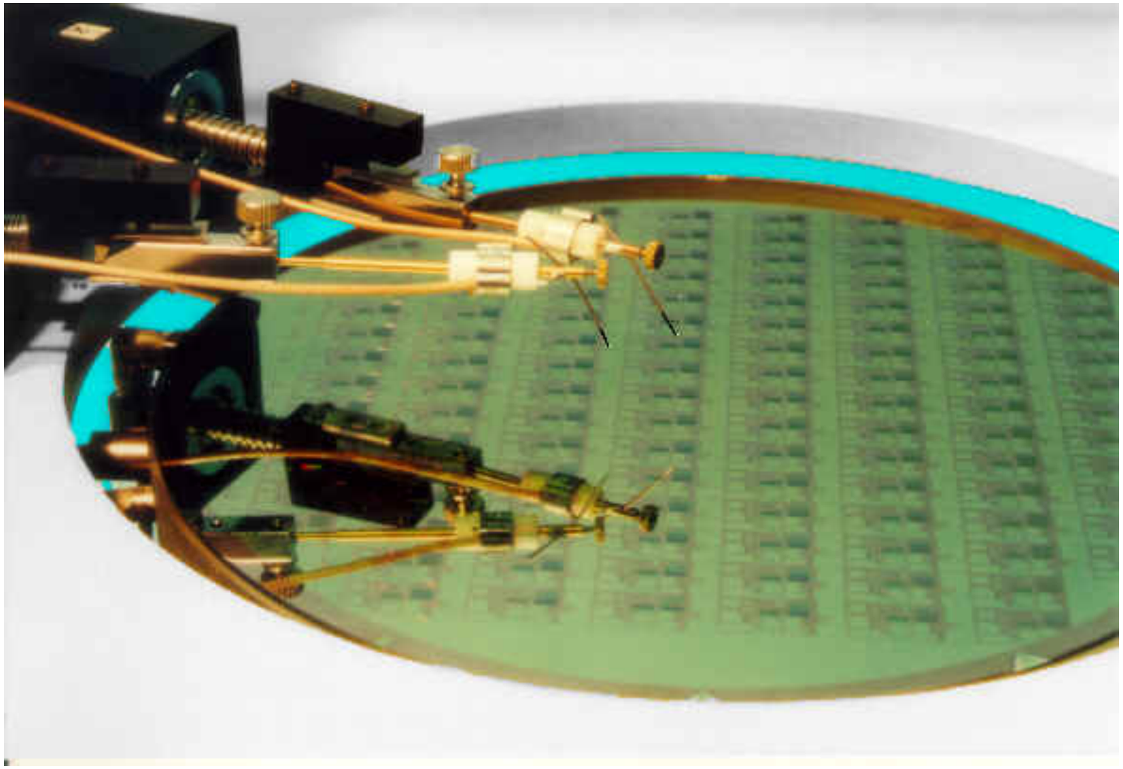
5.4-5.6 Breakdown and Other Non-Ideal…

What is this?

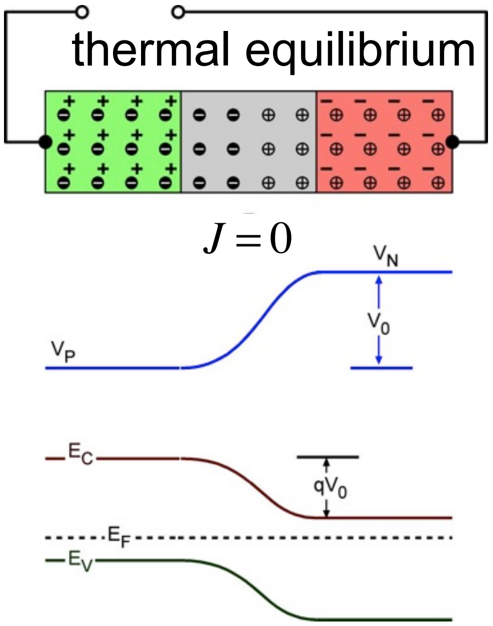
Based on what you see, can you guess what type of device they are testing?



Reminder, the test is next!

Look over the old example test problems BEFORE you come to class, because I spend most of the time answering any questions you may have!

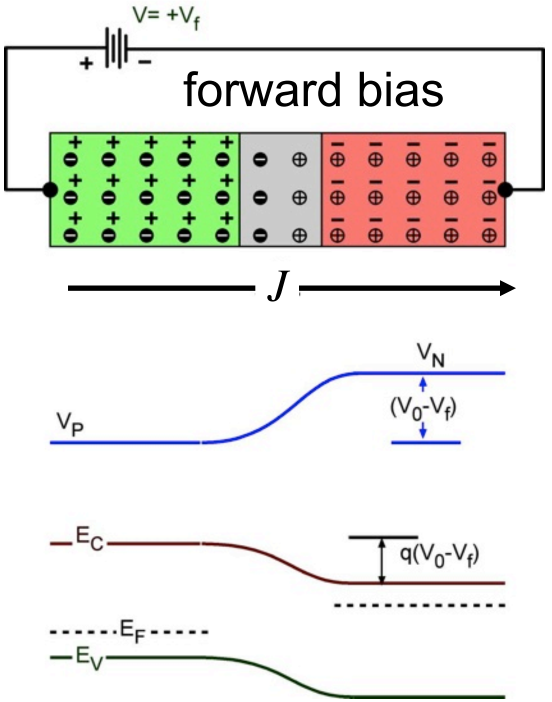
Review…



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

$$J = 0$$

$$I_0 = qA\left(\frac{D_p}{L_p}p_n - \frac{D_n}{L_n}n_p\right)$$



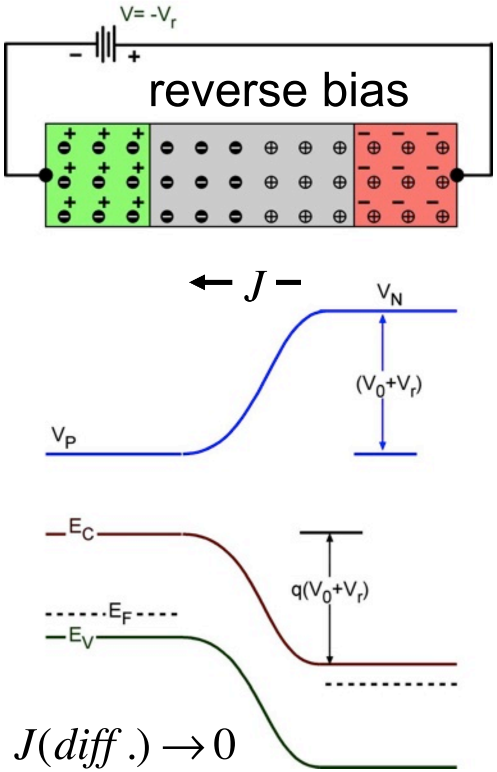
$$J(diff.) >> J(drift.)$$

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

J due to majority carrier diffusion over built-in barrier and across junction.

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

$$I \approx I_0 e^{qV/kT}$$



$$J(diff.) \to 0$$

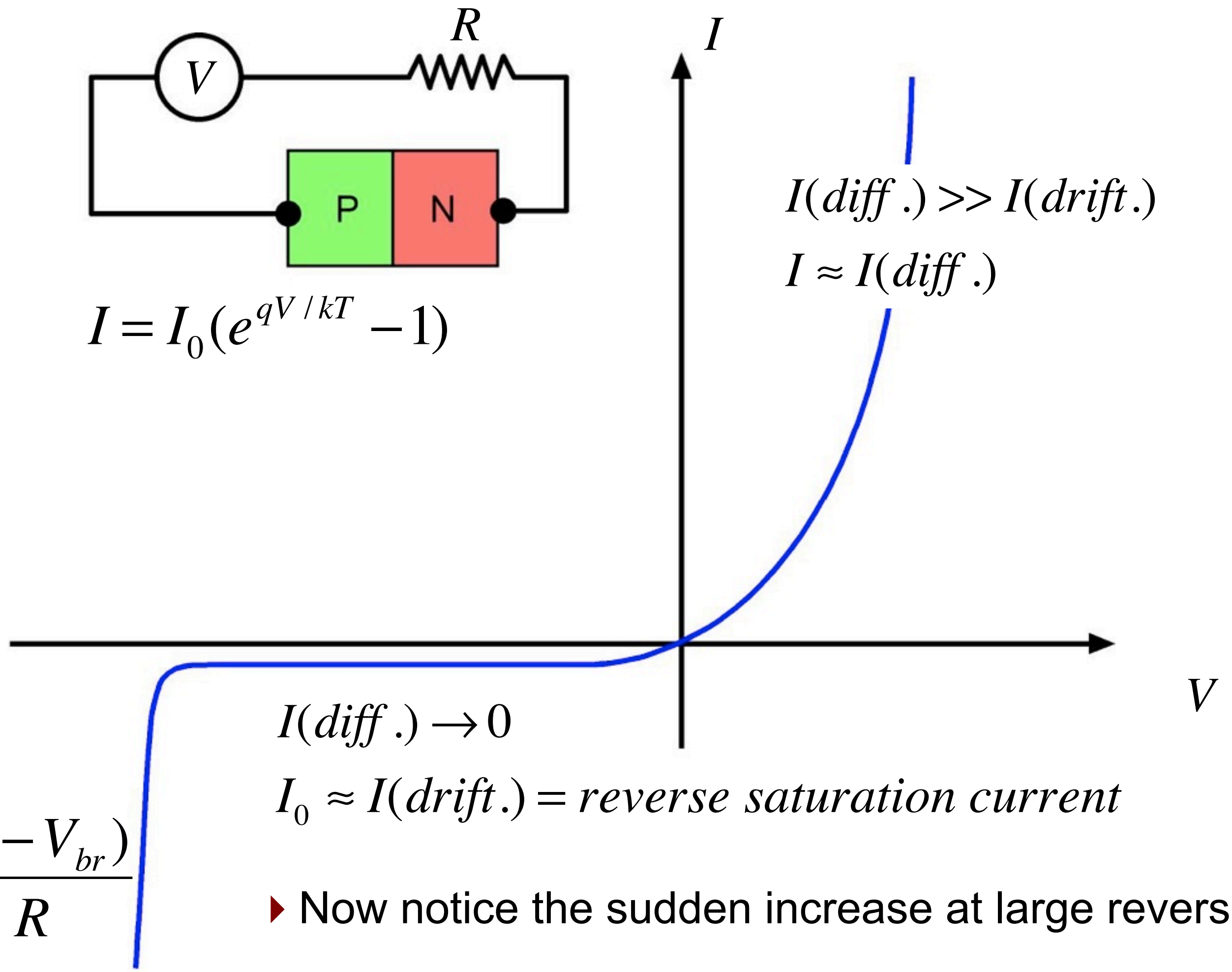
$$J \approx J(drift.) = constant!$$

J due to minority carrier generation near junction, drifts across junction.

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

$$I \approx -I_0$$

Breakdown / Metal-Semicon



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

$$I(diff.) >> I(drift.)$$

$$I \approx I(diff.)$$

$$I(diff.) \rightarrow 0$$

$$I_0 \approx I(drift.) = reverse\ saturation\ current$$

$$I = \frac{(V - V_{br})}{R}$$

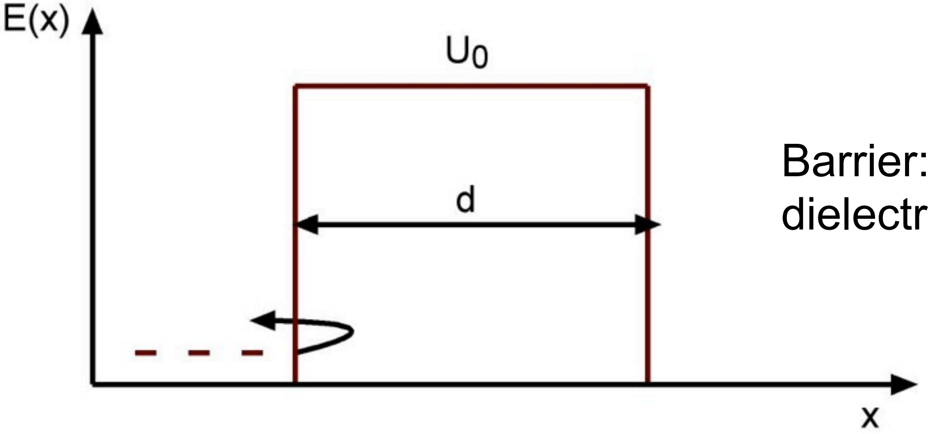
- Now notice the sudden increase at large reverse bias.

PN *designed* for low voltage breakdown - Zener (think tunneling).

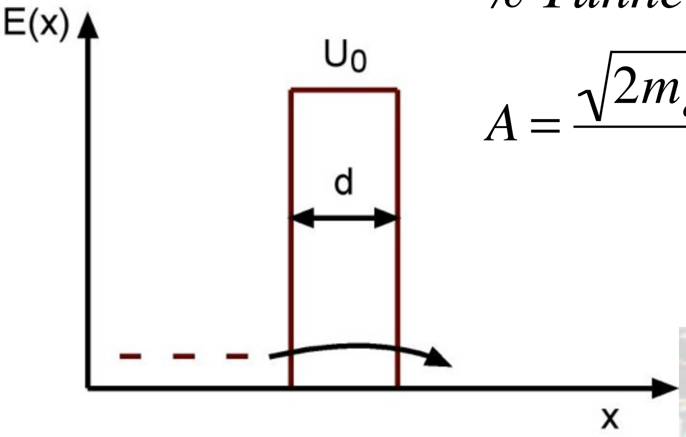
PN *designed* for high voltage breakdown - Avalanche (think lightning).

Talk about Zener 1st…

- Lets talk about Zener 1st.. Who remembers what tunneling is?
- What are my chances of walking through a wall?



Barrier: vacuum, wider bandgap semiconductor, dielectric, *or charge depleted region*…



$$\%\ Tunneling \propto e^{-A\,d}$$

$$A = \frac{\sqrt{2m_e U_o - E}}{\hbar}$$

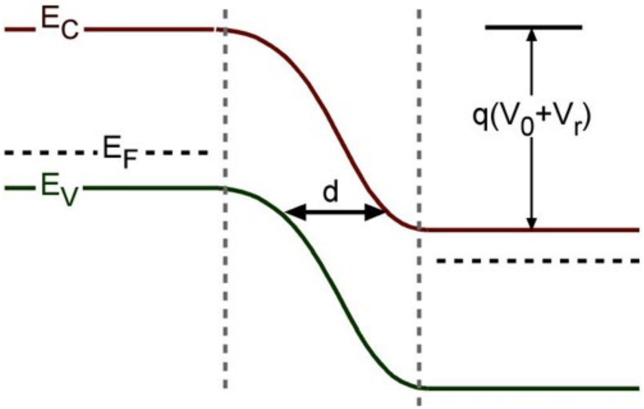
'h-bar' = Planks' constant / 2 PI
4.135 667 33 E−15 eV s

m_e = 'effective' electron mass in crystal

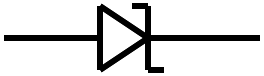
- For a PN junction we can easily change d…

Zener Diodes

- If we can increase the slope of the bands, ***d*** decreases.

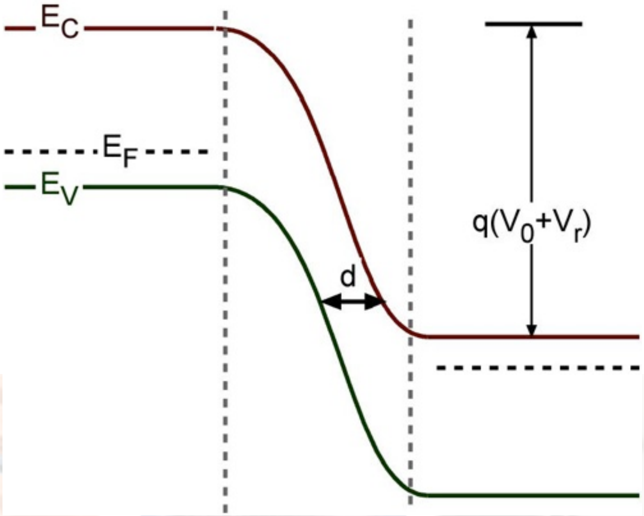


$$\% \, T \propto e^{-A\,d}$$

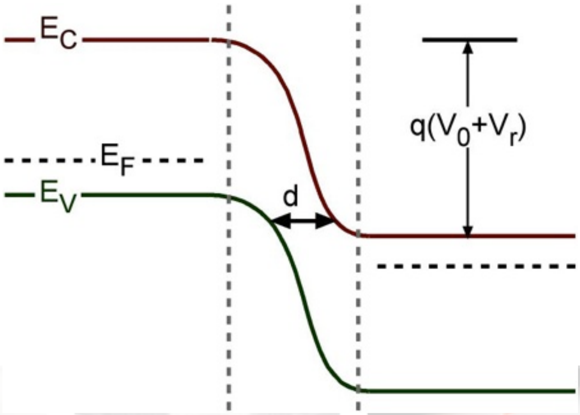


How can we increase the slope?

- Larger reverse bias (but W increases also).

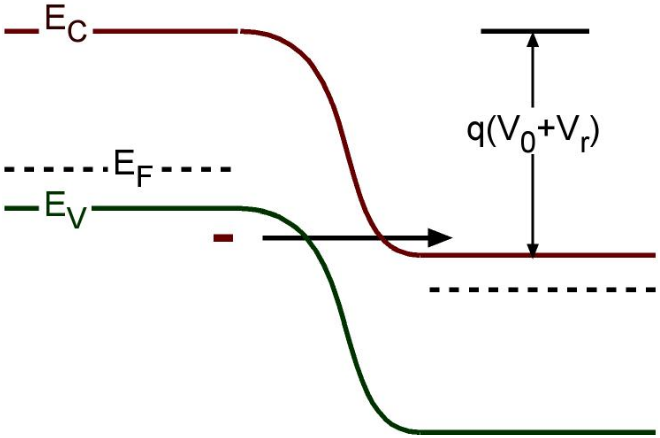


- **Increase the doping** (W decreases!)



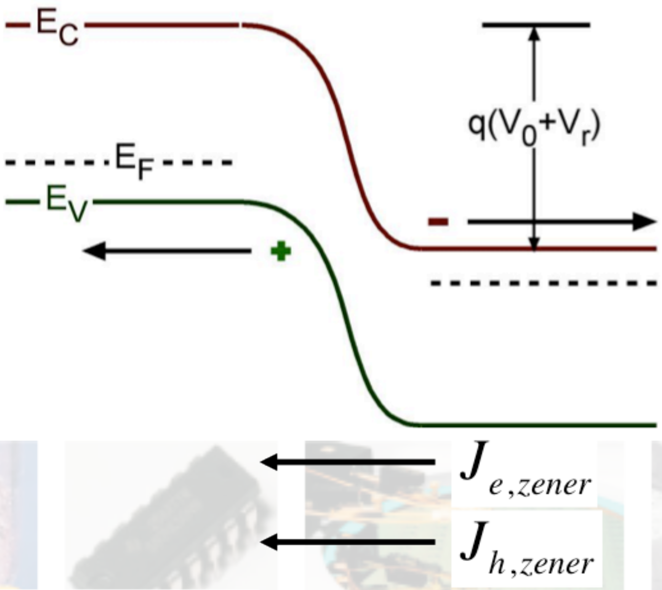
Zener Diodes

- First, an electron tunnels from the valence band…



Ionization of host atoms.
Why not dopants?
- already ionized at 300K
- wrong polarity anyway…

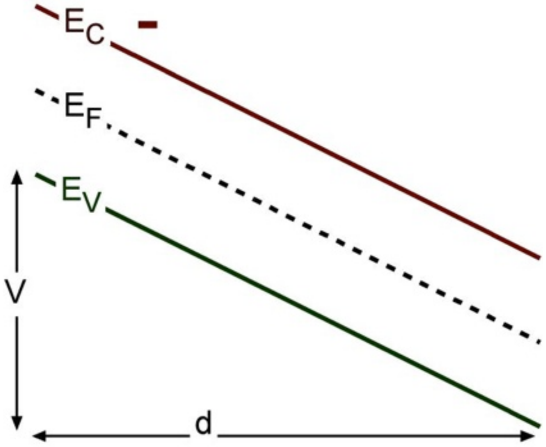
- This creates a hole (think e-h generation, but sideways!)

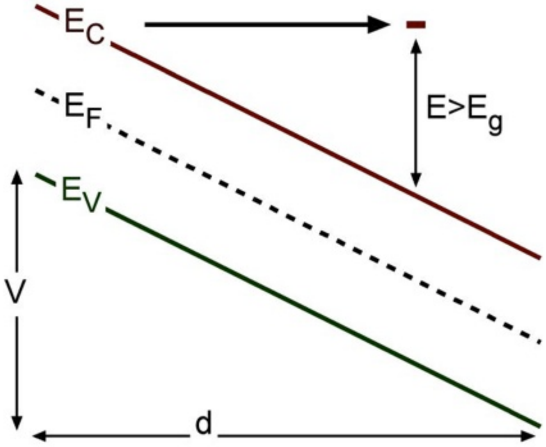


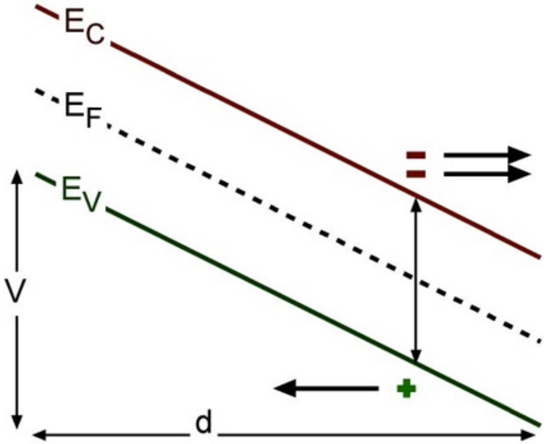
- Can be thought of as electric field ionization.
- However, if the reverse bias becomes too large we encounter another form of breakdown/ ionization…

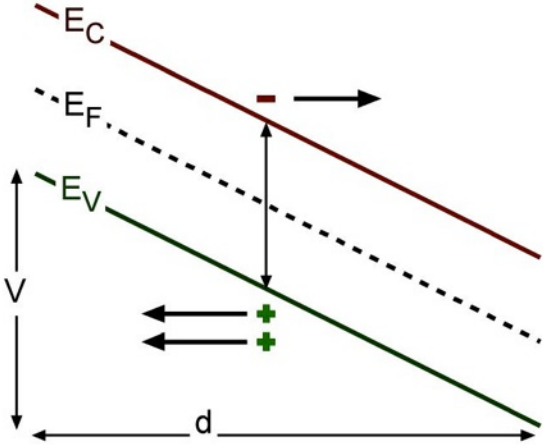
Another Breakdown Mode…

- Looking at this diagram, what did we do to this semiconductor?





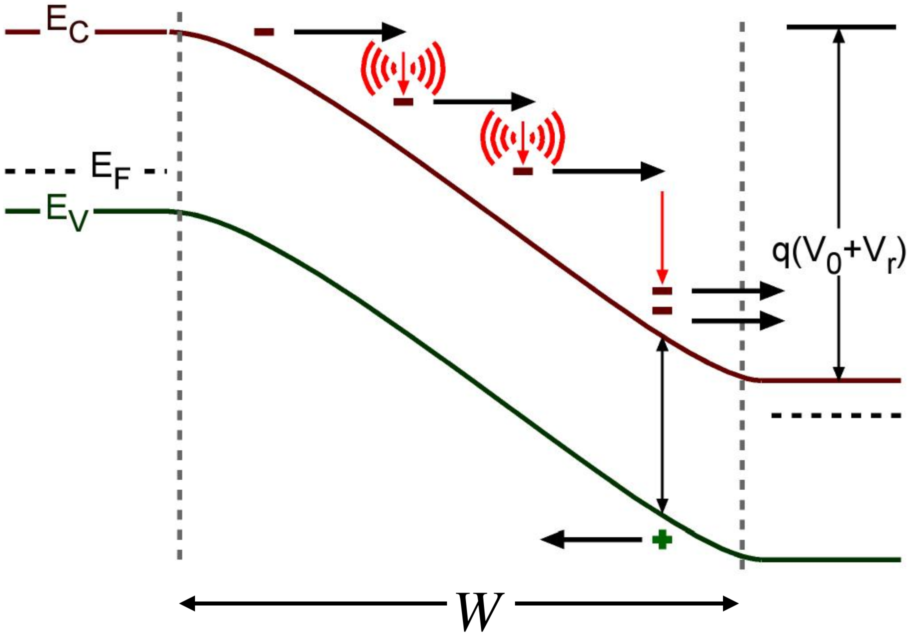




- Probability ‘**P**’ for ionization (otherwise scattering / phonons/ heat)
- **P** not equal for holes/electrons (one can dominate)

Avalanache Breakdown

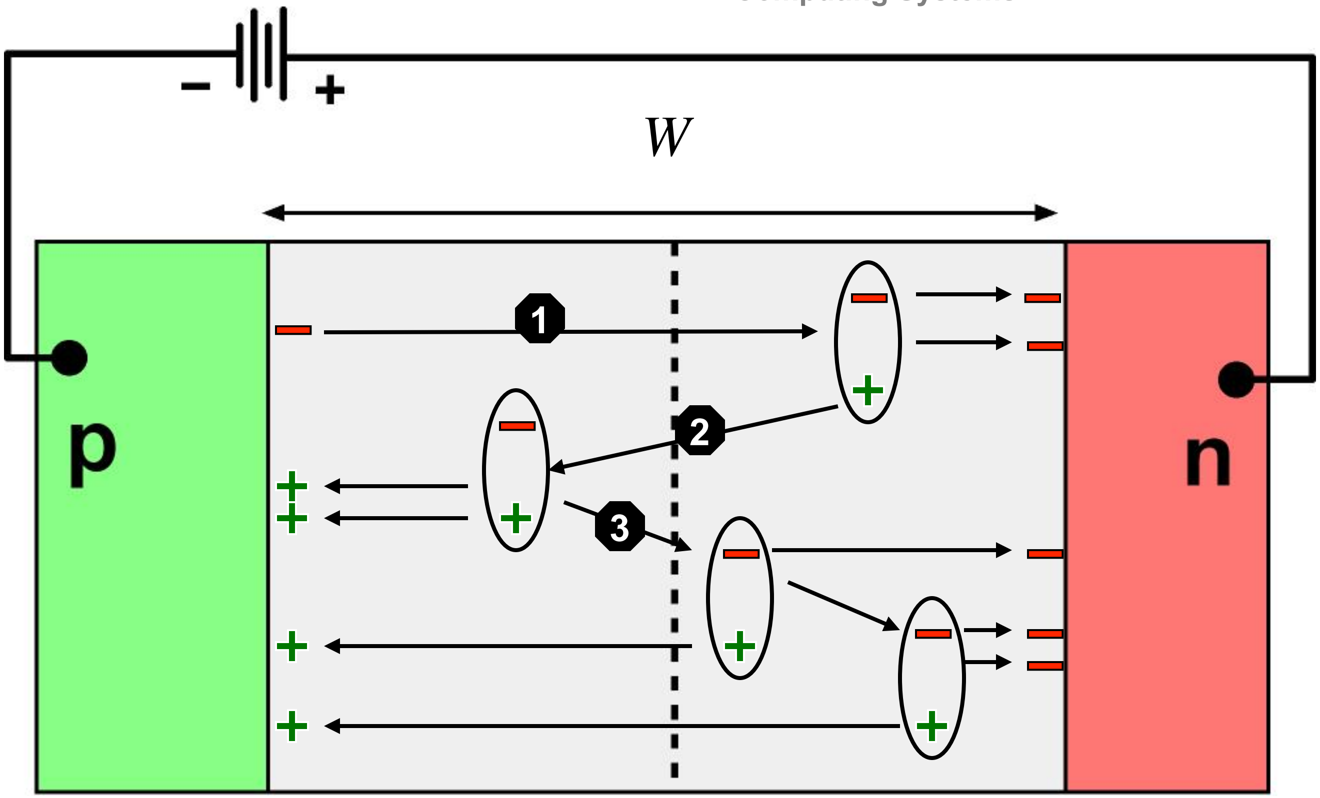
- Avalanche breakdown…



- 0<P<1 for n electrons in (n_{in}) to cause impact ionization…
  - quickly impacts host, other electrons: *Phonons (heat, vibration)*
  - eventually may get to high energy: *impact ionization*

- assume holes have the same chance (P)…
  … if given the same distance to travel

Avalanche Breakdown

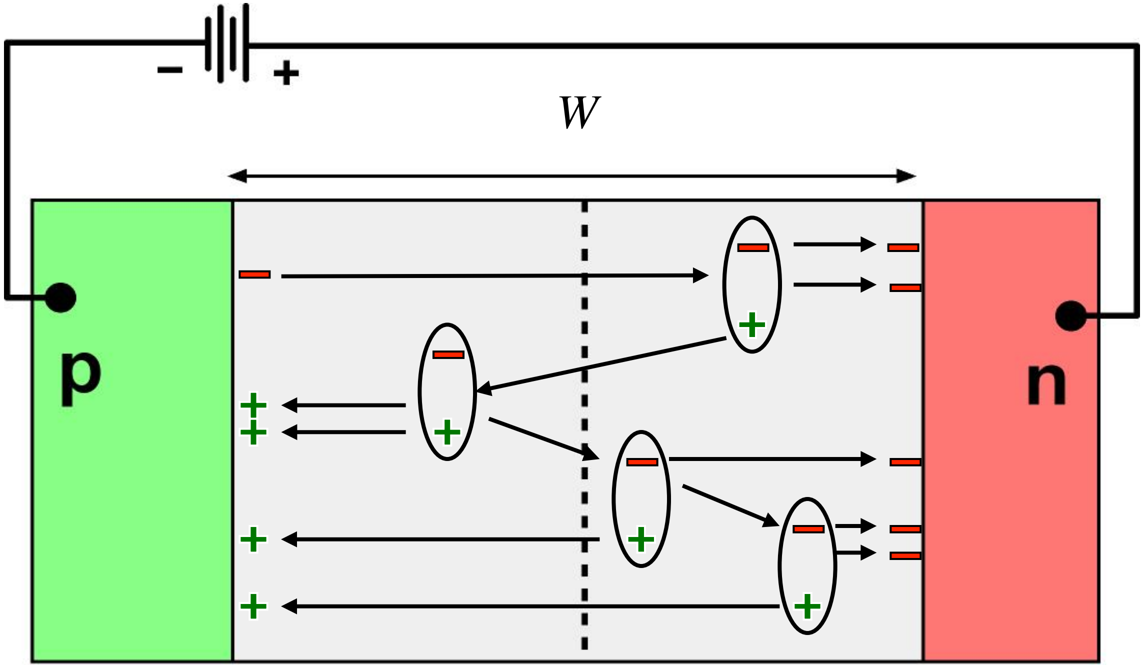


- e^- impact ionizes e^--h^+ with probability P $(0 < P < 1)$
- h^+ has less of chance (not all of W, lower probability)
- however, potential travel distance for new e^--h^+ is still W! still P!

1 n_{in} $\quad n_{in} + n_{in}P$

2 $n_{in} + n_{in}P + n_{in}P \times P$

3 $n_{in} + n_{in}P + n_{in}P \times P + n_{in}P \times P \times P \ldots$



$$n_{out} = n_{in} + n_{in}P + n_{in}P \times P + n_{in}P \times P \times P \ ...$$

$$n_{out} = n_{in}(1 + P + P^2 + P^3 ...) = n_{in}\left(\frac{1}{1-P}\right)$$

$$M = \frac{n_{out}}{n_{in}} = \left(\frac{1}{1-P}\right) \approx \frac{1}{1-(V/V_{br})^n}$$

(3<n<6)

Avalanche Breakdown

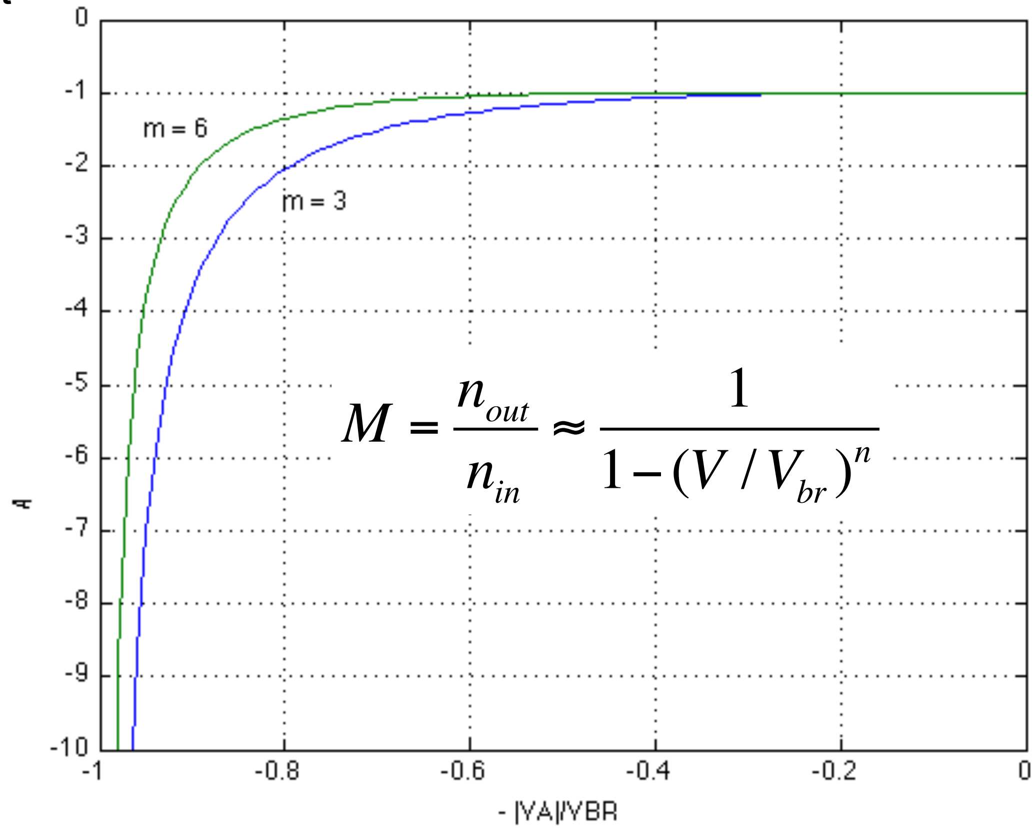
- Mutliplication factor plot (Pierret Ex. 6-5, ‘n’ same as ‘m’)

```
%Exercise 6.5...Multiplication factor
%Initialization

close
clear

%M calculation
x=linspace(0,.99);    %x=|VA|/VBR
M3=1 ./(1-x.^3);      %M when m=3
M6=1 ./(1-x.^6);      %M when m=6

%Plotting result
plot(-x,-M3,-x,-M6); grid
axis([-1 0 -10 0])
xlabel('- |VA|/VBR')
ylabel('- Multiplication factor')
text(-0.8,-2.5,'m = 3')
text(-0.95,-1.5,'m = 6')
```

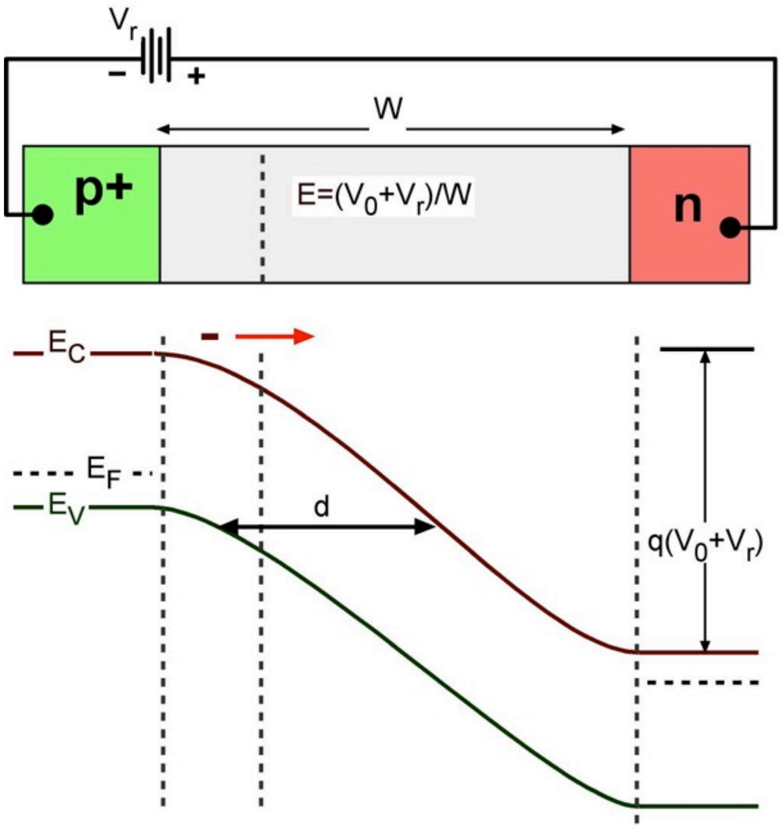


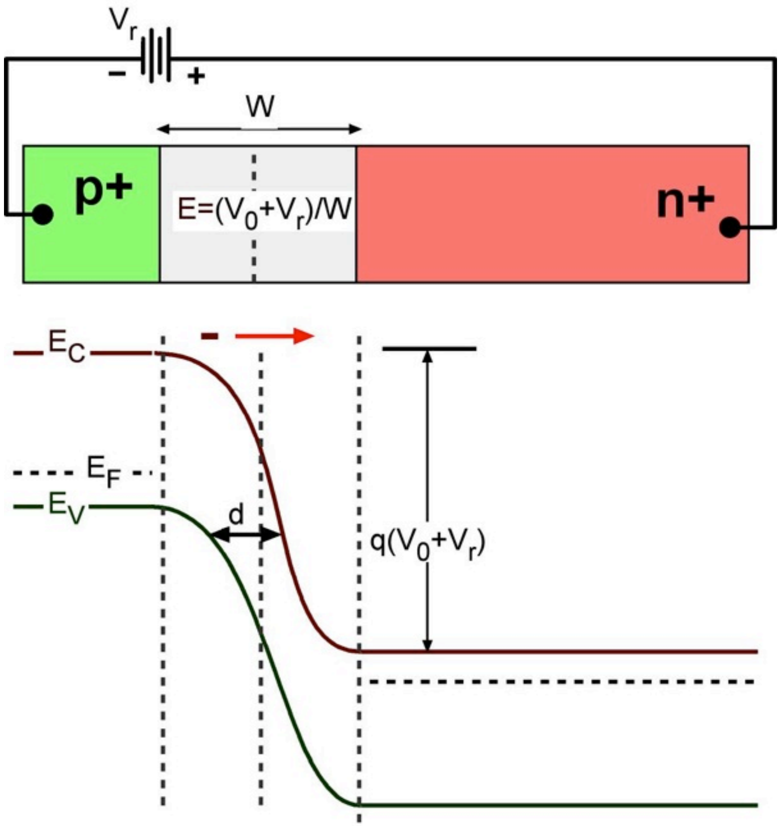
$$M = \frac{n_{out}}{n_{in}} \approx \frac{1}{1-(V/V_{br})^n}$$

- Note, just because you have avalanche does not mean that it can’t be controlled, for example avalanche photodiodes detect photons (light) and internally amplify the detected signal.

- *How do you think they might work? Why have internal amplification?*

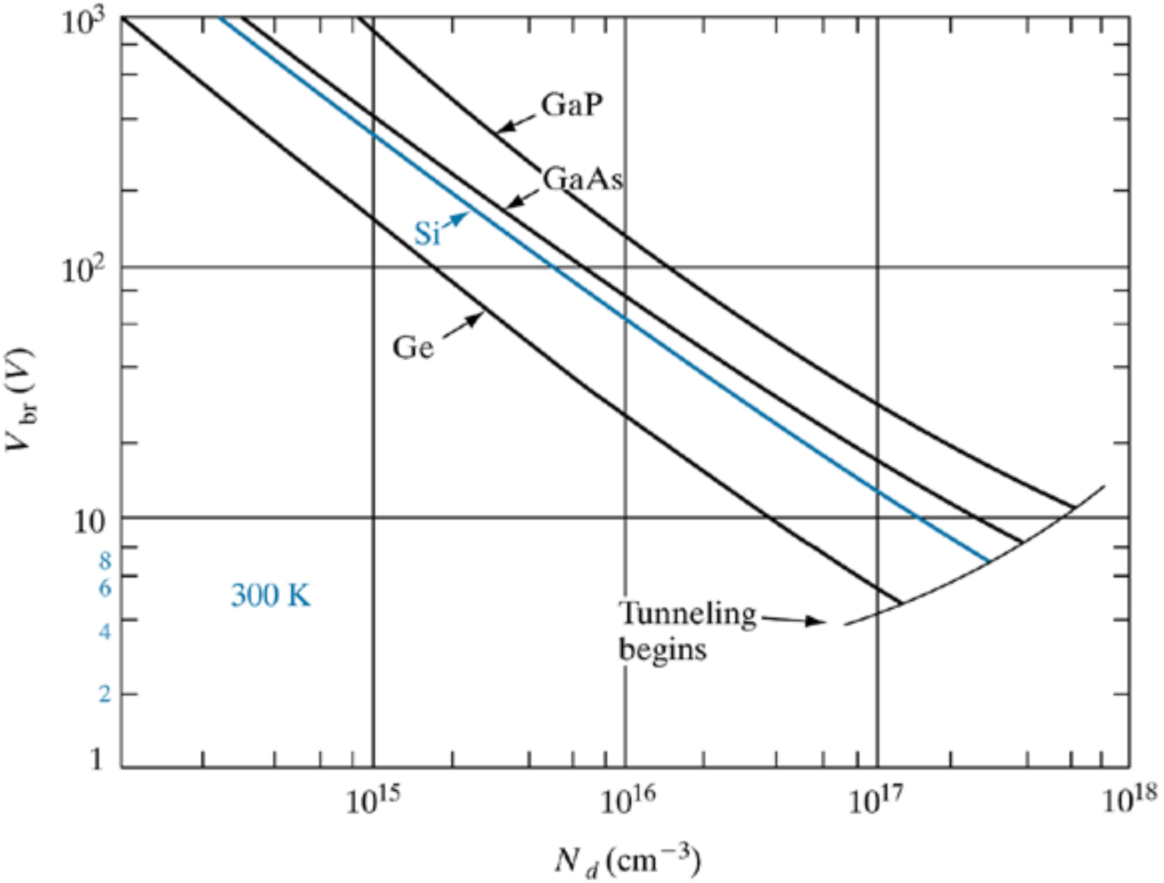
Breakdown Depend. on Doping

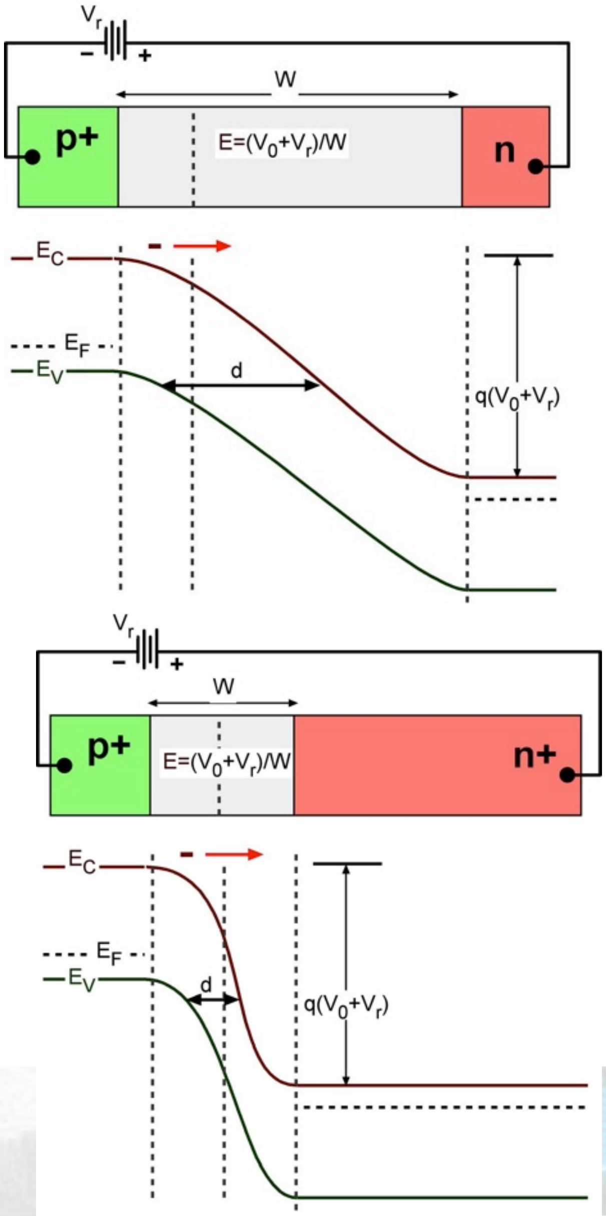




- In practice breakdown is determined by doping on light doped side
  - because that is where V is spread over longest distance (E)

Breakdown Depend. on Doping

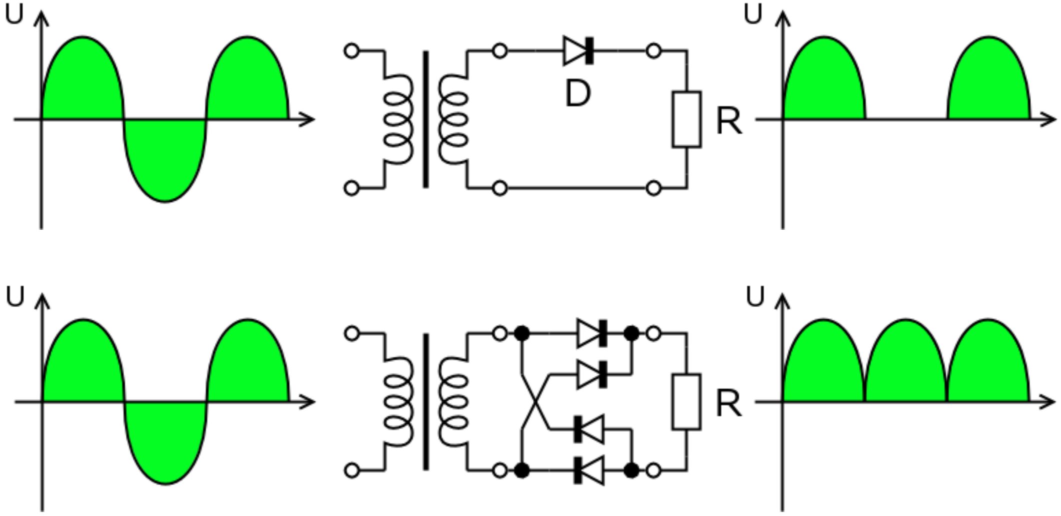




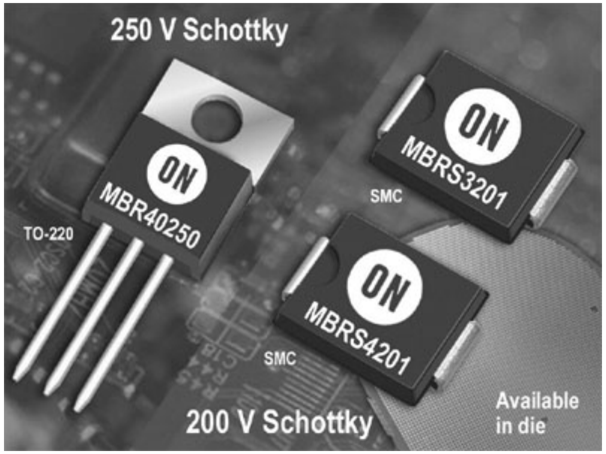
- Effect of Nd… why lower avalanche V?
- Effect of bandgap… why lower avalanche V?
- Effect of bandgap for tunneling?

Applications…

- Design for no Zener when desire rectification..



For plasma/LCD television, power supply, consumer and automotive.



- Higher voltage rectifiers use SiC (E_g=2.86 eV), GaN (E_g=3.4 eV)

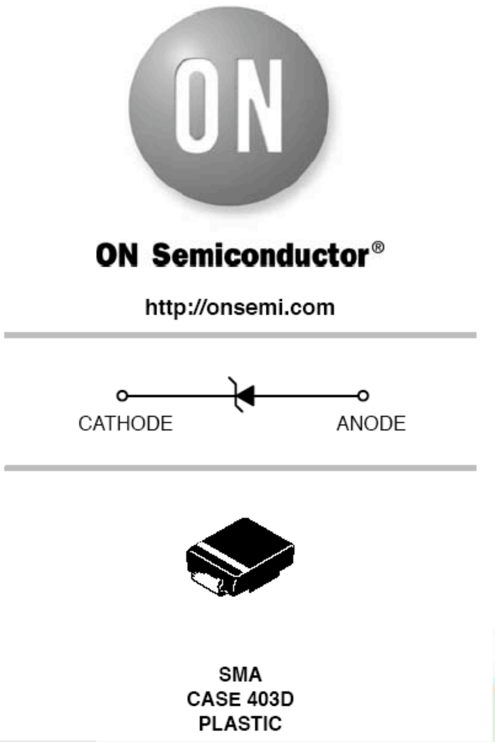
- however, p-type doping in these wide-bandgap semiconductors is very difficult, so often use Schottky diodes (metal / n-type semiconductor)!

Example Spec. Sheet

- Commercial spec sheets…

Do the voltage and current trends make sense? Why?

Think conductivity or max power dissipation….



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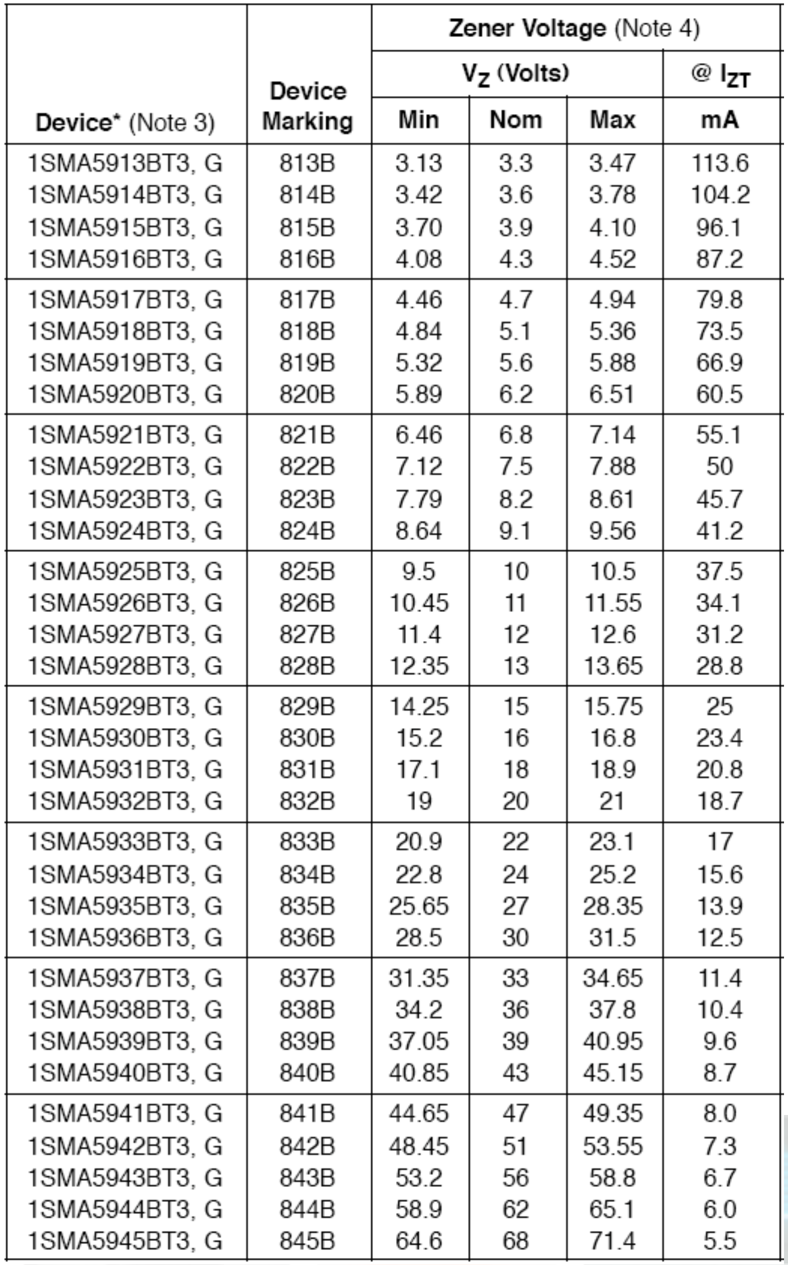
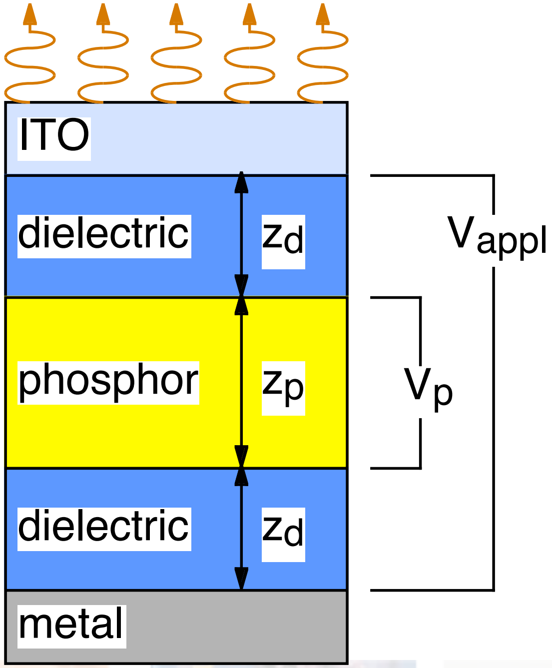


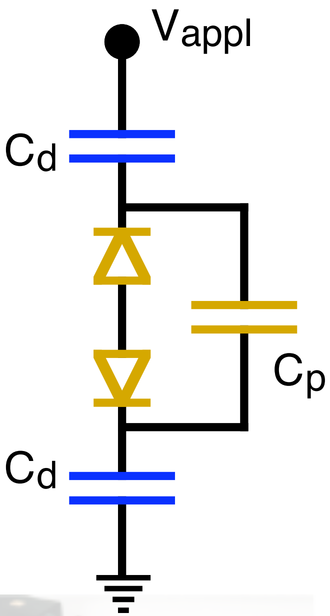
Device* (Note 3)	Device Marking	Zener Voltage (Note 4)			
		V_Z (Volts)			@ I_{ZT}
		Min	Nom	Max	mA
1SMA5913BT3, G	813B	3.13	3.3	3.47	113.6
1SMA5914BT3, G	814B	3.42	3.6	3.78	104.2
1SMA5915BT3, G	815B	3.70	3.9	4.10	96.1
1SMA5916BT3, G	816B	4.08	4.3	4.52	87.2
1SMA5917BT3, G	817B	4.46	4.7	4.94	79.8
1SMA5918BT3, G	818B	4.84	5.1	5.36	73.5
1SMA5919BT3, G	819B	5.32	5.6	5.88	66.9
1SMA5920BT3, G	820B	5.89	6.2	6.51	60.5
1SMA5921BT3, G	821B	6.46	6.8	7.14	55.1
1SMA5922BT3, G	822B	7.12	7.5	7.88	50
1SMA5923BT3, G	823B	7.79	8.2	8.61	45.7
1SMA5924BT3, G	824B	8.64	9.1	9.56	41.2
1SMA5925BT3, G	825B	9.5	10	10.5	37.5
1SMA5926BT3, G	826B	10.45	11	11.55	34.1
1SMA5927BT3, G	827B	11.4	12	12.6	31.2
1SMA5928BT3, G	828B	12.35	13	13.65	28.8
1SMA5929BT3, G	829B	14.25	15	15.75	25
1SMA5930BT3, G	830B	15.2	16	16.8	23.4
1SMA5931BT3, G	831B	17.1	18	18.9	20.8
1SMA5932BT3, G	832B	19	20	21	18.7
1SMA5933BT3, G	833B	20.9	22	23.1	17
1SMA5934BT3, G	834B	22.8	24	25.2	15.6
1SMA5935BT3, G	835B	25.65	27	28.35	13.9
1SMA5936BT3, G	836B	28.5	30	31.5	12.5
1SMA5937BT3, G	837B	31.35	33	34.65	11.4
1SMA5938BT3, G	838B	34.2	36	37.8	10.4
1SMA5939BT3, G	839B	37.05	39	40.95	9.6
1SMA5940BT3, G	840B	40.85	43	45.15	8.7
1SMA5941BT3, G	841B	44.65	47	49.35	8.0
1SMA5942BT3, G	842B	48.45	51	53.55	7.3
1SMA5943BT3, G	843B	53.2	56	58.8	6.7
1SMA5944BT3, G	844B	58.9	62	65.1	6.0
1SMA5945BT3, G	845B	64.6	68	71.4	5.5

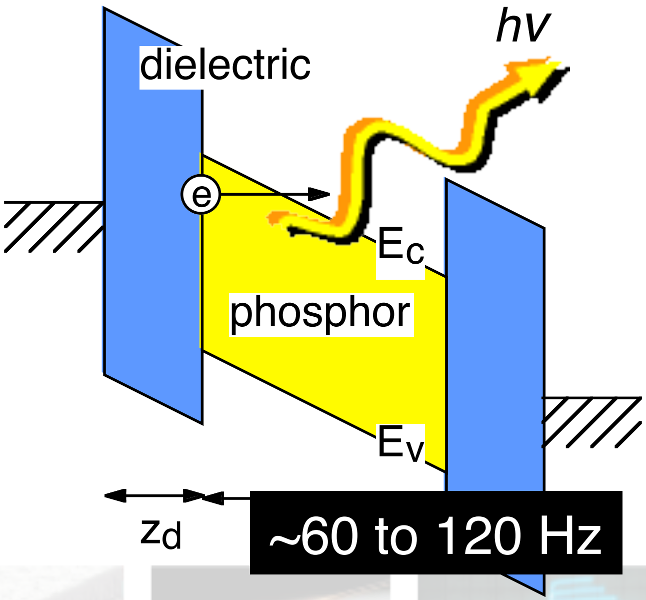
Fun Topic (my Ph.D. work)

Alternately called high-electric field (~1-2 MV/cm) electroluminescence.

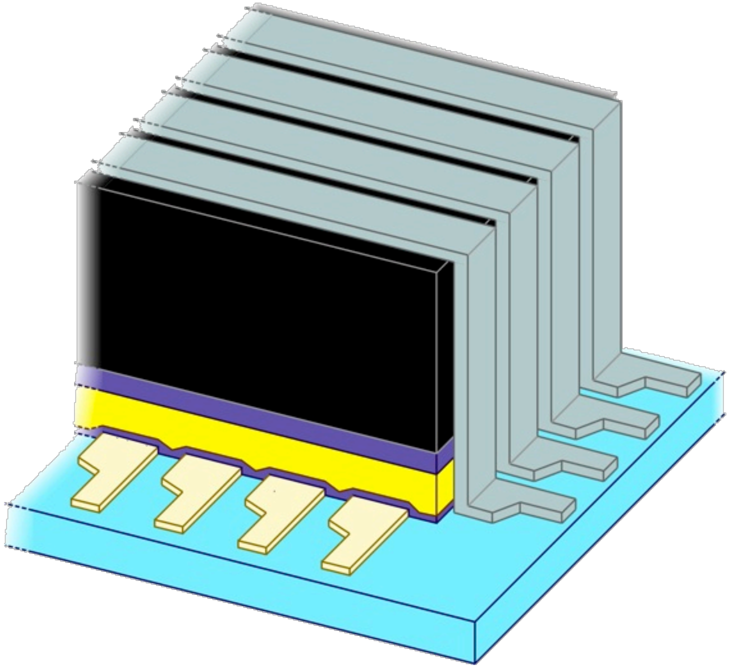
- transparent metal / dielectric / phosphor /dielectric / metal
- AC voltage (~160-200 V) capacitively coupled to phosphor
- hot electron acceleration (~MV/cm) and phosphor excitation (~2-3 eV)



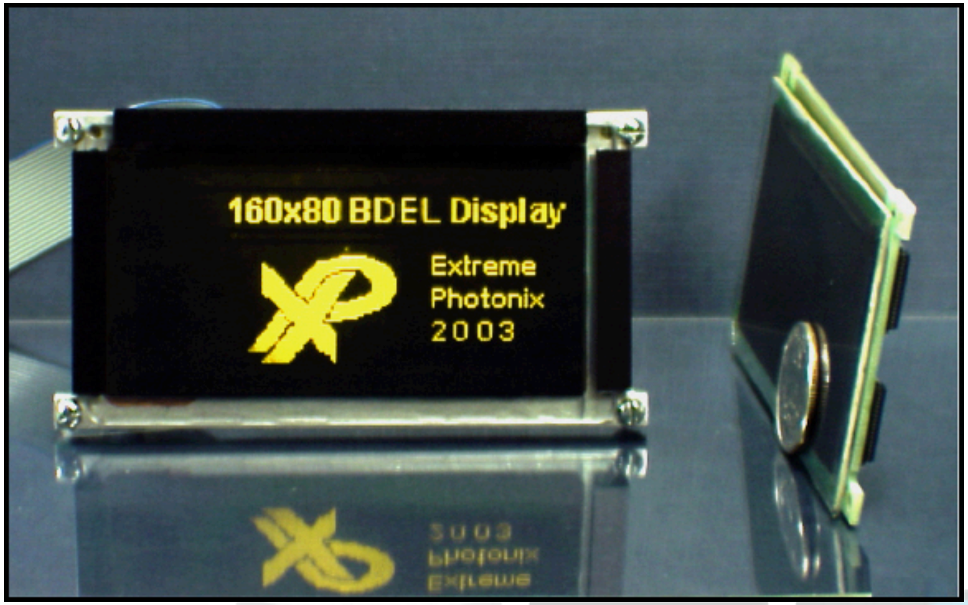




Fun Topic (my Ph.D. work)



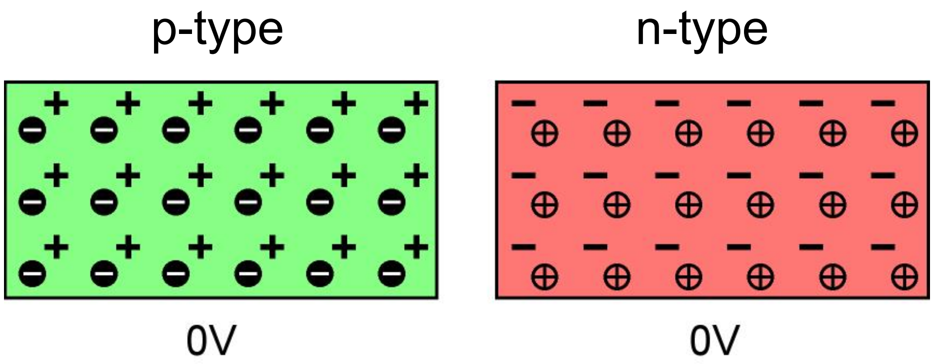
0.5 mm pitch

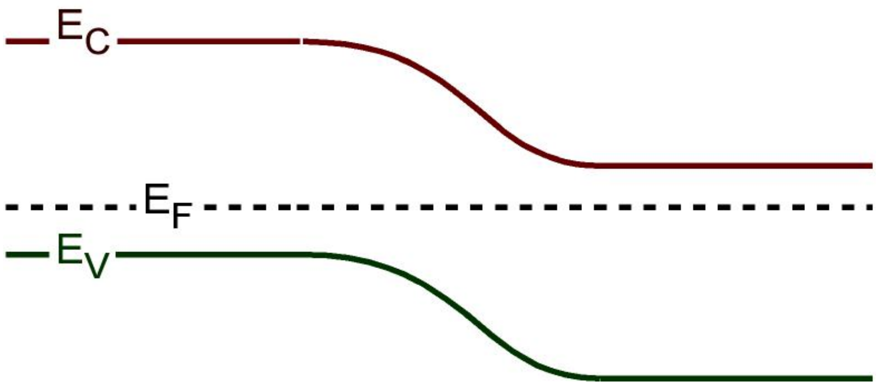


For a full color display you need RGB. Our technology worked great for red, yellow, and was ‘fair’ for green… blue was much worse and not good enough. Why?

Review!

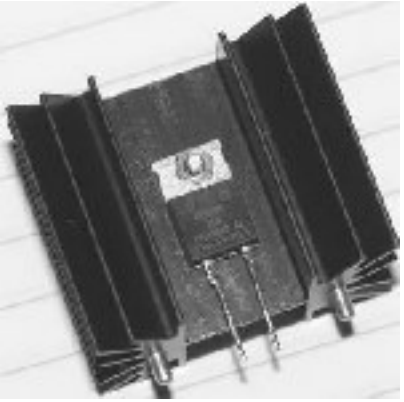
- Zener diodes rely on what type of physics for the current?
- How do we design a diode for Zener operation?
- How do we design a diode for Avalanche operation?
- Can either type be stable, unstable? Do you have to design them correctly and choose a limited operating range?
- For high voltage and high-power applications where we need rectification of an AC signal or power, what type of semiconductors are best?
- What is the main issue with the best semiconductors and how can we overcome that (hint, next lecture…).

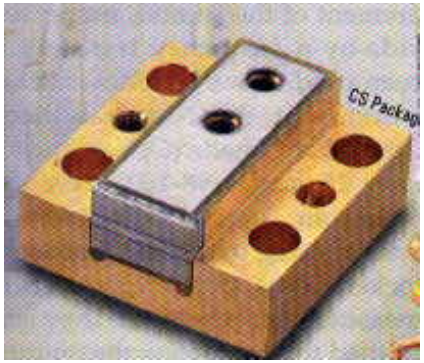




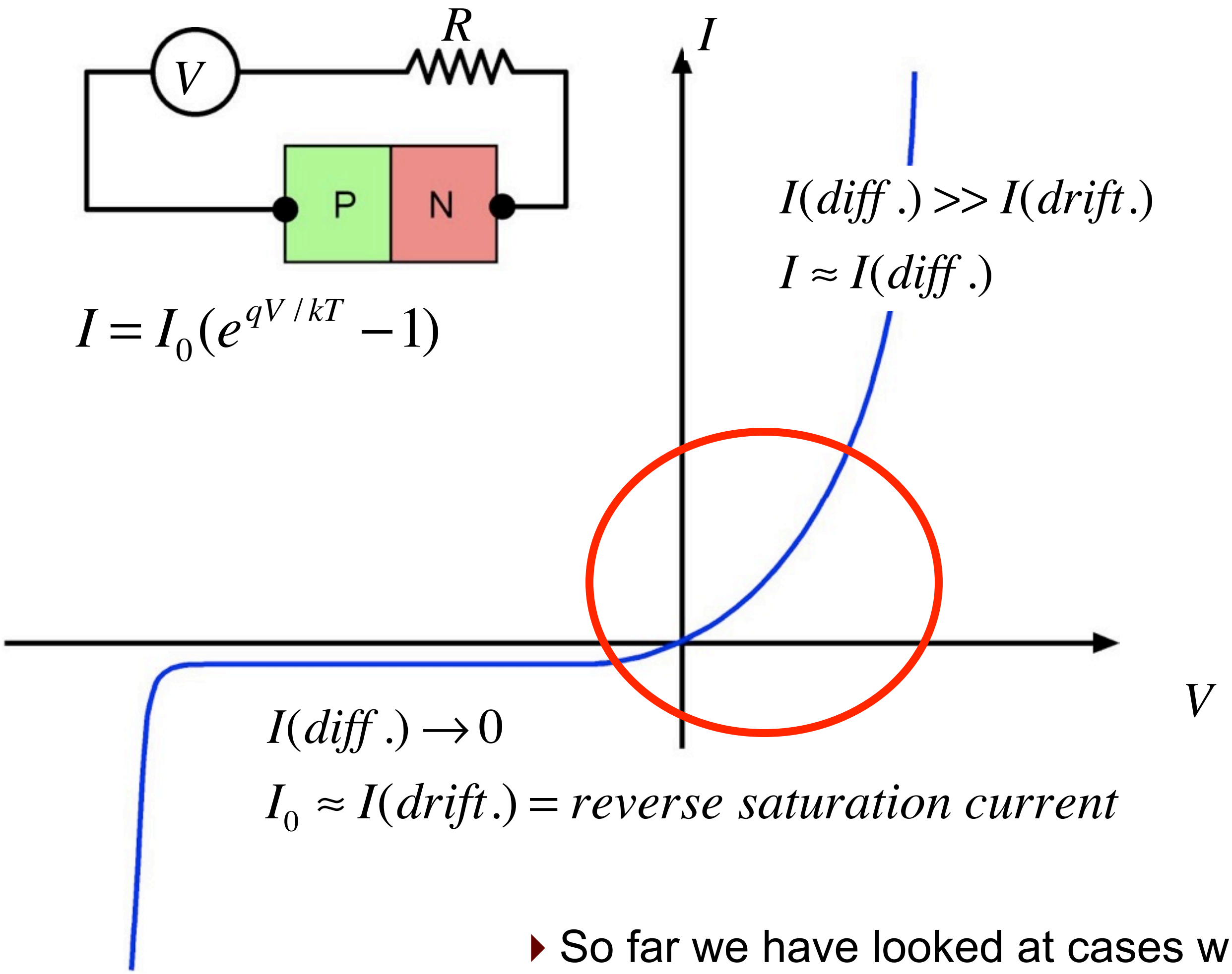
More Non–Ideal Factors

Two terminal devices: power diode, laser diode, and Lumileds Luxeon LED lamp… typ. >100 mA.





The Ideal Diode



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

$$I(diff.) >> I(drift.)$$

$$I \approx I(diff.)$$

$$I(diff.) \rightarrow 0$$

$$I_0 \approx I(drift.) = reverse\ saturation\ current$$

$$I = \frac{(V - V_{br})}{R}$$

- So far we have looked at cases where forward current kicks in immediately after V exceeds kT/q (contact potential).

However, this is the <u>ideal diode equation</u>, what about contact potential??? What will this do to our IV plot?

The Non-Ideal Diode

- Review on contact potential

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

$$\Rightarrow \quad V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n}$$

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

Just says contact potential goes up with doping…

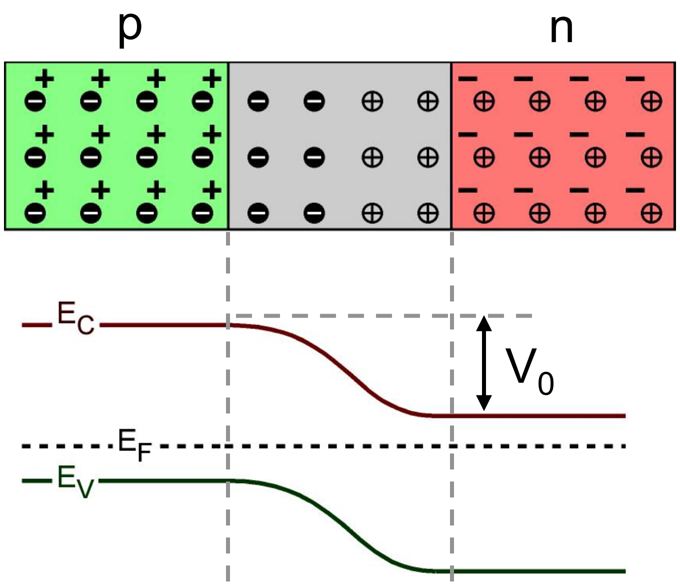
$$p_n = N_v e^{-(E_{Fn}-E_{vn})/kT} = \frac{n_i^2}{N_D}$$

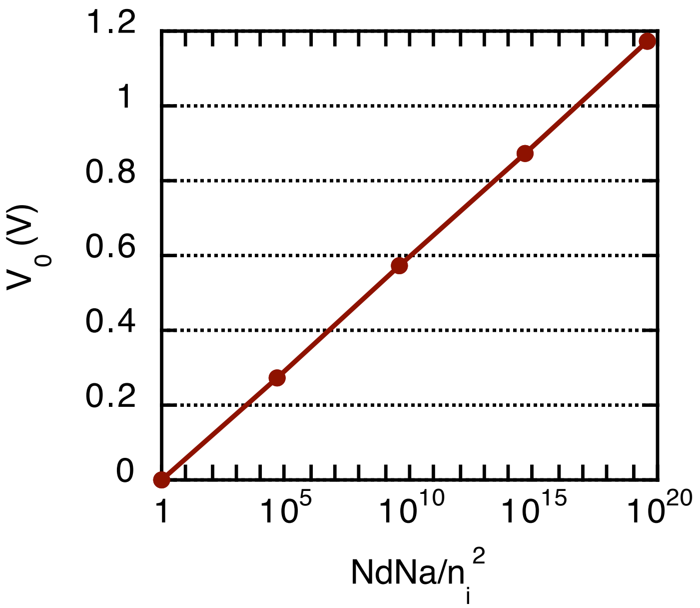
$$p_p = N_v e^{-(E_{Fp}-E_{vp})/kT} = N_A$$

$$\frac{N_V e^{-(E_{Fp}-E_{vp})/kT}}{N_V e^{-(E_{Fn}-E_{vn})/kT}} = e^{qV_0/kT}$$

$$e^{(\cancel{E_{Fn}-E_{Fp}})/kT} e^{(E_{vp}-E_{vn})/kT} = e^{qV_0/kT}$$

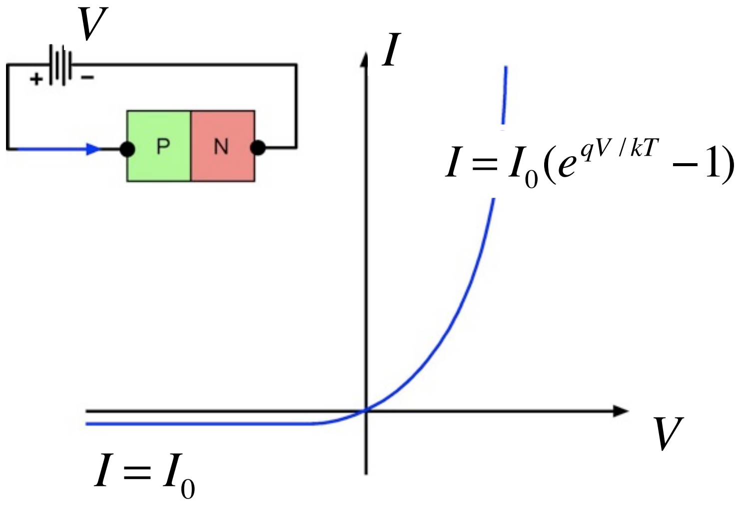
$$\Rightarrow \quad qV_0 = E_{vp} - E_{vn}$$

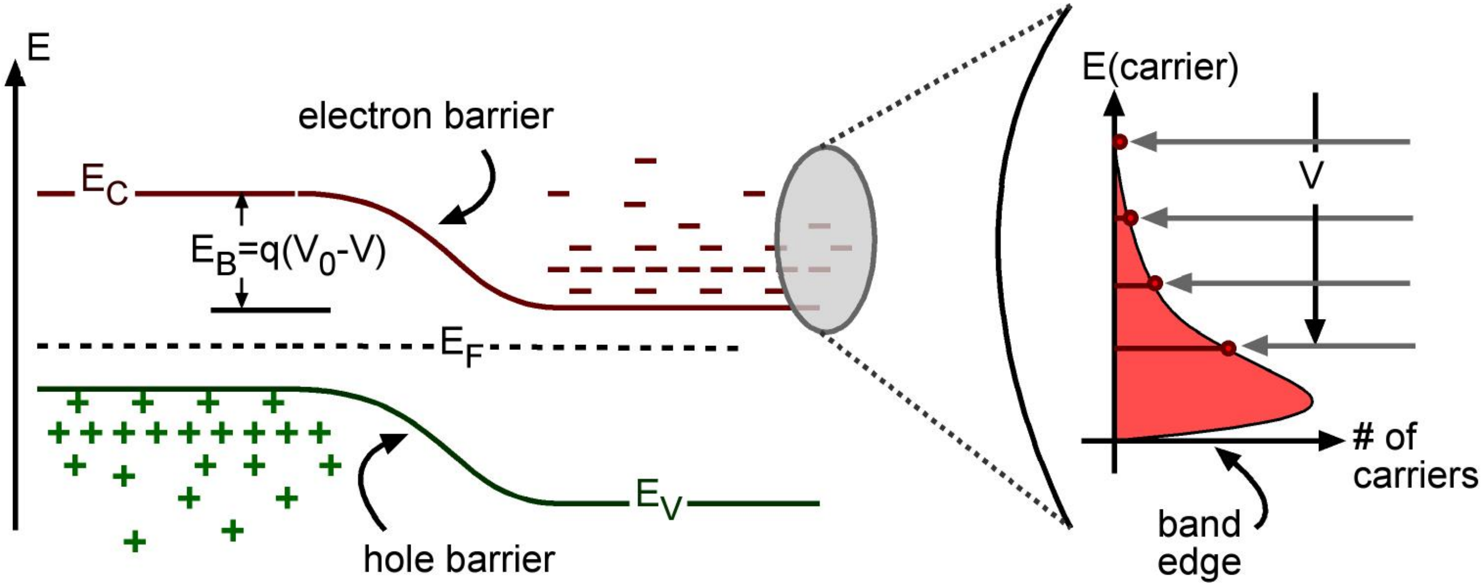




The Non-Ideal Diode

- The ideal diode equation is simpler, but fails to take into account contact potential (V_0).
- How can we correct for this?

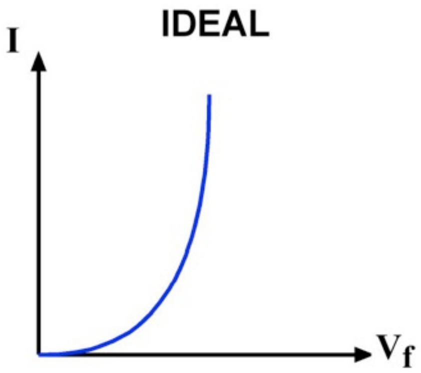


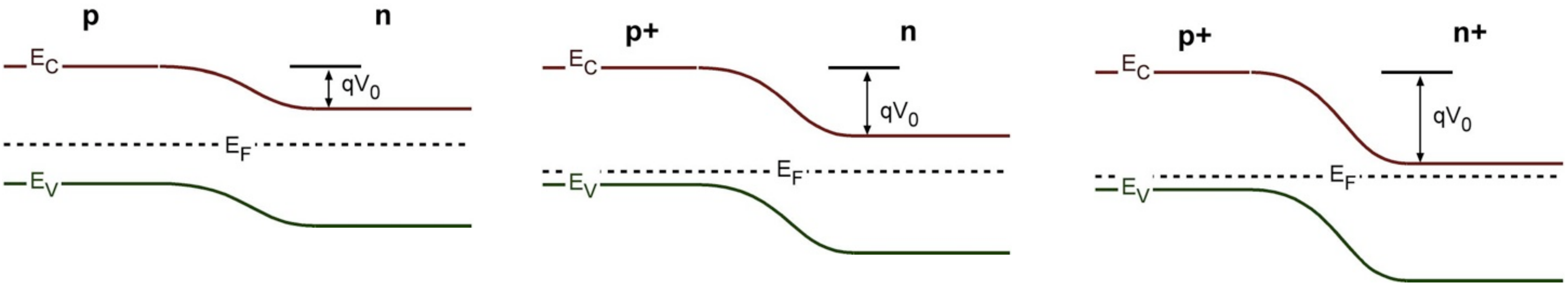


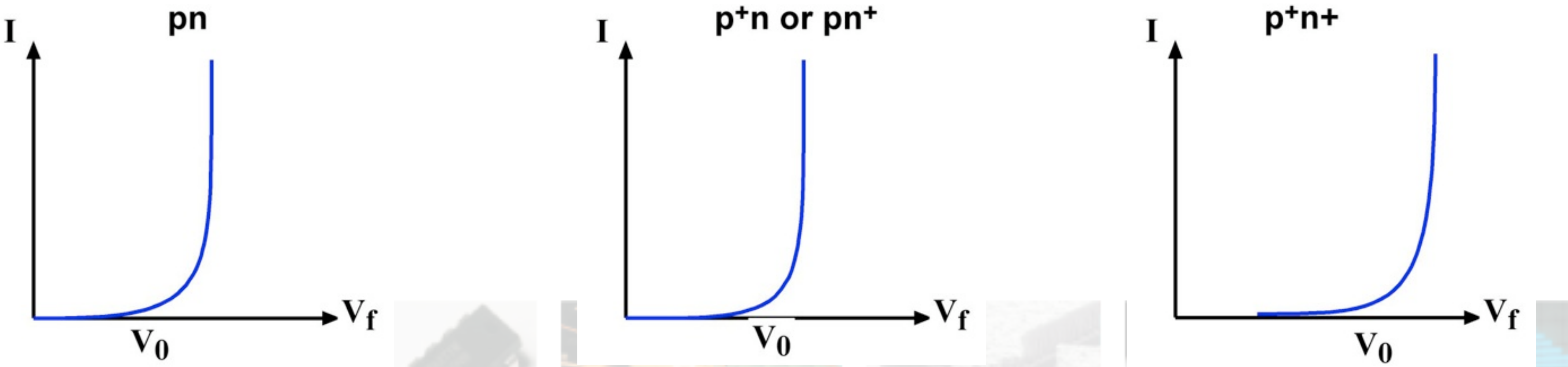
The Non-Ideal Diode

- The ideal diode equation is simpler, but fails to take into account contact potential (V_0).

- How can we correct for this?







The Non-Ideal Diode

- Look at the case for a p+n diode in forward bias…

  … we can get rid of n_p and also the -1.

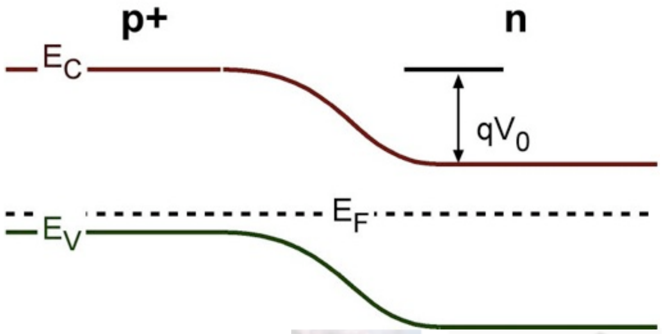
$$p_n = N_v e^{-(E_{Fn}-E_{vn})/kT}$$

$$I = qA\underbrace{\left(\frac{D_p}{L_p}p_n - \frac{D_n}{L_n}n_p\right)}_{I_0}\times(e^{qV/kT}-1)$$

$$\Rightarrow\quad I = qA\frac{D_p}{L_p}p_n\times(e^{qV/kT}-1)\approx qA\frac{D_p}{L_p}p_n\times e^{qV/kT}$$

$$\Rightarrow\quad I \approx qA\frac{D_p}{L_p}N_V\times e^{[qV-(E_{Fn}-E_{vn})]/kT}$$

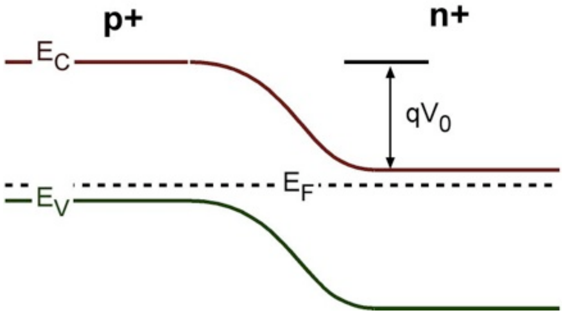
- Because p+, $\left(E_{Fn}-E_{vn}\right) = \left(E_{Fp}-E_{vn}\right) \approx \left(E_{vp}-E_{vn}\right) = qV_0$



- Therefore

$$\Rightarrow\quad I \approx I_0(e^{q(V-V_0)/kT}-1)$$

- Similar assumption of using V_0 for pn+ and for p+n+



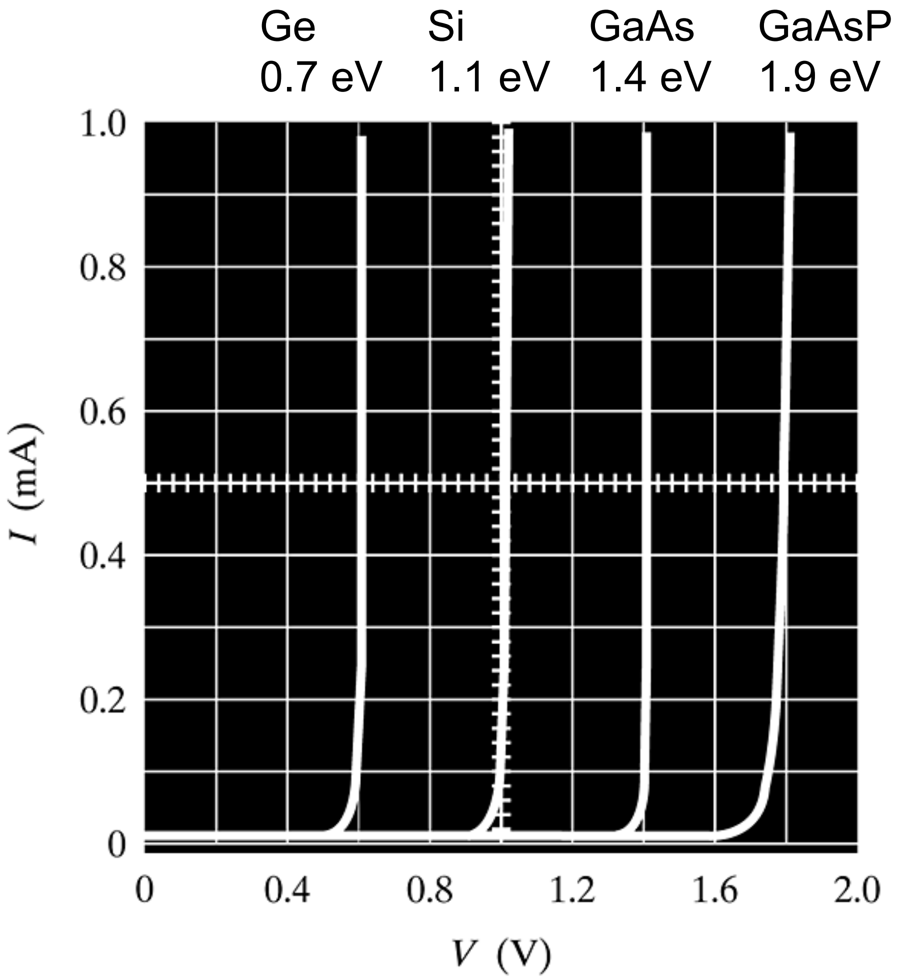
$$V_0 = \frac{kT}{q}\ln\frac{p_p}{p_n} \quad = \quad \frac{kT}{q}\ln\frac{n_n}{p_p}$$

$$I \approx I_0(e^{q(V-V_0)/kT} - 1)$$

- Can V_{PN} exceed V_0???

How could it? If barrier 'disappears' you would get a nearly infinite amount of current (never get there due to over-all device resistance)

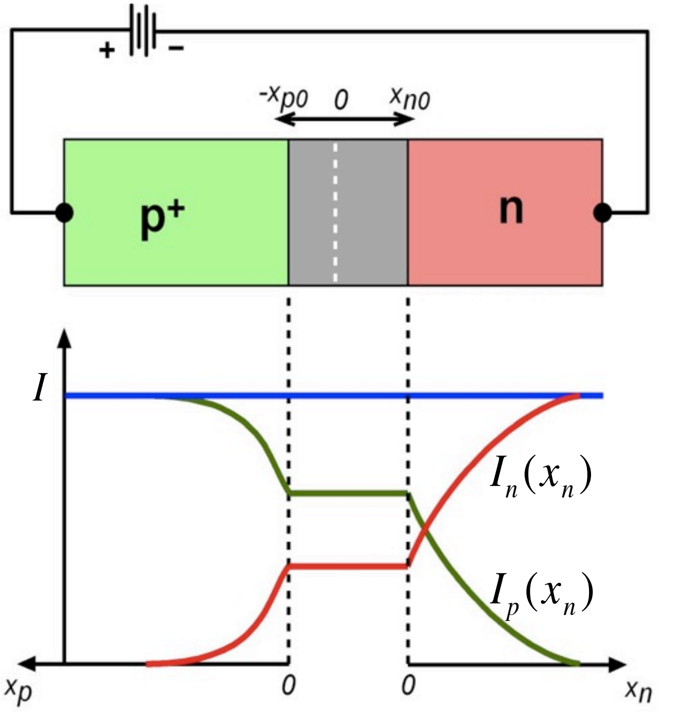
- For p⁺n⁺ the contact potential and turn-on is *almost* E_g



The Non-Ideal Diode

- In forward bias we have assumed:
  1. All recombination just beyond the junctions
  2. No recombination in the transition region

- However…
  * *Low V, Depletion region (W) can be long*
    - see right, what could happen?
  * *Larger V, J(diff) can lead to many carriers…*
    - see right, what could happen?



If we diffuse <u>over</u> 1 hole (q=1) that hole will require us to bring in an electron for recombination so q=2. Considering an electron diffusing <u>over</u> from the other side we get another q=2 for a net charge exchange of q_{total}=4. What happens if our diffusing hole and electron recombine in the space charge region before they make it across (q_{total}=?). qV/kT?

$$W = \sqrt{\frac{2\varepsilon kT}{q^2}\left(\ln\frac{N_A N_D}{n_i^2}\right)\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}$$

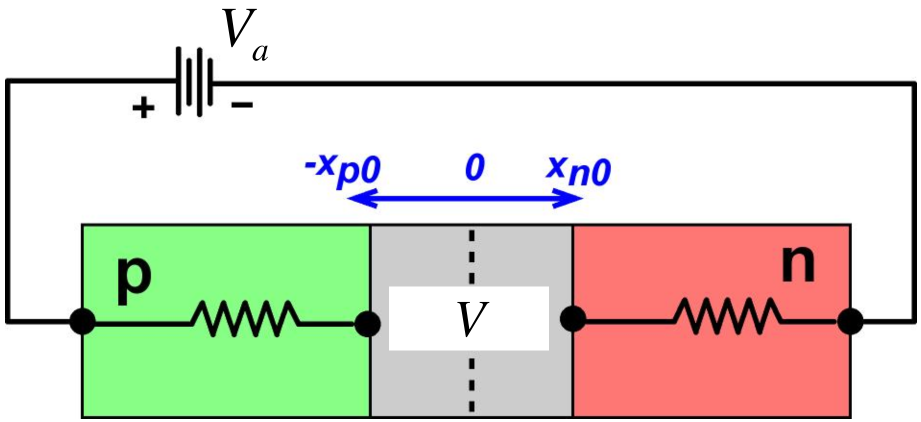
$$D_p = \frac{kT}{q}\mu_p \qquad L_p = \sqrt{D_p \tau_p}$$

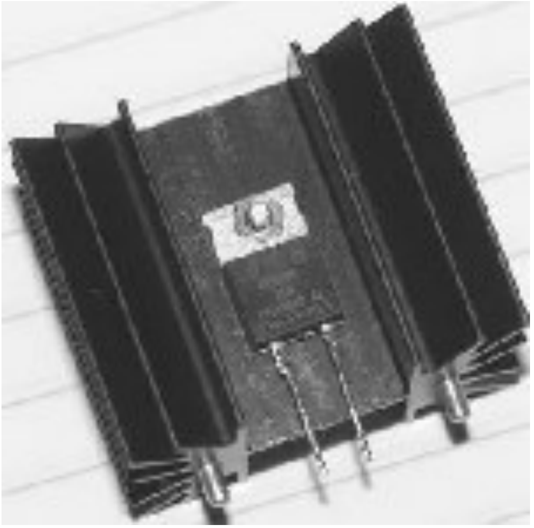
$$\tau_p = \frac{1}{\alpha_r(n_0 + p_0)}$$

- The conventional solution is to introduce ideality factor (1<n<2)

$$I \approx I_0(e^{qV/nkT} - 1)$$

- Ohmic losses are why the power diode has a heat sink… (I^2R)



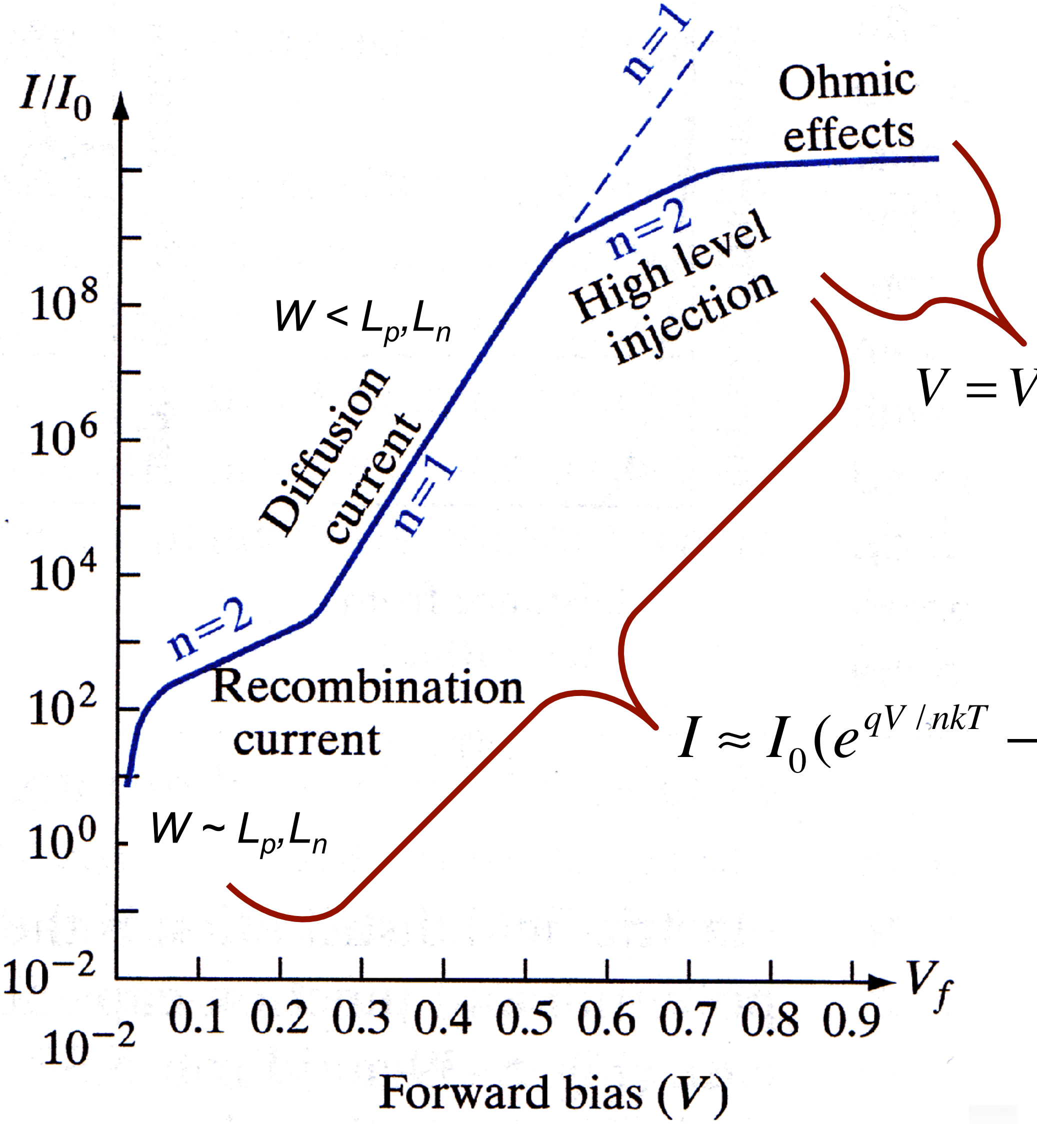


- Also distorts the diode equation…

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

$$V = V_a - I[R_p + R_n]$$

The Non-Ideal Diode



$$V = V_a - I[R_p(I) + R_n(I)]$$

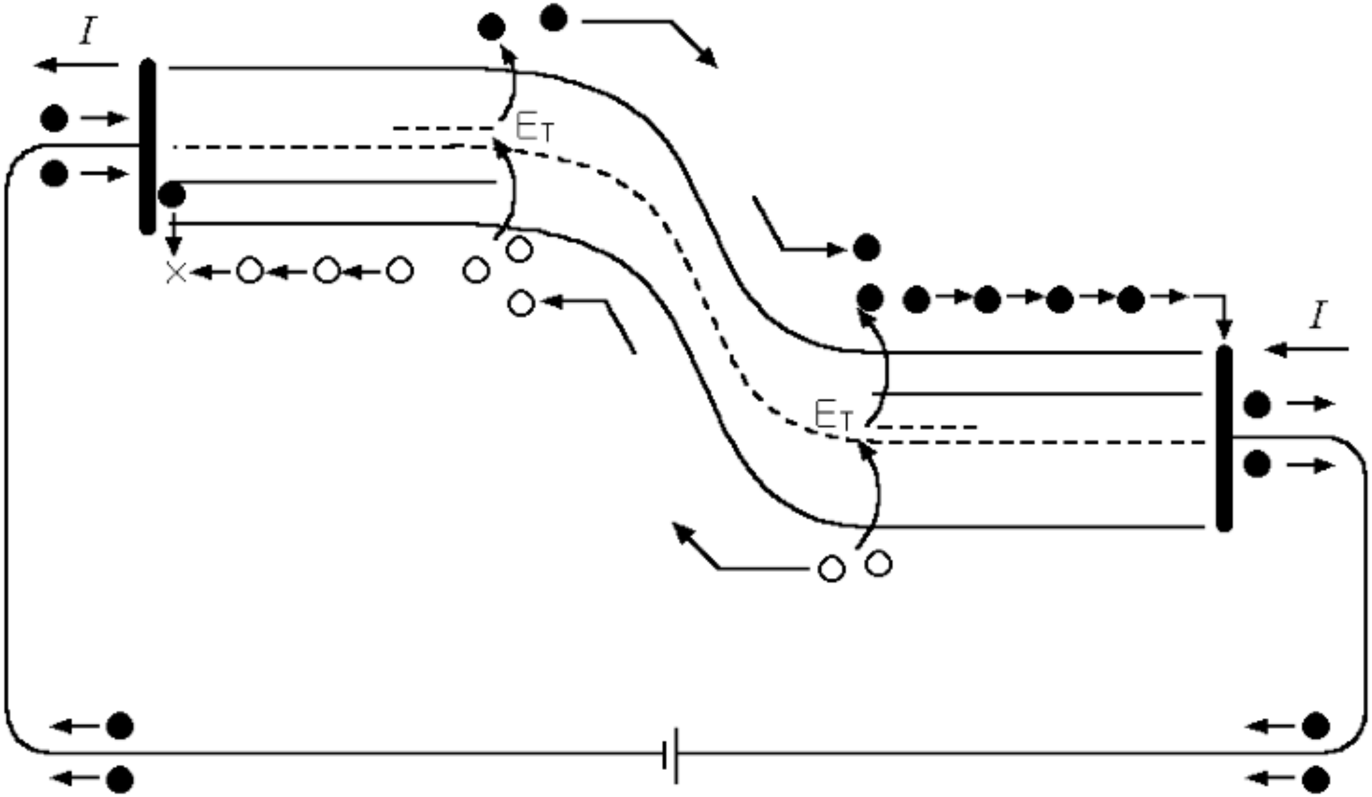
$$(I = V/R)$$

$$I \approx I_0(e^{qV/nkT} - 1)$$

- Pull it all together.
- For any implementation, need to know operation regime…

Be Careful!

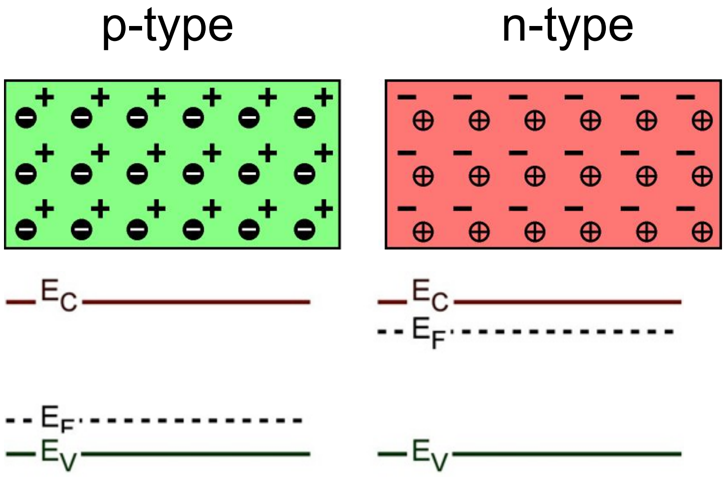
- The WHOLE picture including the metal wires (Pierret Fig. 6.2). Ignore the trap level ‘E_T’ is a more advanced topic not required for basic understanding.



Take home point, is in the circuit, one e-h pair (EHP) is one q through the external circuit….

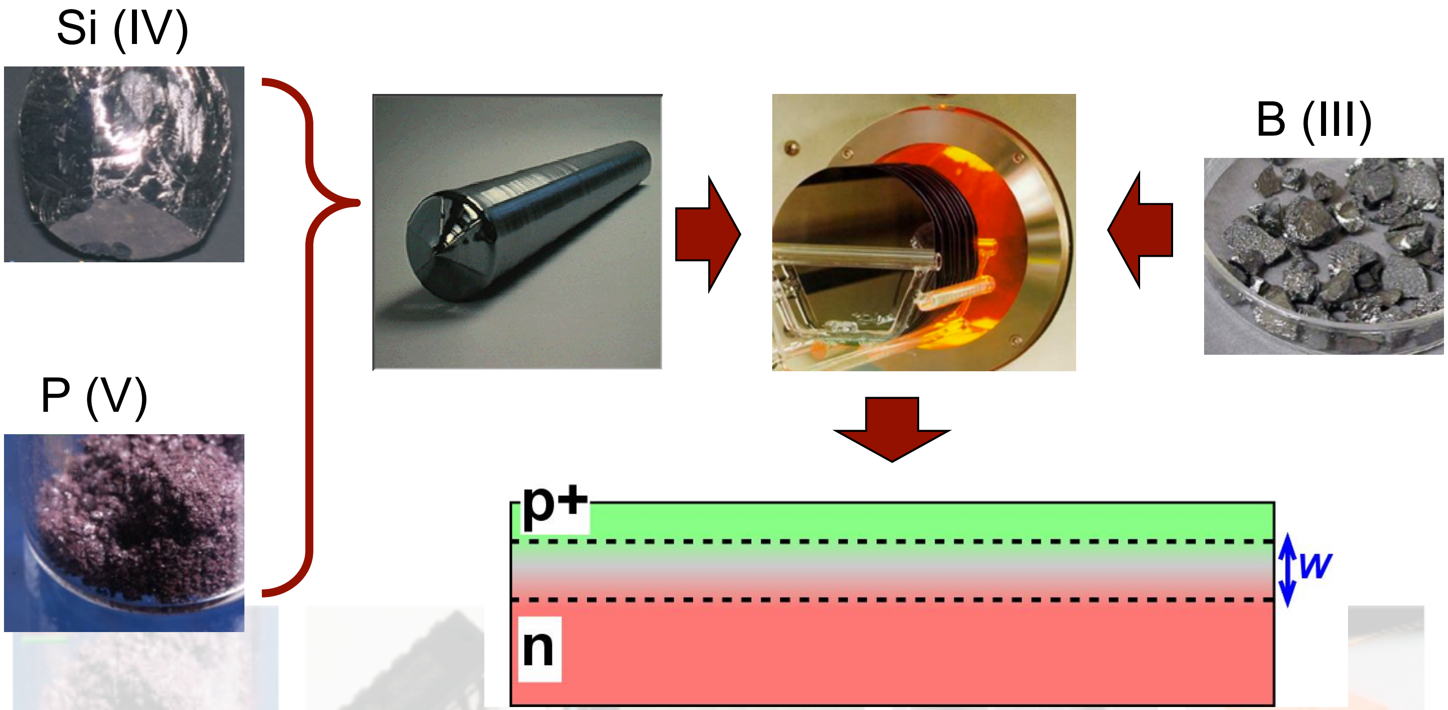
The Non-Ideal Diode

- So far we have assumed this:



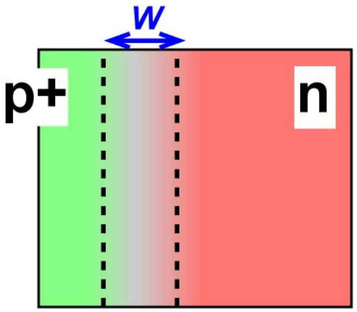
- It is simpler to make an n-type Si wafer and diffuse in a thin p+ layer

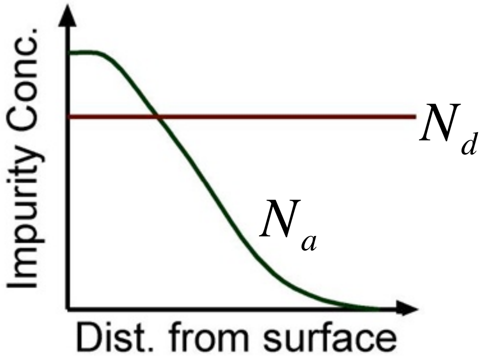
hence all the p+n examples..

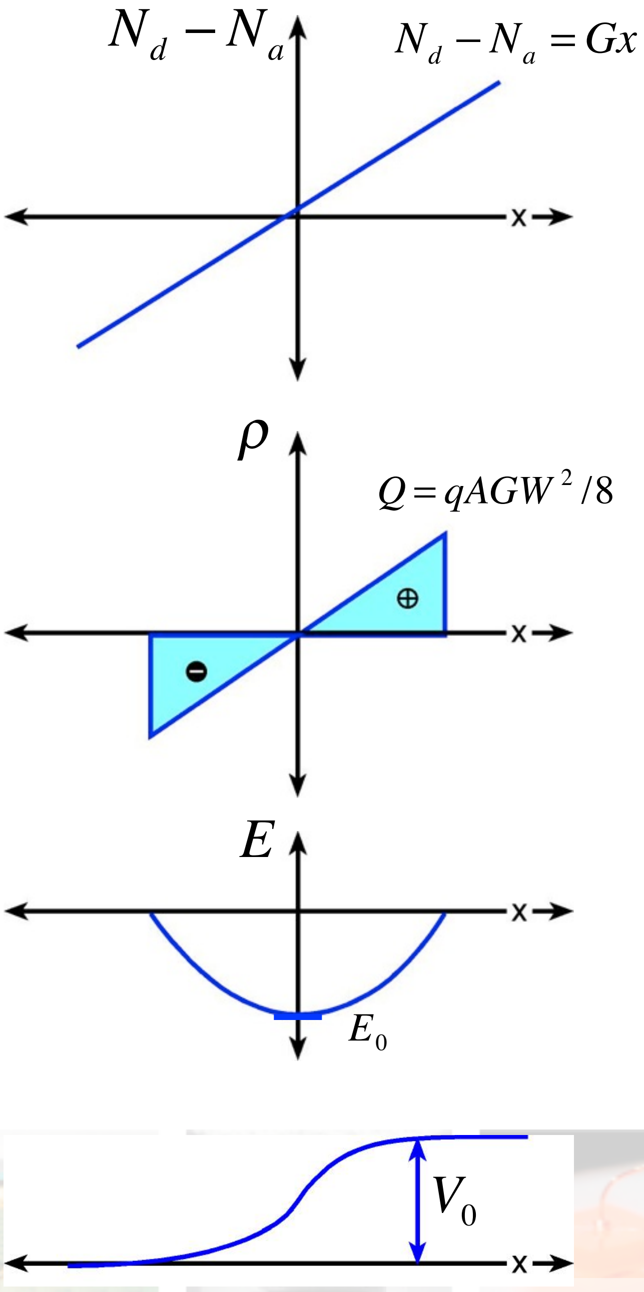


The Non-Ideal Diode

- For most of the transition region we can make a linear doping approximation (Gx)







Review!

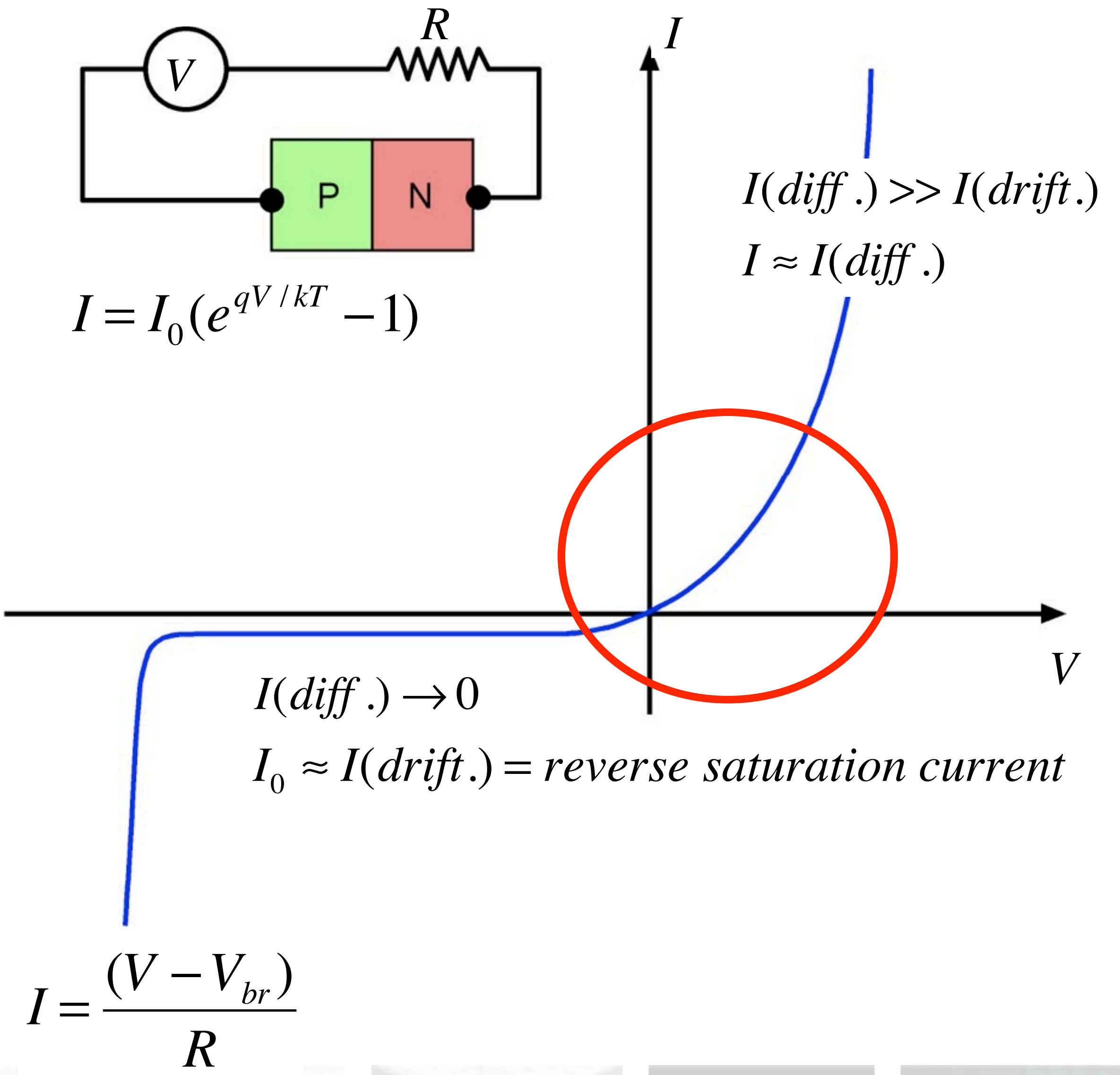
- In forward bias does my diode turn on at 0V? Why? *(S26)*

- If I bias a diode with voltage from reverse voltage to the highest possible forward voltage.

First I should see what?
At zero volts I should see what?
Second I should see what?
Third I should see what?
Fourth I should see what?
Fifth I should see what?

Diodes can swim!

http://www.aps.org/meetings/march/vpr/2011/videogallery/diode.cfm



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

$$I(diff.) >> I(drift.)$$

$$I \approx I(diff.)$$

$$I(diff.) \rightarrow 0$$

$$I_0 \approx I(drift.) = reverse\ saturation\ current$$

$$I = \frac{(V - V_{br})}{R}$$