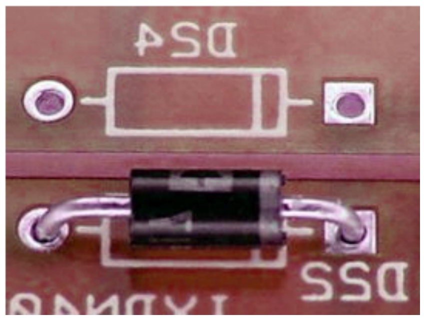
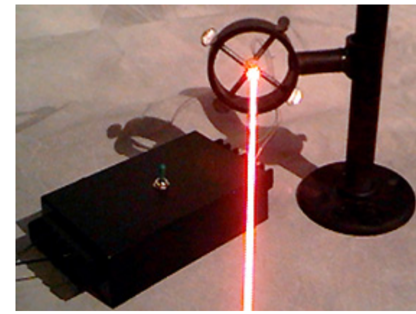
5.3 Forward- and Reverse-Biased PN Junctions

Image is obvious for this lecture … basic definition of what this component does?



This here is also a forward biased diode!



And how about reverse biased diodes for optical fiber receivers?

43 Gbit/s DPSK Balanced Photoreceiver

by Sam Hickman on November 17, 2010

This balanced photoreceiver from u2t Photonics is a differential front-end for 43 Gbit/s DPSK applications and features high differential gain of typically 2800 V/W.

The photoreceiver contains two waveguide-integrated pin-photodiodes on a single chip and a limiting amplifier within one small form factor SMD-package. The limiting amplifier provides a differential output voltage swing of typically 600 mV.

The receiver is suited for DPSK and DQPSK applications at 40G and 100G with rates between 20 and 56 GBaud.

- Zero bias, but we still have currents (but no net current).

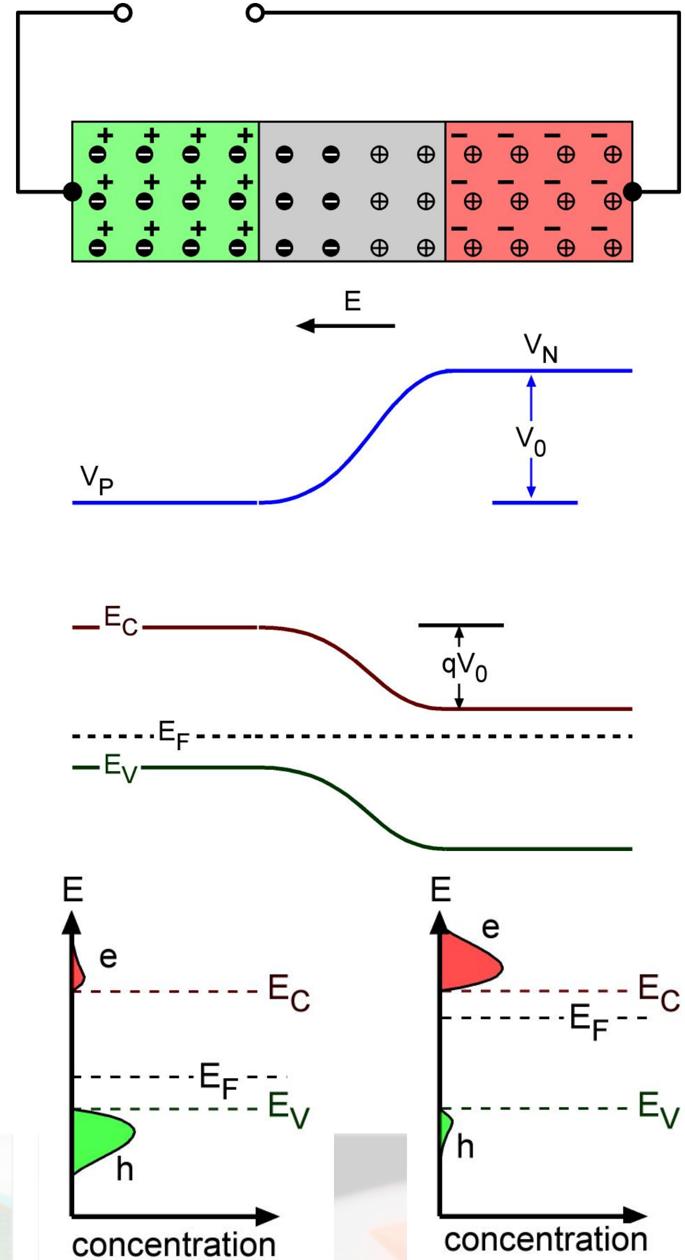
$$J_n(drift) + J_n(diff.) = 0$$

$$J_p(drift) + J_p(diff.) = 0$$

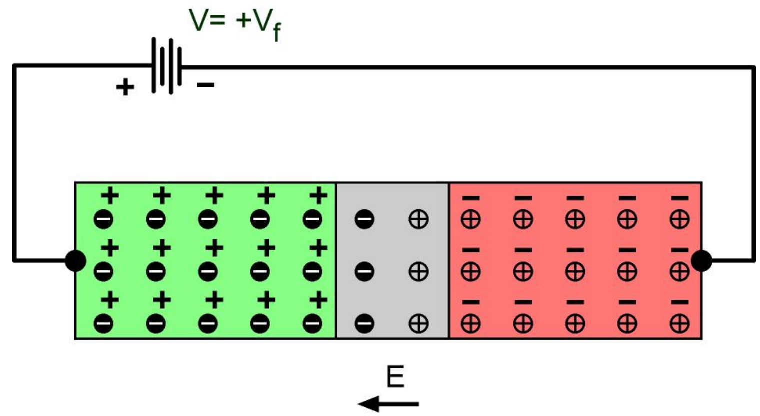
$$q\mu_p p(x)\, \mathrm{E}(x) = qD_p \frac{dp(x)}{dx}$$

- DRIFT: Minority carrier generation near ($<L_n$ or $<L_p$) near junction, swept across (E).

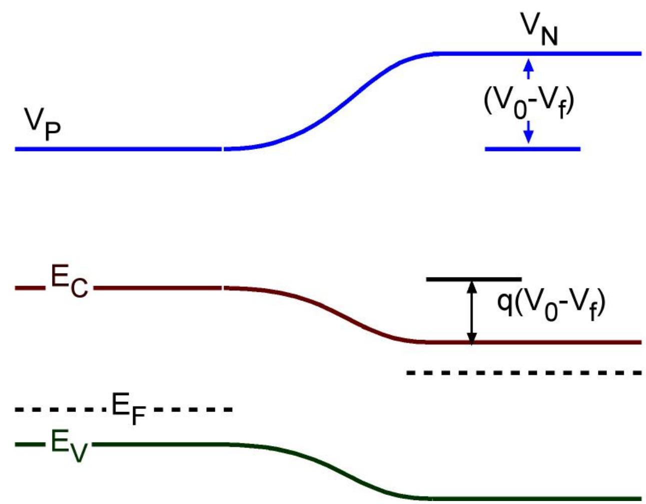
- DIFF: Majority carriers with enough energy to climb barrier (at high E end of dist. tail)



- Forward bias:
  - voltage moves bands!
  - smaller deplet. reg.
  - smaller "V_o" (why? *see gray*)
  - E_C, E_V, E_F



How will my drift or diffusion currents change?



- DRIFT current: <u>NO CHANGE!!!</u>
  - *limited by minority carrier generation rate (not V):*

$$n_p \ or \ p_n$$

- DIFF current: <u>CHANGES</u>
  - *same majority carrier conc.*
  - *same energy distribution*
  - *but lower barrier to climb!*

$$J \sim J(diff.)$$

Net current flow, increases with V_f!

Dept. Electrical Engin. & Computing Systems
UNIVERSITY OF Cincinnati

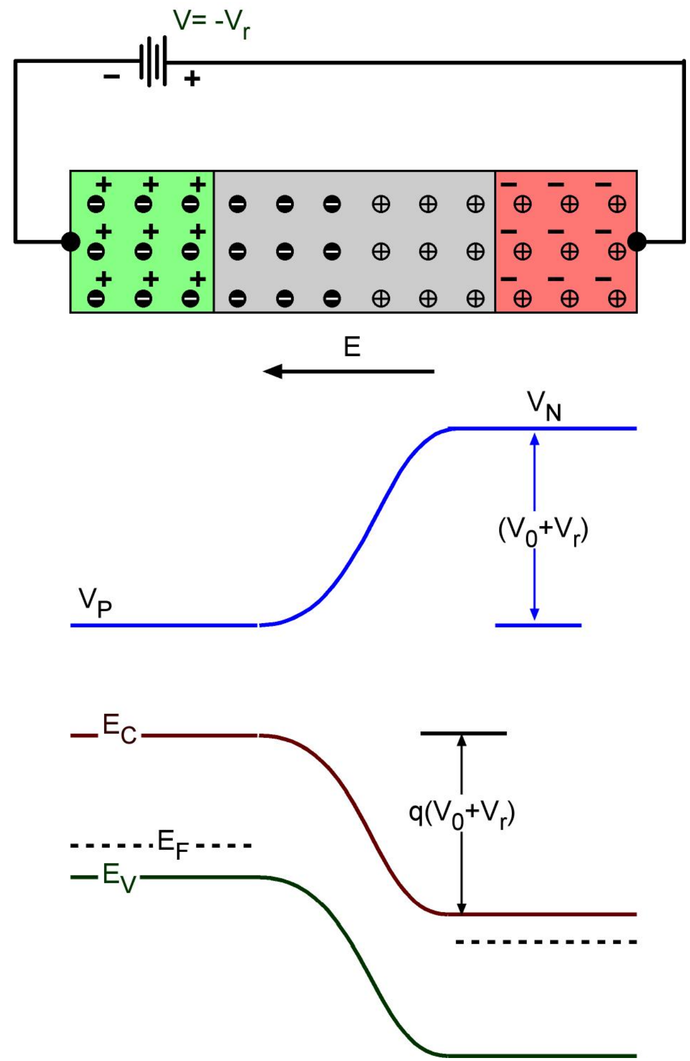
- Reverse bias:
  - wider deplet. reg.
  - larger "V_o" *(again, why?)*
  - E_C, E_V, E_F

How will my drift or diffusion currents change?

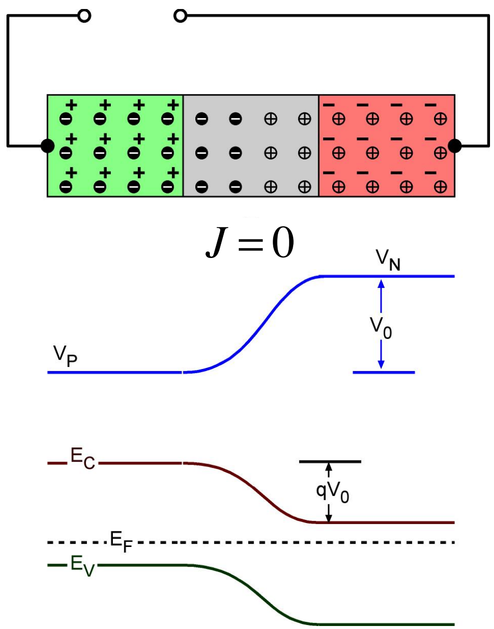
- DRIFT current: <u>NO CHANGE</u>
  - *sure, E-field increases, but…*
  - *limited by minority carrier generation rate (no V)*

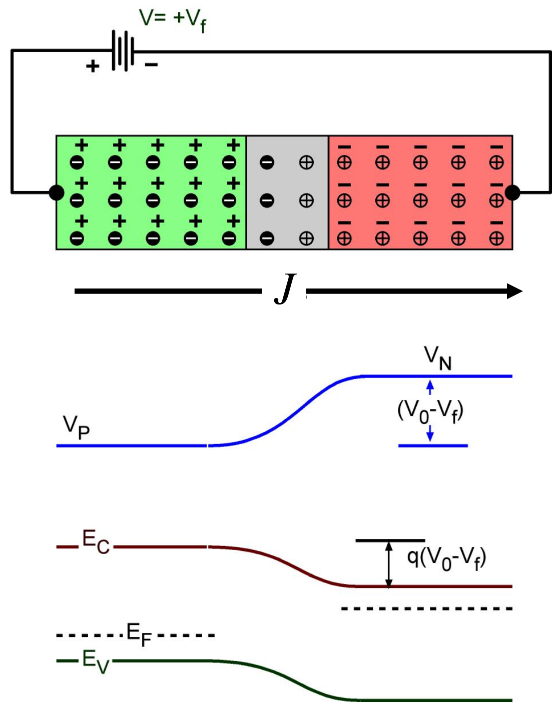
- DIFF current: <u>CHANGES</u>
  - *much larger barrier to climb!*
  - *quickly becomes zero*

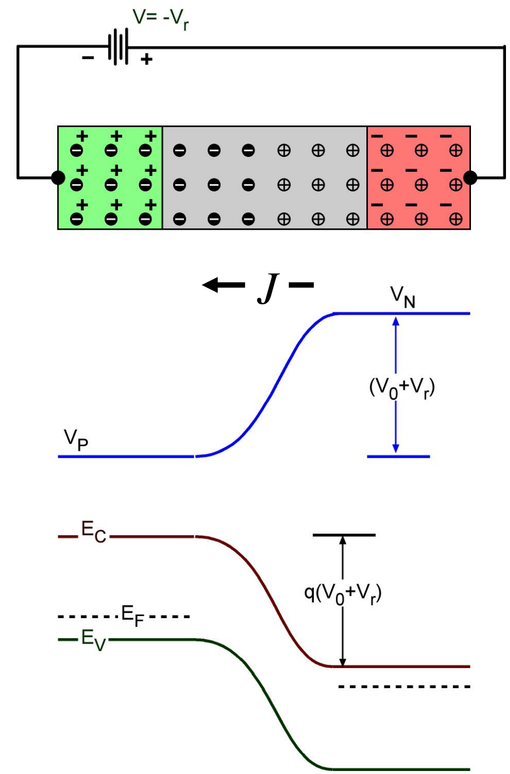
$$J \sim J(drift)$$



Could we use as a temperature sensor? an optical sensor?







- Thermal equilibrium.

$$J(drift) = J(diff.)$$
$$J = 0$$

- Forward bias.

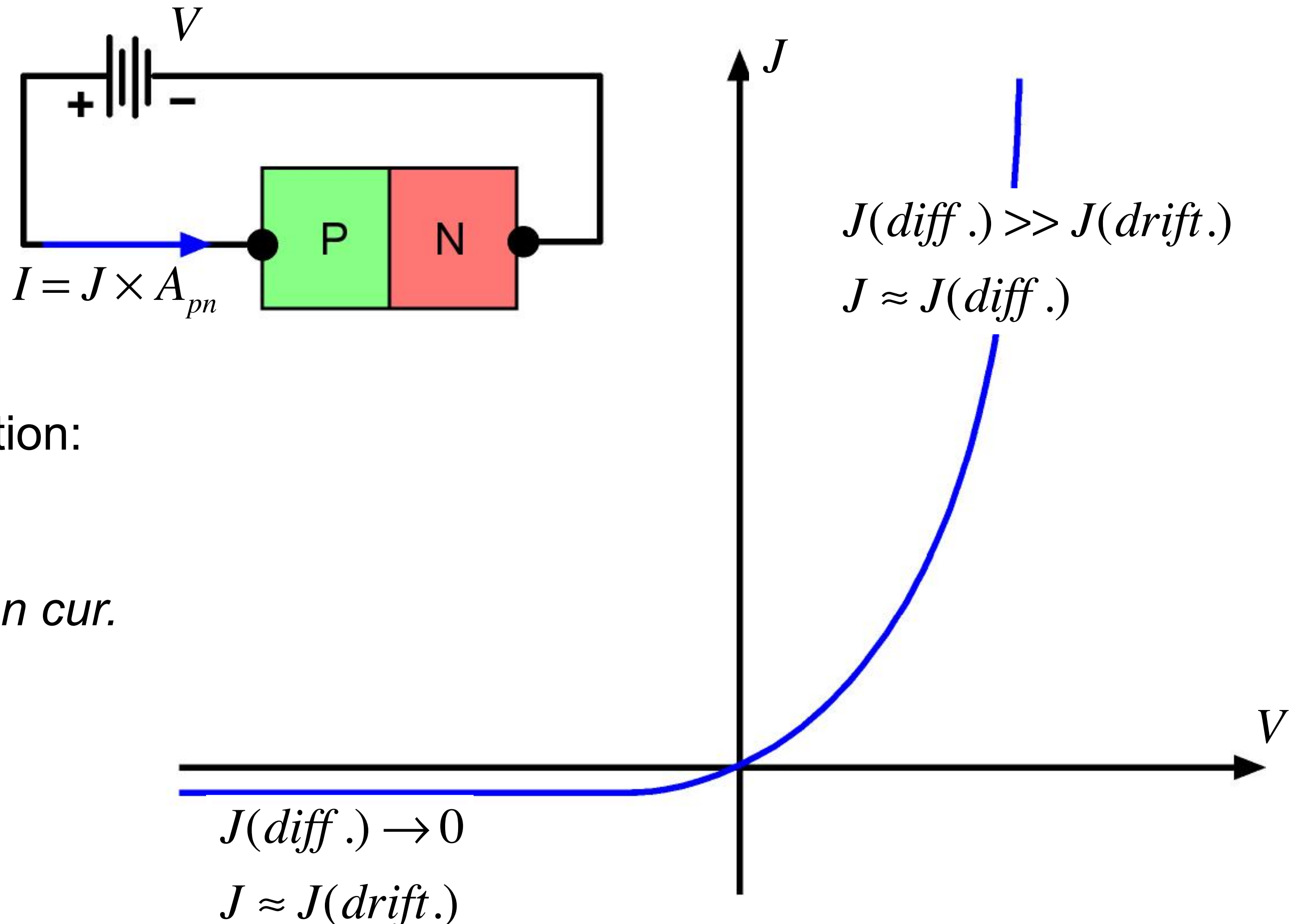
$$J(diff.) >> J(drift.)$$
$$J \approx J(diff.)$$

More voltage, smaller barrier, increase in majority carrier diffusion, increase in current.

- Reverse bias.

$$J(diff.) \rightarrow 0$$
$$J \approx J(drift.)$$

More voltage, larger barrier, only remaining current is minority carrier gen. near the junction.



- <u>Ideal</u> Diode Equation:

$$I = I_0(e^{qV/kT} - 1)$$

I_0 = *rev. saturation cur.*

Key questions:

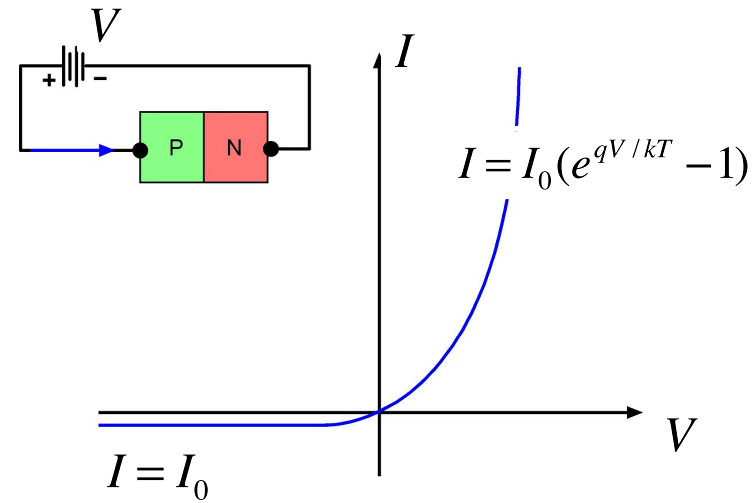
- Why saturate in reverse bias?
- Why cross through (0,0)?
- Why exponential in forward bias?
  (any guesses? exponential…)

- 'Normal' forward voltage:
  - *- no smoke…*
  - *- J_{diff} dominates*
  - *- bit of barrier remains…*

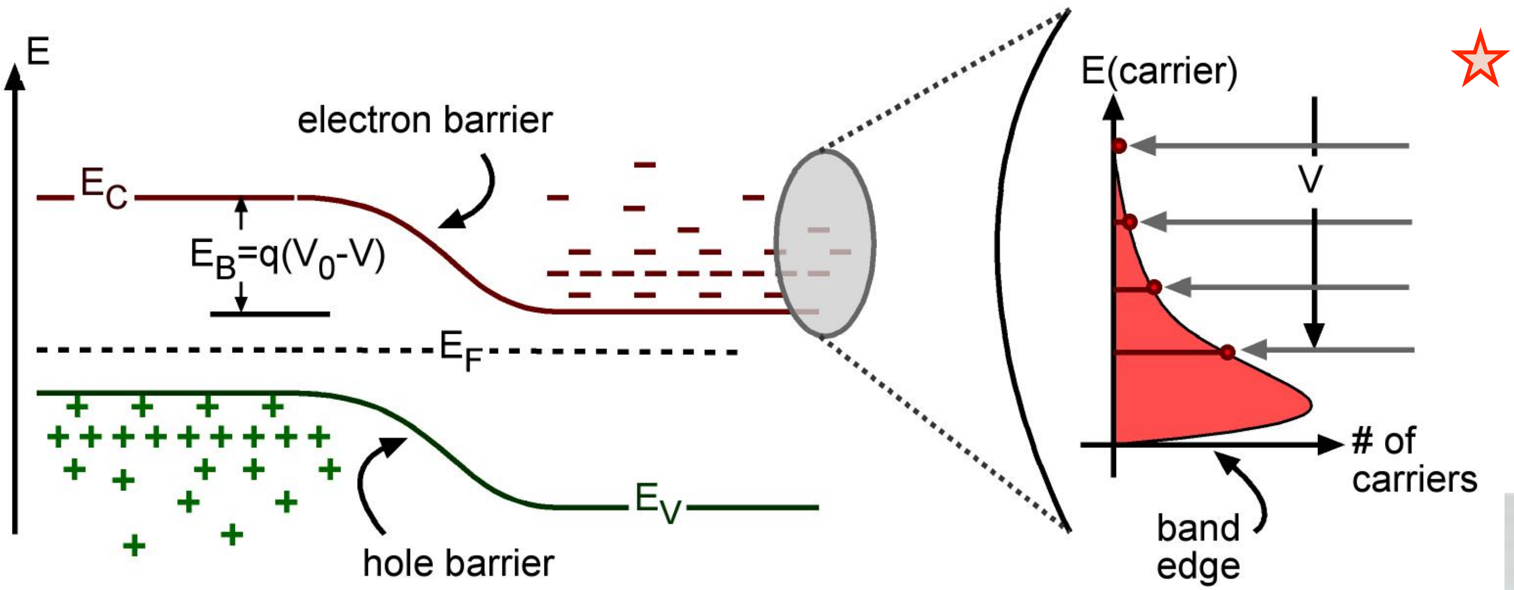
exponential decrease w/ E(carrier)

$$f(E) = 1/(1 + e^{(E-E_F)/kT})$$

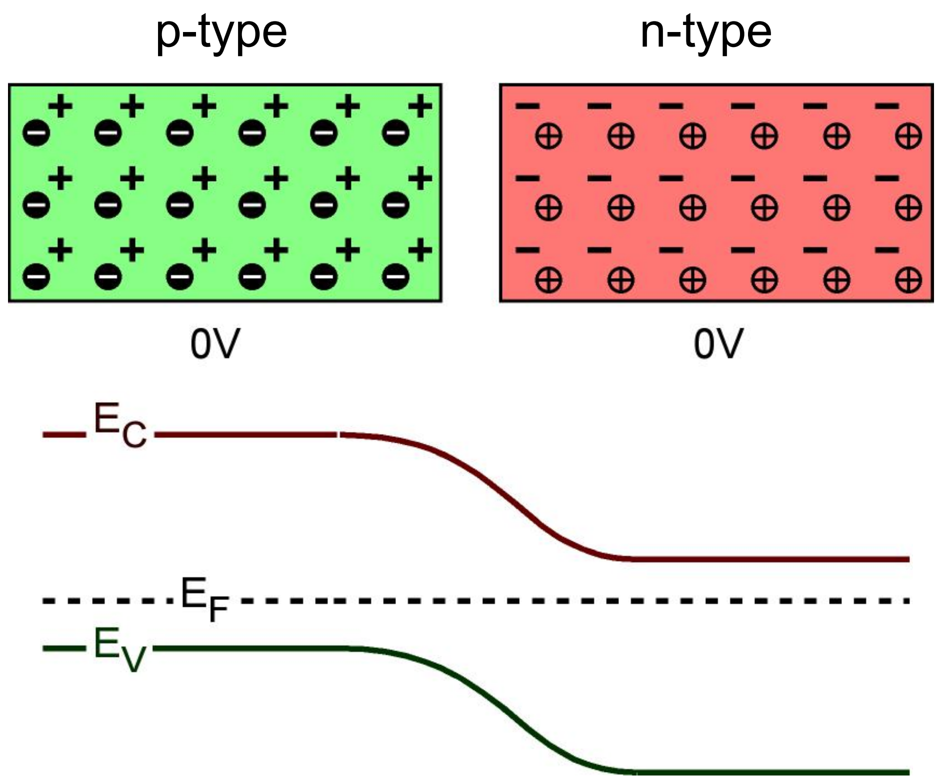
- falls off near band-edge due to density of states, but under normal bias you never get there (which is why we can use 'effective' density of states)



'Normal' forward voltage always on exponential part of curve.



- Positive voltage moves the bands in what direction?
- Which side gets positive voltage to forward bias the diode?
- Why is the current exponential in forward bias? *S7*
- Why is the current in reverse bias constant with voltage? *S4*



- A lot of information…

- The diode equation is critically important.

- Any confusion/questions? Now is the time!

- *Next, let's develop a way to predict reverse saturation current… if we have that we have most of what we need!*

$$I = I_0(e^{qV/kT} - 1)$$

FYI, what we have done so far was 'easy', the next topics are going to get a bit more complicated. (hang on!)

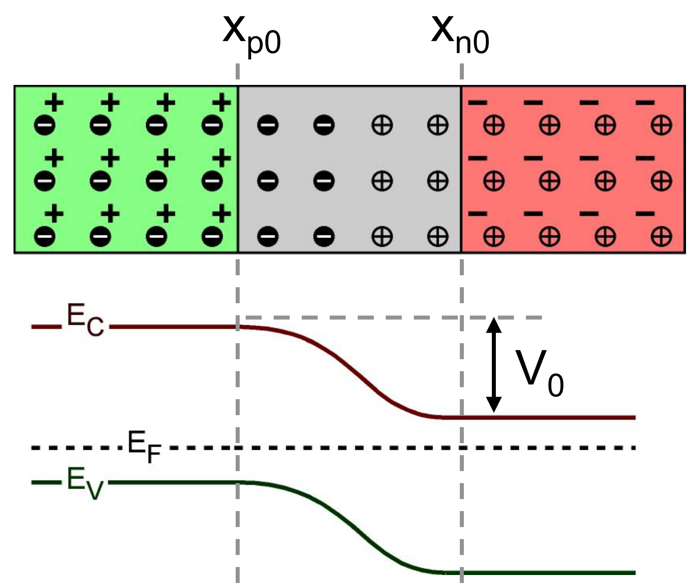
This next section will also be very important for BJTs!

- We use Na/Nd since 2-sides to diode:

$$p_p = N_A \qquad n_n = N_D, \quad p_n = \frac{n_i^2}{N_D}$$

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

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



- Under forward bias, J(diff) increases.
- Under reverse bias, J(diff) decreases.

- J(diff) involves injecting majority carriers across the junction where they then become minority carriers

- Therefore the minority carrier concentration is changed *near the junction:*

$$p(-x_{p0}) \approx p_p$$

$$\frac{p(-x_{p0})}{p(x_{n0})} = e^{q(V_0 - V)/kT} \Rightarrow = e^{qV_0/kT} e^{-qV/kT} \Rightarrow = \frac{p_p}{p_n} e^{-qV/kT} \Rightarrow \frac{p(x_{n0})}{p_n} = e^{qV/kT}$$

basically, this equation says as V approaches V_0, hole conc. gets closer to equal at both depl. edges., makes sense… right?

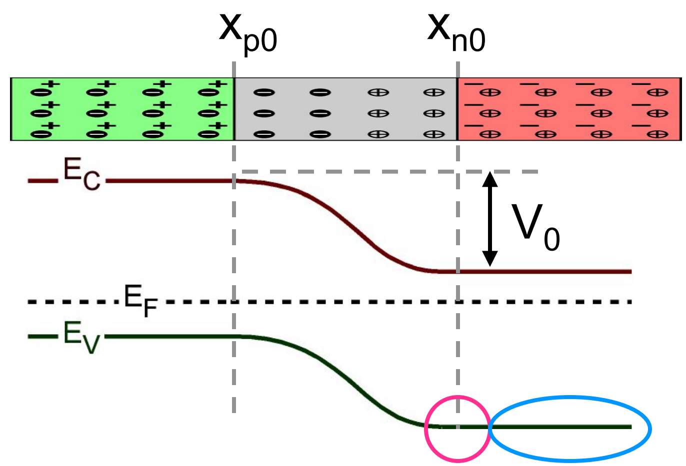
Dept. Electrical Engin. & Computing Systems
UNIVERSITY OF Cincinnati

$$\frac{p(x_{n0})}{p_n} = e^{qV/kT}$$

$$\Delta p_n = p(x_{n0}) - p_n = p_n e^{qV/kT} - p_n$$

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

Interesting, what does this eq. look like?

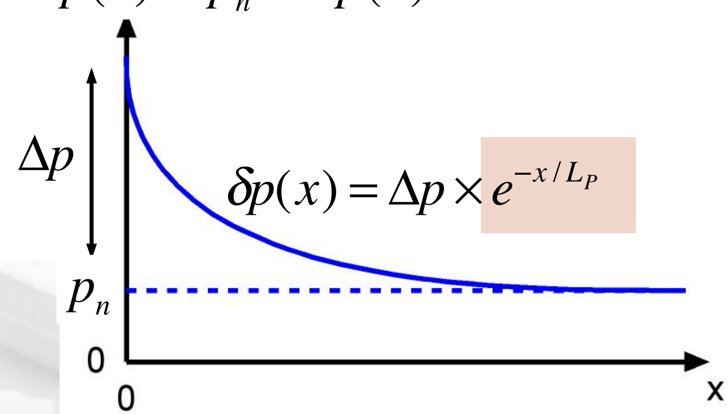


- Forward bias - increased minority carriers *near* the junction: $\Delta p_n = p_n(e^{qV/kT})$
- Reverse bias - NO minority carriers *near* the junction: $\Delta p_n = -p_n \quad (p = 0!)$

Higher or lower compared to what? What is 'near'?
What will the minority carrier concentration look like in this 'near' region?

- Recall from Lecture 2… if we have an abrupt (delta function, like edge of depletion region) excess of holes (Δp) at a point x=0…

$$p(x) = p_n + \delta p(x)$$

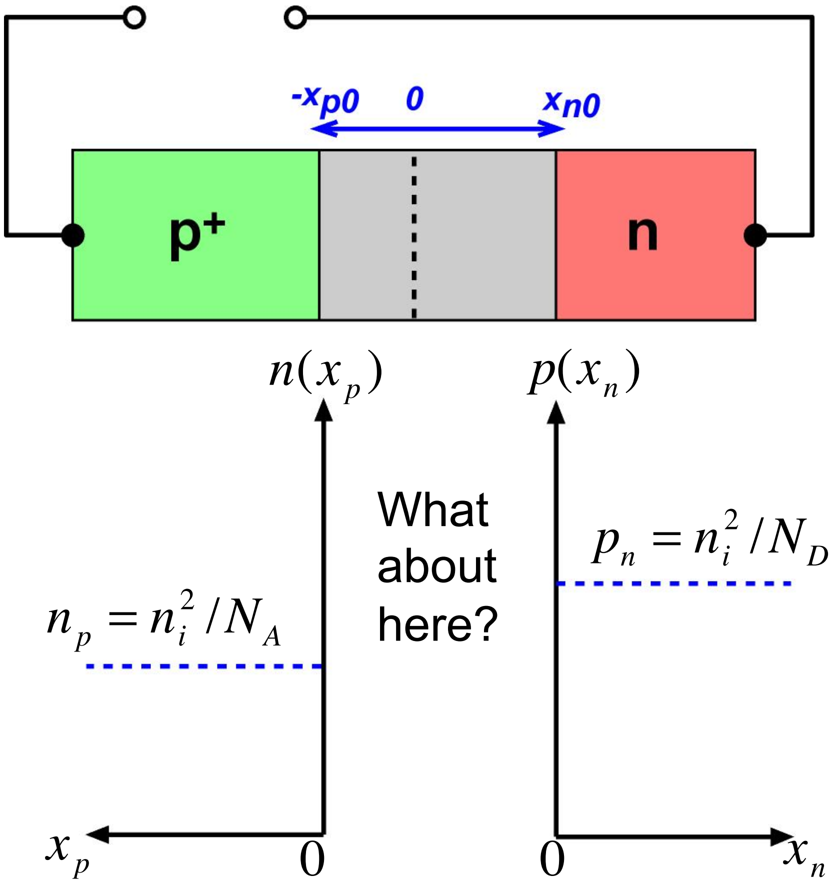


$$L_p = \sqrt{D_p \tau_p}$$
$$\sim 1's\ to\ 100\,\mu m$$

$$D_p = \frac{kT}{q}\mu_p \qquad \tau_p = \frac{1}{\alpha_r(n_0 + p_0)}$$

Dept. Electrical Engin. & Computing Systems
UNIVERSITY OF Cincinnati

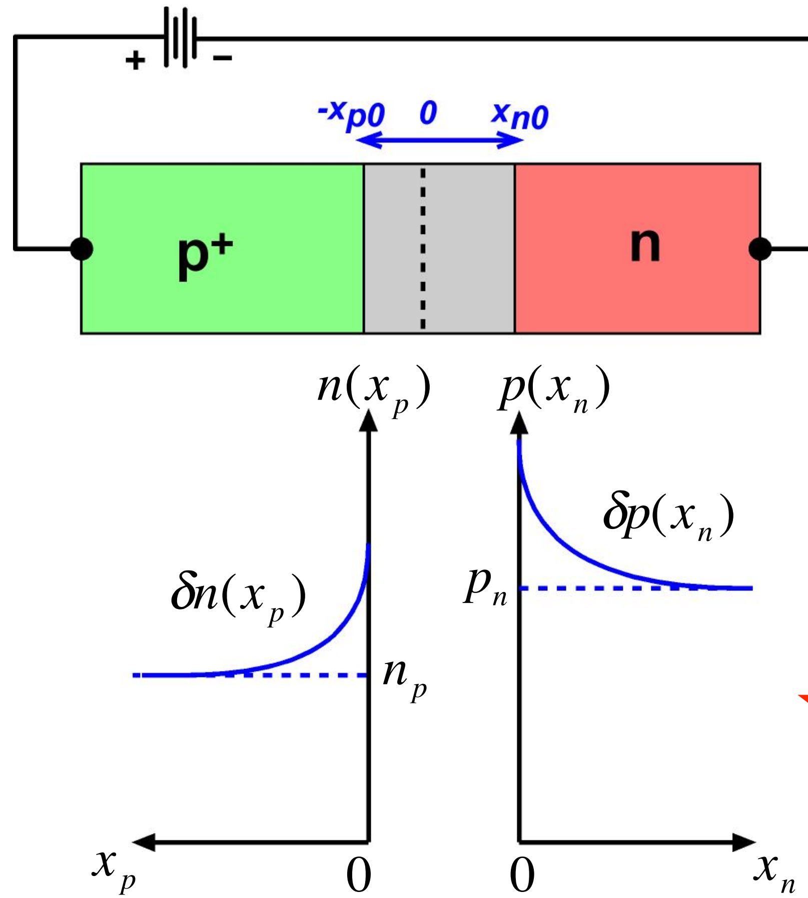
- Introduce new axis, variables



Why is p_n higher than n_p?

Note, difference should be greater, diagram is qualitative (diagram at right is not log scale because carrier conc. lines are not straight).

- Forward bias, diff dominates…

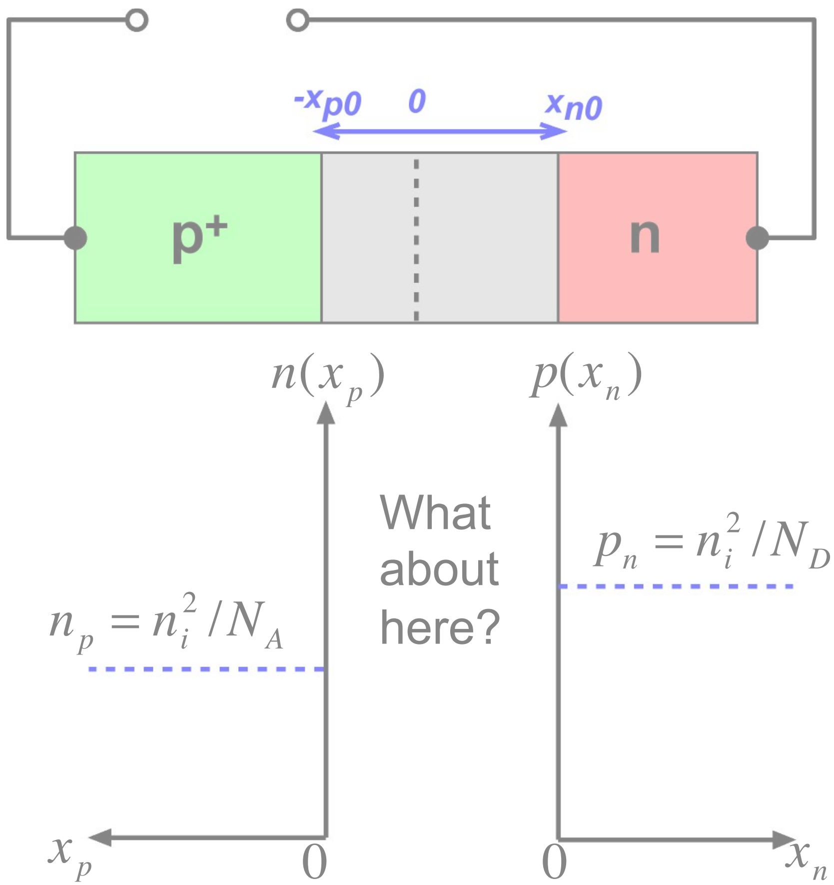


$$\delta n(x_p) = \Delta n_p e^{-x_p / L_n}$$

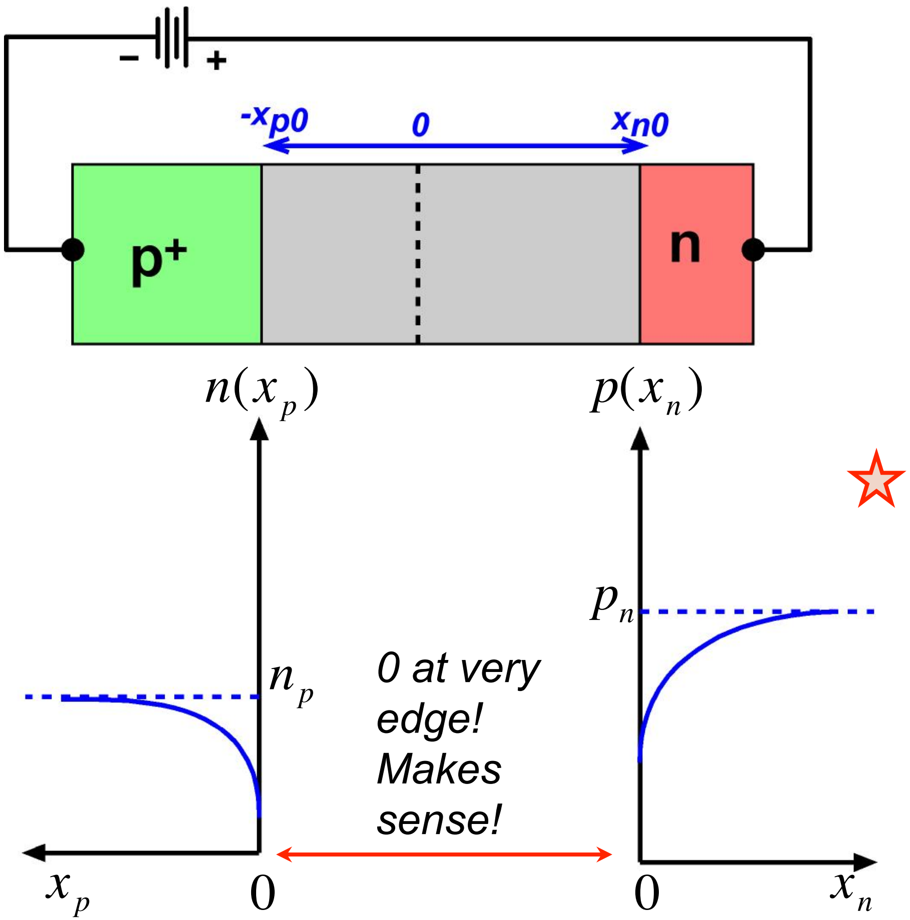
$$\delta n(x_p) = n_p (e^{qV/kT} - 1)\, e^{-x_p / L_n}$$

Dept. Electrical Engin. & Computing Systems
UNIVERSITY OF Cincinnati

- Introduce new axis, variables



- Reverse bias - *J(drift.) dominates*



For V_r>kT/q (V<0) saturates to drift

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

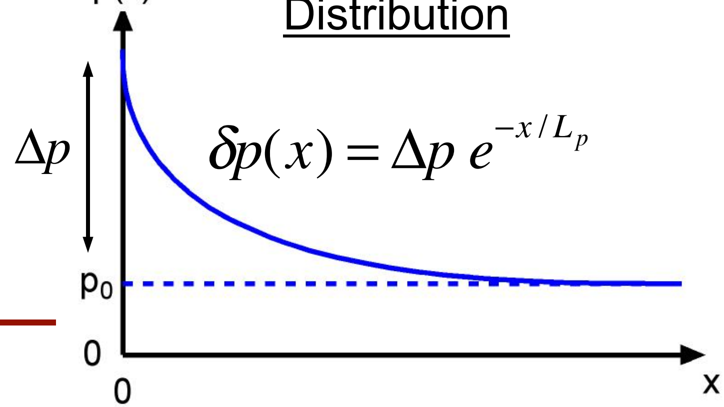
- We already have the Diode Equation: $$I = I_0(e^{qV/kT} - 1)$$

- Lets use our new results to calculate the current <u>components</u> using two methods (both build up to finding I_0)

- First method :
  <u>Diffusion Current</u>

<u>Steady State Δ Distribution</u>

p(x)



$$J_p(x) = -q\, D_p \frac{dp}{dx}$$

$$-q\, D_p \frac{d\delta p}{dx}$$

$$q \frac{D_p}{L_p} \Delta p\, e^{-x/L_P}$$

@x=0

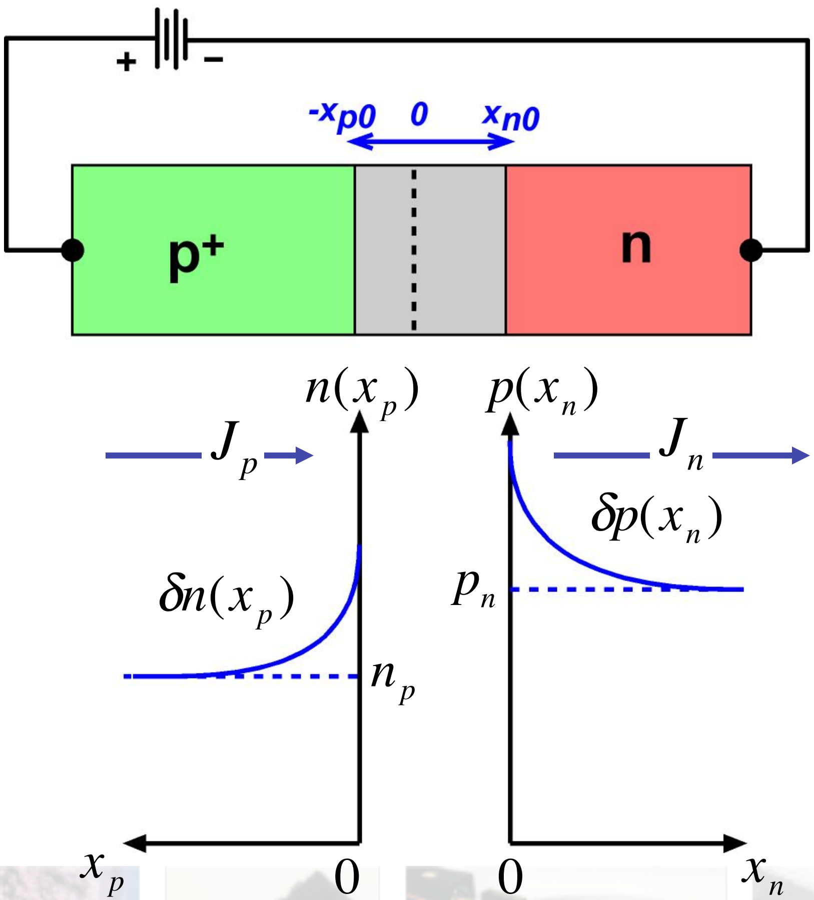
$$q \frac{D_p}{L_p} \Delta p$$

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

$$J_{p,x=0} = q \frac{D_p}{L_p} p_n(e^{qV/kT} - 1)$$

- Therefore in forward bias, our current components are (diff.):

$$J_p(x_n=0)=q\frac{D_p}{L_p}p_n(e^{qV/kT}-1) \qquad J_n(x_p=0)=-q\frac{D_n}{L_n}n_p(e^{qV/kT}-1)$$



- Sum them up using a common axis (+x), and note that they actually add (q is –e in J_n equation above):

$$J=J_p-J_n$$

- Therefore in forward bias, our current components are (diff.):

$$J_p(x_n=0) = q\frac{D_p}{L_p}p_n(e^{qV/kT}-1) \qquad J_n(x_p=0) = -q\frac{D_n}{L_n}n_p(e^{qV/kT}-1)$$

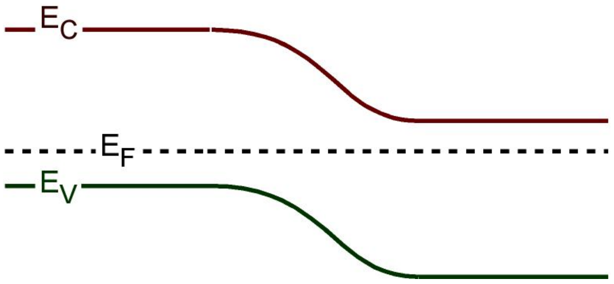
$$J = J_p - J_n$$

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

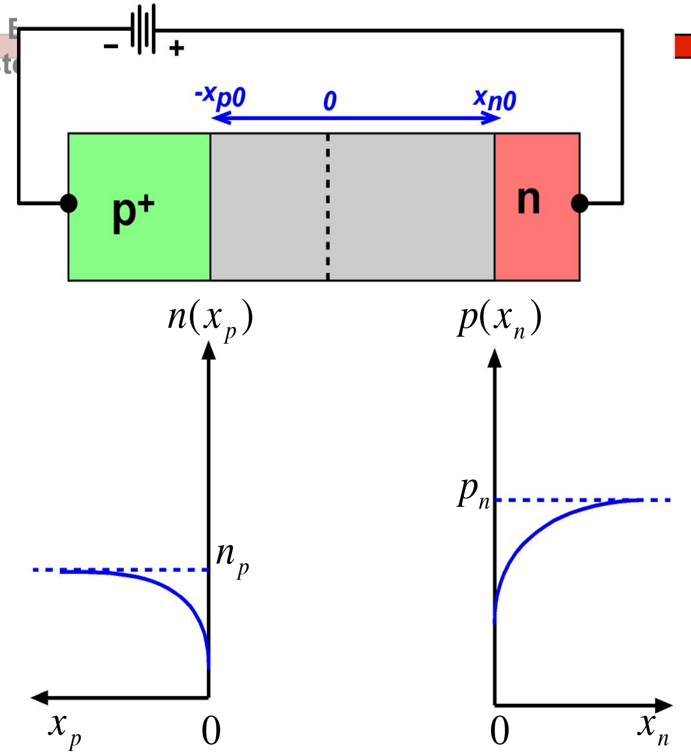
n-side p-side

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

$$I = I_0(e^{qV/kT}-1)$$



- This worked out great, we derived for forward bias and the results inherently give us the reverse bias current as well! (I_0).
- NOTE – at 300K q/kT = 1/0.0259 V. Note the units! Note kT = 0.0259 eV!



FOR p+n:

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

Why?

$$I = I_0(e^{qV/kT}-1)$$

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

REVERSE BIAS:

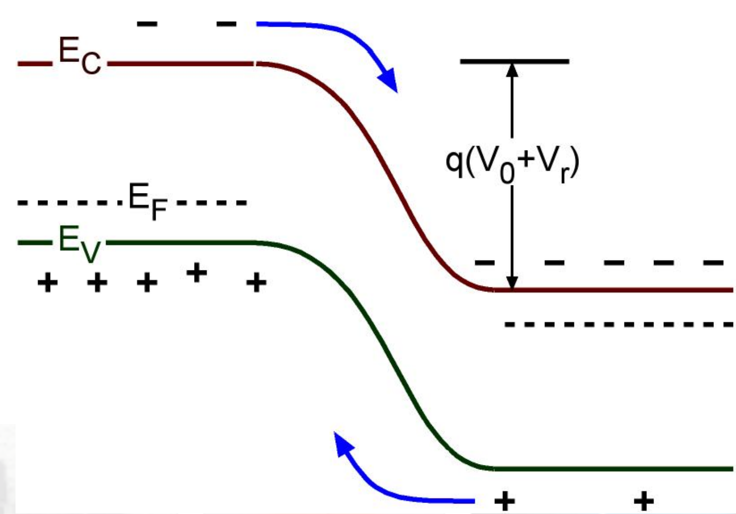
P_p↑ n_p↓ I_0↓ (less e^- avail. on one side for I_{drift}) and I_0 dominated by hole drift from n-side (p_n)

FORWARD BIAS:

Doping increases… larger V_0! Less currrent (I_0).

$$V_0 = \frac{kT}{q}\ln\frac{N_a N_d}{n_i^2}$$

V (ln) feeds into Jdiff (exp, Fermi) … so net effect is almost linear with doping! ($p_n=n_i^2/N_D$)



GENERAL

Doping levels ↑ I_0↓

Doping levels ↓ I_0↑

*Higher doping, less current!? **YES!***

$$L_p = \sqrt{D_p\tau_p} \qquad \frac{D_n}{\mu_n} = \frac{kT}{q} \qquad \tau_n = \frac{1}{\alpha_r(n_0+p_0)}$$

Dept. Electrical Engin. & Computing Systems
UNIVERSITY OF Cincinnati

- Lets use our new results to calculate the current components using another method…

This second method will be important to understanding the next slide…

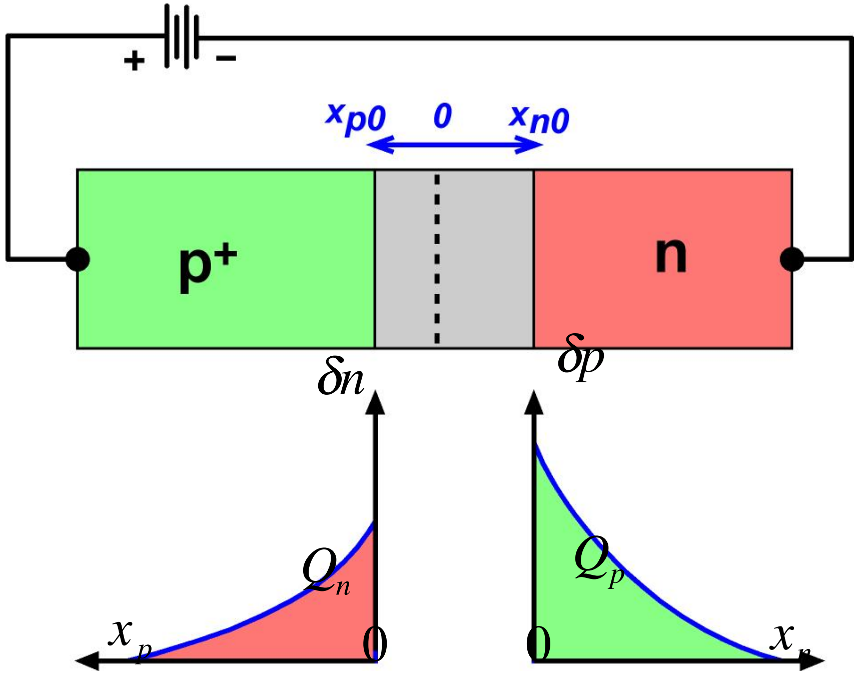
- Second method : Charge

$$Q_p = q\,A\int_0^\infty \delta p(x_n)dx_n$$

$$= q\,A\,\Delta p_n \int_0^\infty e^{-x_n/L_p}dx_n$$

$$= q\,A\,\Delta p_n\left(-L_p e^{-\infty} + L_p e^0\right)$$

$$Q_p = q\,A\,\Delta p_n\,L_p$$



$$I_p(x_n=0) = \frac{Q_p}{\tau_p} = q\,A\,\Delta p_n\,\frac{L_p}{\tau_p}$$

$$I_p(x_n=0) = q\,A\,\Delta p_n\,\frac{D_p}{L_p}$$

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

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

Same result!

Dept. Electrical Engin. & Computing Systems
University of Cincinnati

- I must be constant:

$$I = I_p + I_n$$

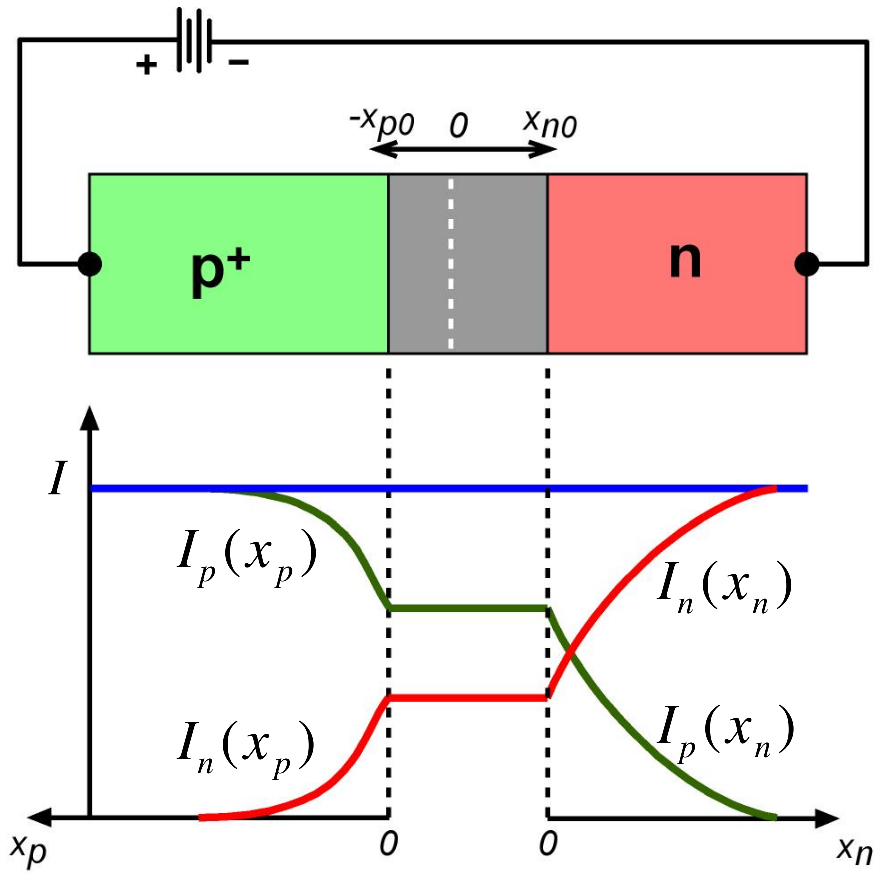
Remember: I_p & I_n were calculated <u>independently,</u> hopefully they add up!

Under forward bias:
(1) Diffusion
(2) Recombination

- Note offset and what dominates for p+n diode:

p+ side - hole diffusion

n side - electrons brought in mainly *just to support hole recombination*

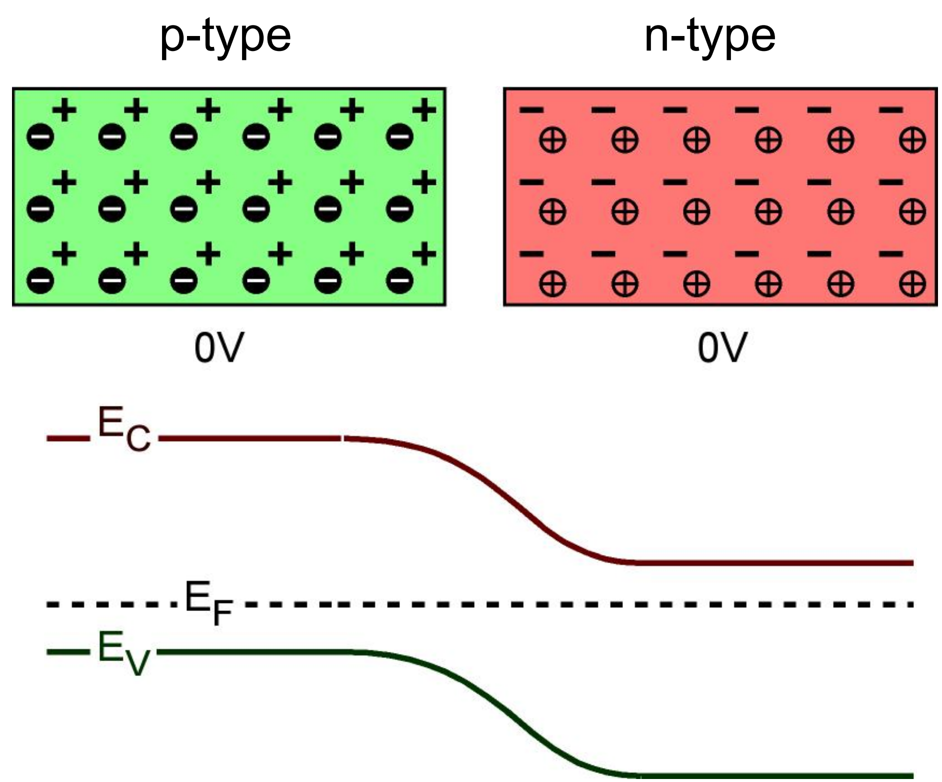


- Key points for forward bias I :

-heavy doped side dominates (but higher doping decreases total I !)
-further away junction (drift, small E)

Review!

- How does doping effect forward bias current, and why is it this way? … *S17*
- How does doping effect reverse bias current, and why? *S17*
- What do the minority carrier profiles for forward bias look like near the depletion region edge? *S12*
- What do the minority carrier profiles for reverse bias look like near the depletion region edge? *S13*
- In the formula shown at right, where do I input my parameters from and why?



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

$$I = I_0(e^{qV/kT} - 1)$$