ECE 116 Lectures 22-23

Current Flow in “ideal” P-N diode

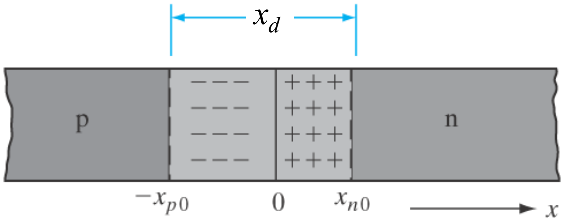
- https://truenano.com/PSD20/chapter4/ch4_4.htm

- Read Ch. 4.4 to 4.4.2.4
- Skim 4.4.4 (“real” diodes, more on this in EE 216)

- Note: “long” diode, i.e. size of diode >> diffusion length

  (W_n, W_p >> L_p, L_n)

- Until now, we talked about unbiased P-N junction.
- Today, biased ($V_A \neq 0$) P-N junction and current flow



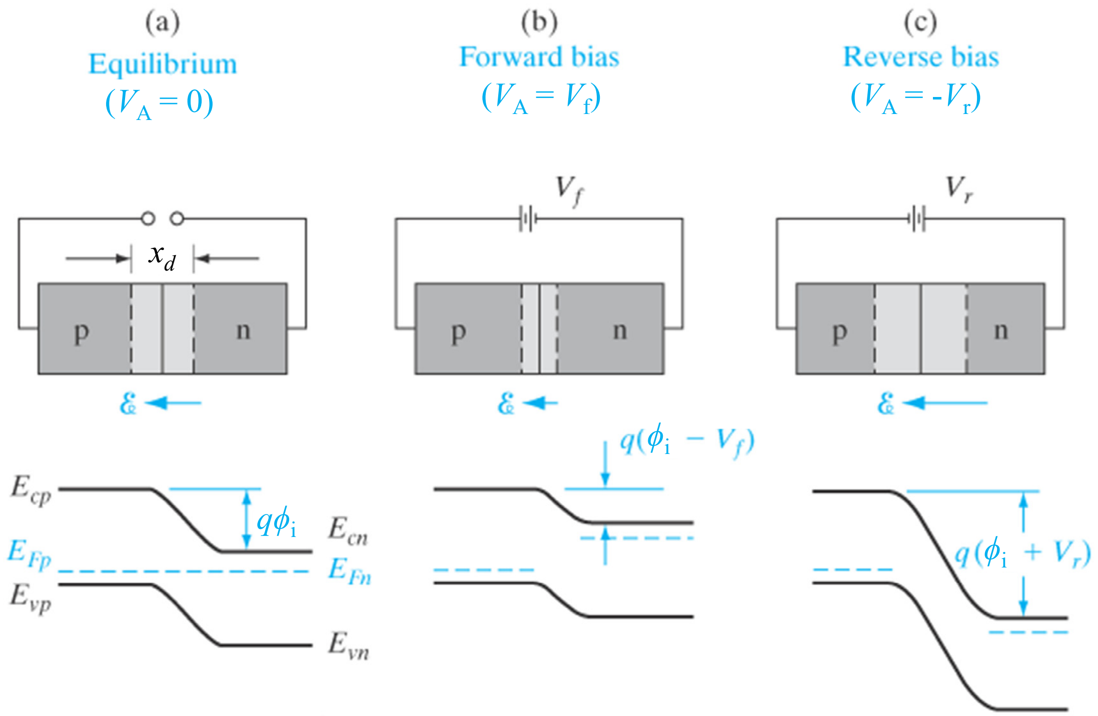
- Draw equilibrium (V = 0) bands:

- Recall built-in voltage and depletion width:

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

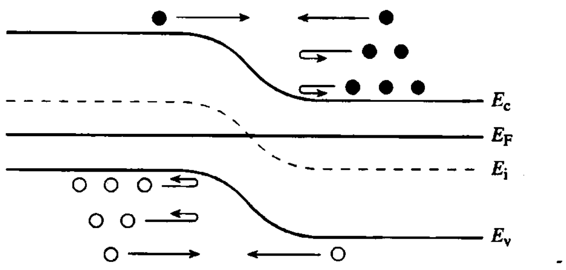
$$x_d = x_n + x_p = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(\phi_i - V)}$$

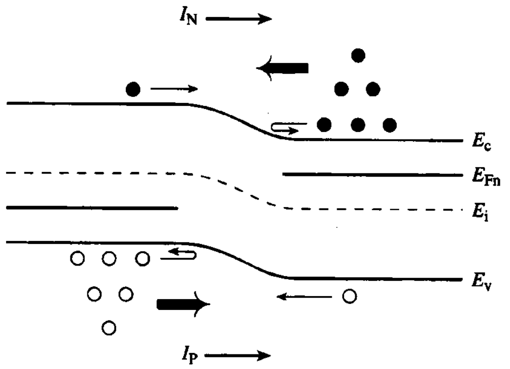
- Qualitative band diagrams with applied voltage:

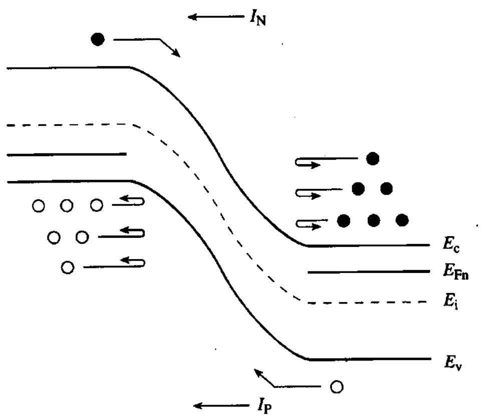


- Current flow in equilibrium (V = 0) → $J_{tot} = 0$

- Qualitative current flow:

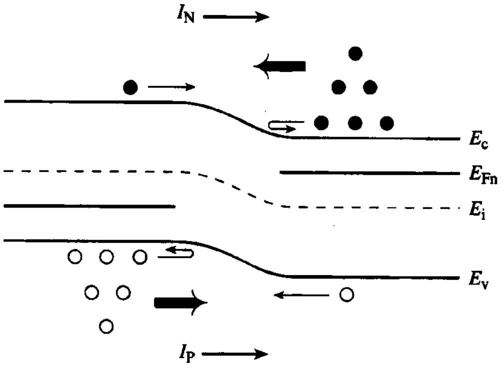






- Qualitatively expect I-V curve to be:

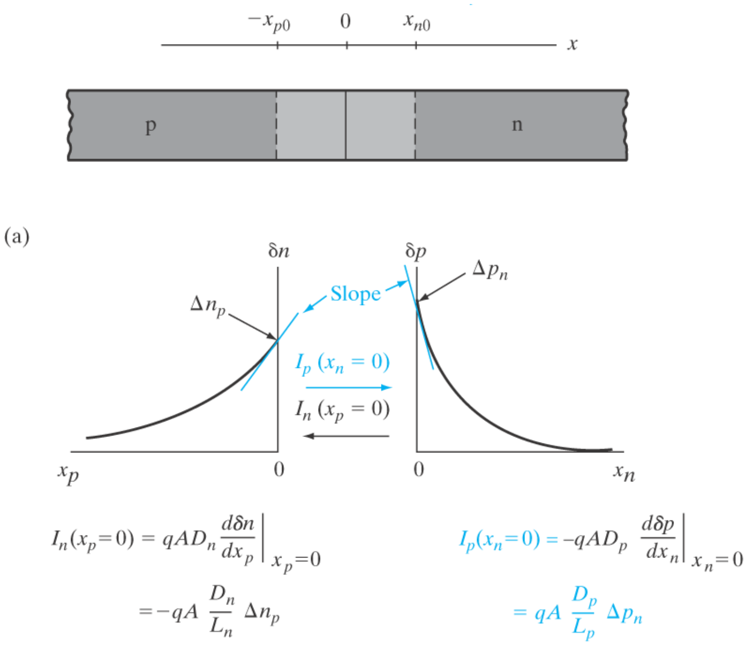
- In forward bias, inside space charge region (SCR):



$$pn = n_i^2 e^{qV/kT}$$

- Where V=V_A is the applied bias and $qV_A = E_{Fn} - E_{Fp}$

- Let's look at the *injected minority carriers* (with lights off)



- On the n-side, injected holes → $\delta p(x)$
- Just at the edge of n-side depletion region:

$$n_n(x_{n0}) = N_D$$

$$p_n(x_{n0}) = (n_i^2/N_D)e^{qV/kT}$$

$$\Delta p_n(x_{n0}) = (n_i^2/N_D)(e^{qV/kT} - 1)$$

- Excess injected holes diffuse into the n-side:

$$\delta p_n(x) = \Delta p_{n0} e^{-x/L_p} = p_{no}(e^{qV/kT} - 1)e^{-x/L_p}$$

(same is true of excess injected electrons on p-side).

- Injected hole diffusion current:

$$J_p = -qD_p\left[\frac{d}{dx}\delta p_n(x')\right] = q\frac{D_p}{L_p} p_{n0}(e^{qV/kT} - 1)e^{-x/L_p}$$

- Where equilibrium hole concentration $p_{n0} = n_i^2/N_D$

(and similar for injected electron diffusion on p-side, just replace subscripts p with n)

- Hole diffusion current proportional to excess hole concentration at any distance x into the n-type region.
- Due to hole current continuity, we can evaluate at $x = x_{n0} = 0$

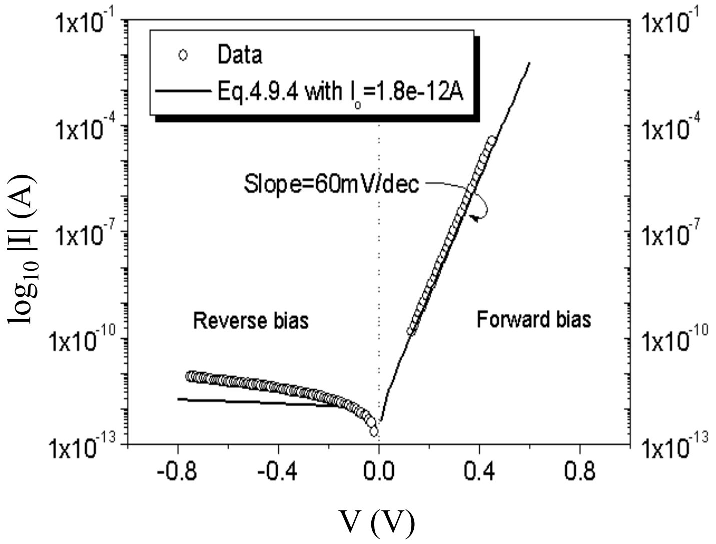
$$J_p = q\frac{D_p}{L_p}\frac{n_i^2}{N_D}(e^{qV/kT} - 1)$$

- We can also write diffusion current for electrons in p-side:

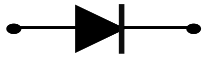
$$J_n = q\frac{D_n}{L_n}\frac{n_i^2}{N_A}\left(e^{qV/kT} - 1\right)$$

- Now total current $J = J_n + J_p$

so finally → $J = qn_i^2\left[\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right]\left(e^{qV/kT} - 1\right)$



This is the SPICE-level model



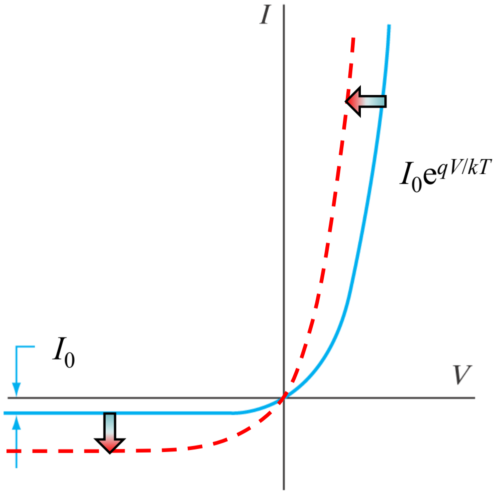
Some “knobs” for engineering pn diodes:

- Doping (N_A, N_D) and material (μ, E_G)

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

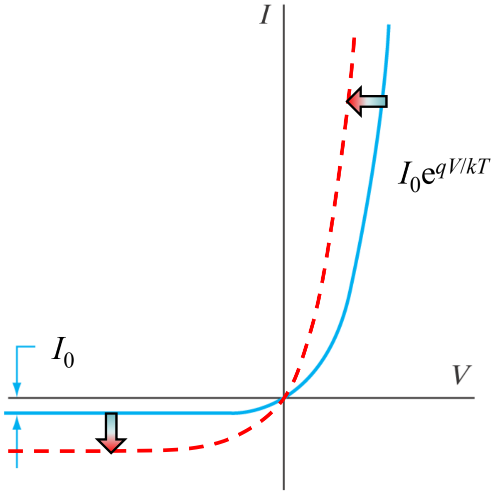
$$I_0 = Aqn_i^2\left(\frac{D_p}{L_pN_d} + \frac{D_n}{L_nN_a}\right)$$

Decrease Doping



N_D, N_A > N_D’, N_A’

Increase Temperature



T < T’

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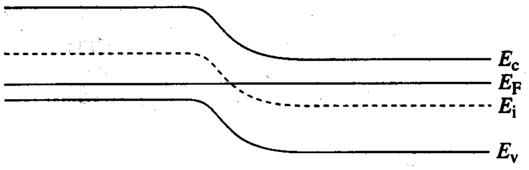
P-N diode carrier injection; reverse bias

Recap diode bias diagrams:

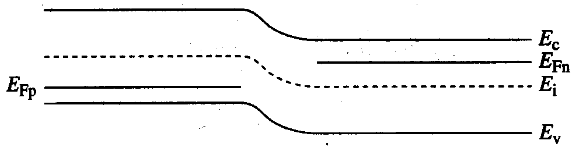
a) equilibrium

b) forward bias (V > 0)

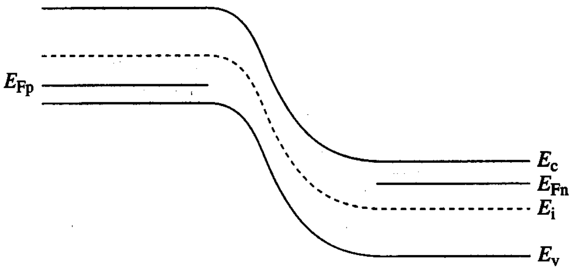
c) reverse bias (V < 0)



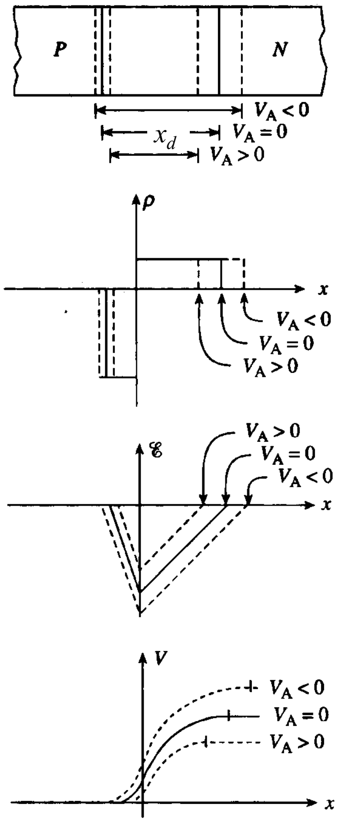
(a) Equilibrium ($V_A = 0$)



(b) Forward bias ($V_A > 0$)



(c) Reverse bias ($V_A < 0$)



- Recap some of the equations:
  - Depletion width $$x_d = x_n + x_p = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(\phi_\mathrm{i} - V)}$$

    (decreases at forward bias, increases at reverse bias) $$x_n = \frac{N_A}{N_A+N_D}x_d \quad x_p = \frac{N_D}{N_A+N_D}x_d$$

  - Maximum electric field $$E_\mathrm{max} = E_0 = \frac{2(\phi_\mathrm{i} - V)}{x_d}$$

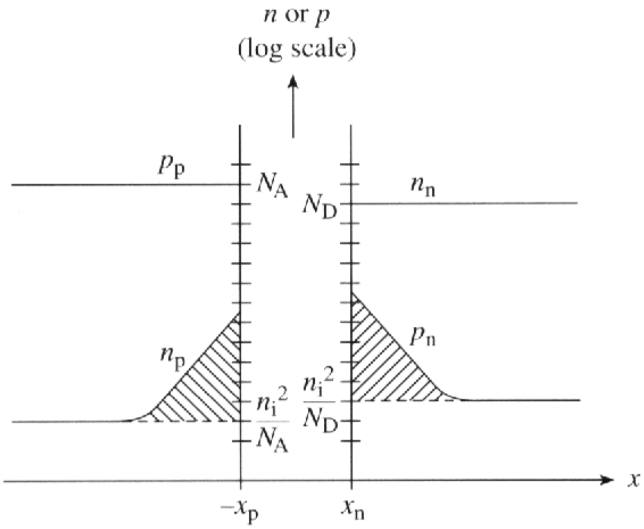
    (decreases at forward bias, increases at reverse bias)

  - Built-in voltage $$\phi_\mathrm{i} - V =$$

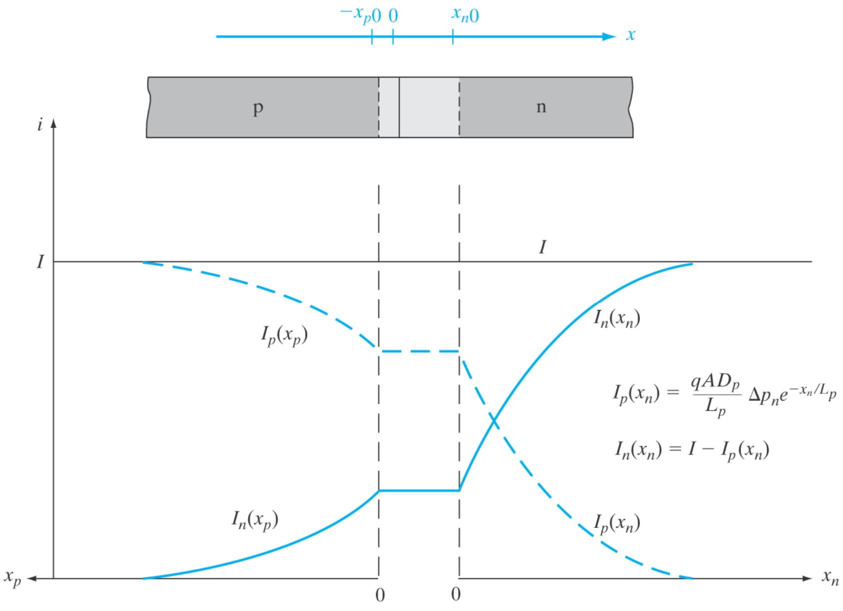
  - Charge stored

- Current density (current $I = J{\cdot}A$) $$J = qn_\mathrm{i}^2\left[\frac{D_n}{L_n N_\mathrm{A}} + \frac{D_p}{L_p N_\mathrm{D}}\right](e^{qV/kT} - 1)$$
- What about an asymmetrically doped junction? Say, p side much more heavily doped ($N_A >> N_D$):

- Remember, current is due to minority carrier injection
- Typically p-n junctions in real life are made by counterdoping. E.g. start with p-type wafer and dope with N_D only at the surface to obtain junction. Eqs. so far readily apply if
  - N_A = net doping on p-side = $(N_A - N_D)_{\text{p-side}}$
  - N_D = net doping on n-side = $(N_D - N_A)_{\text{n-side}}$

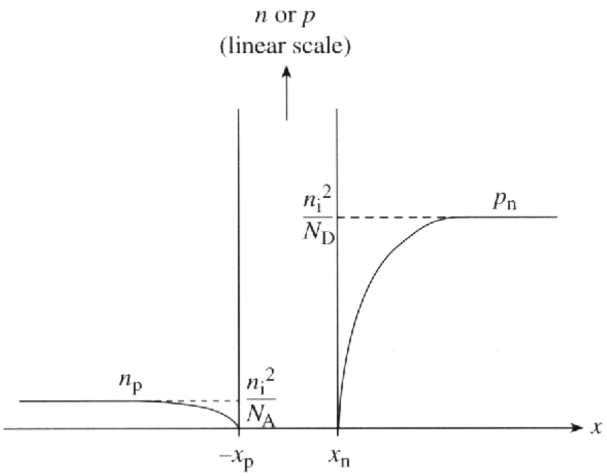


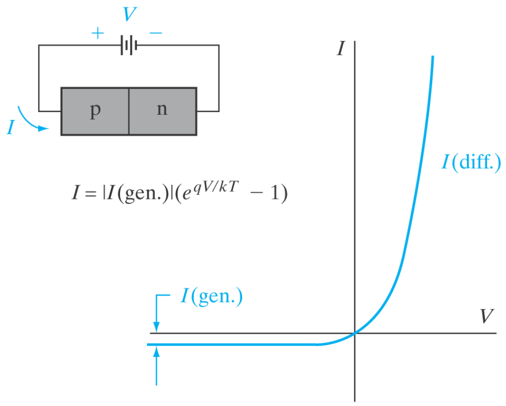
- **Ex:** a p-n junction has N_A=10^{19} cm^{-3} and N_D=10^{16} cm^{-3}. The applied voltage is 0.6 V. a) What are the minority carrier concentrations at the edges of the depletion region? b) What are the excess minority carrier concentrations? c) Sketch δn(x) on the p-side if recombination lifetime is 2 μs.

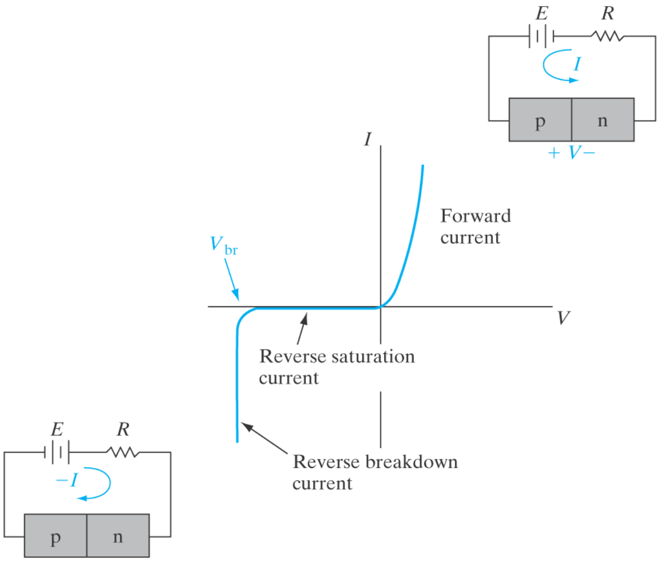


- Current continuity along junction length, J_{TOT} = const.
- As carriers recombine (deep into n- or p-side) the diffusion current is replaced by _______________
- But, we were able to deduce current equation by simple diffusion arguments at the ___________________ where the E-field was just barely zero.

- Reverse bias:
  - Depletion region widens
  - E-field across depletion region __________________
  - Current is due only to minority carrier _______________ across the junction
  - Current is supplied by EHP generation in the ___________________ (what if I change the temperature or turn on the light?)
  - Recall, $J_0 \propto n_i^2$





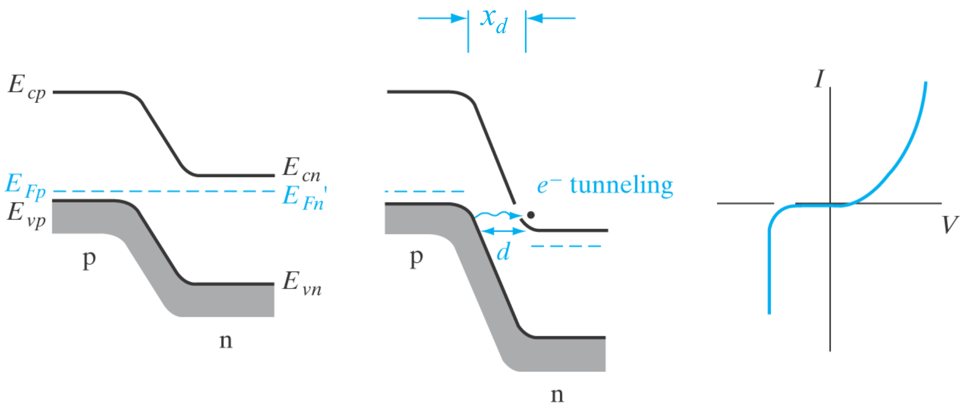


- Junction breakdown when E-field exceeds a critical value. If current continues increasing, then diode _______________ .

Reverse Bias P-N Breakdown (3 types)

1) Zener breakdown:

- Dominant for heavily doped (>10^{18} cm^{-3}) p^+n^+ diodes
- Breakdown at a few Volts (typically < 5 V)



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

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

- Electron tunneling from filled valence states on p-side into (mostly) empty conduction band states on n-side

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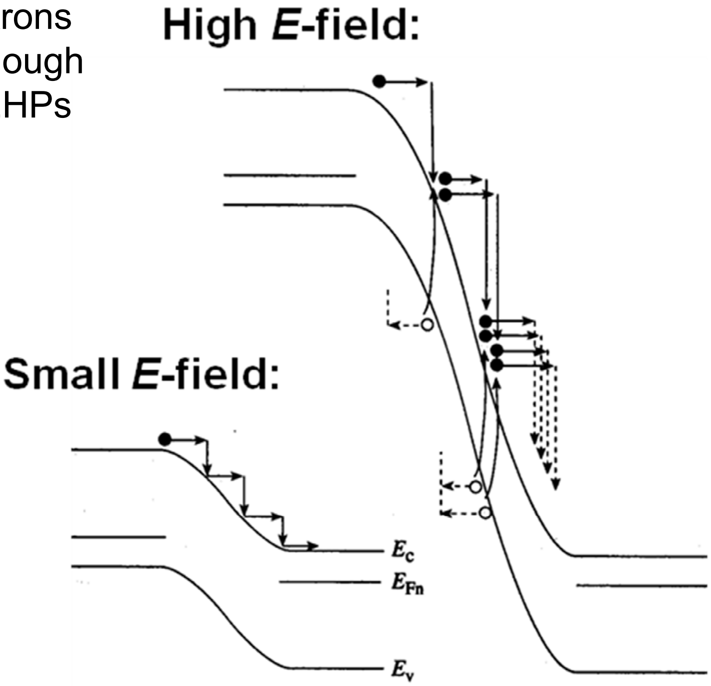
2) Avalanche breakdown

- More lightly doped junctions (<10^{17} cm^{-3})
- Wider depletion region, electrons accelerated across it gain enough energy to create additional EHPs
- Impact ionization and carrier multiplication

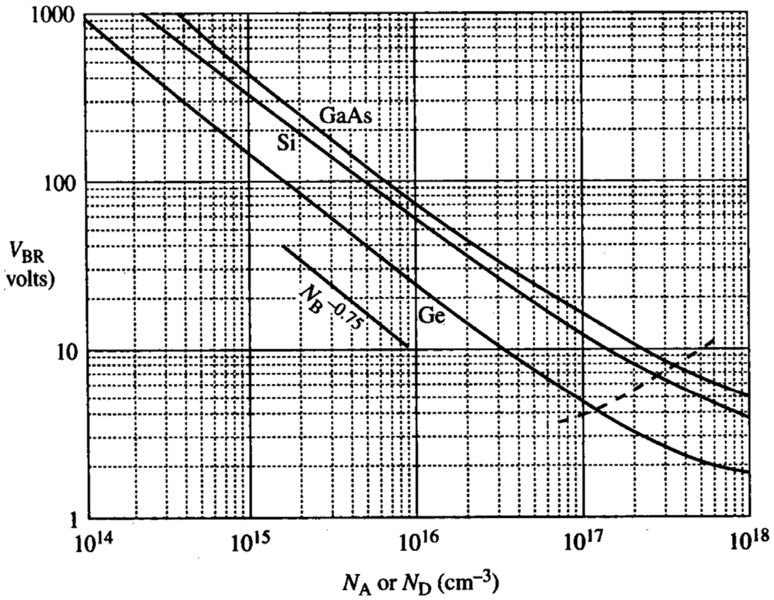
$$V_{BR} \approx \frac{\varepsilon_s \mathcal{E}_{CR}^{\,2}}{2qN}$$

$$\text{if } V_{BR} >> \phi_i$$



- Empirical observation of V_{BR} with doping and material
  - V_{BR} decreases with increasing N (=N_A or N_D)
  - V_{BR} decreases with decreasing E_G

- V_{BR} dependence on temperature:
  - For tunneling (Zener) breakdown…
  - For avalanche breakdown…



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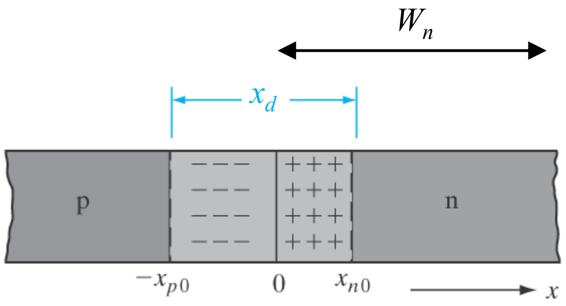
3) Punchthrough breakdown:

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



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

$$x_n = \frac{N_A}{N_A + N_D} x_d\,; \qquad x_p = \frac{N_D}{N_A + N_D} x_d$$