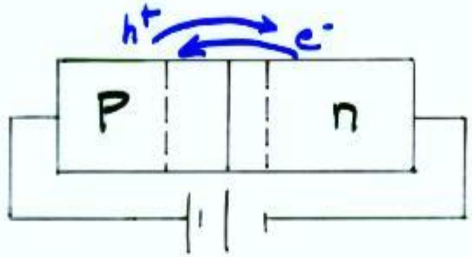
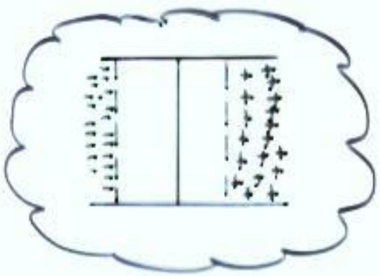
Excess h^+ injected into n-side.



Excess e^- injected into p-side!

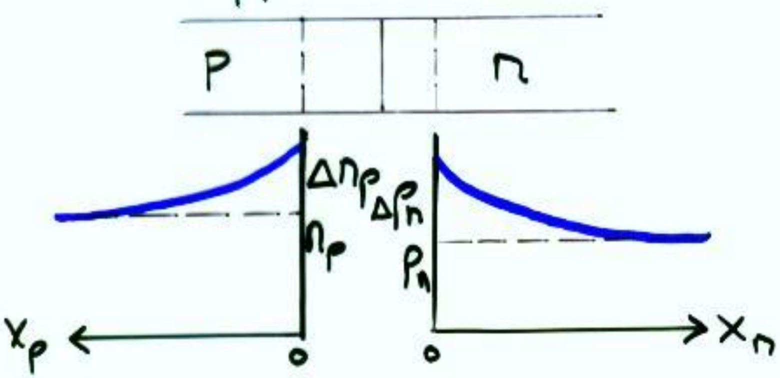


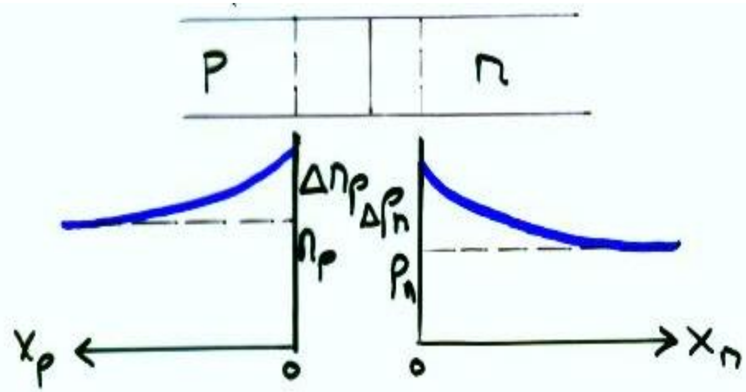
$$\Delta p_n = p_n \left(e^{qV/kT} - 1\right) \; ; \; p_n =$$

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

at the boundary only!

Plus diffusion / recombination:





To simplify solution of differential equation, new x-axis origins (neat trick)

Get exponential as in Lecture 17, page 1

$\delta_n(x_p) =$ =

Since on p-side, use x_p. Since electrons diffusing, use L_n.

Likewise

$\delta_p(x_n) =$ =

(h^+ on n-side)

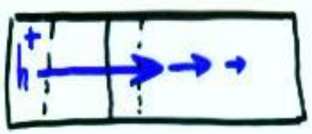
where L_p = minority carrier diffusion length

L_n = " " " "

e^- on p-side

Again, this a big deal since now you know where all the charged particles are and

Can get currents at any point.



Varies due to recombination

$$I_p(x_n) = J_p(x_n)\cdot \underset{\text{area}}{A} = -qAD_p \frac{d\,\delta p(x_n)}{dx_n}$$

Diffusion current for holes

See, e.g., S&B Eq. 5-32

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

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

Likewise, $I_n(x_p) = -qA\frac{D_n}{L_n}n_p\left(e^{qV/kT}-1\right)e^{-x_p/L_n}$

Diffusion current for electrons

$\left\{\text{extra minus sign since } x_p \text{ opposite to } x\text{-direction}\right\}$

Add to get total current.

(assume $\Delta p(x_p=0) = \Delta p(x_n=0)$ and $\Delta n(x_n=0) = \Delta n(x_p=0)$)

No recombination in transition region.

$$I = I_p(x_n=0) - I_n(x_p=0)$$

passing through transition region

{relative to the $+x_n = x$ direction}

$$= q\frac{AD_p}{L_p}\Delta p_n + q\frac{AD_n}{L_n}\Delta n_p$$

$$\boxed{\begin{aligned} \underline{I} &= qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left(e^{qV/kT}-1\right) \\ &= I_o\left(e^{qV/kT}-1\right) \end{aligned}}$$

Diode Equation!

(Ideal Case)

Since all current is in the same direction and everything is in series, total current must be constant throughout the device.

(Individual h^+ and e^- currents can vary but add up to a constant)

Now checkout reverse bias: $V \rightarrow -V$

$$\left(e^{qV/kT} - 1\right) \rightarrow -1 \quad \text{for } V \rightarrow -V_{large}$$

$$I_R = -I_o = -qA\left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right)$$

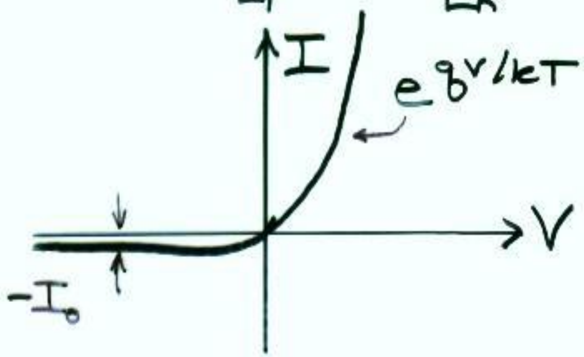
Reverse bias current

Forward Bias Current

$$I_F \simeq I_o \, e^{qV/kT}$$

$$\simeq \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) e^{qV/kT}$$

for V_{large} such that $e^{qV/kT} >> 1$



I-V in terms of fundamental physical parameters

This shows the rectifier character we know and love.

Can also calculate total current another way: Total stored charge Q_n divided by τ_n

+ " " " Q_p " " τ_p

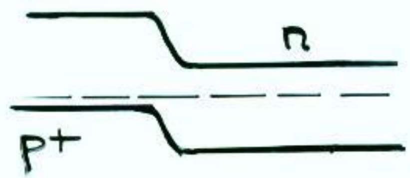
"Charge Control Approximation"

$$Q_p = qA\int_0^\infty \delta p(x_n)\,dx_n \quad \text{and} \quad I_p = \frac{Q_p}{\tau_p} = q\frac{AL_p}{\tau_p}\Delta p_n$$

Diode Equation for Asymmetric Junctions

(Very Common)

Injection from more heavily doped side dominates total current



$|p| \neq |n|$

Equilibrium

$|p| \gg |n|$

p^+ side	n-side
$p_p = N_a$	$n_n = N_d$
$n_p = \dfrac{n_i^2}{N_a}$	$p_n = \dfrac{n_i^2}{N_d}$

$N_a \gg N_d$ so $p_n \gg n_p$. So h^+ injection dominates.

$$I = qA\left[\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}\underbrace{\cancel{n_p}}_{\text{small}}\right]\left(e^{qV/kT}-1\right)$$

$$\simeq qA\,\frac{D_p}{L_p}p_n\left(e^{qV/kT}-1\right)$$

Example: $N_d = 10^{16}\,cm^{-3}$, $N_a = 10^{18}\,cm^{-3}$. $L_p \sim L_n$, $D_p \sim D_n$,

so $p_n = 100 n_p$. Only 1% correction.

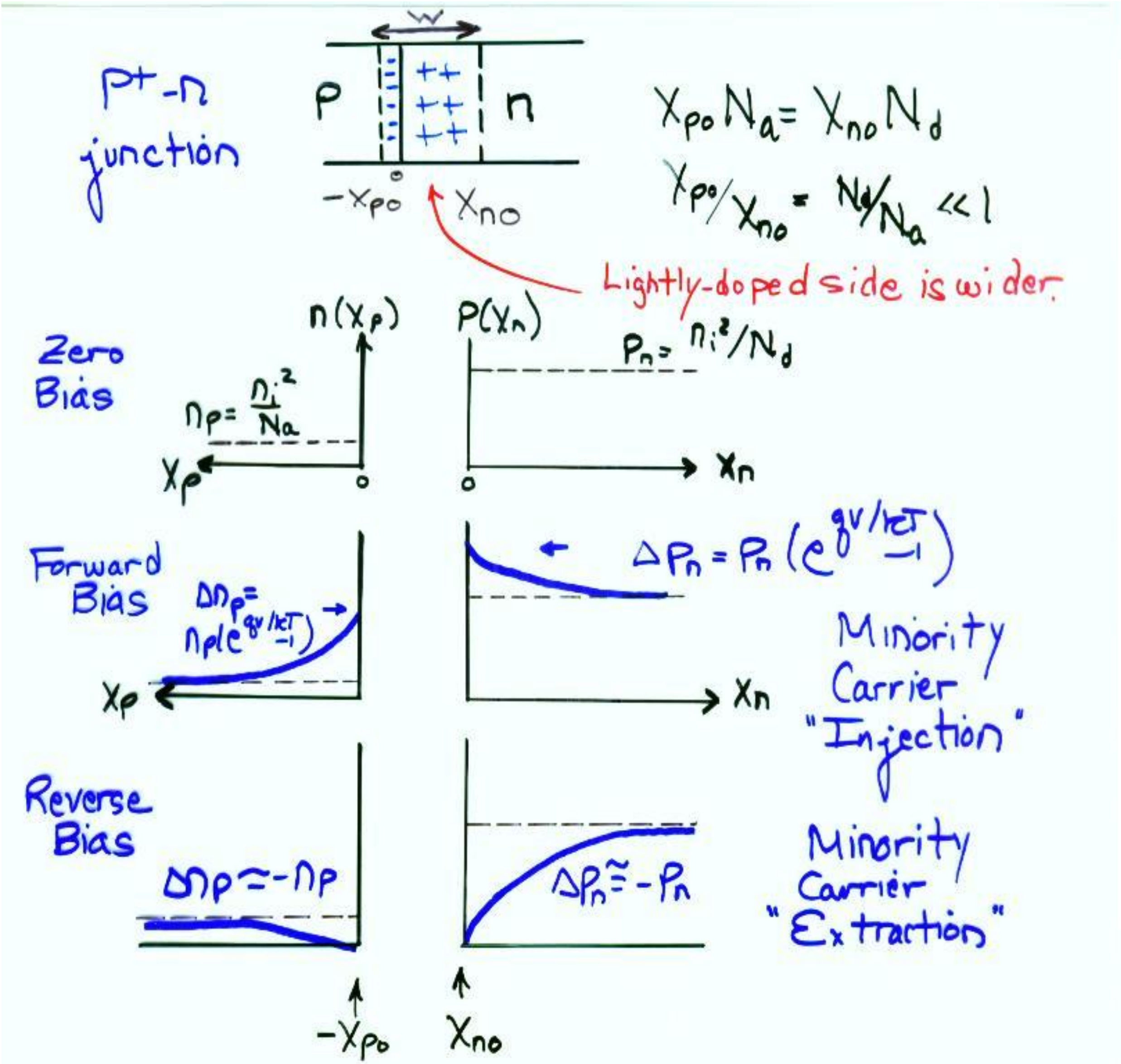
Hole and electron distributions for asymmetric junction:

Different equilibrium minority concentrations

" forward bias distributions

" reverse bias "

" widths



p+-n junction
W
p
n
$-x_{po}$
0
x_{no}
$x_{po} N_a = x_{no} N_d$
$x_{po}/x_{no} = N_d/N_a \ll 1$
Lightly-doped side is wider.
$n(x_p)$
$p(x_n)$
Zero Bias
$n_p = \frac{n_i^2}{N_a}$
$p_n = n_i^2/N_d$
x_p
x_n
0
Forward Bias
$\Delta n_p = n_p(e^{qV/kT} - 1)$
$\Delta p_n = p_n(e^{qV/kT} - 1)$
Minority Carrier "Injection"
Reverse Bias
$\Delta n_p \cong -n_p$
$\Delta p_n \cong -p_n$
Minority Carrier "Extraction"
$-x_{po}$
x_{no}

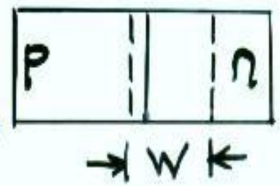
Important to understand all this.

Thermal generation supplies carriers to transition region from the bulk. → reverse saturation current.

From within the diffusion length distance of the edge.

Minority and Majority Carrier Currents

I. Minority Carriers



A. Outside transition region W

1. Drift Current ~ negligible, $n_p(x)$ & $p_n(x)$ low

2. Diffusion Current – depends on gradient

$q D_p \frac{dp}{dx}$, $q D_n \frac{dn}{dx}$ can be large

even if concentrations are low, as long as the gradients are large.

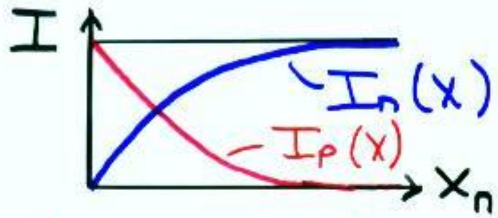
B. Inside transition region W

1. Drift Current ~ zero, almost all carriers swept out.

2. Diffusion Current = constant (assume no recombination inside W.

II. Majority Carriers

Calculate from minority current since $I = I_n + I_p$ in all regions



on n-side

Minority current outside W

$$I_p(x_n) = qA\frac{D_p}{L_p}\Delta p\, e^{-x_n/L_p}$$

$$= qA\frac{D_p}{L_p}\left[p_n\left(e^{qV/kT}-1\right)\right]e^{-x_n/L_p}$$

decreases with x_n

so majority current outside W is:

$$I_n(x_n) = I - I_p(x_n)$$

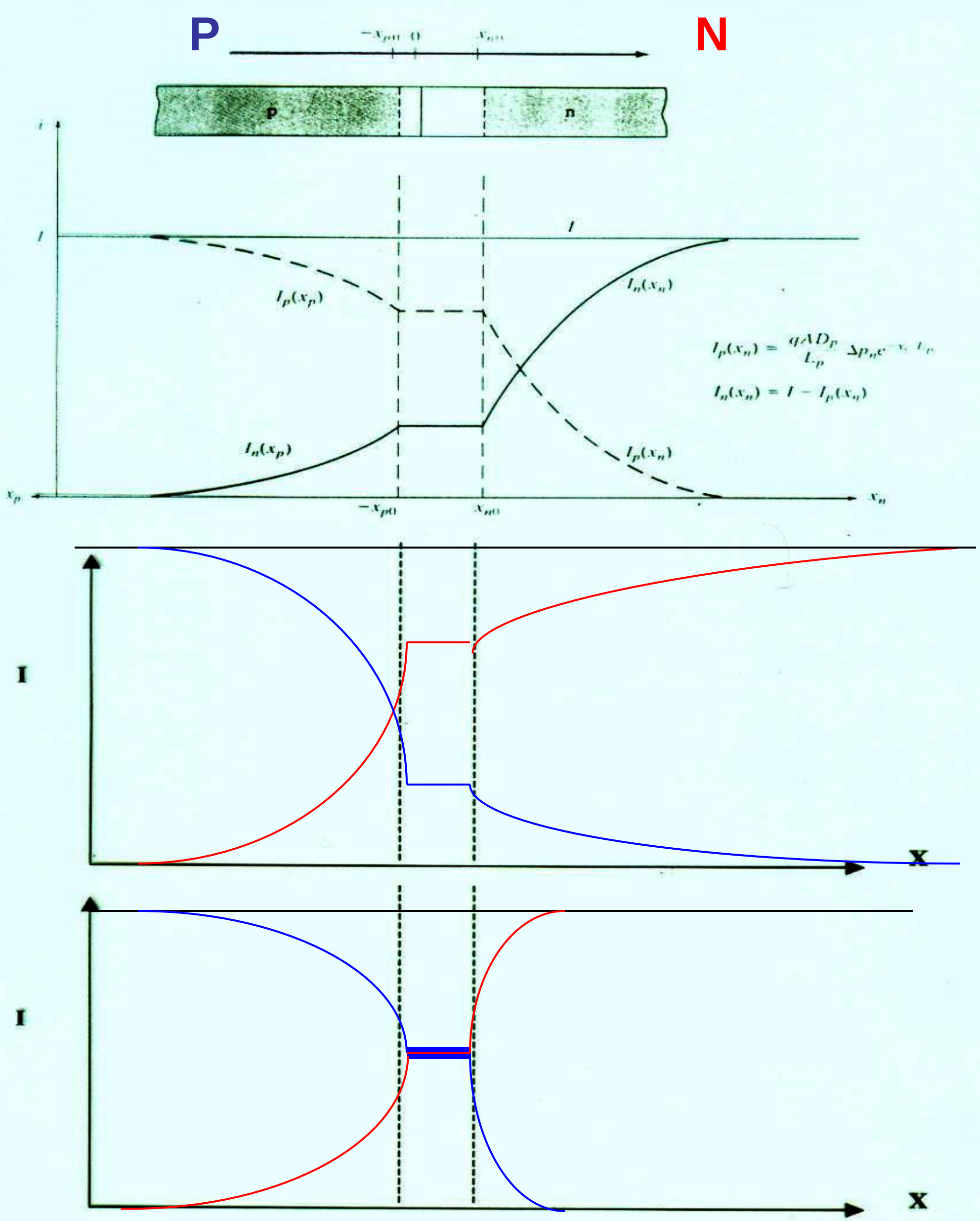
$$= qA\left[\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right]\left(e^{qV/kT}-1\right) - I_p(x_n)$$

$$= qA\left[\frac{D_p}{L_p}\left(1-e^{-x_n/L_p}\right)p_n + \frac{D_n}{L_n}n_p\right]\left(e^{qV/kT}-1\right)$$

Increases with x_n.

- Electric field in neutral region not strictly zero. But carrier concentration so large that $\mathcal{E}$ can be very small and still feed current to transition region.

- Currents far from transition region supply charges needed for recombination as well as " " " injection.



N_a N_d

L_p L_n

N_a $\boxed{}$ N_d

D_p $\boxed{}$ D_n

τ_p $\boxed{}$ τ_n