COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

ELEN E3106/4106 Lecture 14

p-n Junction Breakdown and Narrow Base Diodes

Outline

- Zener breakdown
- Avalanche breakdown
- Punch-through breakdown
- Narrow—base diodes

Assignments:
Reading: Streetman and Banerjee §5.4
Homework 6 due Friday Oct. 24th by 5pm
Exam 2 Tuesday Oct. 28th

Recap of p-n Junctions

- We've (nearly) exhausted the p-n junction. Now we know:

  1) Why and how it conducts current (forward, reverse)
  2) How to calculate depletion width W, field E_0, built-in voltage V_0
  4) How diodes store charge as capacitors in RB (we have not discussed FB capacitance)
  5) How to make optoelectronics based on photodiodes (solar cells, photodetectors, LEDs & lasers)

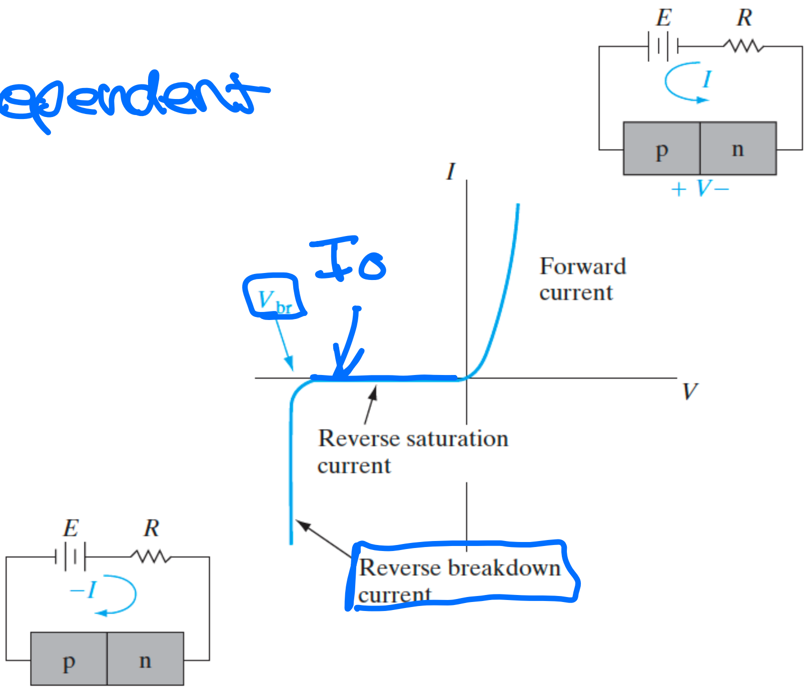
- Today, we have 2 final topics before we get to BJTs!

  6) How diodes break down
  7) Narrow-base diodes

Sources: E. Pop ECE 340 Slides

Reverse-bias Breakdown

- Recall: so far we have found that p-n junction in RB has a small, essentially voltage-independent reverse saturation current, I_0
- This is true until we reach a critical high reverse bias point, called the breakdown voltage (V_{br})
- We can vary V_{br} through choice of doping concentrations
- What happens at V_{br}? Reverse current sharply increase, and relatively large currents can flow with little increase in RB
- Is breakdown reversible? In general, yes. Destructive if overheating occurs

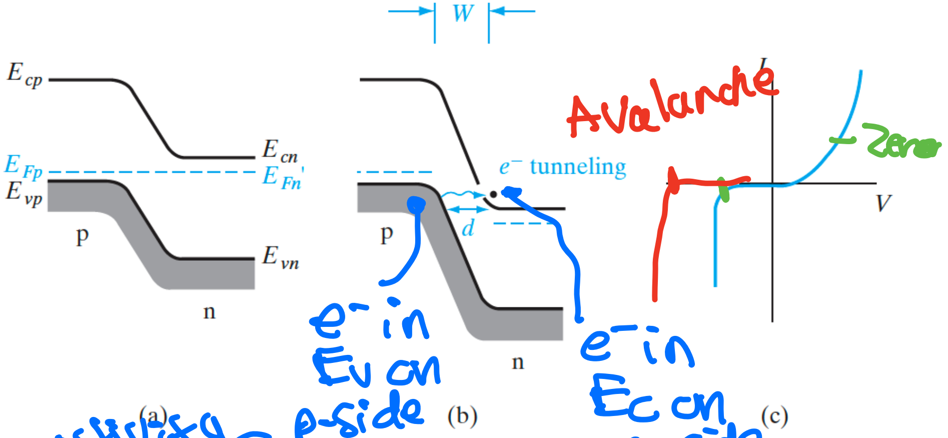


Sources: Textbook

Zener Breakdown

- Dominant for heavily doped junctions (>__10^18__ cm^{-3})
- Dominant at __low RB__ (up to a few volts)
- With narrow barrier in RB, tunneling of e- from p-side filled states in __Ev__ to n-side empty states in __Ec__ can occur
- Tunneling distance __d__ becomes smaller with RB as E-field creates __steeper slope__ for band edges
- Prevalent in heavily doped __p+ - n+__ junction
  - W must only extend __very short__ into each side of junction
  - We are assuming W does not increase very much with __RB__ so *d* can become small (accurate for __low RB__ and heavy doping on both sides)

(a) Heavily doped junction at equilibrium, (b) reverse bias with e- tunneling from p to n, (c) I-V characteristic



permittivity

$$V_{BR} = \frac{\varepsilon_s \mathcal{E}_{CR}^2}{2qN} - V_0$$

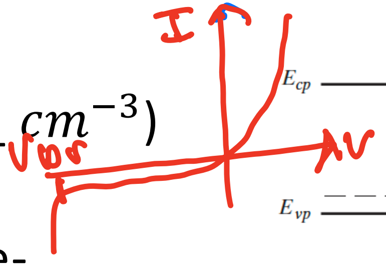
critical electrical field

$$\mathcal{E}_{CR} \approx 10^6 \text{ V/cm}$$

Sources: E. Pop ECE 340 Slides, Textbook

Avalanche Breakdown

- Dominant for more lightly doped (< 10^{18} ____ cm^{-3}) junctions



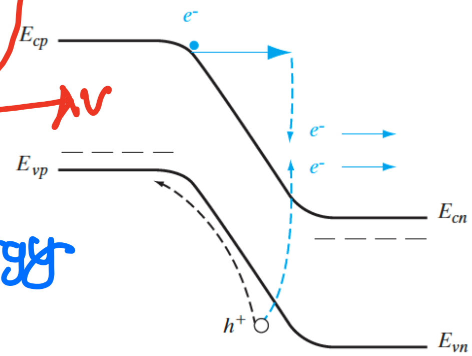
- Because the depletion region is wide ____, e- accelerated across it will gain enough kinetic energy ____ to cause an ionizing ____ collision with the lattice, generating EHP
  - Called impact ionization ____

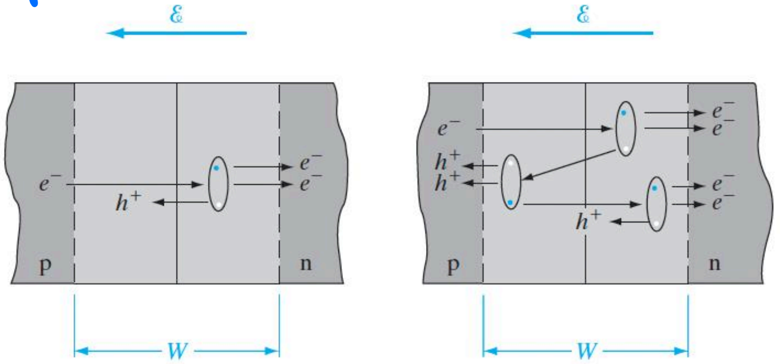
$$V_{BR} \approx \frac{\varepsilon_s \mathcal{E}_{CR}^{\,2}}{2qN}$$

if $V_{BR} >> V_0$

↑ not accurate

1 impact ionization = 1e⁻ and 1h⁺





- The original e- and newly generated e- are both swept to n-side ____, while h+ is swept to p-side ____ --> carrier multiplication ____

- Multiplication can become high if there are many impact ionization events: imagine incoming e- generated EHP, each of these carriers created additional EHPs through impact ionization, and so on

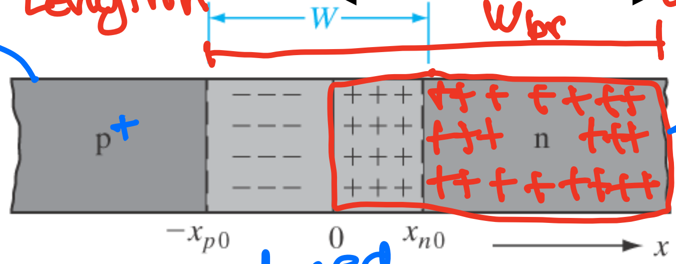
- This avalanche ____ process causes reverse current to increase

(a) EHPs created by impact ionization, (b) band diagram showing primary e- gaining KE in depletion region, creating secondary EHPs (c) Primary, secondary, and tertiary collisions

Sources: E. Pop ECE 340 Slides, Textbook

Punch-through Breakdown

- Occurs when either depletion region "punches through" the entire length of the diode, e.g. $x_n(V)$ = (length of n-side)



- An issue for short, lightly doped regions
  - Recall: W extends primarily into lightly doped side, as W increases with RB ($\propto \sqrt{V}$) it can fill the entire length!

$$W = x_n + x_p = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 - V)}$$

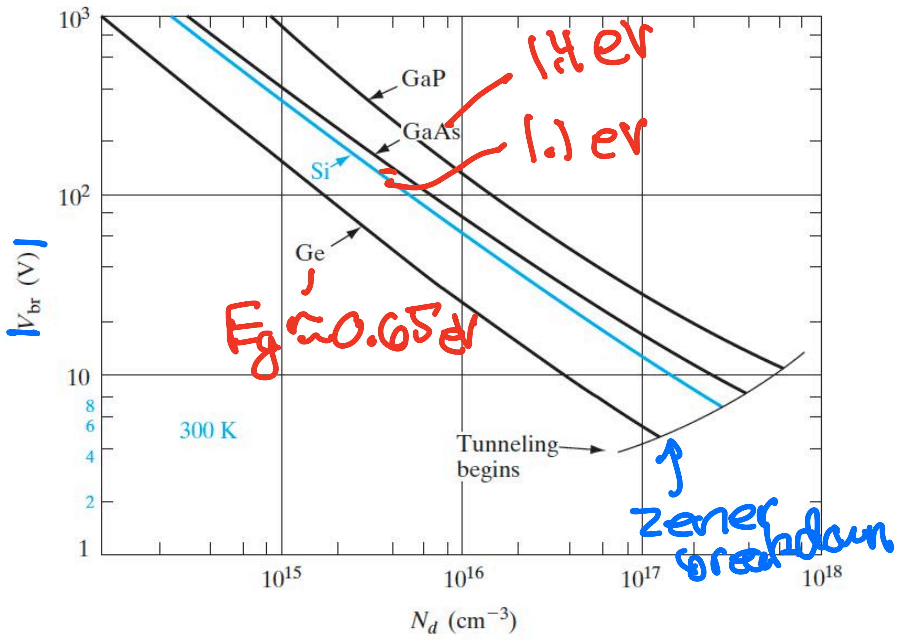
- Result: Breakdown below the value of V_{br} predicted by zener or avalanche breakdown

Sources: E. Pop ECE 340 Slides, Textbook

Empirical Observations on Breakdown

- V_{br} decreases with increased doping, N
- V_{br} decreases with decreasing E_g

What about temperature?



- For tunneling (Zener) breakdown, $|V_{br}|$ ~ decrease minimally with increasing temperature

- For avalanche breakdown,

$|V_{br}|$ ~ increases w/ increasing temperature
→ carriers are scattered before gaining enough K.E. to impact ionize

Sources: E. Pop ECE 340 Slides, Textbook

Problem: Avalanche breakdown

A Ge p+n junction diode has donor doping of $2 \times 10^{15}\ cm^{-3}$ and relative permittivity 16. What will be the minimum thickness of n region that will ensure avalanche breakdown at 300 V reverse bias voltage?

$$N_d = 2 \times 10^{15}\ cm^{-3}$$

$$x_{n0} = \frac{W}{1 + \frac{N_d}{N_a}}$$

For $p^{+}n$ junction, $N_a \gg N_d$, so $\frac{N_d}{N_a} \ll 1$ and $1 + \frac{N_d}{N_a} \approx$ 1 so $x_{n0} \approx$ W

$$W = \sqrt{\frac{2\epsilon}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)(V_0 - V)} \approx \sqrt{\frac{2\epsilon}{q}\left(\frac{1}{N_d}\right)(V_{br})}$$

* V_0 is very small so we ignore it.

$$x_{n0} \approx W = \sqrt{\frac{2(16)(8.85 \times 10^{-14})}{(1.6 \times 10^{-19})}\left(\frac{1}{2 \times 10^{15}}\right)(300V)}$$

(ϵ_0)

$x_{n0} =$ 16.3 *microns*

This is the minimum thickness that will ensure avalanche breakdown rather than punch-through.

Sources: Textbook

Narrow Base Diode

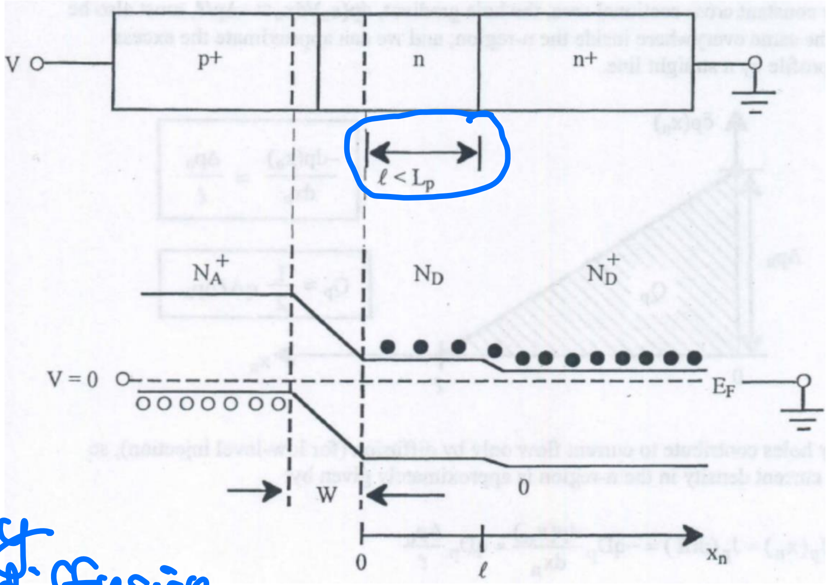
Special case of a BJT

- Before we begin our discussion of BJTs, we need to discuss the narrow-base p-n diode
- The typical minority carrier diffusion length in Si is ~ 10 μm
- But modern device lengths are very small, on the order of 7-100 nm
- This can easily create situations where

l < L_p or L_n ← minority carrier diffusion lengths

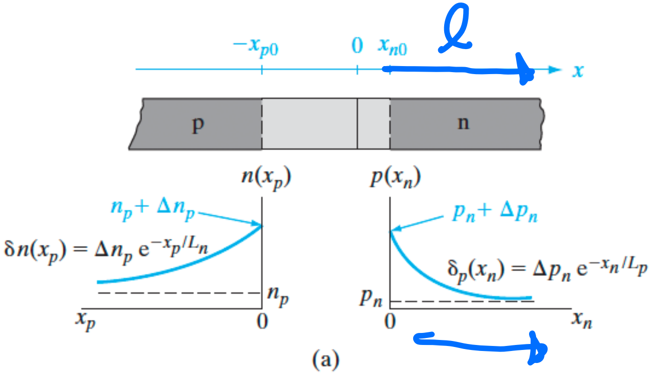
length of QNR

  - Ex. Let's imagine we have a p^+-n diode with an n region width l less than the hole diffusion length
- This is called a narrow base diode



Sources: http://transport.ece.illinois.edu/ECE340F11-Lectures/ECE340Lecture31-NBD.pdf , E. Pop ECE 340 Slides

Excess Minority Carrier Spatial Distributions



- Recall our discussion on the long base diode (exponential decay):

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

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

- But instead of "long" ($l > L_p$) exponential decay:

$$\delta p(x) = \Delta p_{n0} e^{-\frac{x}{L_p}} = \frac{n_i^2}{N_d}\left(e^{\frac{qV}{kT}} - 1\right)e^{-x/L_p}$$

- We have the "narrow" or "short" $(l < L_p)$ approximation (straight line approximation):

$$\delta p(x) = \Delta p_{n0}\left(1 - \frac{x}{l}\right) = \frac{n_i^2}{N_d}\left(e^{\frac{qV}{kT}} - 1\right)\left(1 - \frac{x}{l}\right)$$

At $x=0$, $\delta p = \Delta p_{n0}$
At $x=l$, $\delta p = 0$

- We can think of the (metal) contacts at the end of the p-n junction infinite sink. Note the diode is too narrow (short) for any hole recombination in n-region, so recombination happens at the contact, setting the boundary conditions:

$$\delta p(x = l) = 0$$

$$\delta p(x = x_n) = \Delta p_n = p_n(e^{\frac{qV}{kT}} - 1)$$

Sources: E. Pop ECE 340 Slides, Textbook

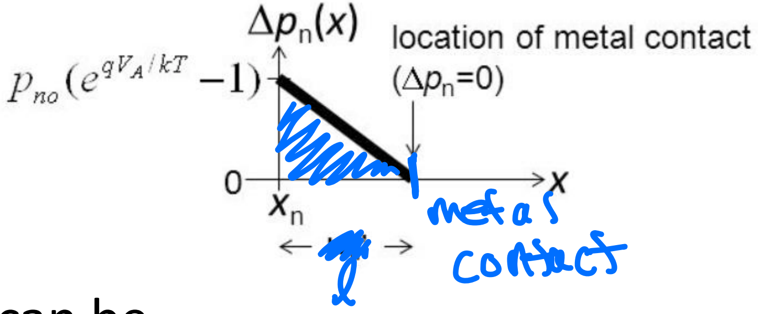
Current in Narrow Base Diode

- Total injected (stored) minority charge at FB is the area under the triangle. Remember excess carrier distribution is a linear function of distance:

$$Q_p = \frac{1}{2} q\Delta p(Al) = \frac{1}{2} qAl \frac{n_i^2}{N_D}\left(e^{qV/kT} - 1\right)$$

- The hole concentration gradient using the straight approximation:

$$\frac{dp}{dx} = \frac{-\Delta p_n}{l}$$



- Assuming low-level injection, hole diffusion current can be written:

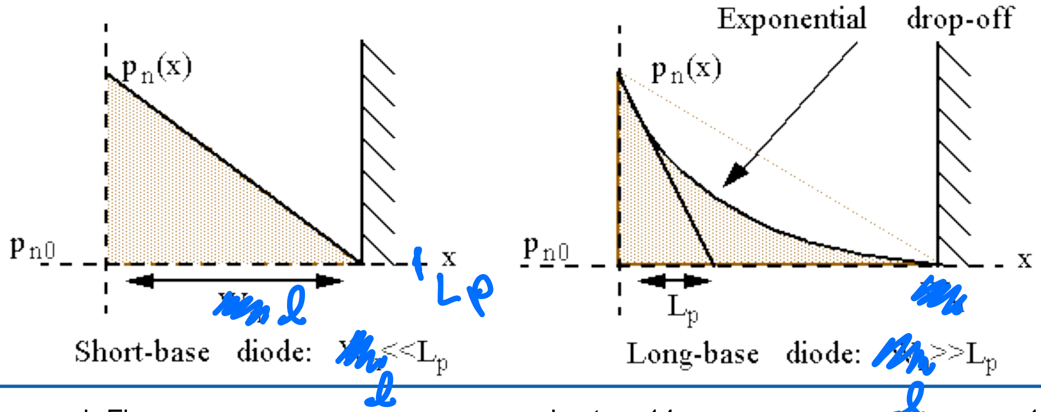
$$J_p = -qD_p\left(\frac{dp}{dx}\right) = +qD_p\frac{\Delta p_n}{l} = +\frac{qD_p}{l}\left(\frac{n_i^2}{N_d}\right)\left(e^{\frac{qV}{kT}} - 1\right)$$

- Compare with "long" diode diffusion current: $J_p = q\frac{D_p}{L_p}\frac{n_i^2}{N_D}(e^{qV/kT} - 1)$

Sources: https://slideplayer.com/slide/11660804/ , E. Pop ECE 340 Slides

Current in Narrow Base Diode

- l ___replace___ L_p in the denominator of the diode equation since l << L_p
- Because of constant gradient (___slope___), J_p is constant in narrow QNR because no holes are lost due to ___recombination___ as they diffuse to the metal contact!
- Shorter QNR -> steeper concentration gradient -> ___higher___ current in narrow base diode than "long" diode for the same voltage
- Total diode current if:
  - It's a p⁺-n (N_A >> N_D) diode: $J = J_p$
  - It's a p-n (N_A ~ N_D) diode: $J = J_p + J_n$



Sources: E. Pop ECE 340 Slides, ece-research.umn.edu