$: average time between collisions

Δx: " distance electrons travel between collisions

of e^- going from $x \to x+\Delta x$: $\frac{n(x)}{2} A \cdot \Delta x$

of e^- " " $x+\Delta x \to x$: $\frac{n(x+\Delta x)}{2} \cdot A\Delta x$

$$J(x) = \underbrace{-\overset{\text{electrons}}{q}\left[\frac{n(x)-n(x+\Delta x)}{2}\right]}_{\text{charge}} \cdot A\Delta x \times \frac{1}{\Delta\tau} \times \frac{1}{A} = q\frac{\Delta x^2}{2\Delta\tau}\left[\frac{n(x+\Delta x)-n(x)}{\Delta x}\right]$$

$$= qD\frac{\partial n}{\partial x}$$

D diffusion constant

$$D = \frac{\Delta x^2}{2\Delta\tau}$$

Diffusion Current

The current due to the diffusion of electrons is proportional to the gradient of electron density:

$$J_n(x) \propto \frac{dn(x)}{dx} \qquad J_n(x) = qD_n \frac{dn(x)}{dx}$$

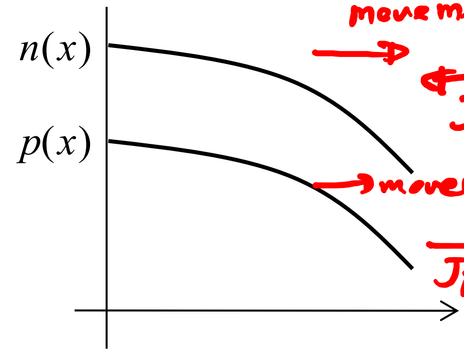
$\vec{J}_n = q D_n \vec{\nabla} n$

The coefficient D_n is the diffusion constant for electrons with a unit of cm^2/s. Note that the diffusion current does not require an electric field.

The current due to the diffusion of holes is proportional to the gradient of hole density:

$$J_p(x) = -qD_p \frac{dp(x)}{dx}$$

$\vec{J}_p = -q D_p \vec{\nabla} p$



movement e^-

J_n $\quad \frac{dn}{dx} < 0$

movement h^+

J_p $\quad \frac{dp}{dx} < 0$

The coefficient D_p is the diffusion constant for holes with a unit of cm^2/s.

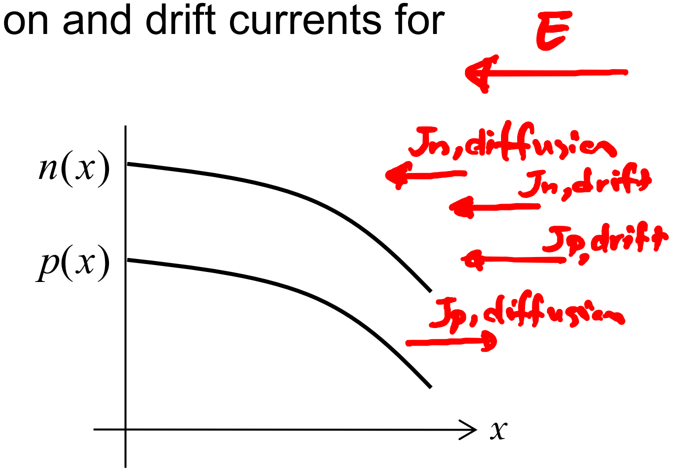
	D_n (cm^2/s)	D_p (cm^2/s)
Ge	100	50
Si	35	12.5
GaAs	220	10

$\vec{J} = \vec{J}_n + \vec{J}_p$

Drift and Diffusion Currents

The total current in a semiconductor is the sum of diffusion and drift currents for both electrons and holes:

$$J(x) = J_n(x) + J_p(x)$$



drift — electric field — diffusion

$$J_n(x) = q\mu_n n(x)E(x) + qD_n \frac{dn(x)}{dx}$$

$$J_p(x) = q\mu_p p(x)E(x) - qD_p \frac{dp(x)}{dx}$$

The diffusion constant and drift mobility are related:

$$D_n = \frac{\Delta x^2}{2\Delta\tau} = \frac{v_{avg}^2 \cdot \Delta\tau^2}{2\cancel{\Delta\tau}} = \frac{kT}{m_n^*} \cdot \Delta\tau = \frac{kT}{q} \cdot \boxed{\frac{q\,\Delta\tau}{m_n^*}} = \frac{kT}{q}\mu_n$$

μ_n

The kinetic energy of electron is given by:

$$K.E. = \frac{m_n^* v_{avg}^2}{2} = kT \rightarrow \frac{v_{avg}^2}{2} = \frac{kT}{m_n^*}$$

Einstein relation

$$\frac{D_n}{\mu_n} = \frac{kT}{q} = V_{th} \qquad \frac{D_p}{\mu_p} = \frac{kT}{q} = V_{th}$$

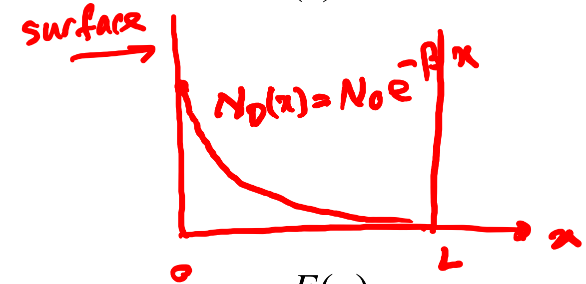
	D_n (cm^2/s)	D_p (cm^2/s)	μ_n (cm^2/Vs)	μ_p (cm^2/Vs)
Ge	100	50	3900	1900
Si	35	12.5	1350	480
GaAs	220	10	8500	400

Examples

1. An intrinsic Si is doped with a variable donor atoms with a density of $N_D(x) = N_0 e^{-\beta x}$

(a) In equilibrium total current $J(x) = 0$, what is the built-in electric field $E(x)$ in the semiconductor?

(b) Sketch a band diagram as a function of x.



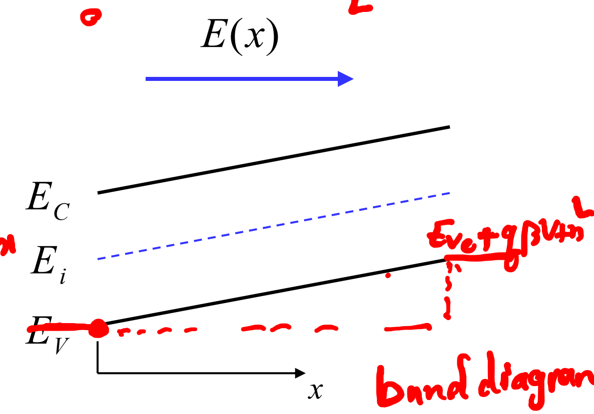
majority carriers $\rightarrow$ $n(x) \simeq N_D(x) = N_0 e^{-\beta x}$

$$J_n(x) = q\mu_n n(x) E(x) + q D_n \frac{dn(x)}{dx}$$

$$= q\mu_n n(x) E(x) + q\mu_n V_{th} \cdot \frac{dn}{dx}$$

$$= q\mu_n N_0 e^{-\beta x} E(x) + q\mu_n V_{th} (-\beta) N_0 e^{-\beta x}$$

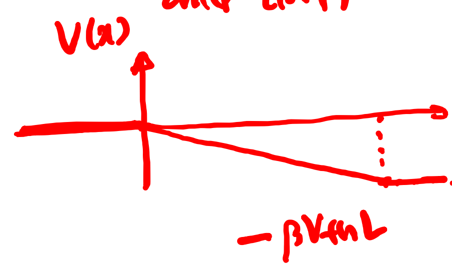
$$= q\mu_n N_0 e^{-\beta x} \left[E(x) - \beta V_{th} \right]$$



If $E(x) = \beta V_{th}$ then $J_n(x) = 0$ by local balance of diffusion and drift

$$E(x) = -\frac{dV}{dx} \rightarrow V(x) = \int_0^x -E(x)\,dx = -\beta V_{th} x$$

$V(0) = 0$



Temperature and Field Dependence of Mobility

Mobility (diffusion constant) should be ideally constant. In reality it is not. Note that if mobility is constant the conductivity will change only with carrier density.

$\mu_n = \frac{q\tau_n}{m_n^*} = \frac{D_n}{V_{th}}$ $\quad \mu_n = \frac{\langle v_d \rangle}{\mathcal{E}}$

$\langle v_d \rangle \rightarrow$ average drift velocity

$\mathcal{E} \rightarrow$ electric field

e⁻ → high T

e⁻ → low T

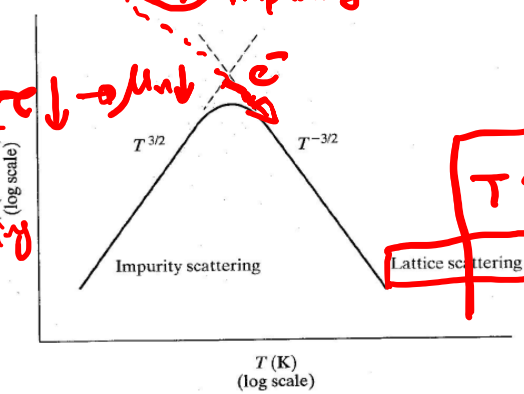
e

ion impurity

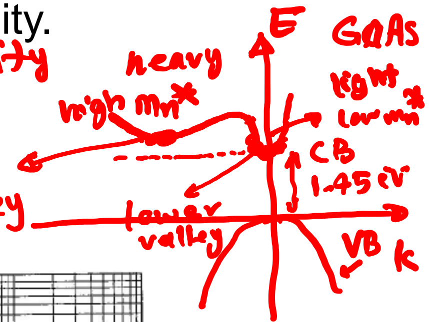
e⁻

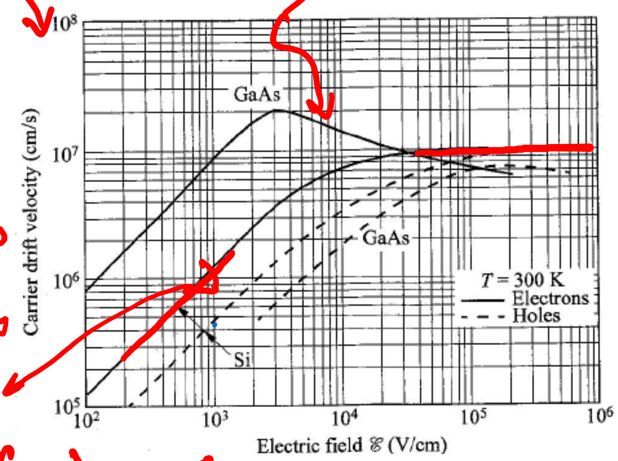
low T → τ ↓ → μ_n ↓

impurity scattering



T ↑ → more collisions with lattice → τ_n ↓ → μ_n ↓





$V_{n,sat} = 10^7$ cm/s

saturation velocity

slope is μ_n

low field

high field

T dependence: Mobility depends on lattice scattering and impurity scattering.

Ionized impurity scattering (t_{ion})

Lattice scattering (t_{lat})

$$t_{col}^{-1} = t_{ion}^{-1} + t_{lat}^{-1}$$

Electric field dependence of mobility.

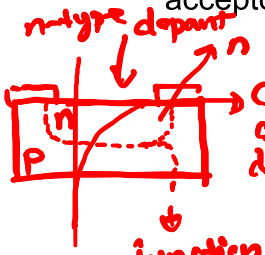
- Scattering limited drift velocity
- Hot electrons
- GaAs negative differential conductivity

Streetman & Banerjee, Solid State Electronic Devices

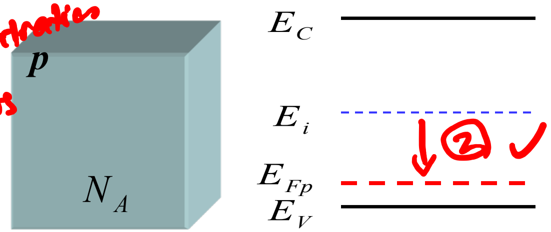
Sze & Ng, Physics of Semiconductor Devices

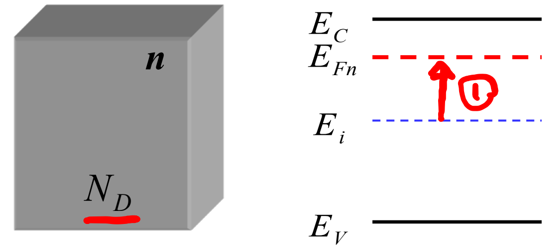
PN Junctions

A PN junction is formed by putting p-type and n-type semiconductors in contact. Let's assume that we have an acceptor dopant density N_A and a donor dopant density N_D for p-type and n-type semiconductors, respectively.



x_j ($N_D = N_A$)





Majority carriers: holes $p_{p0} = N_A$
Minority carriers: electrons $n_{p0} = n_i^2 / N_A$

Majority carriers: electrons $n_{n0} = N_D$
Minority carriers: holes $p_{n0} = n_i^2 / N_D$

equilibrium

Fermi energy: $E_V - E_{Fp} = kT \ln \frac{N_A}{N_V}$ or $E_i - E_{Fp} = kT \ln \frac{N_A}{n_i}$ (2)

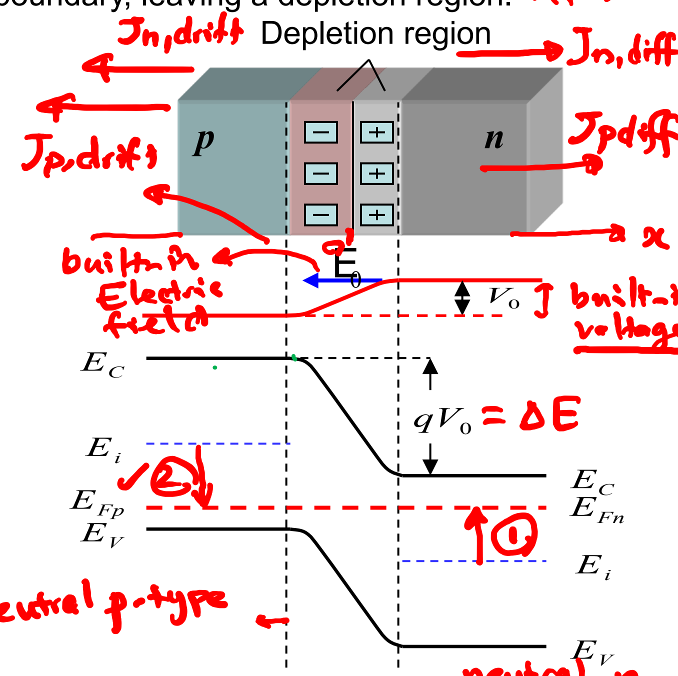
$E_{Fn} - E_C = kT \ln \frac{N_D}{N_C}$ or $E_{Fn} - E_i = kT \ln \frac{N_D}{n_i}$ (1)

When the junction is formed, electrons and holes rush and recombine in the boundary, leaving a depletion region.

e^- movement diffusion

The depletion region has fixed ions left after depletion of free electrons and holes. Acceptor atoms (p-type) leave negative ions and donor atoms (n-type) leave positive ions. As a result, the charge density in the n-type depletion region is $+qN_D$ and in the p-type depletion region is $-qN_A$. In the remaining regions of the PN junction, the material is neutral and charge density is zero.

When no voltage is applied and no current is flowing, the Fermi energy is the same in all parts of the device. This Fermi energy alignment can only be achieved by a band bending that causes a potential barrier V_0 at the junction.



built-in voltage

$$qV_0 = \underbrace{E_{Fn} - E_i}_{1} + \underbrace{E_i - E_{Fp}}_{2} = kT \ln \frac{N_D}{n_i} + kT \ln \frac{N_A}{n_i} = \boxed{kT \ln \frac{N_A N_D}{n_i^2}}$$

$$V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

V_{th}

Depletion Region

We need to solve Poisson's equation in the depletion region to relate potential V and width of depletion region W.

$N_A = 10^{16}$ cm^{-3} $N_D = 10^{18}$ cm^{-3}

potential

$$\frac{\partial^2 \phi}{\partial x^2} = -\rho/\epsilon$$

ρ → charge density

ϵ → dielectric constant

Poisson's equation

$$\boxed{dE/dx = \rho/\epsilon}$$

$$E = -\frac{\partial \phi}{\partial x}$$

$$\frac{dE}{dx} = \frac{q}{\varepsilon}(p - n + N_D - N_A)$$

① $dE/dx = \frac{qN_D}{\epsilon} \to E(x) = \frac{qN_D}{\epsilon}x + C \to E(x_{n0}) = 0 \to \underline{E(x) = \frac{qN_D}{\epsilon}(x - x_{n0})}$

$E_0 = E(0) = -q/\epsilon \, N_D x_{n0}$

② $dE/dx = -qN_A/\epsilon \to E(x) = -\frac{qN_A}{\epsilon}x + C \to \underline{E(x) = -\frac{qN_A}{\epsilon}(x + x_{p0})}$

$E_0 = -q/\epsilon \, N_A x_{p0}$

$Q = qAx_{p0}N_A = qAx_{n0}N_D$

negative positive

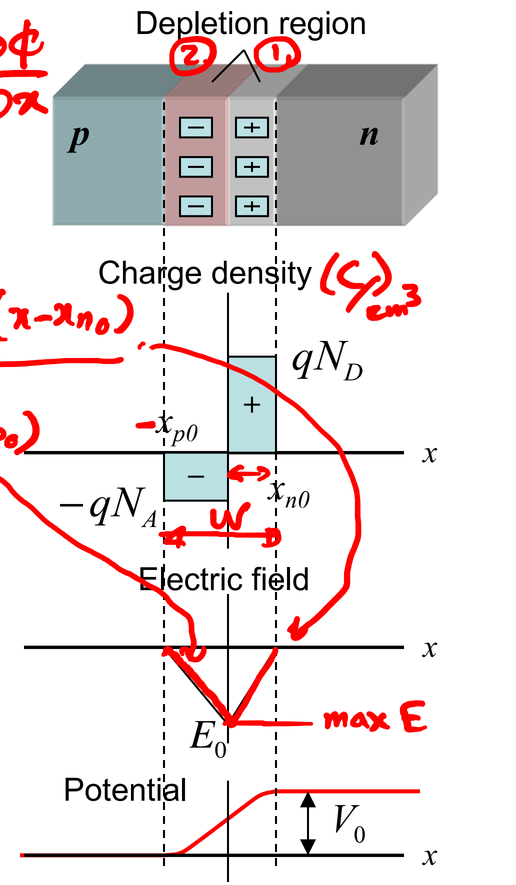
depletion width $W_0 = x_{n0} + x_{p0}$

cross section area

→ $x_{n0} + x_{n0}\frac{N_D}{N_A} = W_0 \to$

$x_{n0}\left(1 + \frac{N_D}{N_A}\right) = W_0$

$x_{p0}\left(1 + \frac{N_A}{N_D}\right) = W_0$



$$\underline{E_0 = -\frac{q}{\varepsilon}x_{p0}N_A} = \underline{-\frac{q}{\varepsilon}x_{n0}N_D}$$

Depletion Region

$n_i = 10^{10}\ \text{cm}^{-3}$ @ 300 K

$N_A = 10^{16}$ cm^{-3} $\quad N_D = 10^{18}$ cm^{-3}

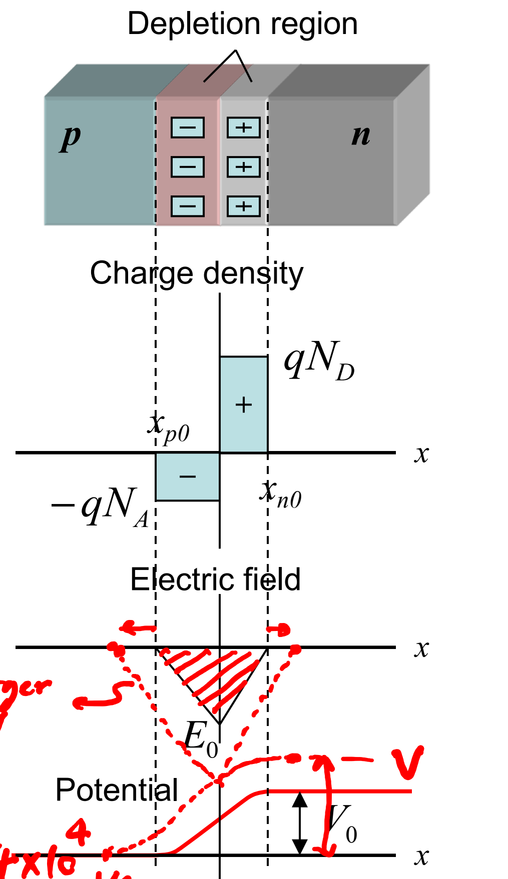
$W_0 = x_{n0} + x_{p0}$

$V = -\int E \cdot dx \longrightarrow V_0 = -\int_{-x_{p0}}^{x_{n0}} E \cdot dx$

$V_0 = + \frac{1}{2} E_0 \cdot W_0 = \frac{1}{2} \frac{q}{\epsilon} x_{n0} N_D \cdot W_0 \longrightarrow$

$= \frac{q}{2\epsilon} \cdot \frac{W_0}{1 + \frac{N_D}{N_A}} N_D W_0 =$

$$\boxed{V_0 = \frac{q}{2\epsilon} \frac{N_A N_D}{N_A + N_D} W_0^{\,2}}$$



Example

$V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2} = \quad = 25.9\ \text{mV} \ln \frac{10^{18} \times 10^{16}}{10^{20}} = 832\ \text{mV}$

$W_0 = \sqrt{\frac{2\epsilon}{q} V_0 \frac{N_A + N_D}{N_A N_D}} = 306\ \text{nm}$

$\epsilon = \overset{\epsilon_r}{11.3} \times \underbrace{8.85 \times 10^{-12}}_{\epsilon_0}\ \text{F/m}$

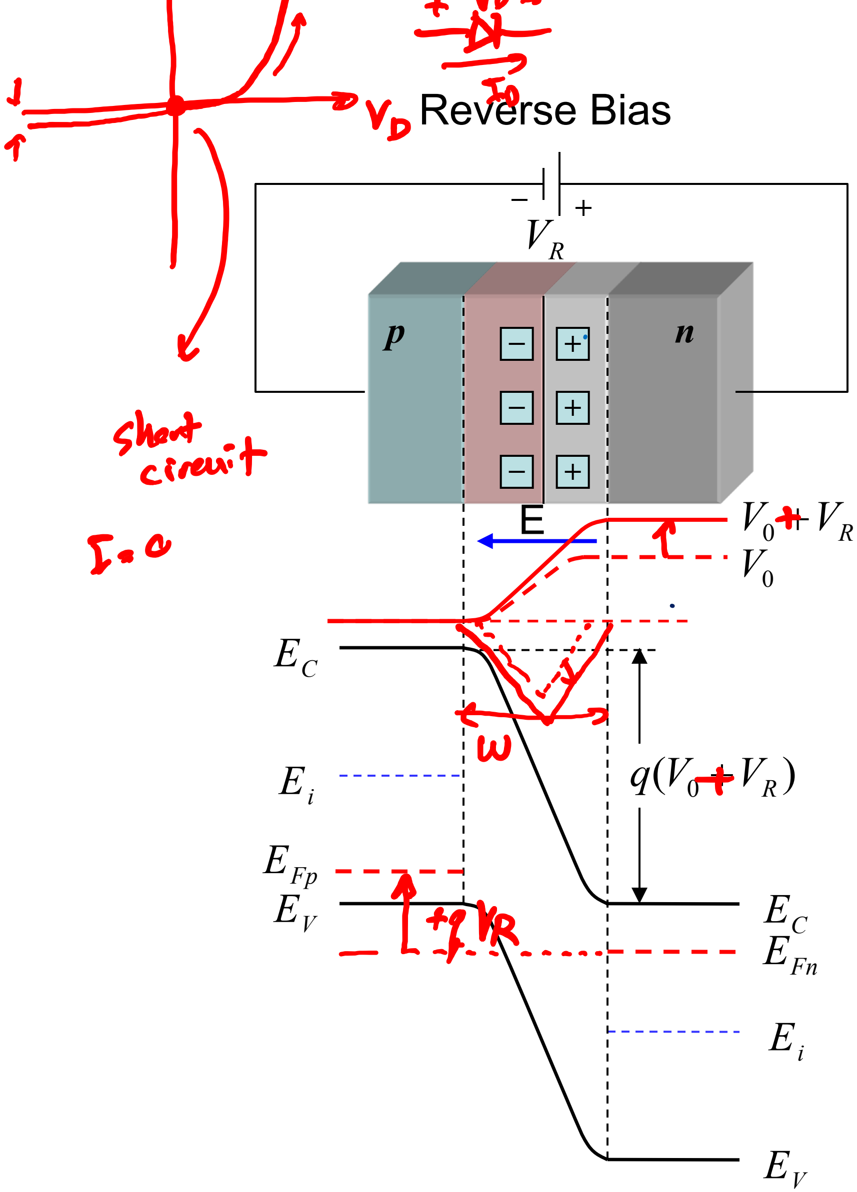
larger W

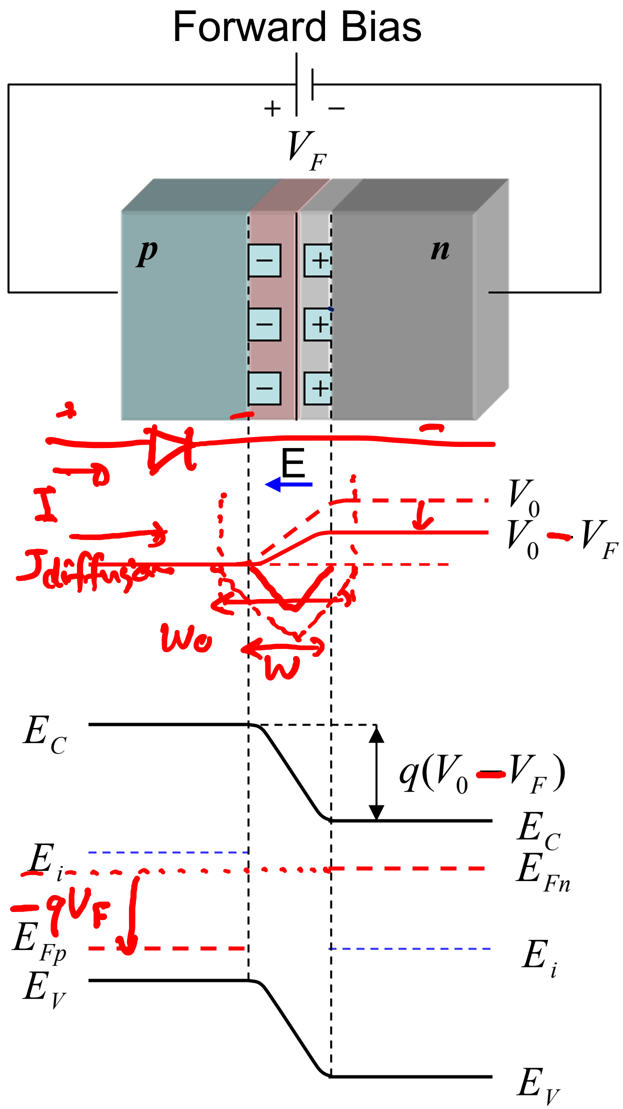
$x_{n0} = \frac{W_0}{1 + N_D/N_A} = 3\ \text{nm}$, $x_{p0} = 303\ \text{nm}$, $E_0 = \frac{2V_0}{W_0} = 5.4 \times 10^4\ \text{V/cm}$

When we connect a battery: $V_0 - V \rightarrow$ applied voltage

$W(V) = \sqrt{\frac{2\epsilon}{q} (V_0 - V) \frac{N_A N_D}{N_A + N_D}}$

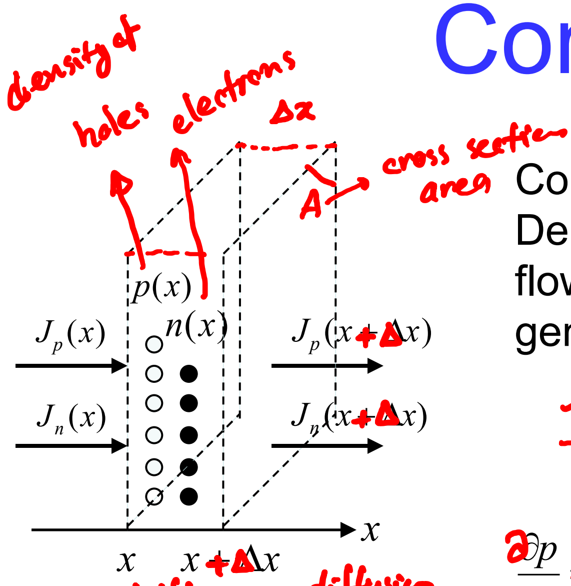
Forward and Reverse Bias





Reverse bias increases depletion region width *W* and forward bias reduces it.

Continuity Equation



Continuity equation is basically charge conservation. Densities of electrons and holes at a point change only by flow of electrons and holes from other locations or local generation and recombination. Therefore for holes:

$$\frac{J_p(x)\cdot \cancel{A}\cdot \Delta t}{q} - \frac{J_p(x+\Delta x)\cdot \cancel{A}\,\Delta t}{q} + (g-r)\cancel{A}\,\Delta x\cdot \Delta t = \Delta p(x,t)\cdot \cancel{A}\,\Delta x$$

$$-1/q\left[\frac{J_p(x+\Delta x)-J_p(x)}{\Delta x}\right] + g - r = \frac{\Delta p}{\Delta t}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + g - r \rightarrow \text{3D: } \partial p/\partial t = -1/q\,\vec{\nabla}\cdot\vec{J}_p + g - r \quad \text{(continuity eq. for holes)}$$

drift diffusion

$$J_p = q\mu_p p\,\mathcal{E} - qD_p\frac{\partial p}{\partial x} \rightarrow J_p = -qD_p\frac{\partial p}{\partial x}$$

Let's assume $\mathcal{E} = 0$ no drift

diffusion current

$$\rightarrow \frac{\partial p}{\partial t} = -\cancel{1/q}\,(\cancel{-q})\,D_p\frac{\partial^2 p}{\partial x^2} + g - r$$

Similarly for the density of electrons we have:

$$\frac{J_n(x).A.\Delta t}{-q} - \frac{J_n(x+\Delta x)A\,\Delta t}{-q} + (g-r)A\,\Delta x\,\Delta t = \Delta n(x,t)A\,\Delta x \rightarrow$$

$$1/q\left[\frac{J_n(x+\Delta x)-J_n(x)}{\Delta x}\right] + g - r = \frac{\Delta n}{\Delta t}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + g - r \rightarrow \text{3D: } \frac{\partial n}{\partial t} = 1/q\,\vec{\nabla}\cdot\vec{J}_n + g - r$$

$$J_n = q\mu_n n\,\mathcal{E} + qD_n\frac{\partial n}{\partial x} \rightarrow J_n = qD_n\frac{\partial n}{\partial x} \rightarrow \frac{\partial n}{\partial t} = D_n\frac{\partial^2 n}{\partial x^2} + g - r$$

If assume $\mathcal{E} = 0$

In steady-state, $\frac{\partial n}{\partial t} = 0$ and $\frac{\partial p}{\partial t} = 0$. The continuity equations reduce to
or DC

$$\left[\begin{array}{l} 0 = D_p\dfrac{\partial^2 p}{\partial x^2} + g - r \\ 0 = D_n\dfrac{\partial^2 n}{\partial x^2} + g - r \end{array}\right]$$

Minority Carrier Current

We user the continuity equation for minority carriers (holes) in the n-type semiconductor. We have a (semi-infinite) n-type semiconductor with uniform doping density of N_D, the majority and minority carrier densities are:

Neutral n $\quad x_n \to p_n(x_n)$

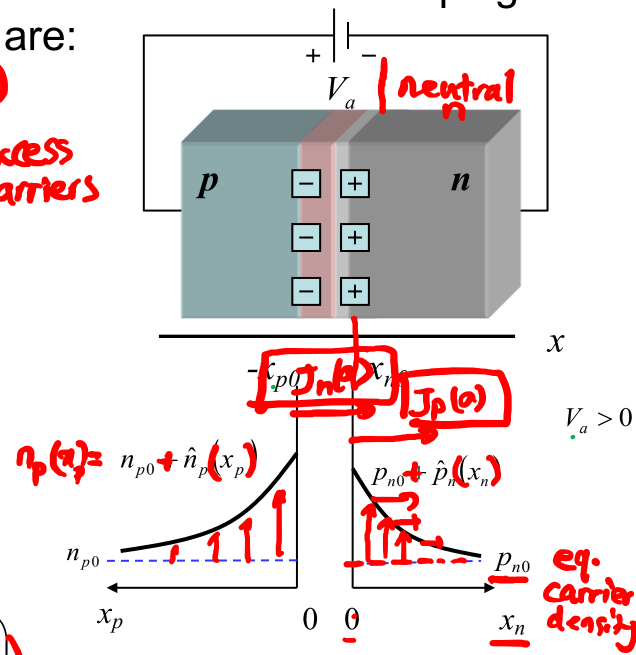
$p_n(x_n) = p_{n0} + \hat{p}_n(x_n)$

excess carriers

$\mathcal{E} = 0 \to$ no drift, Also assume DC, steady-state

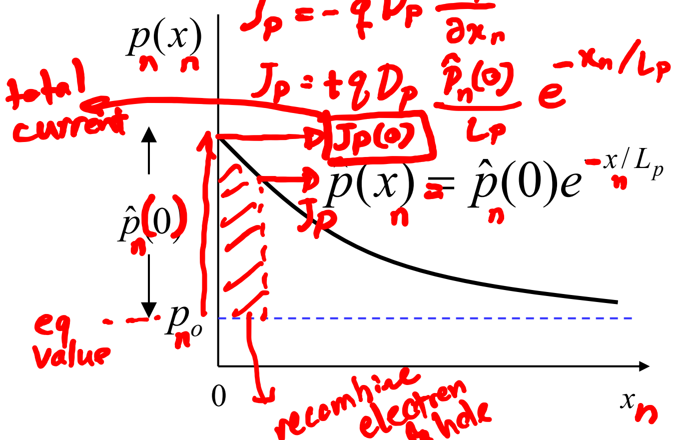
Simplified continuity equation $\Big\} \to D_p \dfrac{\partial^2 p_n(x_n)}{\partial x_n^2} + g - r = 0$

$\cancel{g_{th}} - \cancel{\alpha_r n_o p_o} - \dfrac{\hat{p}_n(x_n)}{\tau_p} = 0$



$J_p = -q D_p \dfrac{\partial p_n}{\partial x_n}$

$J_p = +q D_p \dfrac{\hat{p}_n(0)}{L_p} e^{-x_n/L_p}$



$$D_p \frac{\partial^2 \hat{p}_n(x_n)}{\partial x_n^2} - \frac{\hat{p}_n(x_n)}{\tau_p} = 0$$

$$\frac{\partial^2 \hat{p}_n(x_n)}{\partial x_n^2} - \frac{1}{L_p^2}\hat{p}_n(x_n) = 0$$

$$\hat{p}_n(x_n) = A\exp\left(-\frac{x_n}{L_p}\right) + B\exp\left(\frac{x_n}{L_p}\right)$$

$$L_p = \sqrt{D_p \tau_p}$$

Similar equation can be found for density of minority carriers (electrons) in a semi-infinite p-type semiconductor.

$$D_n \frac{\partial^2 \hat{n}_p(x_p)}{\partial x_p^2} - \frac{\hat{n}_p(x_p)}{\tau_n} = 0 \qquad \hat{n}_p(x_p) = A\exp\left(-\frac{x_p}{L_n}\right) + B\exp\left(\frac{x_p}{L_n}\right) \qquad L_n = \sqrt{D_n \tau_n}$$

Current in PN Junction

The density of minority holes on n side (p_n) will change as a function of external voltage V_a.

When there is no voltage applied

$V_{th} = \frac{kT}{q} = 25.9\,mV$ @ 300K

When a voltage is applied the density of minority carriers change: $p_n(0) = p_{n0}e^{qV_a/kT}$ $= p_{n0} e^{V/V_{th}}$ law of junction

The density of excess holes will be:

$$\hat{p}_n(0) = p_n(0) - p_{n0} = p_{n0}\left(e^{qV_a/kT}-1\right) = p_{n0}\left(e^{V/V_{th}}-1\right)$$

$$\hat{p}_n(x_n) = \hat{p}_n(0)\, e^{-x_n/L_p} = p_{n0}\left(e^{V/V_{th}}-1\right) e^{-x_n/L_p}$$

$$J_p = -q D_p \frac{\partial \hat{p}_n}{\partial x_n} = -q D_p \left(\frac{-1}{L_p}\right) p_{n0}\left(e^{V/V_{th}}-1\right) e^{-x_n/L_p}$$

$$\boxed{J_p(0) = q \frac{D_p}{L_p} p_{n0}\left(e^{V/V_{th}}-1\right)}$$

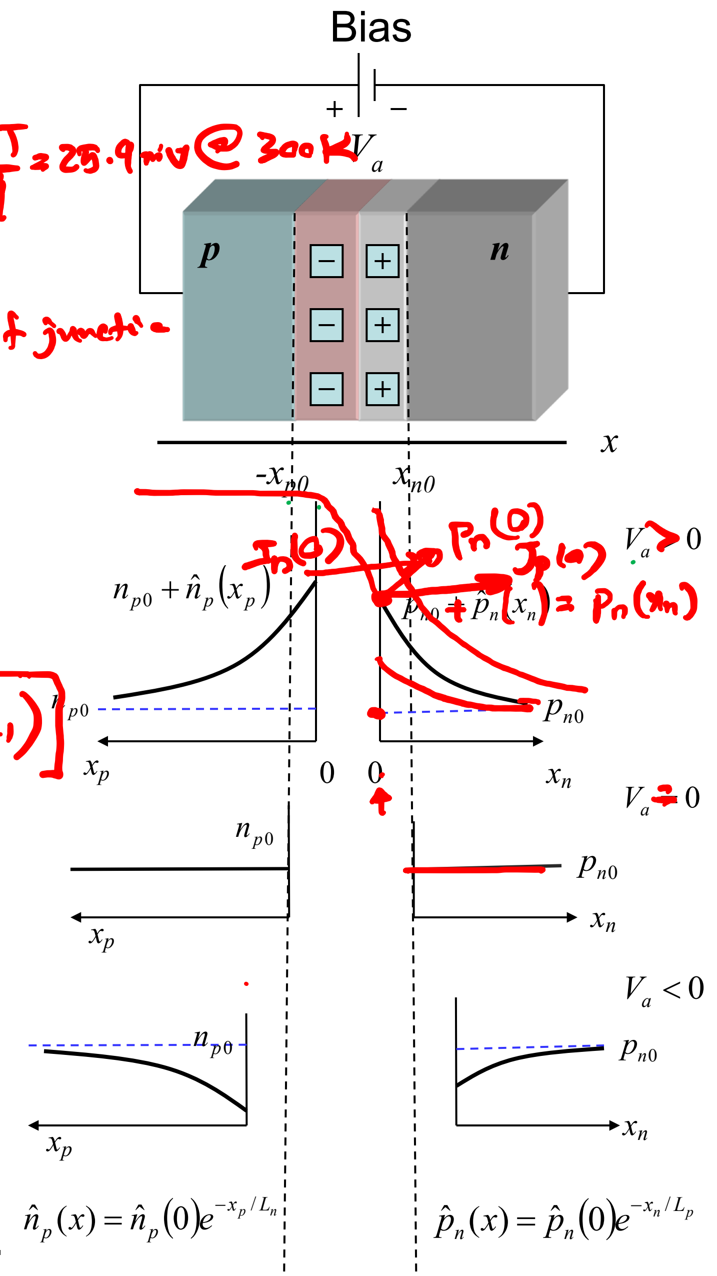
Similar equation can be written for minority electrons on p side: $n_p(0) = n_{p0} e^{V/V_{th}}$

$$\hat{n}_p(0) = n_p(0) - n_{p0} = n_{p0}\left(e^{qV_a/kT}-1\right) = n_{p0}\left(e^{V/V_{th}}-1\right)$$

$$\hat{n}_p(x_p) = \hat{n}_p(0)\, e^{-x_p/L_n} = n_{p0}\left(e^{V/V_{th}}-1\right) e^{-x_p/L_n}$$

$$J_n = q D_n \frac{\partial \hat{n}_p}{\partial x_p} = -q D_n \frac{1}{L_n} n_{p0}\left(e^{V/V_{th}}-1\right) e^{-x_n/L_p}$$

$$\boxed{J_n(x_p=0) = q \frac{D_n}{L_n} n_{p0}\left(e^{V/V_{th}}-1\right)}$$



Remember these equations are also valid for negative V_a.

Current Voltage Characteristics for Diodes

Now we can write the total current by adding hole and electron currents

$$J_{diff,p} = q\frac{D_p}{L_p}\hat{p}_n(0) = q\frac{D_p}{L_p}p_{no}\left(e^{V/V_{th}}-1\right)$$

$$J_{diff,n} = q\frac{D_n}{L_n}\hat{n}_p(0) = q\frac{D_n}{L_n}n_{po}\left(e^{V/V_{th}}-1\right)$$

$$I_{diode} = A\left(J_{diff,n} + J_{diff,p}\right) = qA\underline{\underline{\left(\frac{D_p}{L_p}p_{no} + \frac{D_n}{L_n}n_{po}\right)}}\left(e^{V/V_{th}}-1\right)$$

$p_{no} \to n_i^2/N_D$, $n_{po} \to n_i^2/N_A$

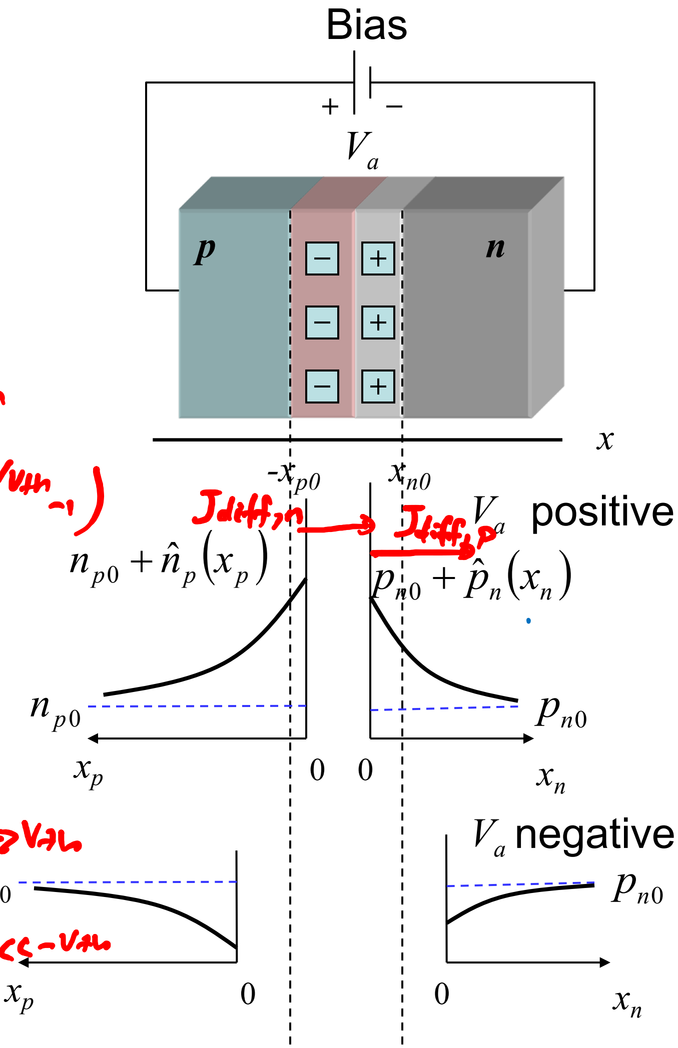
A: cross section area

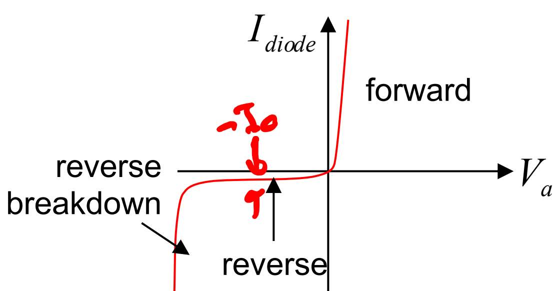
I_0 is called reverse saturation current, why?

$$I_0 = qA\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)n_i^2$$

$$J_0 = \frac{I_0}{A}$$

$$I = I_0\left(e^{V/V_{th}}-1\right) = \begin{cases} I_0 e^{V/V_{th}} & V \gg V_{th} \\ -I_0 & V \ll -V_{th} \end{cases}$$





Real Diode Characteristics

$\boxed{J/J_0 = e^{V/V_{th}} - 1}$ ideal

Forward bias:

- Generation-recombination region (a) $(e^{V/2V_{th}} - 1)$
- Diffusion-current region (ideal) (b)
- High-injection region (c)
- Series resistance region (d)

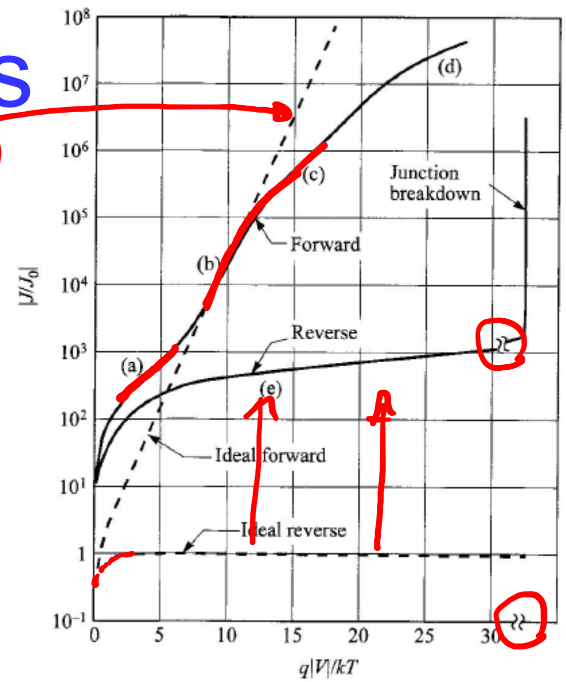


Fig. 11 Current-voltage characteristics of a practical Si diode. (a) Generation-recombination current region. (b) Diffusion-current region. (c) High-injection region. (d) Series-resistance effect. (e) Reverse leakage current due to generation-recombination and surface effects.

Reverse bias:

- Reverse leakage due to generation-recombination and surface effects

Zener breakdown:

- Heavily doped junctions: small depletion region
- Large field > 10^6 V/cm in W causes *field ionization* of host atoms.

Avalanche breakdown:

- In lightly doped junctions: *impact ionization* of host atoms by energetic carriers.
- Large field > 10^6 V/cm in W causes ionization of atoms.

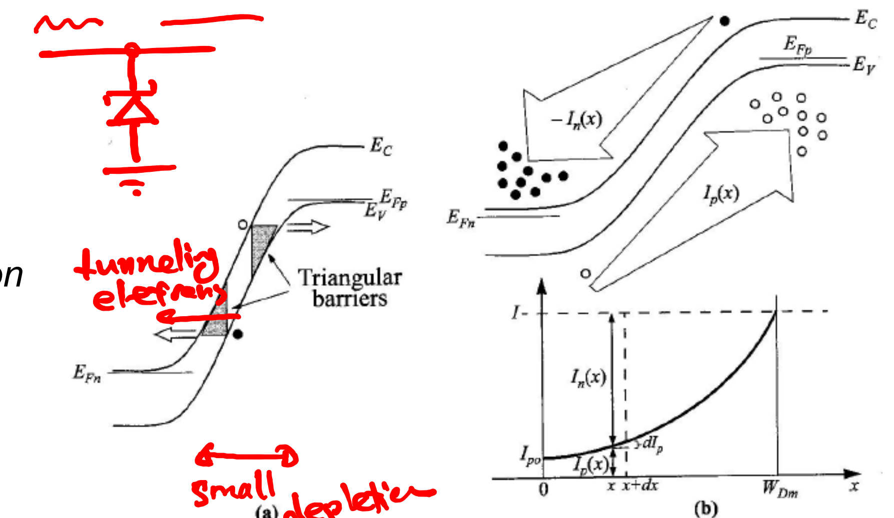


Fig. 15 Energy band diagrams showing breakdown mechanisms of (a) tunneling and (b) avalanche multiplication (example initiated by hole current I_{po}).

Depletion Region Recombination

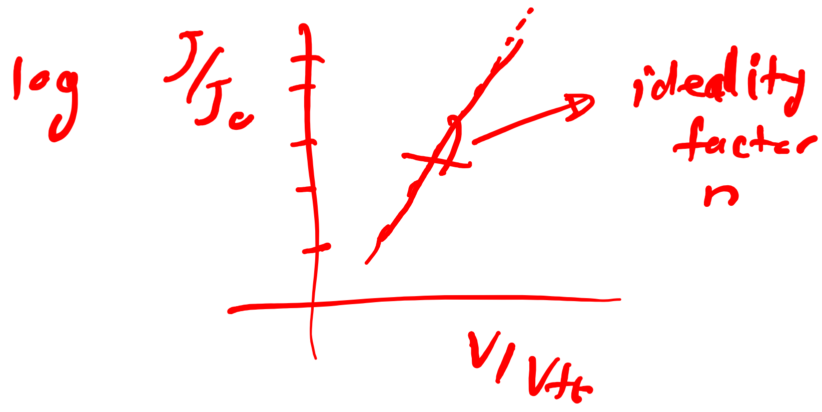
There is recombination and generation in the depletion region too.

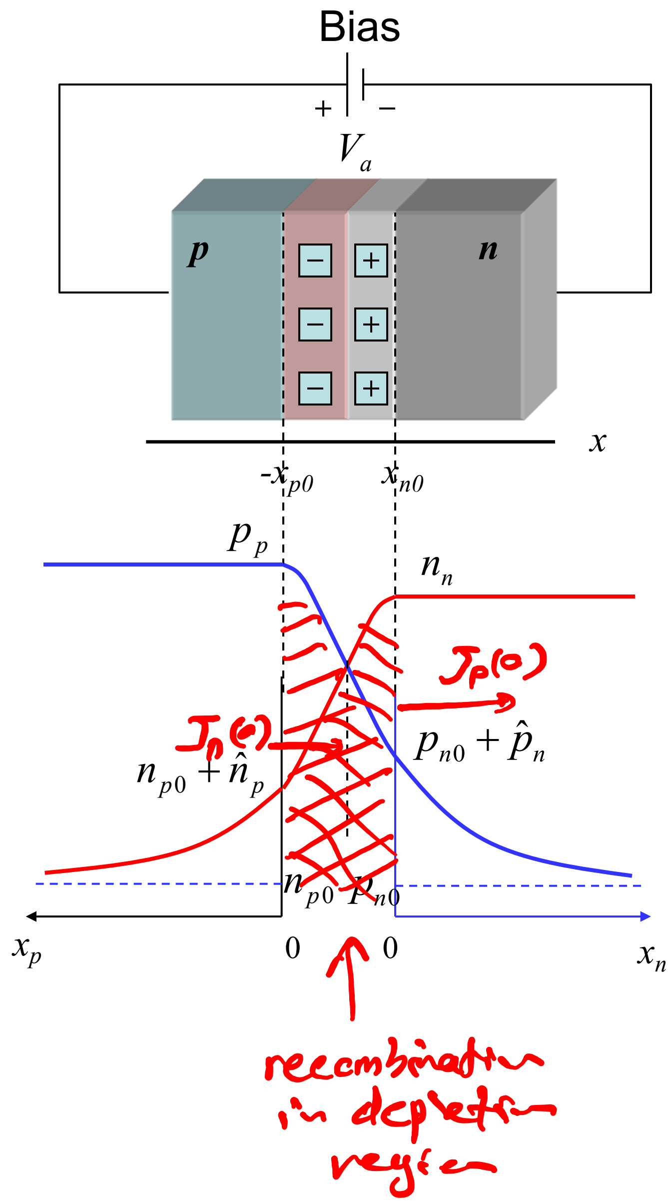
$$I_{recombination} \approx I_0'\left(e^{\frac{qV_a}{2kT}}-1\right)$$

So total current can be effectively written as

$$I_{diode} = I_0\left(e^{\frac{qV_a}{nkT}}-1\right) = I_0\left(e^{V/nV_{th}}-1\right)$$

$1 < n < 2$ is called the ideality factor.





Diode Capacitance

small signal model

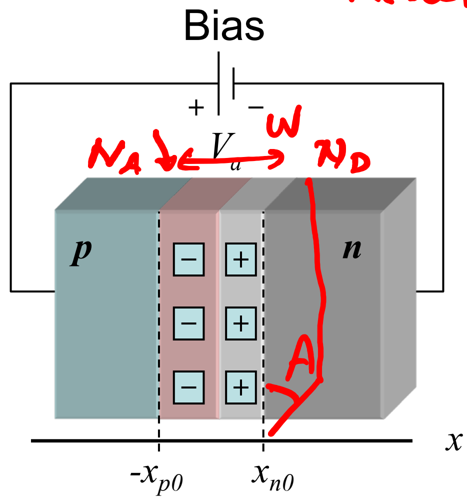
The charge in depletion region can be written as:

$$|Q_j| = qAx_{p0}N_A = qAx_{n0}N_D$$

$$|Q_j| = qA\frac{N_AN_D}{N_A+N_D}W$$

$W = f(V_a)$

$$C_j = \left|\frac{dQ_j}{dV}\right| = \frac{\epsilon A}{W} = \epsilon A\sqrt{\frac{q}{2\epsilon(V_0-V_a)}\frac{N_AN_D}{N_A+N_D}}$$



In the reverse region, junction capacitance C_j is dominant.

In the forward region, storage capacitance C_s is dominant:

→ total charge of hole profile

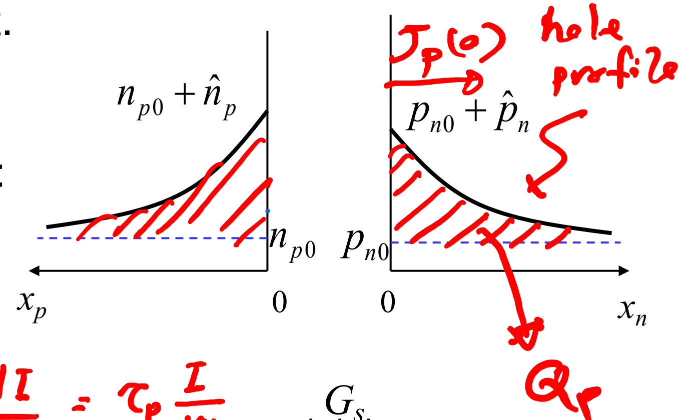
$$Q_p = I\tau_p = qAL_pp_ne^{qV_a/kT}$$

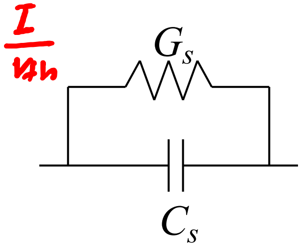
$$C_s = \frac{dQ_p}{dV} = \frac{q}{kT}I\tau_p = \frac{I}{V_{th}}\cdot\tau_p$$

$$G_s = \frac{dI}{dV} = \frac{q}{kT}I = \frac{I}{V_{th}}$$

$$C_s = \frac{dQ_p}{dV} = \tau_p\frac{dI}{dV} = \tau_p\frac{I}{V_{th}}$$

$$C_s = \frac{I}{V_{th}}(\tau_p+\tau_n)$$





small signal model

Light Emitting Diodes

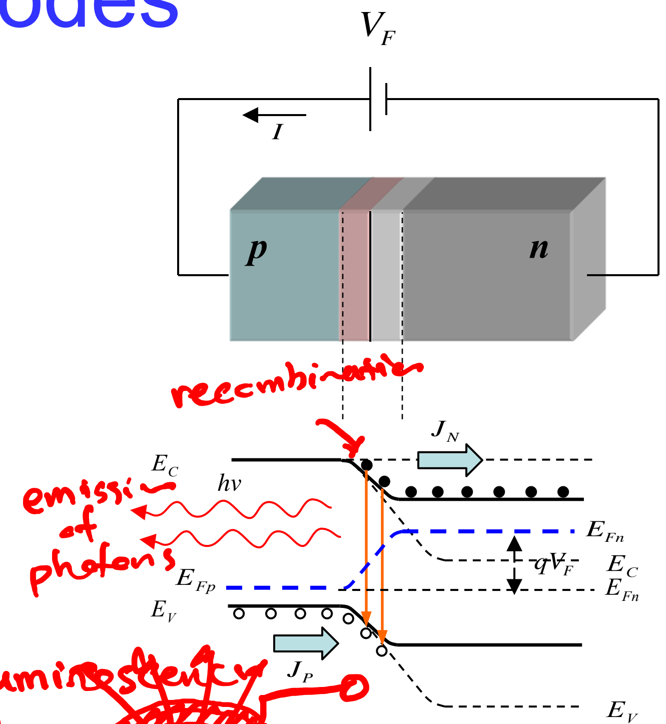
A light emitting diode (LED) can be built based on a PN junction diode.

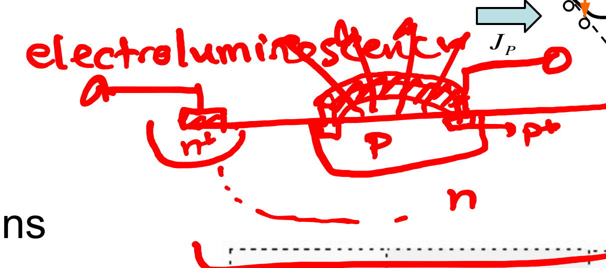
By applying a positive bias V_F, the depletion regions shrinks and barrier potential decreases.

Electrons from the n-side and holes from the p-side of the junction are pushed toward depletion region and recombine. Recombination energy in a good LED is emitted as a photon as shown in the figure.

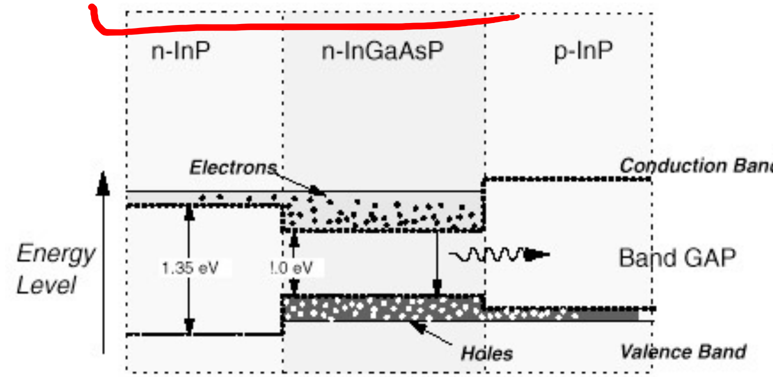
The wavelength of emission is determined by the bandgap of the semiconductor:

$$E_{ph} = h\nu \sim E_g$$





Often real LEDs are made from heterojunctions made from junctions of different semiconductors. Also thin emission layers are used for accurate setting of emission of wavelength:

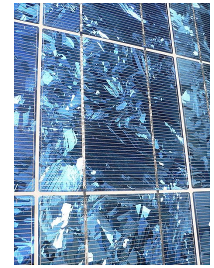


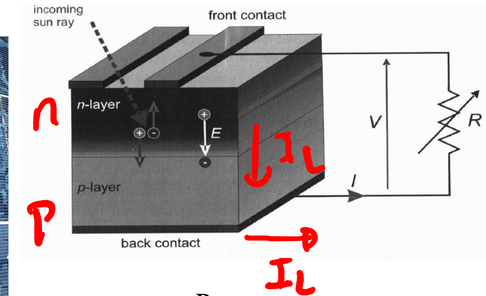
Bandgap boundaries are denoted by dotted lines

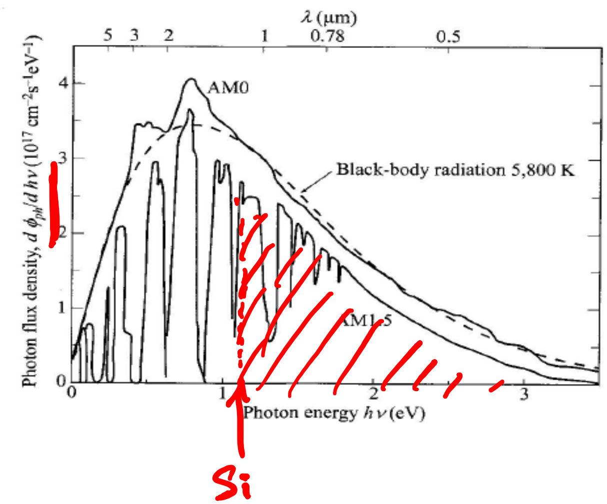
Solar Cells

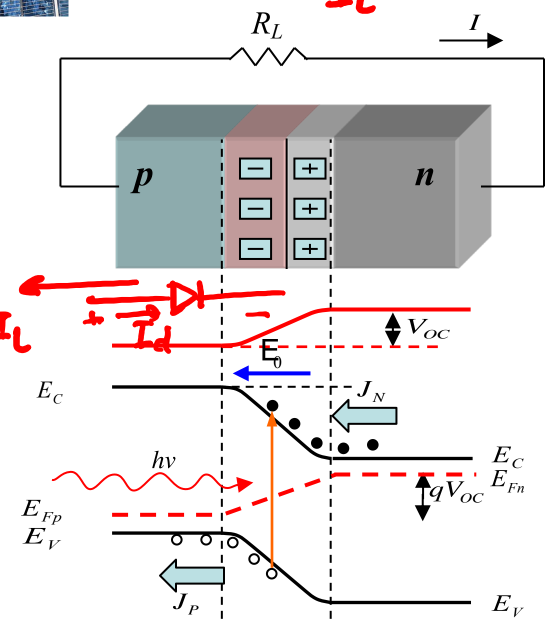
Solar radiation photons will generate electron-hole pairs (EHPs) that will be swept toward the electrodes by the built in electric field, resulting in a photocurrent I_L.

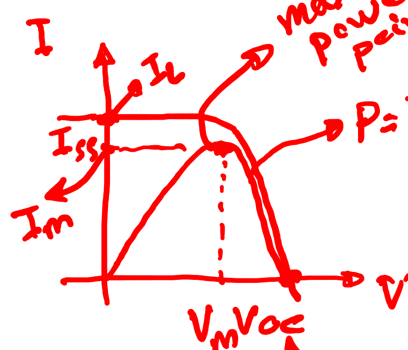
The flux of photons ($d\phi_{ph}/dh\nu$) is a function of photon energy







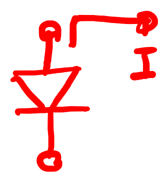




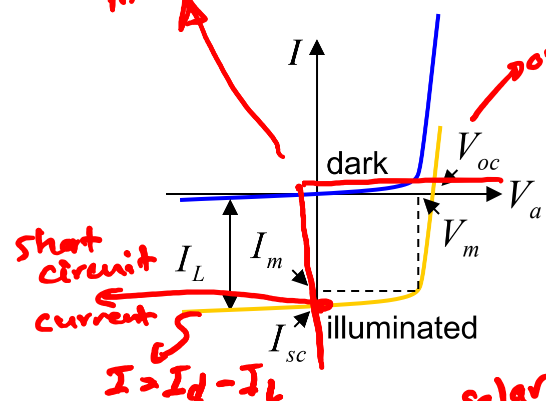
$$I_L(E_g) = Aq\int_{E_g}^{\infty} \frac{d\phi_{ph}}{dh\nu}\,dh\nu$$

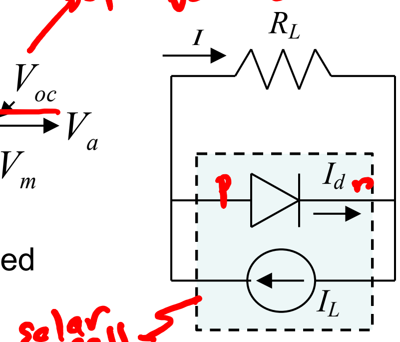
photocurrent

$$I = I_d - I_L = I_0\left(e^{\frac{qV_a}{kT}} - 1\right) - I_L$$



$$P = I_{diode}V = I_0\left(e^{\frac{qV}{kT}} - 1\right)V - I_L V$$





The power conversion efficiency: $\eta = \dfrac{P_{max}}{P_{in}}$

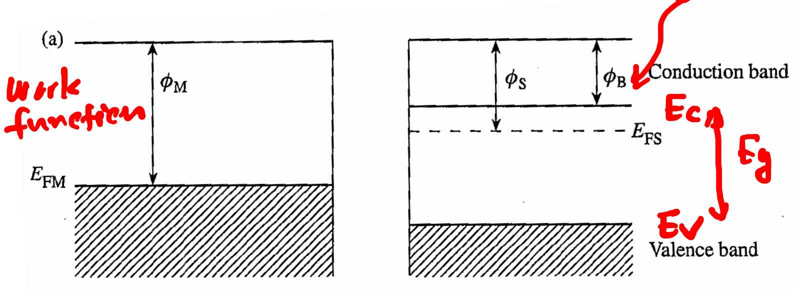
Schottky Diode: Metal-Semiconductor Junctions

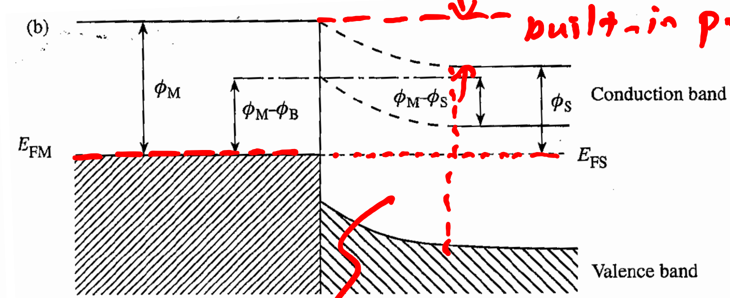
By putting a semiconductor in contact with a metal we can form a Schottky junction:
Two main cases will happen:

Schottky diode

$\phi_M - \phi_s$ built-in potential

$\phi_M > \phi_S$

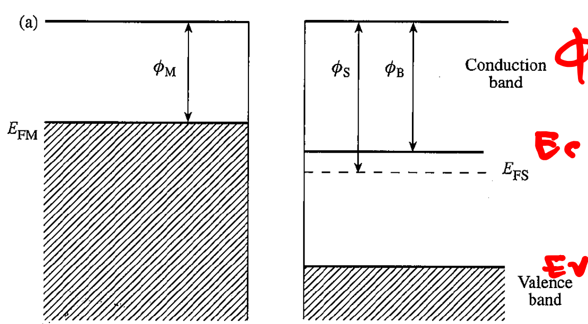


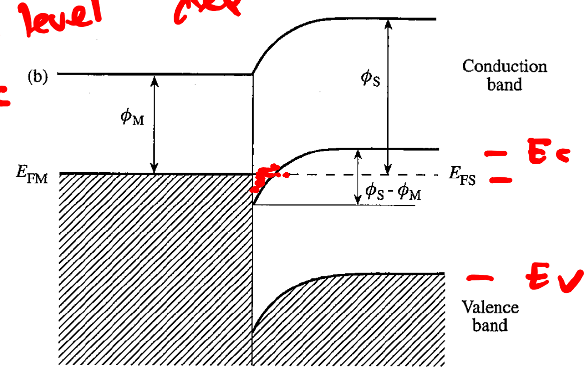


depletion

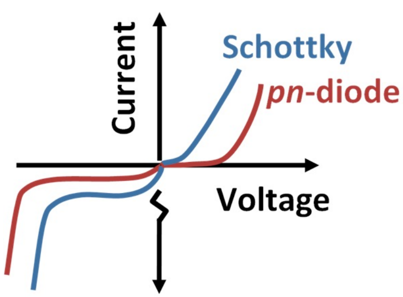
ϕ_B = vacuum level - Ec

$\phi_M < \phi_S$



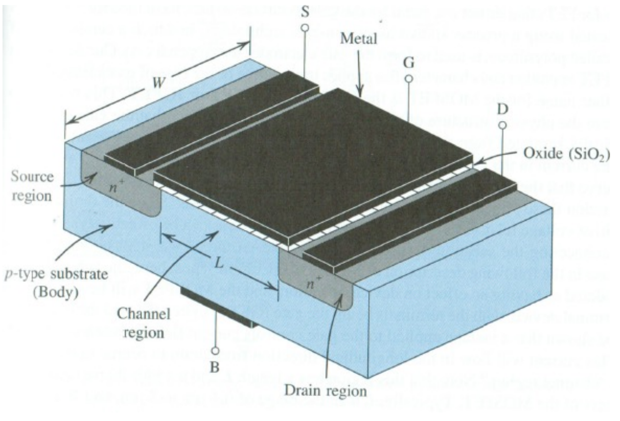


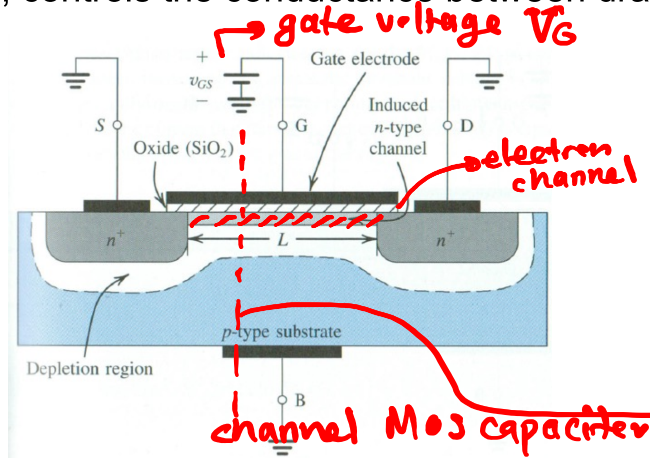
Ohmic juctn

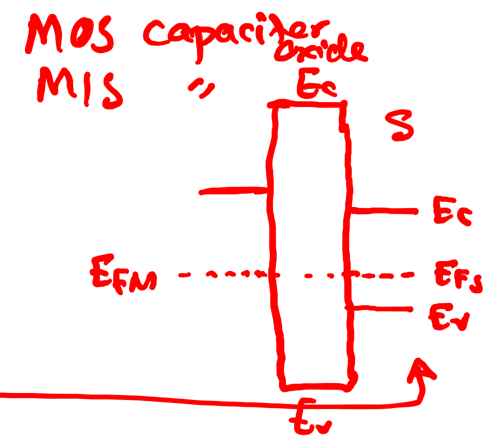


MOSFETs

Metal oxide semiconductor field effect transistors (MOSFETs) are the most important electronic device used in electronic industry. As seen in the figure, the gate electrode, which couples with the semiconductor substrate capacitively, controls the conductance between drain and source.







In this figure, the substrate is p-type. By applying a positive voltage to the gate, electrons are attracted to the surface and an electron channel is formed (*inversion*). Applying a more positive gate voltage will attract more electrons and the resistance between drain and source becomes smaller. The criteria for strong inversion is that the surface potential be equal to:

channel turn on

$$\phi_s = 2\phi_f = 2\frac{kT}{q}\ln\frac{N_a}{n_i}$$

positive negative

$$Q_m = -Q_d + Q_n \rightarrow Q_n = Q_m - Q_d$$

band bending at surface

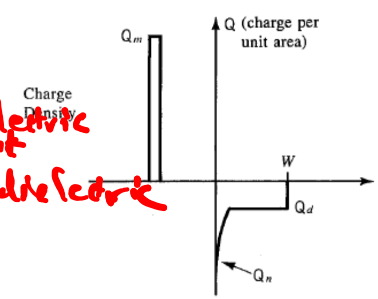
$$Q_m = C_i(V_G - \phi_s) \rightarrow C_i = \frac{\varepsilon_0\varepsilon_i}{d}$$

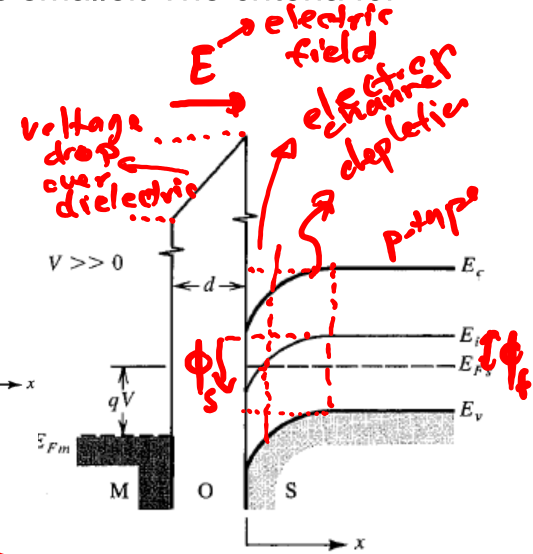
relative dielectric constant

d → thickness of dielectric

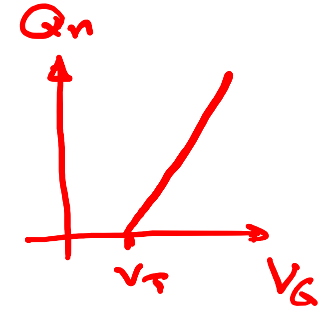
$$Q_n = -C_i\left(V_G - \phi_s + \frac{Q_d}{C_i}\right) = -C_i(V_G - V_T)$$

$$V_T = \phi_s - Q_d/C_i$$ threshold voltage





Linear and Saturation Regimes



$Q_n = -C_i(V_G - V_T) \rightarrow Q_n(x) = -C_i\big(V_G - V_T - V(x)\big)$

$dR_{ch}(x) = \rho(x)\frac{dx}{W} = \frac{dx}{\mu_n Q_n(x)\, W}$

charge density

$\frac{\Delta V(x)}{I} = \frac{dx}{\mu_n W(-C_i)\big(V_G - V(x) - V_T\big)} \rightarrow$

$\mu_n W(-C_i)\int_0^{V_D}\big(V_G - V_T - V(x)\big)\,dV(x) = I\int_0^L dx \rightarrow \mu_n W C_i\left[(V_G-V_T)V_D - \frac{V_D^2}{2}\right] = IL$

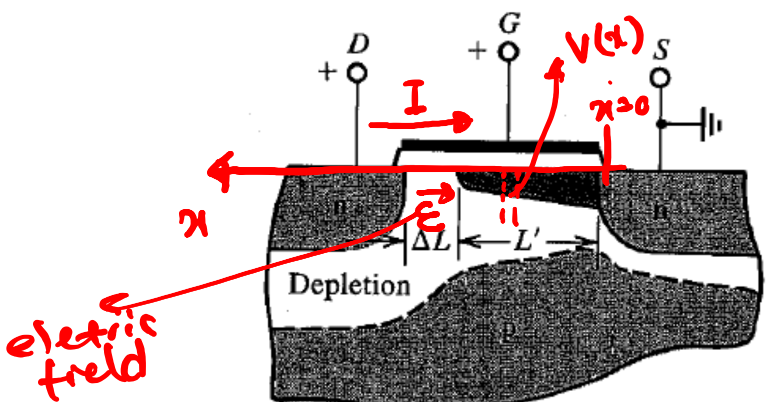
$I = \mu_n \frac{W}{L} C_i\left[(V_G-V_T)V_D - V_D^2/2\right]$ linear region

$V_G - V_T - V_D > 0 \rightarrow V_{GD} > V_T$

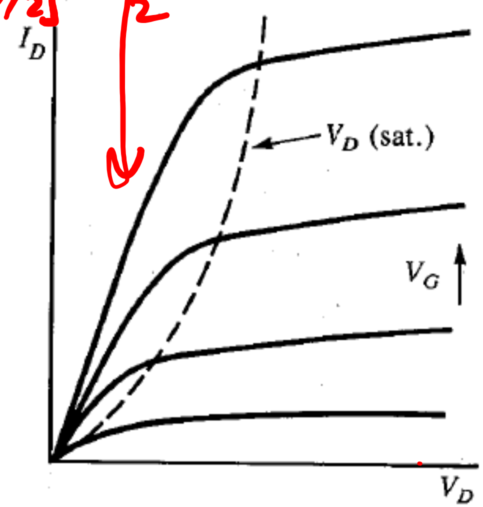
$V_{GD} = V_T \rightarrow$ sat point $\rightarrow V_{Dsat} = V_G - V_T$

$I = \mu_n \frac{W}{L} C_i\left[(V_G-V_T)(V_G-V_T) - (V_G-V_T)^2/2\right] = \frac{\mu_n C_i}{2}\frac{W}{L}(V_G-V_T)^2$

saturation region

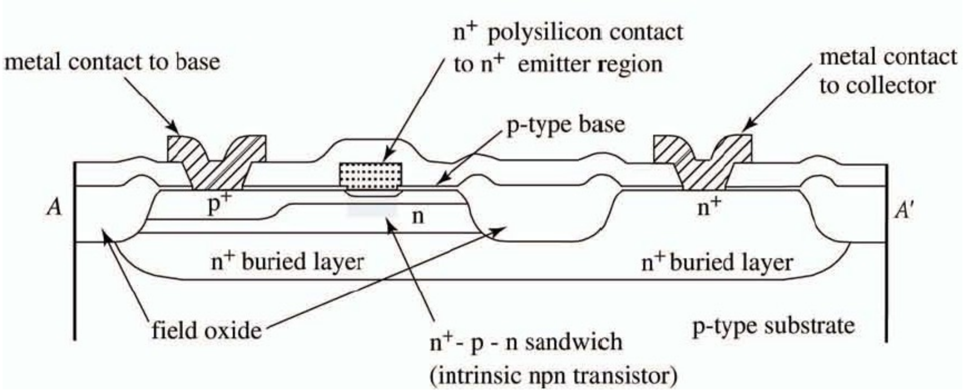


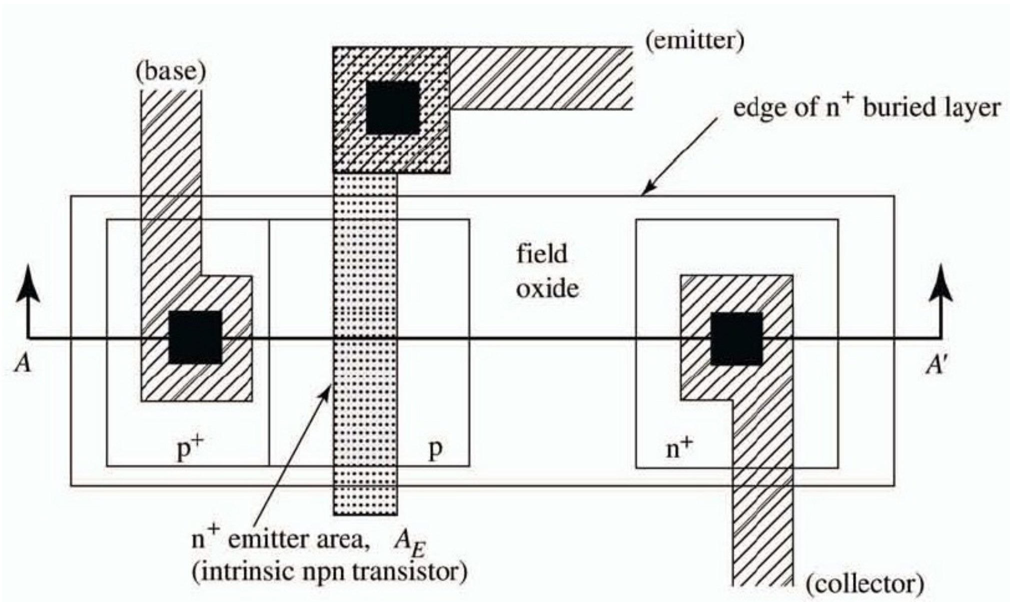
(a)



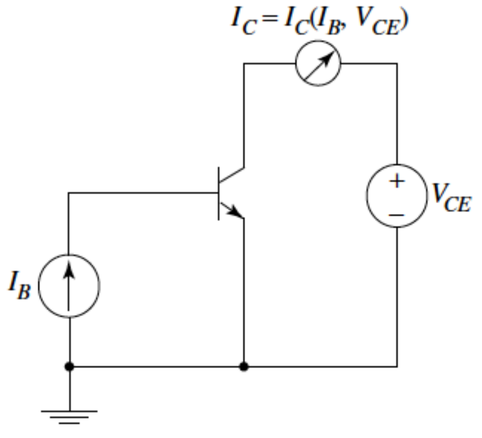
(b)

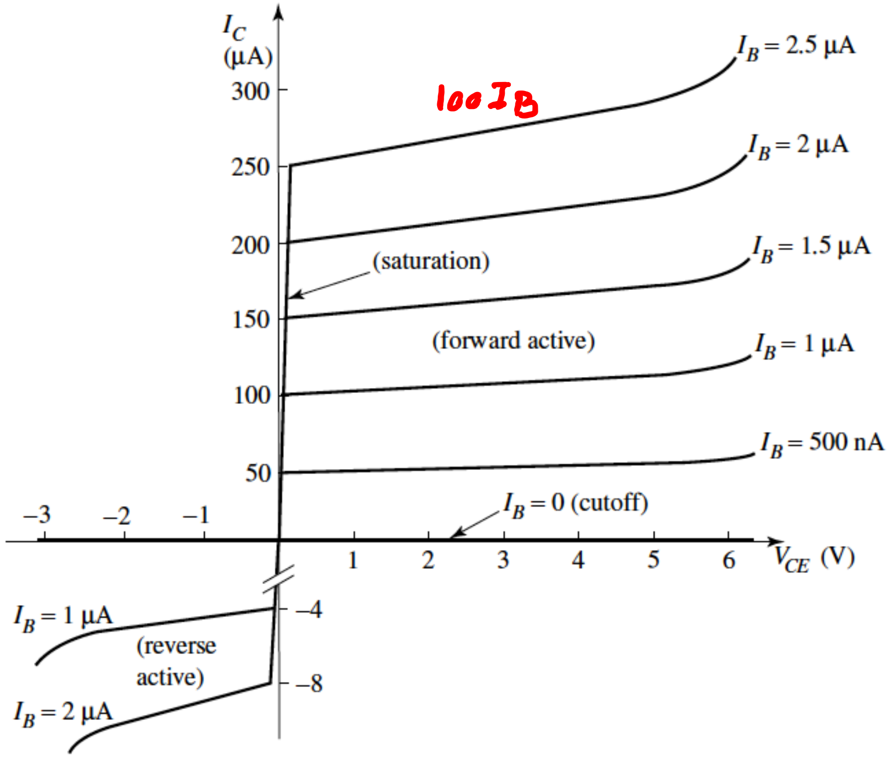
Bipolar Junction Transistor (BJT)





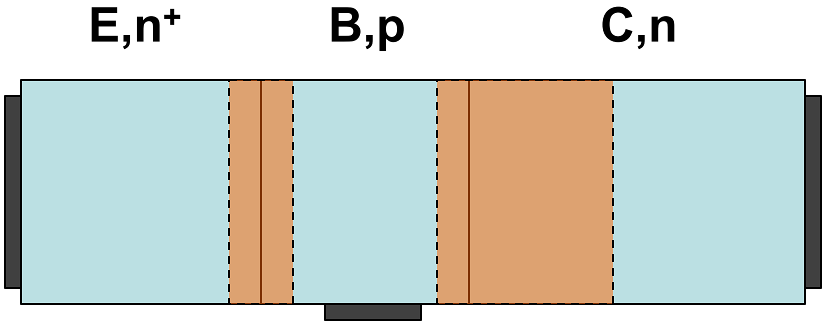
Transistor Operation



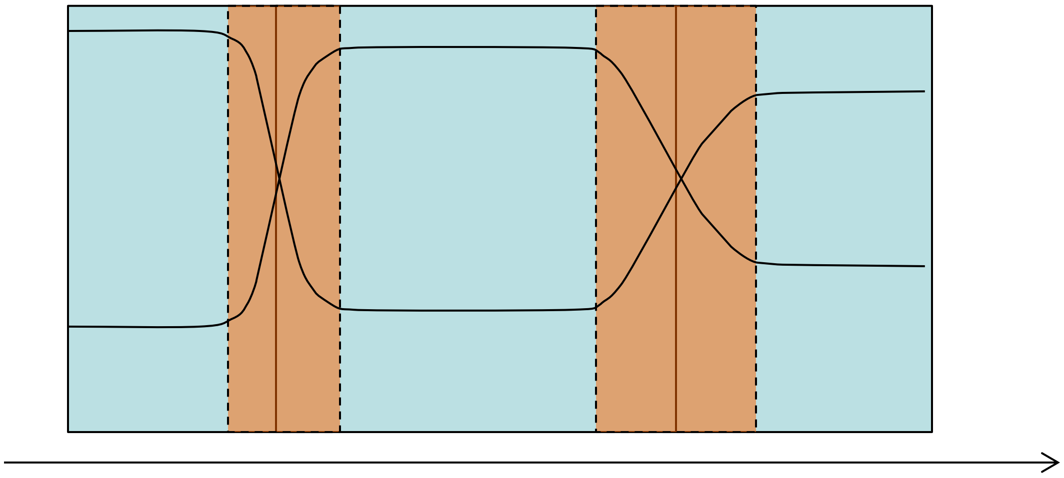


BJT Regions and Currents

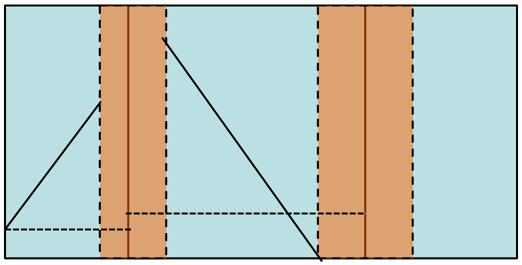
Positive bias for BE junction
Negative bias for BC junction



Carrier Profiles



Current components



$$n_{pB}(0) = n_{pB0} e^{V_{BE}/V_{th}}$$

$$J_{nB} = qD_n \frac{dn_{pB}}{dx} =$$

$$p_{nE}(-x_{BE}) = p_{nE0} e^{V_{BE}/V_{th}}$$

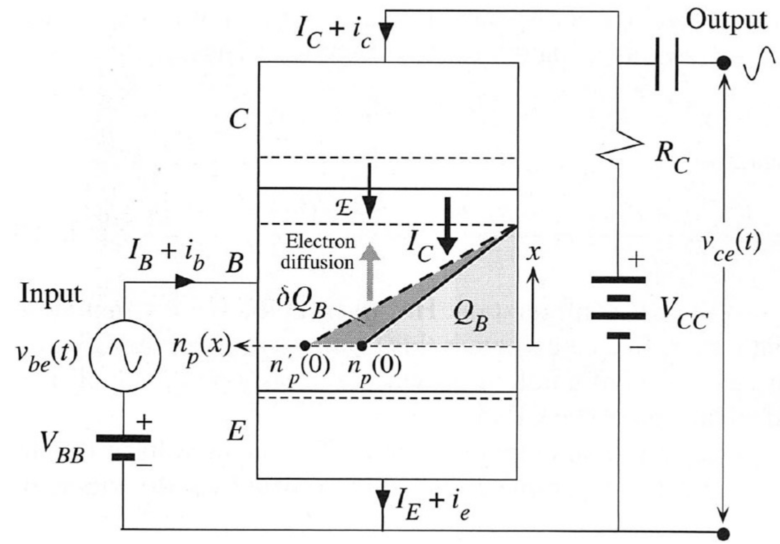
$$J_{pE} = -qD_p \frac{dp_{nE}}{dx} =$$

Current Gain

$$\alpha_F = \frac{I_C}{I_E}$$

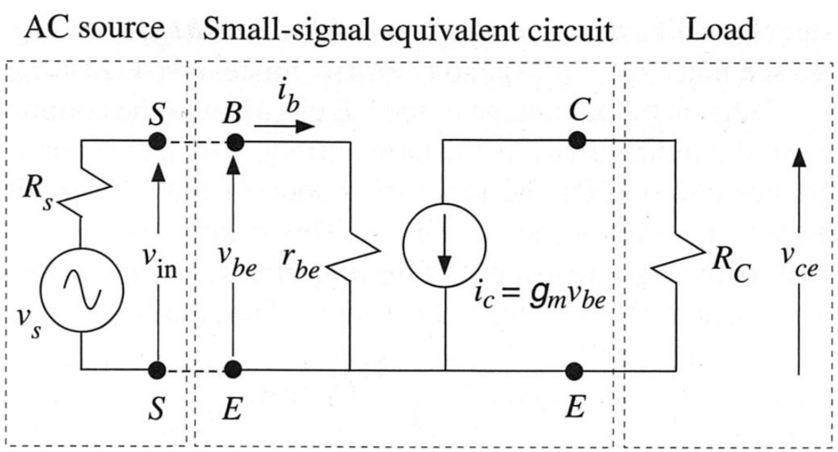
$$\beta_F = \frac{I_C}{I_B}$$

Common Emitter

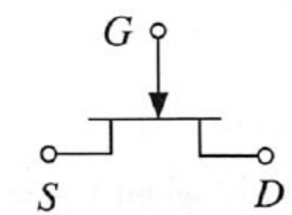


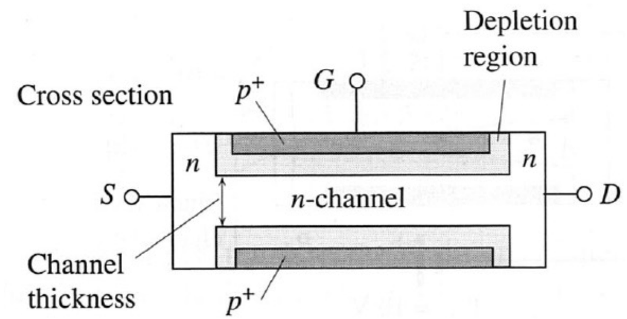
$$r_{be} = \frac{v_{be}}{i_b}$$

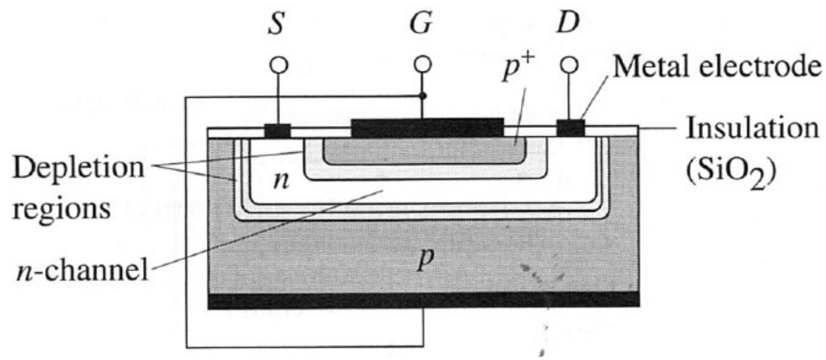
$$g_m = \frac{i_c}{v_{be}}$$

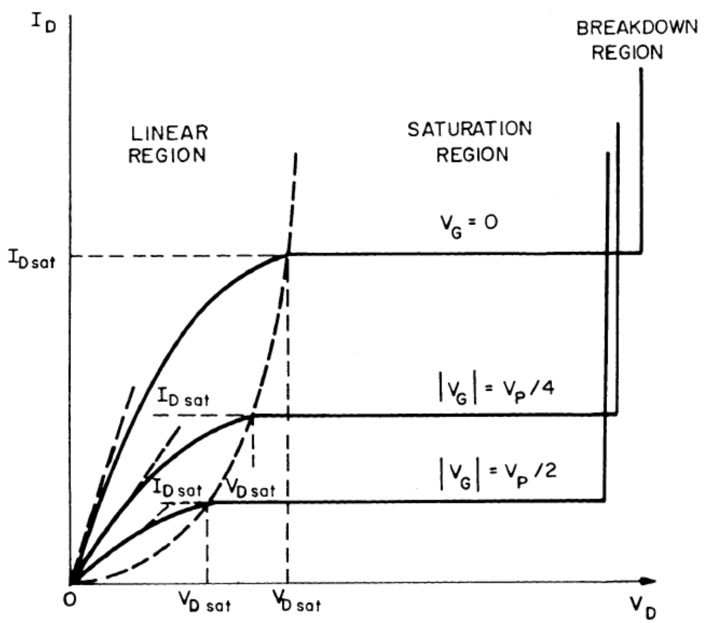


Junction Field Effect Transistor (JFET)

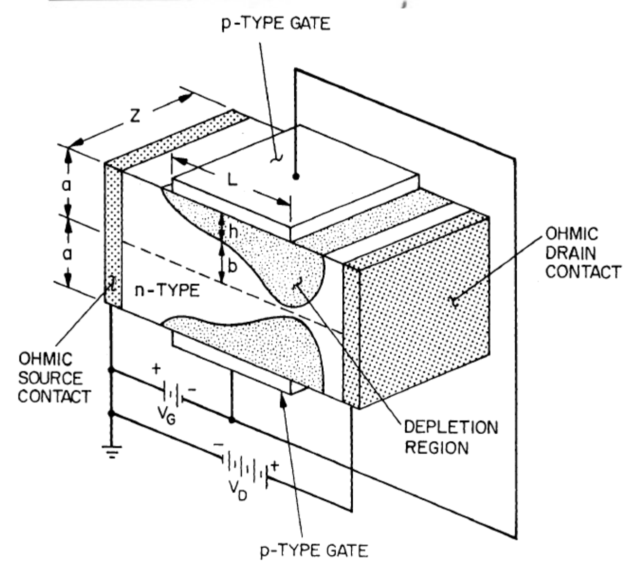




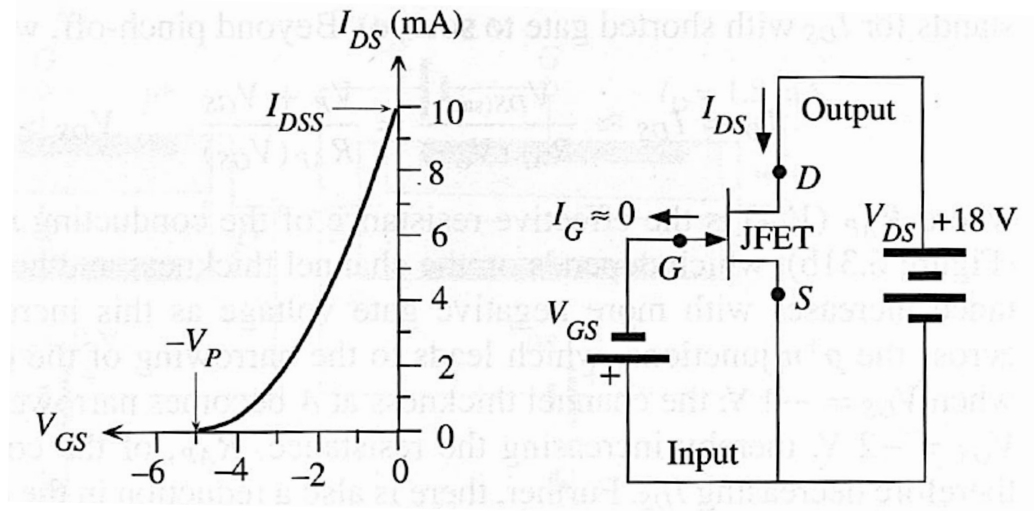


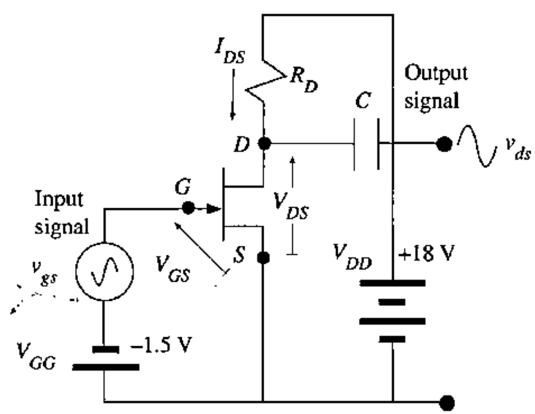


(from Sze)



Junction Field Effect Transistor (JFET)





(a)