ECE 340 - Semiconductor Electronics
Monday, 28 August 2017

22 nm scale currently, > GDP 4% → 2%
→ harder to follow Moore's law

semiconductors - more flexible than
conductors or insulators

device scaling

challenges: many, heating, etc.

tricks: More "Moore", Beyond Moore

unannounced quizes

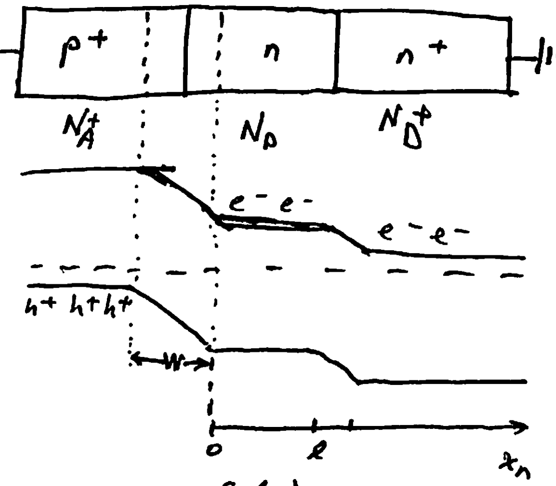
See course website.

Solid State Electronic Devices
Streetman & Banerjee, 7th.

ECE 340 (drift?)

$$J_p(x_n) \simeq J_p(\text{diff.}) = -qD_p \frac{dp(x_n)}{dx_n} = q D_p \frac{\Delta p_n}{\ell}$$

$$I_p(x_n) = A J_p(\text{diff}) = qA\frac{D_p}{\ell} p_n \underbrace{(e^{qV/kT}-1)}_{=\Delta?}$$



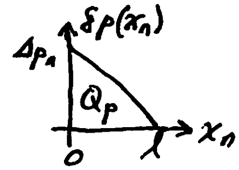
$$I_n(\text{recomb.}) = \frac{Q_p}{\tau_p} = \frac{\frac{1}{2} qA\,\ell\Delta p_n}{\tau_p}$$

space-charge neutrality

$$= \frac{qA\ell}{2\tau_p} p_n (e^{qV/kT}-1)$$

$$I_n(\text{recomb.}) = I_p(x_n=0) - I_p(x_n-\ell)$$

$$= I_p(x_n=0)\left[\frac{\ell^2}{2L_p^2}\right]$$

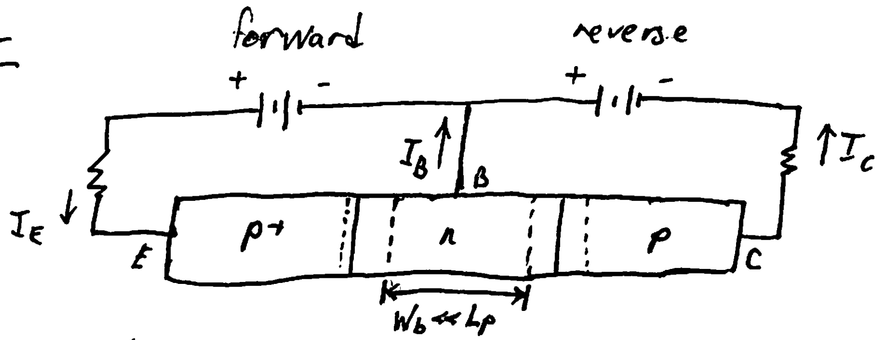


$$I_p(x_n=0) = qA\frac{D_p}{L_p}\Delta p_n \operatorname{ctnh}\left(\frac{\ell}{L_p}\right)$$

$$= qA\frac{D_p}{L_p}\Delta p_n\left[\frac{L_p}{\ell}+\frac{\ell}{3L_p}\right] = qA\frac{D_p}{\ell}\Delta p_n \frac{\ell}{L_p}\left[\frac{L_p}{\ell}+\frac{\ell}{3L_p}\right] = qA\frac{D_p}{\ell}\Delta p_n\left[1+\frac{\ell^2}{3L_p^2}\right]$$

$$I_n(\text{inj.}) = qA\frac{D_p}{L_n} n_p (e^{qV/kT}-1)$$

BJT



$$I_E = I_B + I_C$$
$$V_{BE} > 0$$
$$V_{CB} < 0$$

$$I_{E_p} = \gamma I_E$$

$$\gamma = \frac{I_{E_p}}{I_{E_p}+I_{E_n}}$$ γ emitter injection efficiency

$$I_{C_p} = B I_{E_p} = B\gamma I_E$$ B ~~base~~ transport factor

$$\simeq \alpha I_E$$ α current transfer ratio

$$\beta = \left(\frac{I_C}{I_B}\right)_{\text{normal mode}} = \frac{\alpha}{1-\alpha}$$

$$-\frac{d\,\delta p(x_n)}{dx_n} = \frac{\Delta p_E - \Delta p_C}{W_b}$$ neglect for normal mode

$$I_C = qA\frac{D_p}{W_b}\Delta p_E = qA\frac{D_p}{W_b} p_n (e^{qV_{EB}/kT}-1)$$

$$I_E = I_{E_p} + I_{E_n}$$

$$\simeq qA\left[\frac{D_p}{W_b} p_n + \frac{D_n^E}{L_N^E} n_p^E\right]\left(e^{qV_{EB}/kT} - 1\right)$$

$$\gamma = \left[1 + \frac{I_{E_n}}{I_{E_p}}\right]^{-1} \simeq \left[1 + \frac{D_n^E}{L_n^E}\frac{W_b}{D_p}\frac{n_p^E}{p_n}\right]^{-1} \approx \frac{1}{1 + \frac{\mu_n^E}{\mu_p^B}\frac{W_b}{L_n^E}\frac{N_D^B}{N_A^E}}$$

$$Q_p = qA\,\tfrac{1}{2}W_b\left(\Delta p_E + \underbrace{\Delta p_C}_{}\right)$$

neglect for normal mode. Why?

$$I_B(\text{recomb.}) = \frac{Q_p}{\tau_p} \simeq \frac{qAW_b}{2\tau_p} p_n\left(e^{qV_{EB}/kT} - 1\right)$$

$$I_B(\text{inj.}) = I_{E_n} = \frac{qAD_n^E}{L_n^E} n_p^E\left(e^{qV_{EB}/kT} - 1\right)$$

$$I_B = I_B(\text{recomb.}) + I_B(\text{inj.})$$

$$\beta \overset{\gamma\to 1}{=} \frac{I_C}{I_B(\text{recomb.})} = \frac{B}{1-B} = \frac{\frac{qAD_p}{W_b}\Delta p_E}{\frac{qAW_b}{2\tau_p}\Delta p_E} = \frac{2L_p^2}{W_b^2} \quad \text{for } W_b \ll L_p$$

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

$$B \approx 1 - \frac{1}{2}\left(\frac{W_b}{L_p}\right)^2 \quad \text{for } W_b \ll L_p$$

$$Q_p = I_B(\text{recomb.})\,\tau_p$$

$$I_C = \frac{Q_p}{\tau_t}$$ transit time $\tau_t \ll \tau_p$ "ideal" transistor

$$\beta \overset{\gamma\to 1}{=} \frac{I_C}{I_B(\text{recomb.})} = \frac{\tau_p}{\tau_t} \gg 1$$

$$\approx \frac{2L_p^2}{W_b^2}$$

$$\Rightarrow \tau_t = \frac{W_b^2}{2D_p}$$

Common-Emitter Amplifier

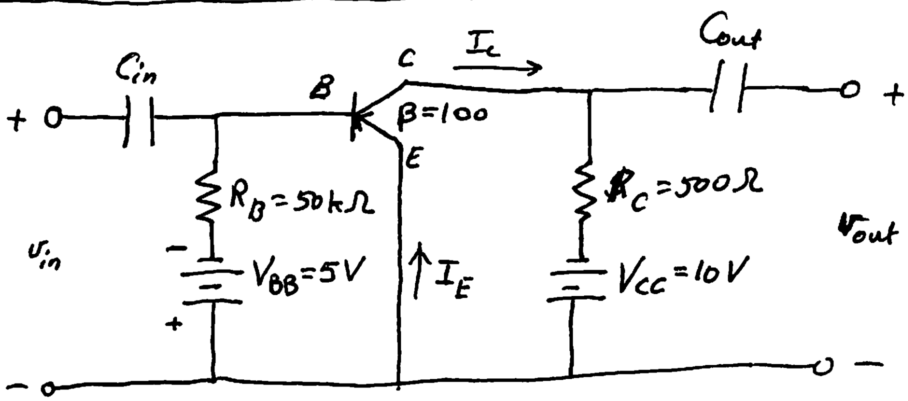
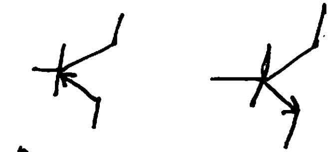
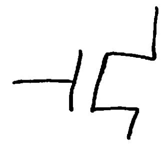


Fig. 7-4



p-n-p   n-p-n



$I_E = I_B + I_C$

DC bias levels

emitter junction forward biased $V_{EB} > 0$

collector junction reverse biased $V_{CB} < 0$

$$I_C = \beta I_B \approx I_{ES}\left(e^{qV/kT} - 1\right)$$

$$I_{ES} \approx qA\left(\frac{D_p}{W_b} p_n + \frac{D_n^E}{L_n^E} n_p^E\right)$$

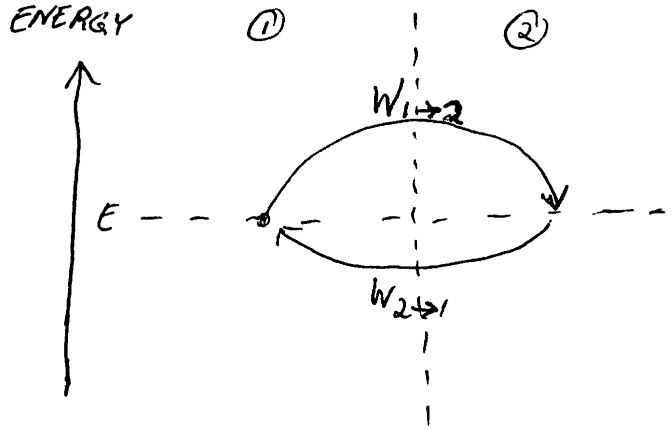
I_{ES} saturated

$$V_{BB} = V_{EB} + I_B R_B$$

$$I_B = \frac{V_{BB} - V_{EB}}{R_B}$$

ECE 340 ~~23~~ Mon 25 Sept Lecture – Leburton

Fermi Level Invariance at Equilibrium (T)



$W_{1\to 2}$ (RATE/cm^3): # of ELECTRONS TRANSFERRING FROM ① to ② /s/ UNIT VOLUME

$W_{2\to 1}$ ② to ①

At equilibrium,

$W_{1\to 2} = W_{2\to 1}$

$W_{1\to 2} \propto \underbrace{\cancel{N_1(E)}\, f_1(E)}_{\text{\# of } e^- \text{ at } E \text{ in } ①}\ \overbrace{N_2(E)[1-f_2(E)]}^{\text{\# of empty states at } E \text{ in } ②}$

$\parallel$

$W_{2\to 1} \propto \underbrace{N_2(E)\, f_2(E)}_{\text{\# of } e^- \text{ at } E \text{ in } ②}\ \overbrace{\cancel{N_1(E)}[1-f_1(E)]}^{\text{\# of empty states at } E \text{ in } ①}$

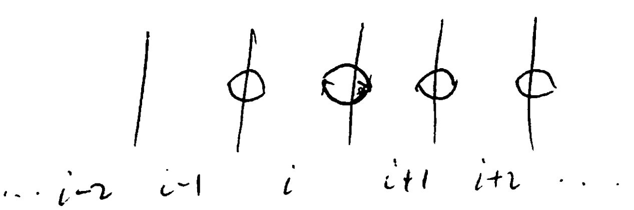
From $W_{1\to 2} = W_{2\to 1}$: $f_1(E)[1-f_2(E)] = f_2(E)[1-f_1(E)]$

$f_1(E) = f_2(E)$

$$\frac{1}{1+\exp\left(\frac{E-E_{F_1}}{kT}\right)} = \frac{1}{1+\exp\left(\frac{E-E_{F_2}}{kT}\right)}$$

$\Rightarrow E_{F_1} = E_{F_2}$ IFF $T_1 = T_2 = T$

GENERALIZATION: SYSTEM PARTITION



$E_{F_i} = E_{F_{i-1}}$

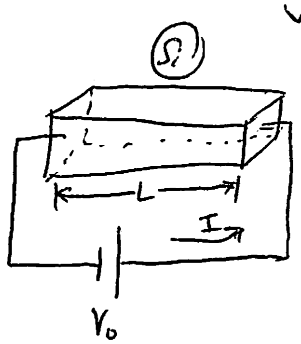
$E_{F_i} = E_{F_{i+1}}$

EQUILIBRIUM ↔ CONSTANT FERMI LEVEL

DRIFT $(\vec{\mathcal{E}}) \Rightarrow \vec{V}_d = \mu \vec{\mathcal{E}}$, $\mu = \frac{q}{m^*} \bar{t}$

Mobility $(cm^2/V\text{-}s)$ (scattering time) effective mass

$\vec{J}_n = q n_0 \vec{v}_d \qquad I_n = J_n A$



If $N_d = 10^{17}/cm^3 \Rightarrow (T = 300\,k)\, n_0 = 10^{17}/cm^3$

$\mathcal{E} = \frac{V_0}{L} = \frac{1}{10^{-3}} = 1 kV/cm$

$\mu_n(N_d = 10^{17}/m^3) = 1000\ cm^2/V\text{-}s$

$J_n = 1.6 \times 10^{-19} \times 10^{17} \times 10^3 \times 10^3 = \underline{1.6 \times 10^4\ A/cm^2}$

ECE 340 27 September Lecture - Prof. Leburton

semiconductors - doping, temperature, light effects

Chapter 4

Excess carriers in semiconductors

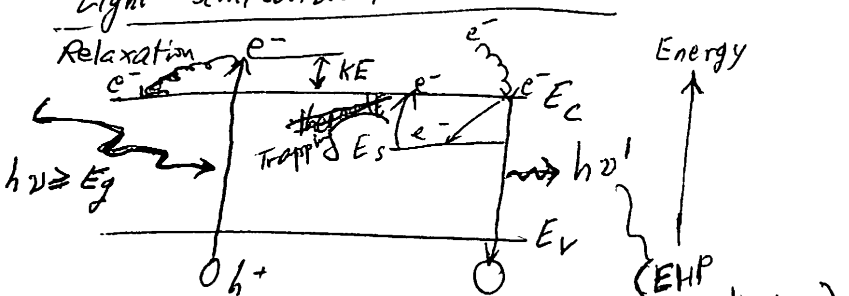
creation of carriers in excess of the thermal equilibrium values
⇒ device operation

Because excess carriers dominate the conduction process in semiconductor materials

Several ways of creation of Excess carriers:
- optical absorption
- electron bombardment
- inspect across a p-n junction

optical absorption
- photo conductive properties
- EHP Recombination
- carrier trapping

Light - Semiconductor Interaction



EHP Generation

Relaxation - similar to a car slowing down w/o gas due to friction
collisions w/ lattice etc.

$\nu' < \nu$

Trapping - e^- remitted due to thermal energy

E_s - local defect
e^- cannot move

Absorption Law: Optical Properties of Semiconductor

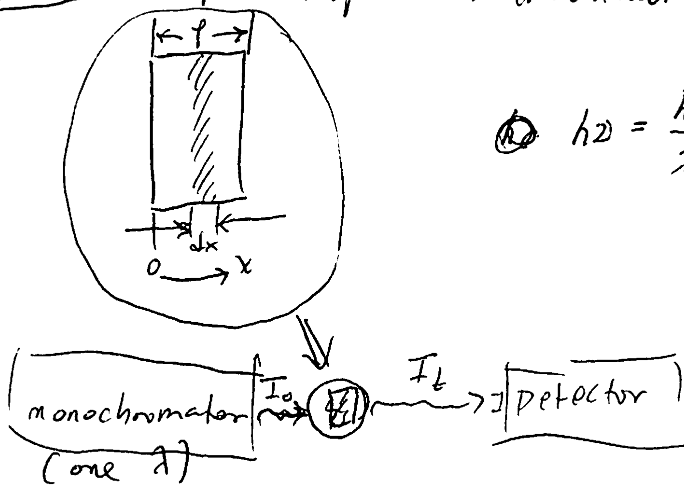


Figure 4.2 Optical Absorption Experiment

$h\nu = \frac{hc}{\lambda}$ ← speed of light

Between x and $x + dx$

$$dI = -\alpha(\lambda) I(x)\, dx$$

$$\frac{dI}{dx} = -\alpha(\lambda) I(x)$$

↑ Proportionality coefficient

$\alpha(\lambda)$: independent of x
But depends on:
- Wavelength
- Temperature
- Material

Solution: $\begin{cases} I(\lambda) = I_o e^{-\alpha(\lambda) x} \\ I_t = I_o e^{-\alpha(\lambda) \ell} \end{cases}$ ℓ: sample thickness

$\alpha(\lambda)$: absorption coefficient (cm^{-1})

$$\alpha(\lambda) = \frac{1}{\ell} \ln \frac{I_o}{I_t}$$

α negative — gain — lasers

Wavelength dependence of α

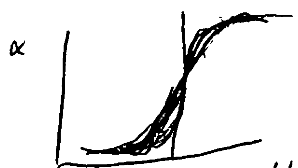


Fig 4-3

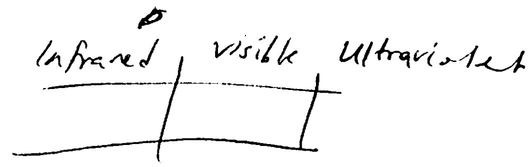


Fig 4-4

Luminescence (not incandescence (heated materials)) (e.g., for LEDs)

Light emission resulting from a return to equilibrium

~ opposite to absorption

According to the ~~excitation~~ excitation mechanism:

relaxation order: pico seconds
photoluminescence: nanoseconds

- photoluminescence ← photon absorption
- cathode luminescence ← high-energy electron
- Electroluminescence ← current flowing through the sample

1) Photoluminescence

b) Phosphorescence: slow process (phosphors)

a) e- excitation: EHP creation

b) Relaxation (lattice scattering): heat

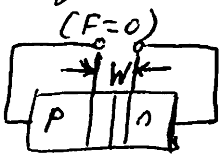
c) trapping (delay)

ECE 340 Mon 23 Oct Lecture — Leburton

(a) Equilibrium $(F=0)$

(b) Forward bias

(c) Reverse bias

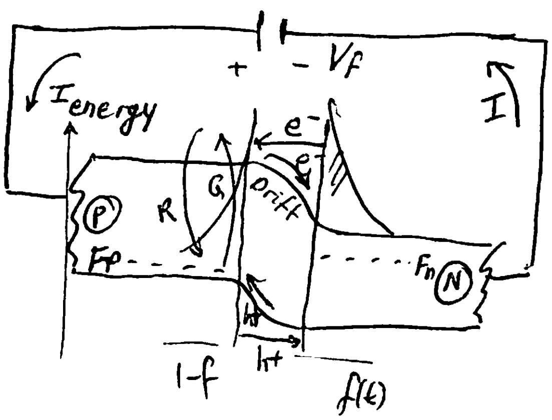


Particle flow	Current	
→	→	Hole diffusion
←	←	Hole drift
←--	→	Elec diffusion
--→	←--	Elec drift

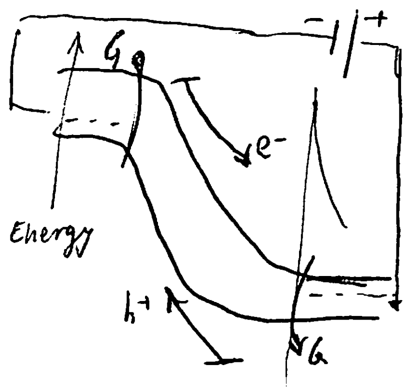
Particle flow	Current
→	←
→	←
←---	---→
--→	←--

Particle flow	Current
→	→
←	←
←--	--→
---→	←--

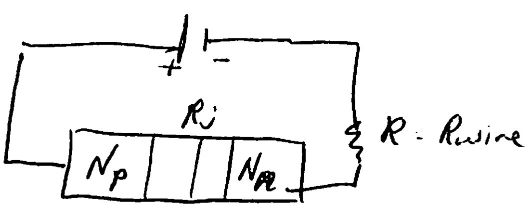
Carrier Injection (Forward Bias)



- Reverse Bias



(L.L.I.) — Low Level Injection : $n, p \ll N_a, N_d$



$$V_f = \cancel{RI} + (\cancel{R_{N_n}} + \cancel{R_{N_p}} + R_j) I$$

Carrier Injection: (Forward-Reverse-Biased Junctions)

FROM $V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n} = \frac{kT}{q} \ln \frac{n_n}{n_p}$

$$\boxed{\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{\frac{qV_0}{kT}}}$$

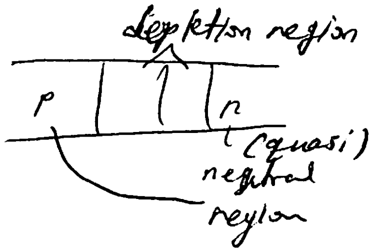
Non-Equilibrium: Low-level injection

[illegible]

So Neutral Region Length >> $L_{\{p,n\}}$ $\Big\{$ ⇒ excess carriers will recombine entirely in the neutral region.

$\delta p(x_n) = \Delta p(x_{no}) = e^{-x_n/L_p}$

$\delta n(x_p) = \Delta p(-x_{po}) = e^{-x_p/L_n}$



Current

$$I_p = -qAD_p \frac{d\delta p}{dx_n} = qA \frac{D_p}{L_p} \overbrace{p_n\left(e^{\frac{qV}{kT}} - 1\right)}^{\Delta p} e^{-x_n/L_p}$$

Area: A

$$I_n = qAD_n \frac{d\delta n}{dx_p} = -qA \frac{D_n}{L_n} \underbrace{n_p\left(e^{\frac{qV}{kT}} - 1\right)}_{\Delta n} e^{-x_p/L_n}$$

$$\boxed{I = I_0\left(e^{\frac{qV}{kT}} - 1\right)}$$

saturation - current flat as a function of the bias

$n_p = \frac{n_i^2}{N_A}$

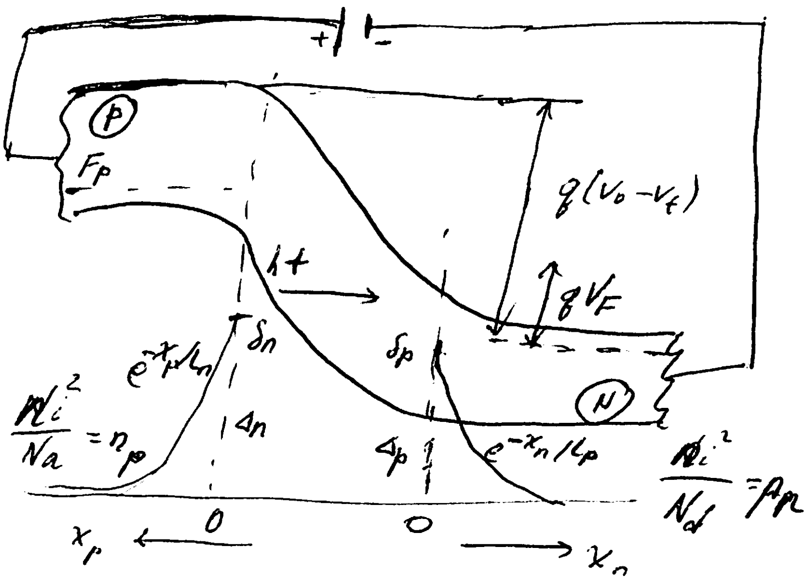
$p_n = \frac{n_i^2}{N_D}$

$p_n = \frac{n_i^2}{N_D}$ $\quad n_p = \frac{n_i^2}{N_A}$

p^+-n: If $N_a >> N_d \Rightarrow p_n >> n_p$

p-n^+: $\quad << \quad\quad <<$

Carrier Injection (Forward Bias)



$$\delta p(x_n) = \Delta p\, e^{-x_n/L_p}$$

Area under curve $\quad Q_p = qA\int_0^\infty dx_n\, \delta p(x_n)$

$Q_n = qA\,\Delta n\, L_n$

$\underbrace{\text{stored charge}}_{\text{minority carrier}}$ in n-side

$= qA\,\Delta p\, L_p$

$\frac{Q_n}{\tau_n}$

$\frac{Q_p}{\tau_p}$ recombination current

Total current: $\frac{Q_n}{\tau_n} + \frac{Q_p}{Q_p}$ # of injected carriers that are recombined.

$= qA\left(\frac{\Delta n L_n}{\tau_n} + \frac{\Delta p L_p}{\tau_p}\right)$

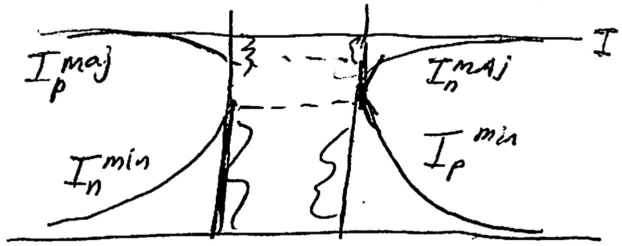
$$\Delta n = n_p\left(e^{\frac{qV_F}{kT}} - 1\right) = \frac{n_i^2}{N_A}\left(e^{\frac{qV_F}{kT}} - 1\right)$$

$$\Delta p = p_n\left(e^{\frac{qV_f}{kT}} - 1\right) = \frac{n_i^2}{N_d}\left(e^{\frac{qV_F}{kT}} - 1\right)$$

$$I_{tot} = qA\left(\frac{n_i^2}{N_A}\frac{L_n}{\tau_n}\frac{D_n}{D_n} + \frac{n_i^2}{N_d}\frac{L_p}{\tau_p}\frac{D_p}{D_p}\right)\left(e^{\frac{qV_f}{kT}} - 1\right)$$

$$\boxed{I_{tot} = qA\left(\frac{n_i^2}{N_A}\frac{D_n}{L_n} + \frac{n_i^2}{N_D}\frac{D_p}{L_p}\right)\left(e^{\frac{qV_f}{kT}} - 1\right)}$$

$$I_p^{min} = -qAD_p \frac{d}{dx_n} \delta p(x_n)$$



$$I_n^{min} = qAD_n \frac{d}{dx_p} \delta n(x_p)$$

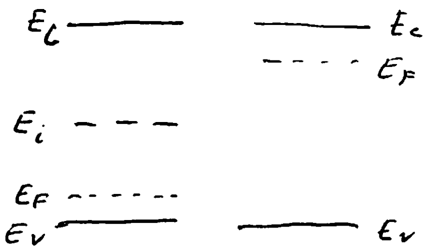
$$I_n^{min}(x_p=0) + I_p^{min}(x_n=0) = I_{tot}$$

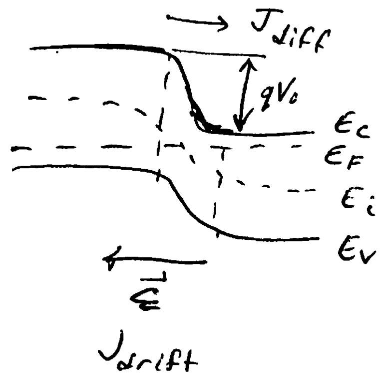
Average: 25.97 /40

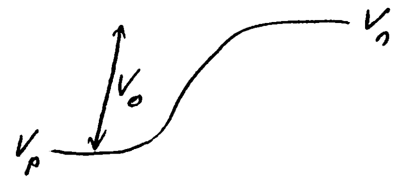
σ : 9.25

Regrades due Friday

ECE 340 HKN Review







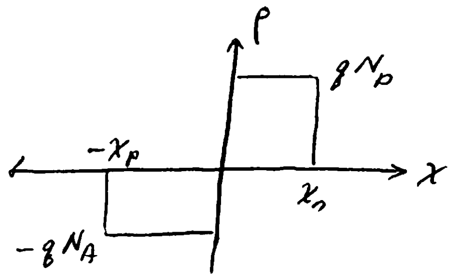
$V_0 = F_p - F_n$

$$\vec{J}_{diff,n} = \vec{J}_{drift,-}$$

$$q p \mu_p \mathcal{E} = q p D_p \frac{dp}{dx} = 0$$

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

$$\frac{p_p}{p_n} = e^{qV_0/kT}$$



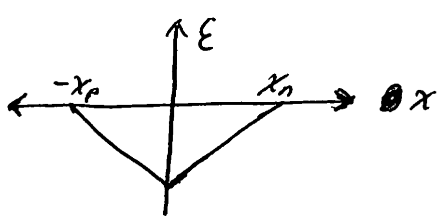
$$q N_A x_p = q N_D x_n$$

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon}$$

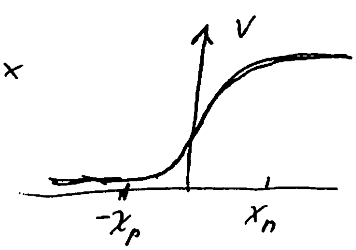
$$\frac{d\vec{E}}{dx} = \frac{\rho}{\epsilon}$$

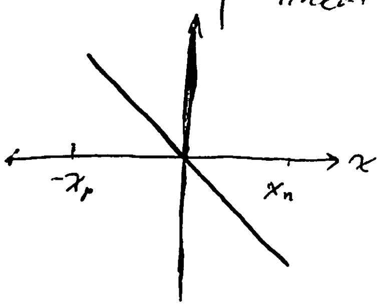
p-region: $\frac{d\mathcal{E}}{dx} = \frac{-qN_A}{\epsilon}$

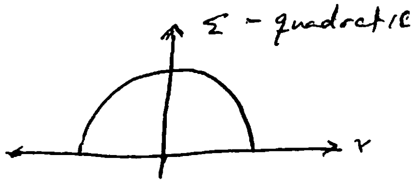
n-region: $\frac{d\mathcal{E}}{dx} = \frac{qN_D}{\epsilon}$



$$\Delta V = -\int_{-x_p}^{x_n} \vec{\mathcal{E}}\, dx$$







V - cubic

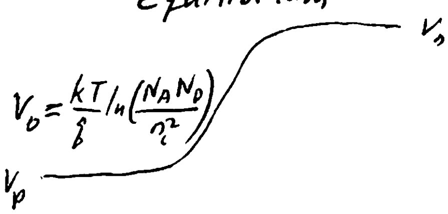
$W = x_n + x_p$

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right]^{1/2}$$

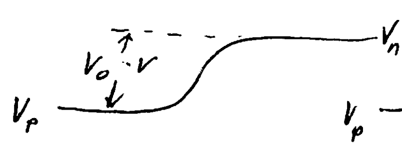
$V_0 - V$

Equilibrium

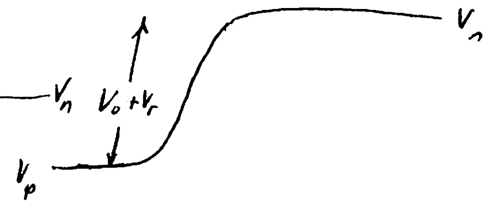
$V_0 = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$

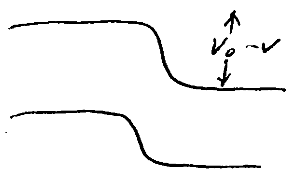


Forward bias



Reverse bias

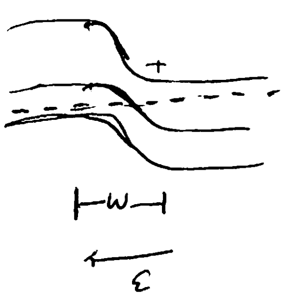




lower built-in field
depletion region shrinks
b/c less charge exposed
less bias introduced

less diffusion current
drift current
insensitive to voltage

higher built-in field



$J_{th} \propto (w + L_p + L_n)$

$$J = J_0(\underbrace{e^{qV/kT}}_{\text{Diffusion}} \underbrace{-1}_{\text{Drift}})$$

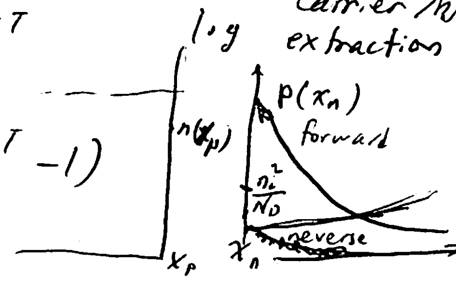
$$\frac{p(-x_p)}{p(x_n)} = e^{q(V_0 - V)/kT}$$

$$\frac{p(x_n)}{p_n} = e^{qV/kT}$$

$$\Delta p = p(e^{qV/kT} - 1)$$

$$J_p = -qD_p \frac{d\Delta p}{dx}$$

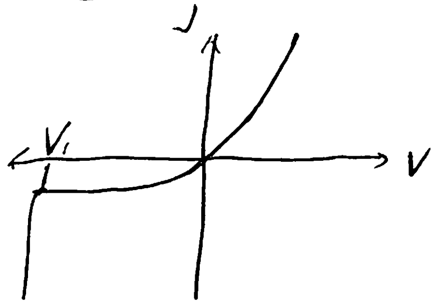
Minority carrier injection/extraction



$$J = \left(q\frac{D_p}{L_p}p_n + q\frac{D_n}{L_n}n_p\right)\left(e^{q\Delta V/kT} - 1\right)$$

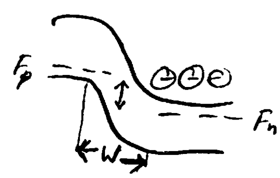
$$\Delta p(x) = p_n\left(e^{qV/kT} - 1\right)e^{-x/L_p}$$

$$\Delta n(x) = n_p\left(e^{qV/kT} - 1\right)e^{-x/L_n}$$



Zener

- Tunneling



- high doping

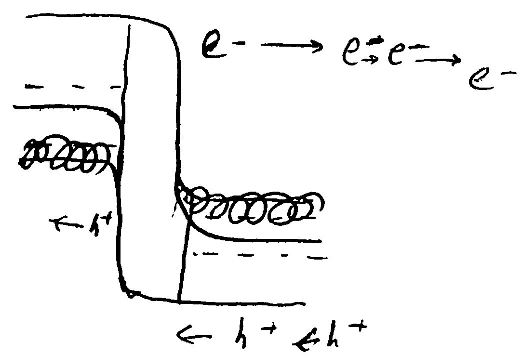
$$W \propto \left(\frac{1}{N_A} + \frac{1}{N_D}\right)^{1/2}$$

Tunneling current $\propto \dfrac{\Delta E}{kT}$

T ↑ → easier to tunnel

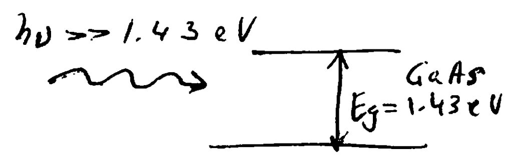
Avalanche

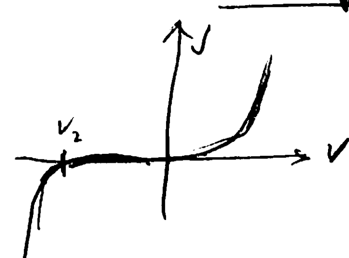
- carrier Multiplication



high magnitude voltage

relatively low doping



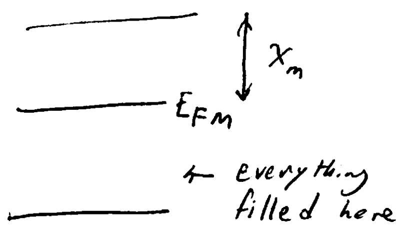


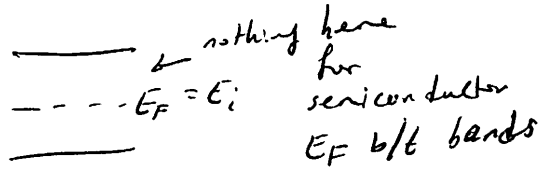
$T_2 > T_1$

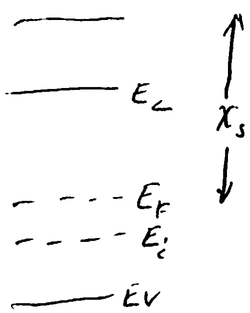
$|V_2| > |V_1|$

$$C \approx \frac{\epsilon A}{W}$$

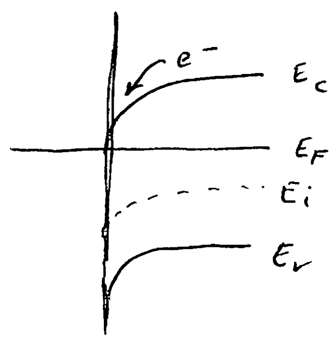
$$W = \left[\frac{2\epsilon (V_0 - V)}{q} \frac{1}{N_D} \right]^{1/2} \quad p^+n$$







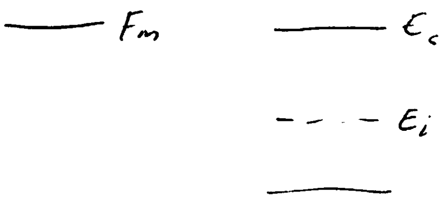
n type



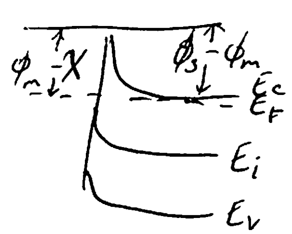
Ohmic contact

material more n-type at junction than in bulk

$$n \propto \exp\left(\frac{E_c - F_n}{kT}\right)$$



	n-type	p-type
Rectifying/Shottky	$\phi_m > \phi_s$	$\phi_s > \phi_m$
Ohmic	$\phi_s > \phi_m$	$\phi_m > \phi_s$

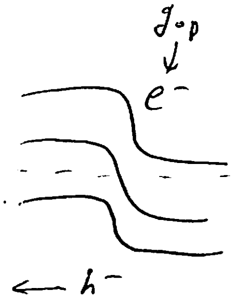


Si $h\nu = 1.2$ eV

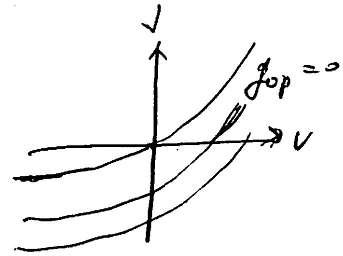
GaAs $E_g \approx$ 1.43 eV

Optoelectronics

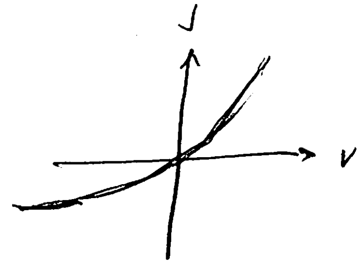
- photodiode
- solar cell
- LED/laser



$+L_n + L_p + W|$

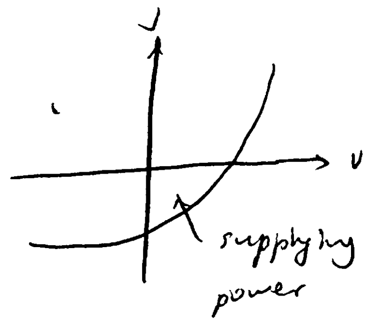


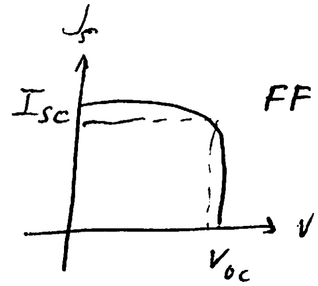
$$\tilde{J} = J_{th}\left(e^{qV/kT} - 1\right) - J_{op}$$



increase photon flux does nothing b/c photons not absorbed

solar cells





$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

solar cell – want long carrier ~~xxx~~ lifetimes

laser – ~~xxx~~ short carrier lifetimes / high recombination

LEDs – spontaneous, random polarization/orientation

laser – coherent, same orientations

lasers

E_c

$F_n - F_v > E_g$

E_v

Reverse bias – temperature dependence – Zener / Avalanche breakdown

$T\uparrow$ Zener tunneling ←
require higher mag voltage to breakdown

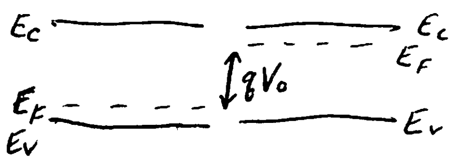
Avalanche
" lower " "

ECE 340 Monday 13 Nov Lecture

Review for MT II.

Midterm - Ch. 5 & 8. No Ch. 6.

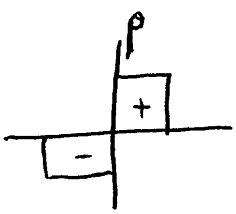
Form PN junction Built-in potential

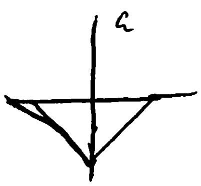


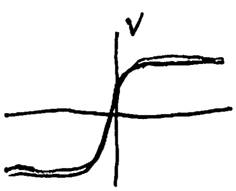
Space charge

Assume only ionized donors in the depletion region

doping high → shallow side $\underbrace{\text{side}}_{\text{penetration}}$







Key Eqns

Forward and reverse bias on pn junction

Forward: smaller total elec field
ext + built in in diff directions

Reverse: ext + built in in same dir
larger total elec field

Current flow in pn junction:
hole diffusion, hole drift, electron diffusion, electron drift

Equilibrium

Forward bias, minority carrier diffusion

$$\delta p(x_n) = \Delta p\, e^{-x_n/L_p}$$

Excess carrier distribution

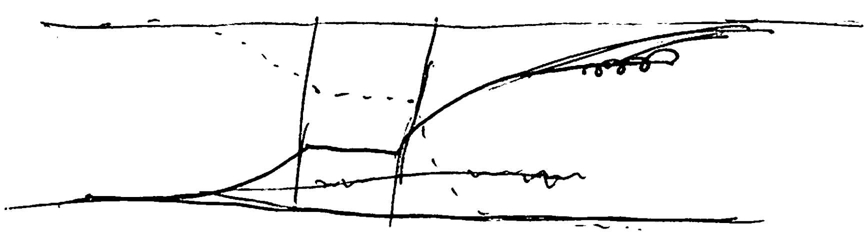
Diffusion current

Hole diffusion current

$$I_p(x_n) = -qAD_p \frac{d\,\delta p(x_n)}{dx_n} = qA\frac{D_p}{L_p}\delta p(x_n)$$

$$I_p(x_n = 0) = qA\frac{D_p}{L_p}\Delta p_n = qA\frac{D_p}{L_p} p_n(e^{qV/kT} - 1)$$

Drift and diffusion in forward bias



Quasi-Fermi level at Forward Bias

$$n_n p_n e^{qV_f/kT} = n_i^2 e^{(qV/kT)} = n_i^2 e^{(F_n - F_p)/kT}$$

only at equilibrium $np = n_i^2$

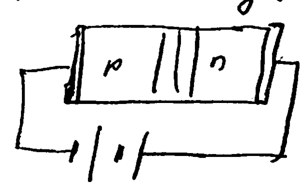
PN junction at reverse bias

Barrier larger

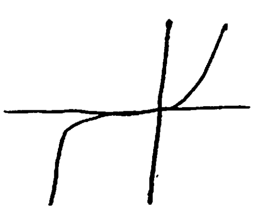
$$\Delta p = p_n[e^{q(-V_r)/kT} - 1] \approx -p_n$$

$$\Delta n \approx -n_p$$

punch-through



Reverse Bias Breakdown



Zener Breakdown
- High doping
- Occurs at low voltages

Avalanche Breakdown
- Low doping
- Occurs at high voltages

penetration depth = depletion length

pn junction capacitance

AC signal

$$C_j = \frac{dQ}{dV} = A\sqrt{\frac{q\epsilon}{2(V_0-V)}\frac{N_d N_a}{N_A+N_d}} = \boxed{\frac{\epsilon A}{W} = C_j}$$

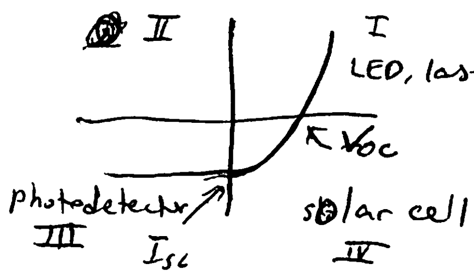
junction capacitance

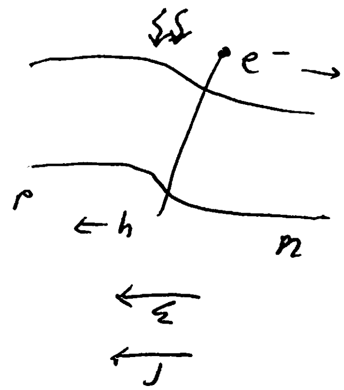
diffusion capacitance

OPTOELECTRONICS

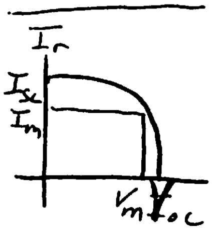
Current in an illuminated junction

$$I = I_{th}\left(e^{qV/kT}-1\right) - I_{op}$$





Solar cell figure-of-merit



$$P_m = I_m V_m$$

Fill factor

$$FF = \frac{I_m V_m}{I_{oc} V_{oc}}$$

"how square" the curve is

Efficiency

η

Photodiode figure of merit

Internal quantum efficiency

$$\eta_{in} = \frac{J_{op}/q}{P_{abs}/h\nu}$$

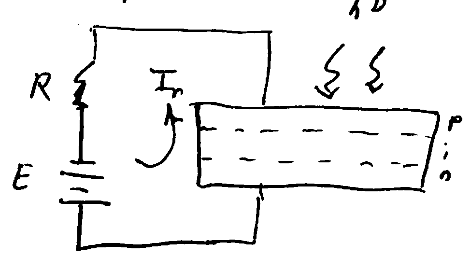
External quantum efficiency

$$\eta_{ext} = \frac{J_{op}/q}{P_{in}/h\nu}$$

Efficiency high, large depletion width

Responsitivity / frequency, sm depl. width

$h\nu$



Light-emitting diode

$h\nu_{out} =$

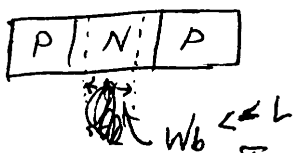
Laser

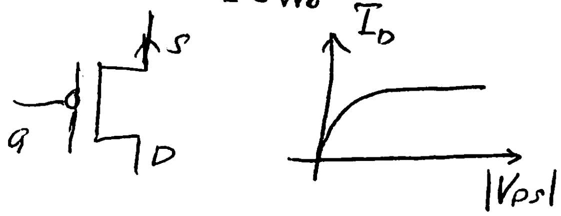
ECE 340 Wed 6 December Lecture

Prof. Kim

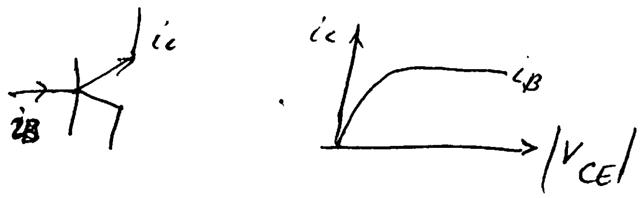
PNP BJT

! W is not depletion width of N region



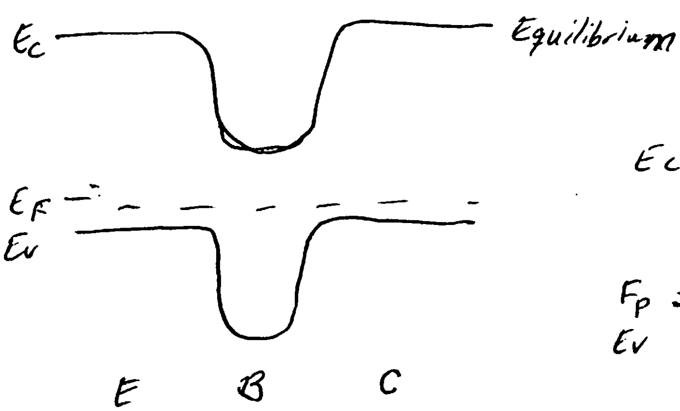


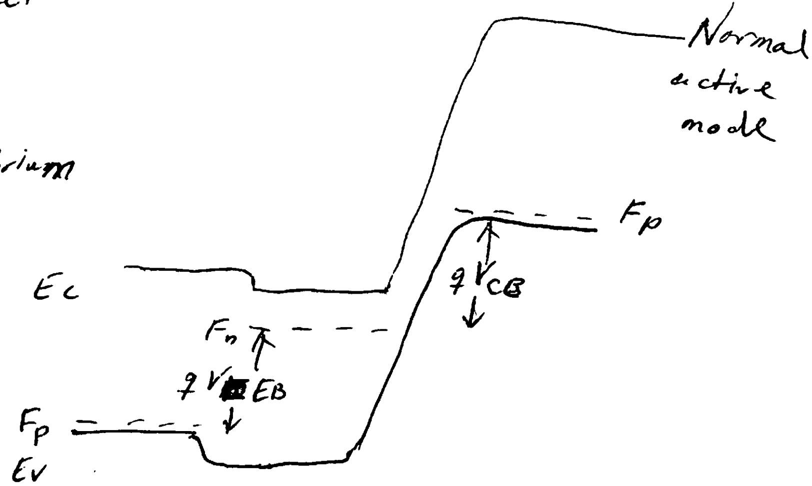
Voltage controlled



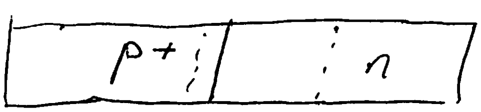
current controlled

Energy Band Diagram





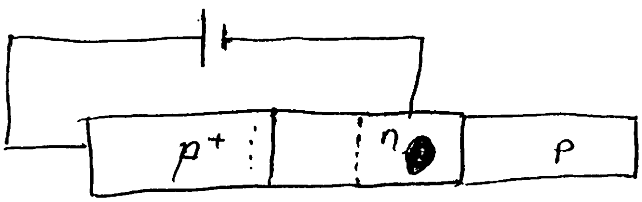
PNP BJT



G − R = 0 at equilibrium

R = 0 at reverse bias

↳ G only



$I_E = I_{En} + I_{Ep}$

$\gamma = \dfrac{I_{Ep}}{I_E}$

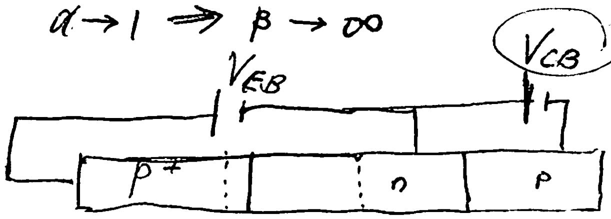
$I_C = I_{Cp} = B I_{Ep} = B\gamma I_E = \alpha I_E$

$\beta = \dfrac{I_C}{I_B}$

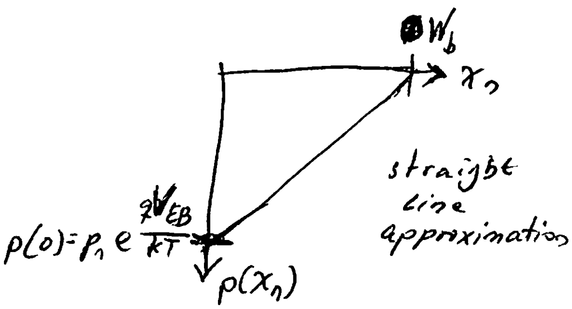
$I_B = I_{En} = (1-\gamma) I_E$

$\gamma < 1$

$\alpha \to 1 \Rightarrow \beta \to \infty$



negative b/c reversely biased



positive direction down

$\Delta p = p - p_n$

Emitter Current

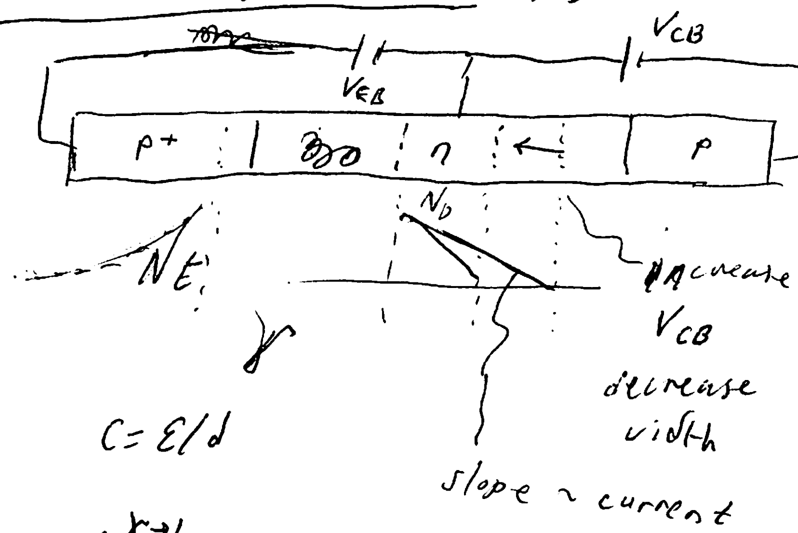
$\dfrac{n_i^2}{N_A^E}$

Emitter Injection Efficiency:

$$\gamma = \frac{1}{1 + \dfrac{\mu_n^E}{\mu_p^B}\dfrac{W_b}{L_n^E}\dfrac{N_D^B}{N_A^E}}$$

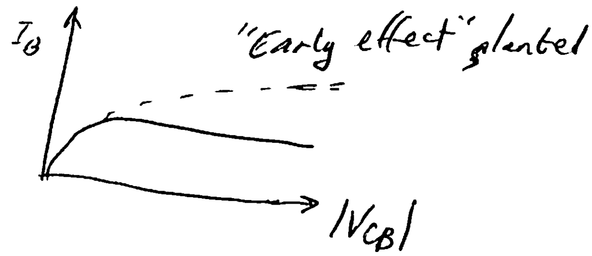
material properties – cannot change

ECE 340 Wed 6 December p.3



$C = \mathcal{E}/d$

Punch thru



$\beta \quad \gamma \to 1$

$$I_E = \cancel{I_{E_n}} + I_{E_p}$$

$$\gamma = \frac{I_{E_p}}{I_{E_n} + I_{E_p}}$$

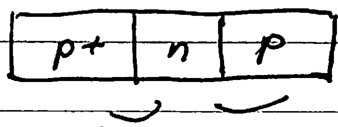
I_{E_n} = 0

$$\beta\gamma = \frac{I_C}{I_B(\text{recomb})} = \frac{B}{1-B} = \frac{\frac{qAD_p}{W_p}\Delta p_E}{\frac{qAW_b}{2\tau_p}\Delta p_E} = \frac{2L_p^2}{W_b^2}, \text{ for } W_b \ll L_p$$

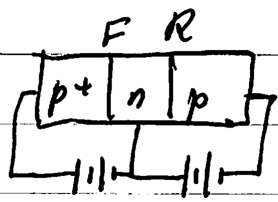
Transit Time

$$\tau_t = \frac{W_b^2}{2D_p} \qquad \tau_p = \frac{L_p^2}{D_p} \qquad L_p = \sqrt{D_p \tau_p}$$

ECE 340 11 Dec Mon lecture

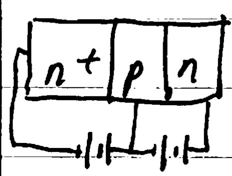


forward bias reverse bias



PNP BJT

normal operating mode : amplification



NPN BJT

Collector current

Base current

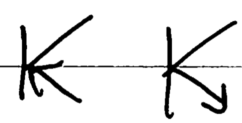
- recombination current - some amount supplied every τ time

- injection current.

→ Current gain (for $\gamma = 1$)

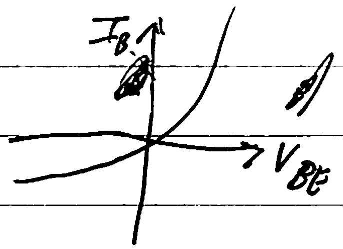
$$\beta_{\gamma=1} = \frac{I_C}{I_B(\text{recomb})} = \frac{2D_p\tau_p}{W_p^2}$$

Common-emitter amplifier and small signal current gain



PNP NPN

$$I_B = qA\left(\frac{W_b}{2\tau_p} p_n + \frac{D_n^E}{L_p} n_{po}^E\right)\left(e^{qV_{cd}/?}\right)$$



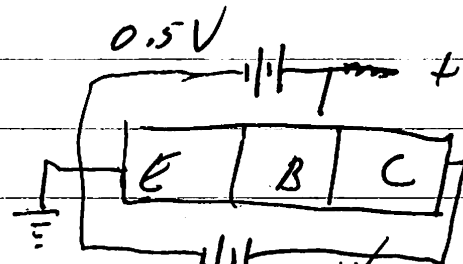
What is the voltage that fall on the BJT?
What is the collector current?
Output characteristic
- similar to MOSFET.

$$G_{EB} = \frac{dI_B}{dV_{EB}} = \frac{q}{kT} I_B$$

$$I_B = \frac{V_{BB} - V_{BE}}{R}$$

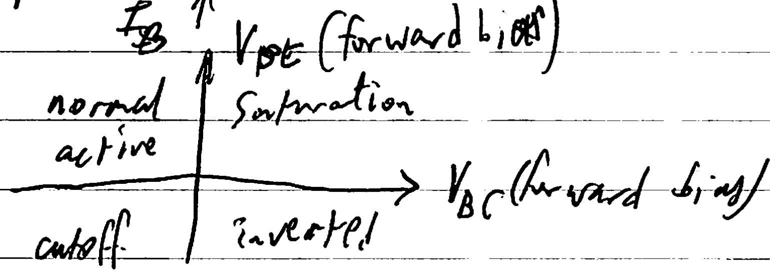
Voltage gain: $\frac{V_{out}}{V_{in}}$

Example



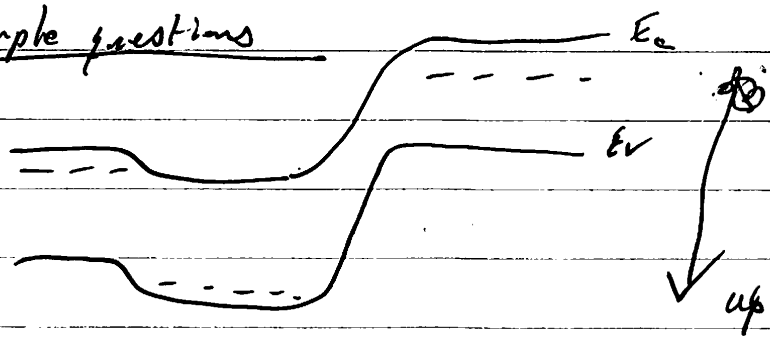
Emitter $N_D = 2\times10^{18}/cm^3$
Base $N_A = 2\times10^{17}/cm^3$
Collector $N_D = 6\times10^{16}/cm^3$

$\beta = \frac{I_C}{I_B}$ ↑

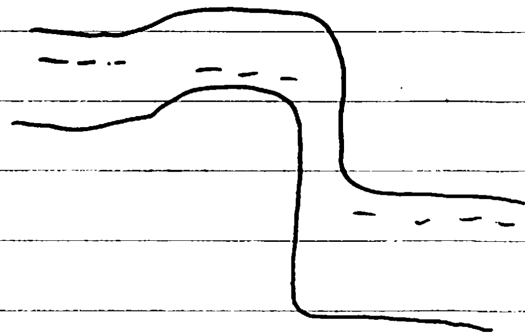


Example questions

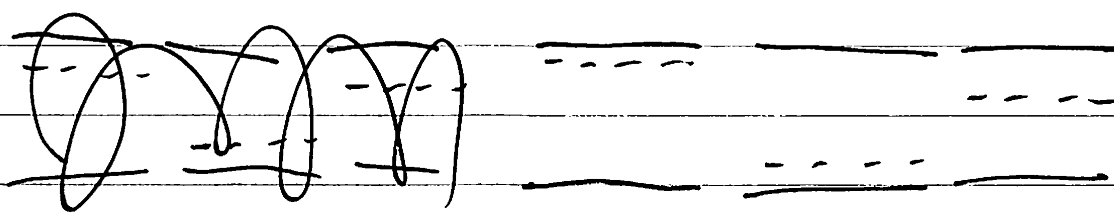
a)

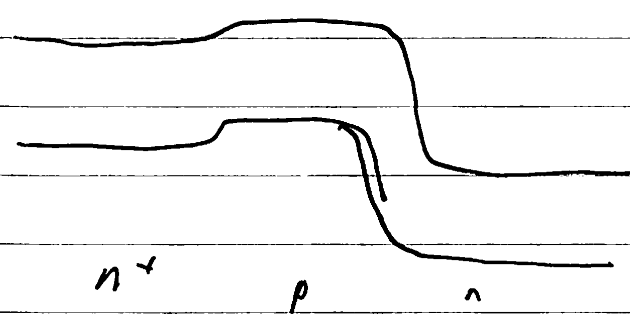


b)



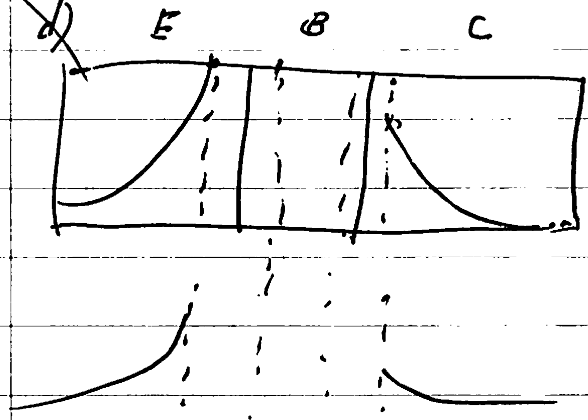
At equilibrium





c) $\boxed{E \mid B \mid C}$

d)



Always np so for npn it is V_{BE}

V_{BC}