ECE 340: Semiconductor Electronics

Chapter 5: Junction (part II)

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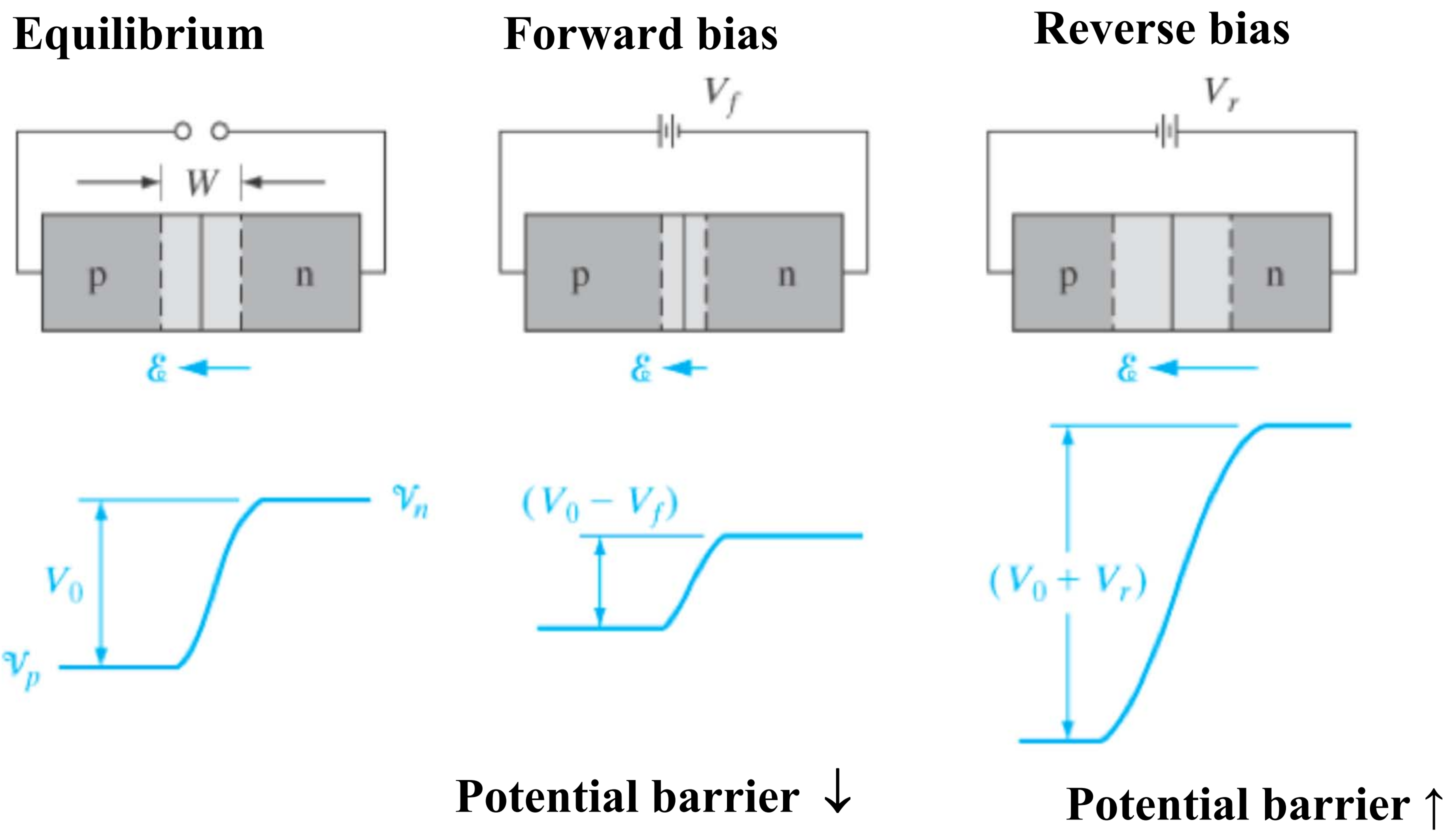
Outline

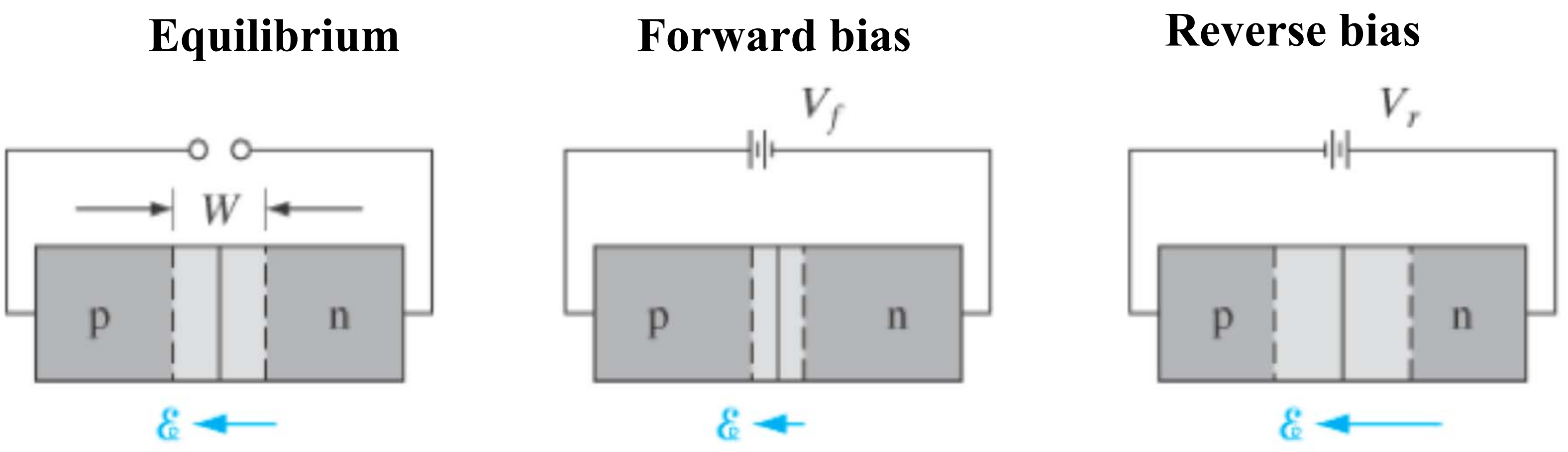
- Forward- and reverse-biased junctions; steady state conditions
  - Qualitative description of current flow at a junction
  - Carrier injection
  - Reverse bias
- Reverse-bias breakdown
  - Zener breakdown
  - Avalanche breakdown
  - Rectifiers
  - The breakdown diode

Bias and potential barrier



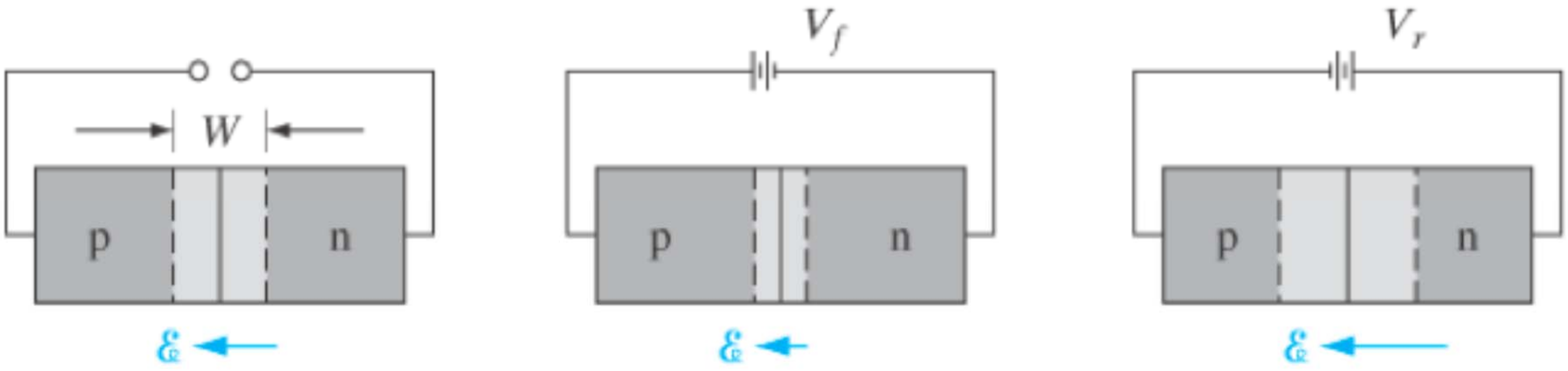
- Forward bias is referring to p region has a positive external voltage bias relative to n.
- Forward bias raise the potential on the p side relative to the n side, → lowering the potential barrier

Bias and field



- For forward bias, applied electric field opposes the built-in field, → field decreases
- For reverse bias, applied electric field is in the same direction as the equilibrium field → field increases

Bias and depletion width



- Field is produced by charge, a smaller field implies less charge, so the depletion width under forward bias (lower field) is smaller
- the depletion width under reverse bias (higher field) is larger

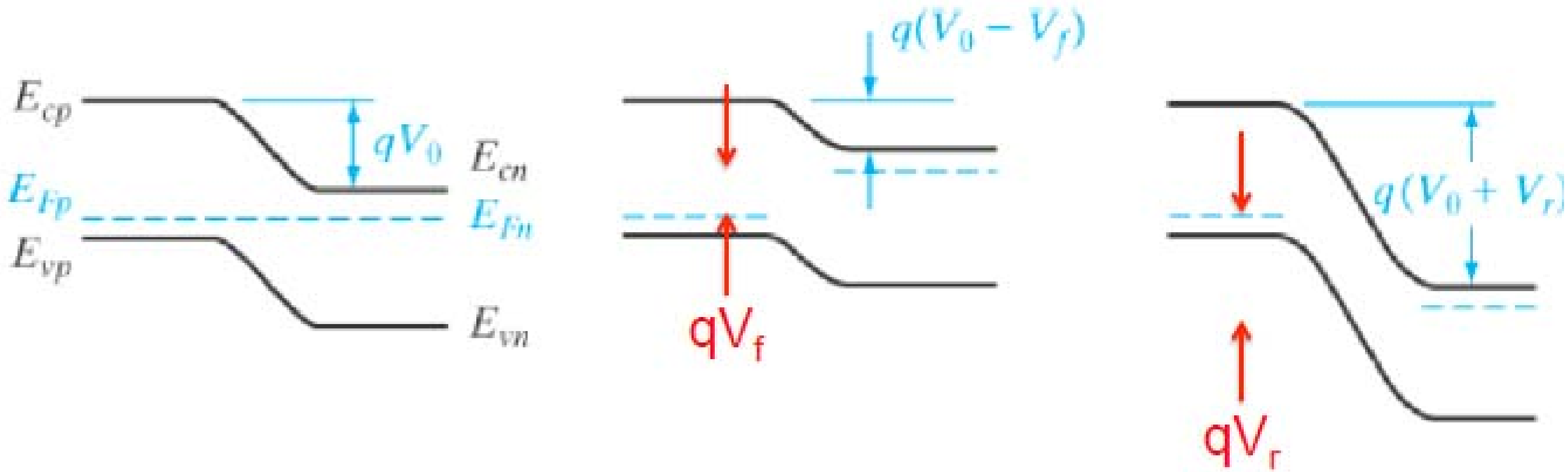
Applied voltage

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

Forward bias: $V_a = V_f$

Reverse bias: : $V_a = -V_r$

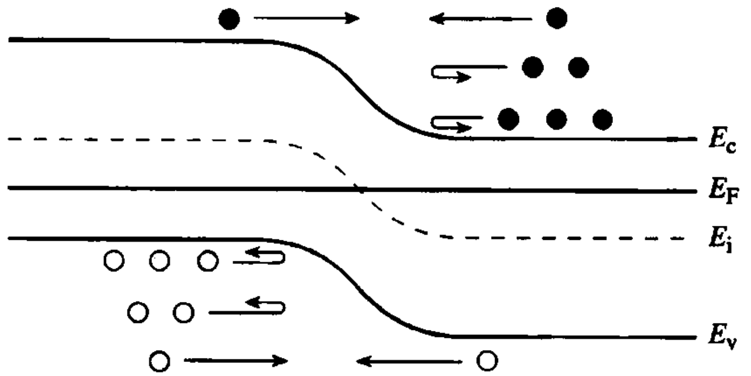
Bias and Fermi-level separation



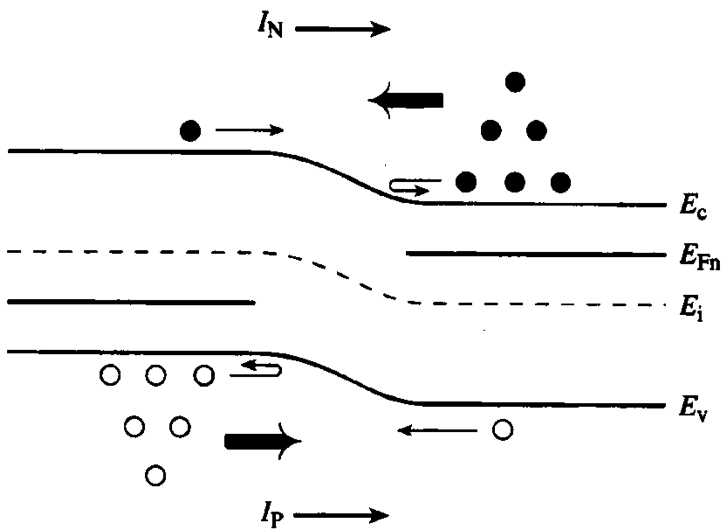
- When we apply voltage, we are no longer in equilibrium
- The application of a voltage creates a difference in the electrochemical potential across the junction boundary.
- The Fermi levels becomes separated by an energy of "q" times the applied voltage
- The band separation is q$(\boldsymbol{V_0}-\boldsymbol{V_a})$

Current flow in pn junction:

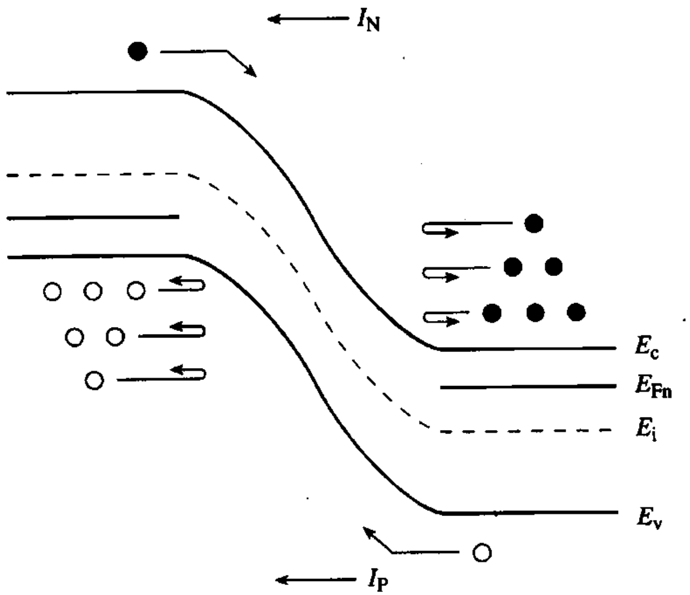
Equilibrium



Forward bias

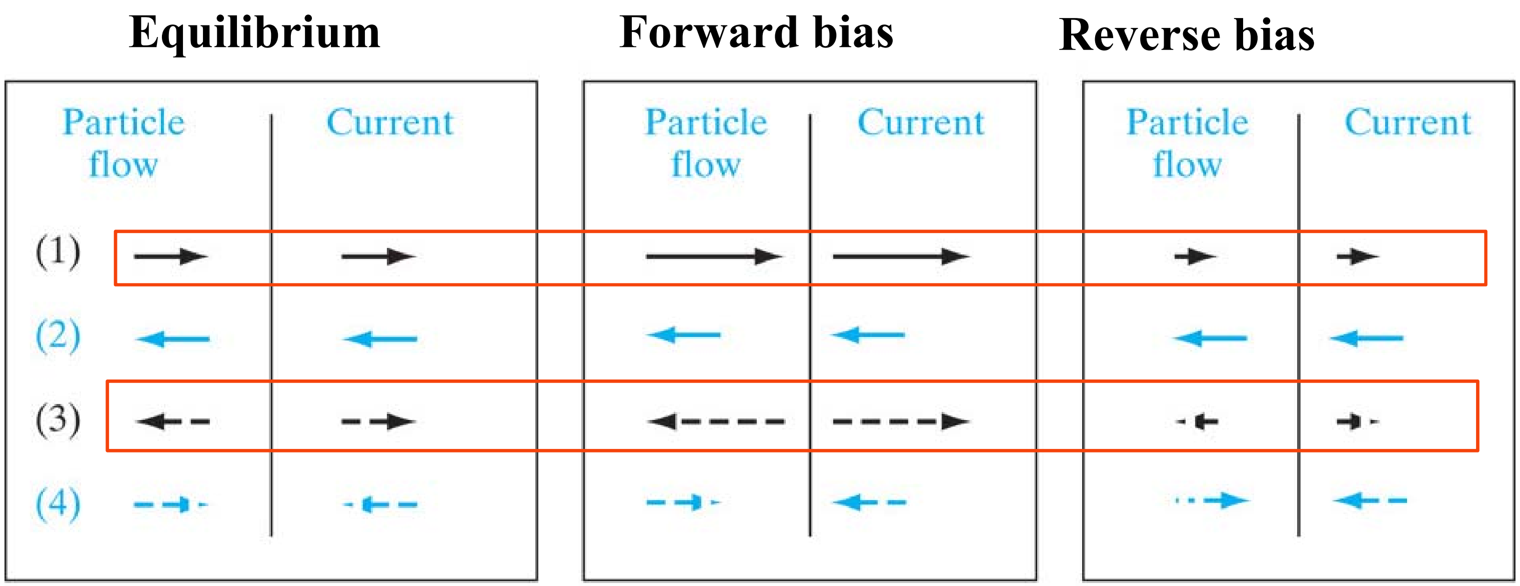


Reverse bias



Diffusion current

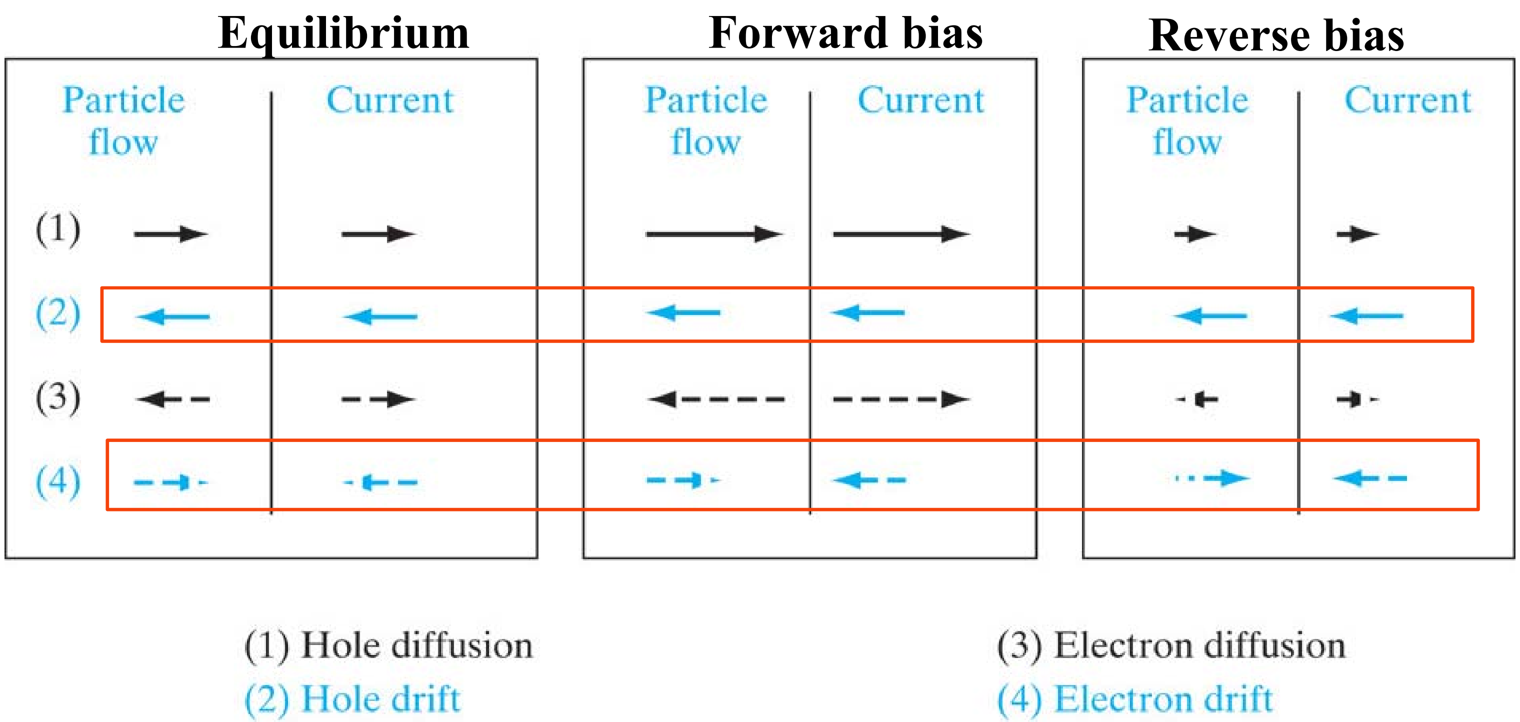
- Diffusion current is composed of majority carrier surmounting the potential barrier to diffuse to the other side of the junction
- For forward bias, barrier is lower → higher diffusion current
- For reverse bias, barrier is higher → lower diffusion current



(1) Hole diffusion
(2) Hole drift
(3) Electron diffusion
(4) Electron drift

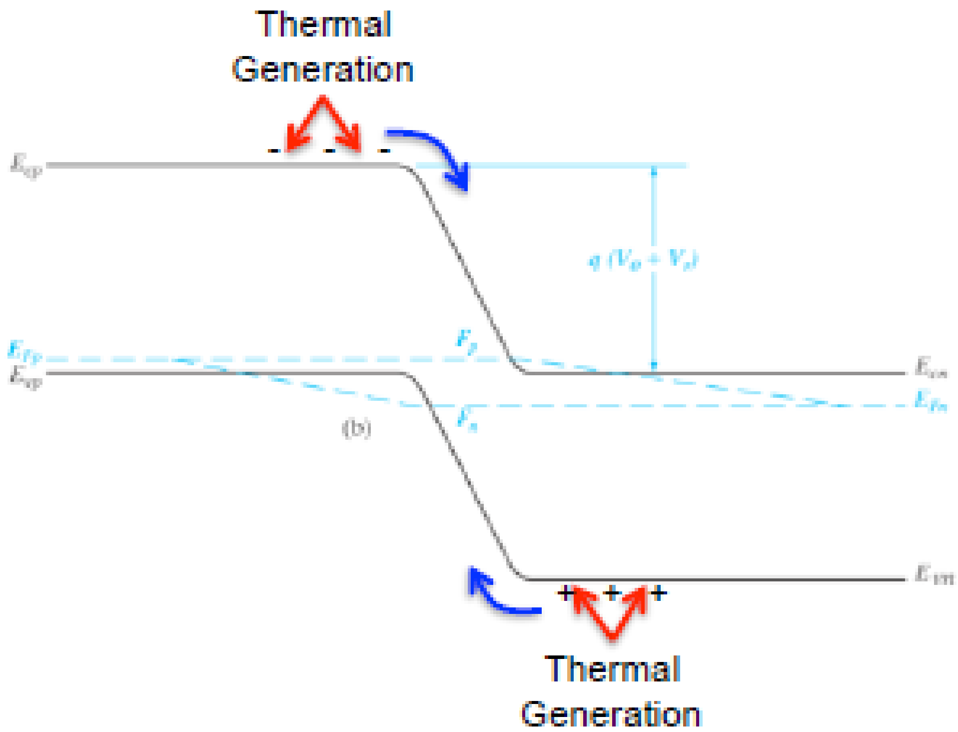
Drift current

- Drift current is insensitive to the barrier height or field, since the drift current is limited by "how often" carriers are swept down the barrier, not by "how fast".



Drift current (continued) --- Generation current

- The supply of the minority carrier for drift current is generated by thermal excitation of EHP.
- The resulting current is called the generation current.



- The reverse saturation current is a drift current, but the minority carriers arrive at the depletion region by way of diffusion

Total current

- Reverse bias:

$$I(diff.) \approx 0 \qquad I = I(gen.) \quad \text{Define } I_0 = |I(gen.)|$$

- At equilibrium ($\boldsymbol{V_a}$=0):

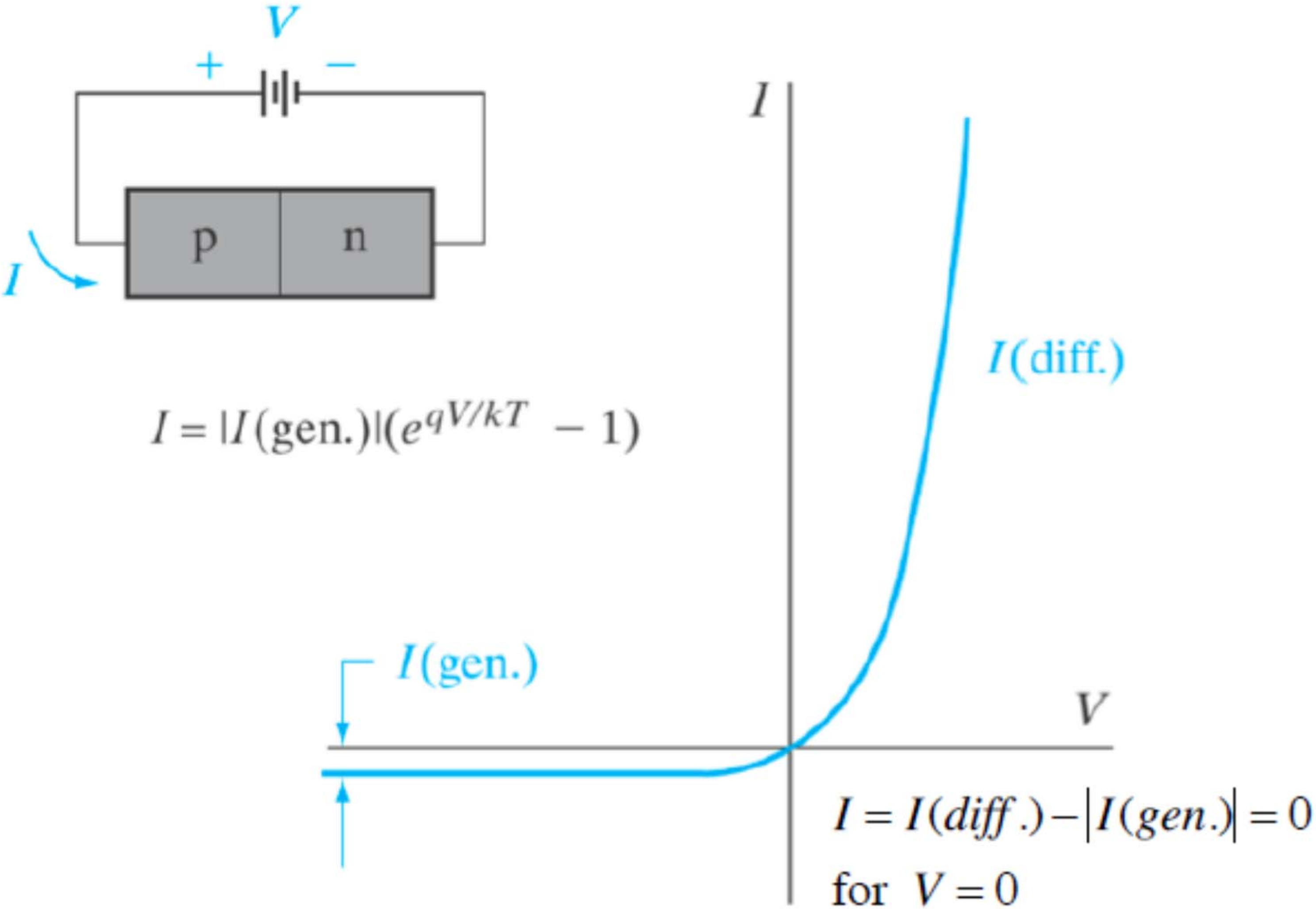
$$I = I(diff.) - |I(gen.)| = 0 \qquad I(diff.)@0V = I_0$$

- Forward bias

$$I(diff.) \approx I_0 e^{qV_a/kT}$$

$$\Rightarrow \quad I = I_0(e^{qV_a/kT} - 1)$$

pn Junction I~V Characteristic



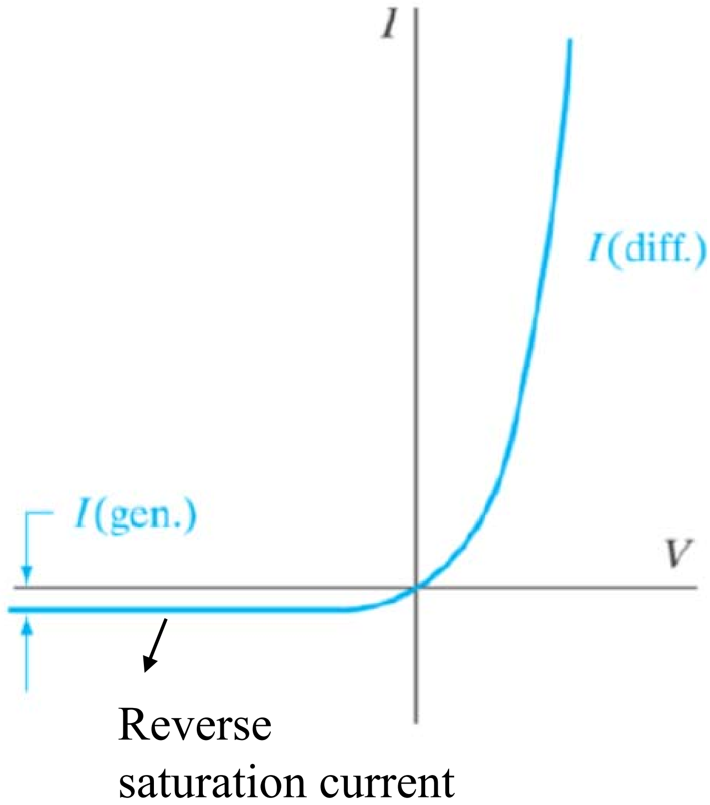
$$I = |I(\text{gen.})|(e^{qV/kT} - 1)$$

$$I = I(diff.) - |I(gen.)| = 0$$

for $V = 0$

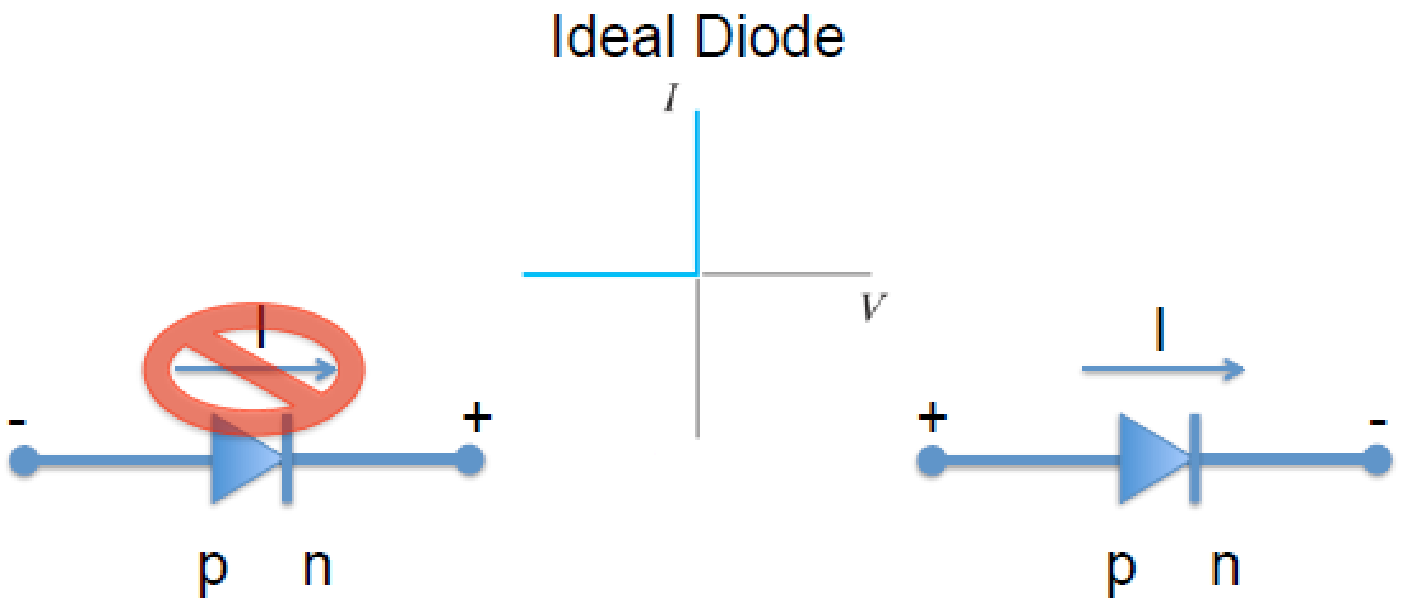
Question

- When temperature increase at the junction, what will happen to the reverse saturation current $I(gen.)$?
  - (a) increase
  - (b) decrease
  - (c) stay the same



Terminology

- Rectifier: A device that passes current in one bias direction (positive to negative) and blocks the flow of current in the opposite bias direction (negative to positive)



- **Ex:** An abrupt silicon p-n junction has p-side $N_A = 10^{18}$ cm^{-3}, and n-side $N_D =$ 5×10^{15} cm^{-3}. . A) How wide is the depletion region with applied V = 0, 0.5 and -2.5 V. B) What is the maximum electric field, and C) the potential across the n-side for these external V's.

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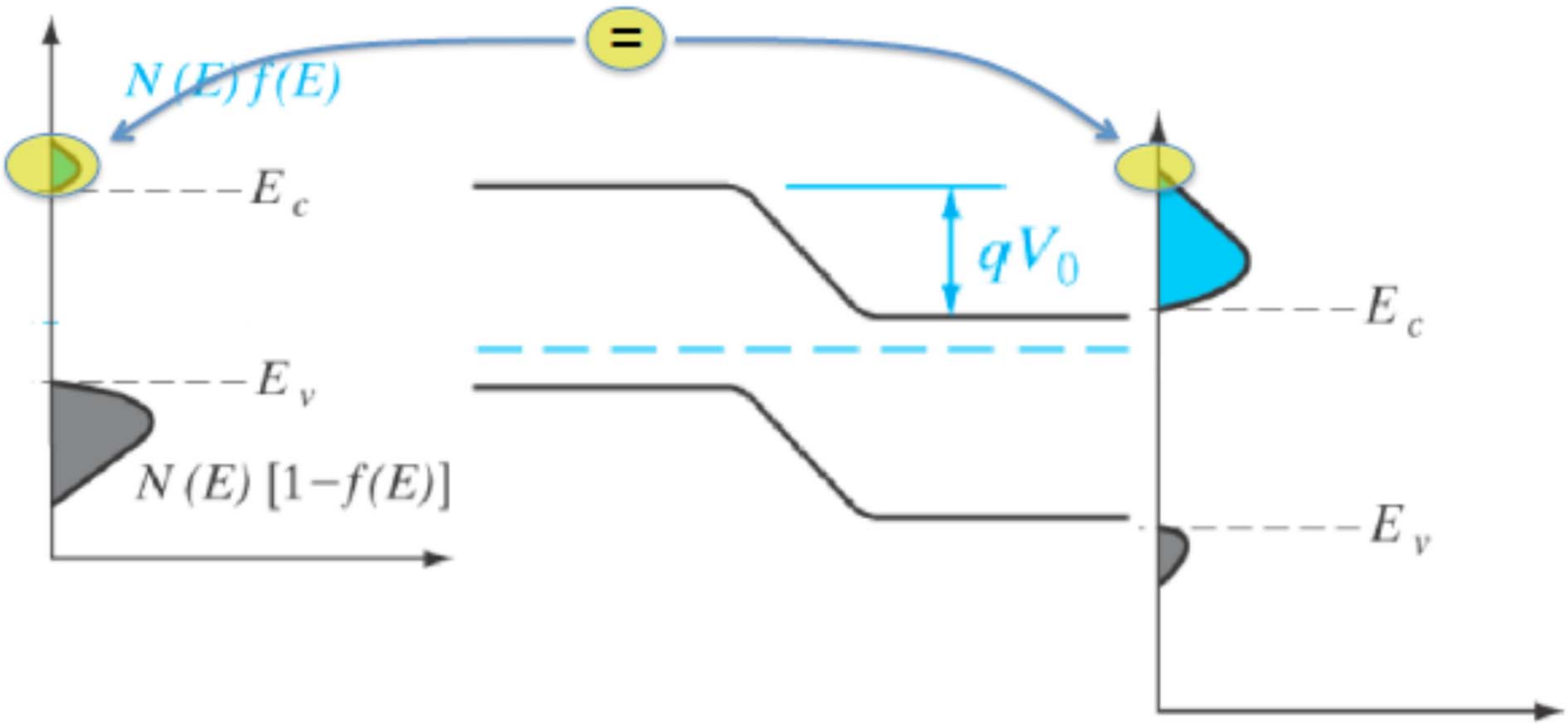
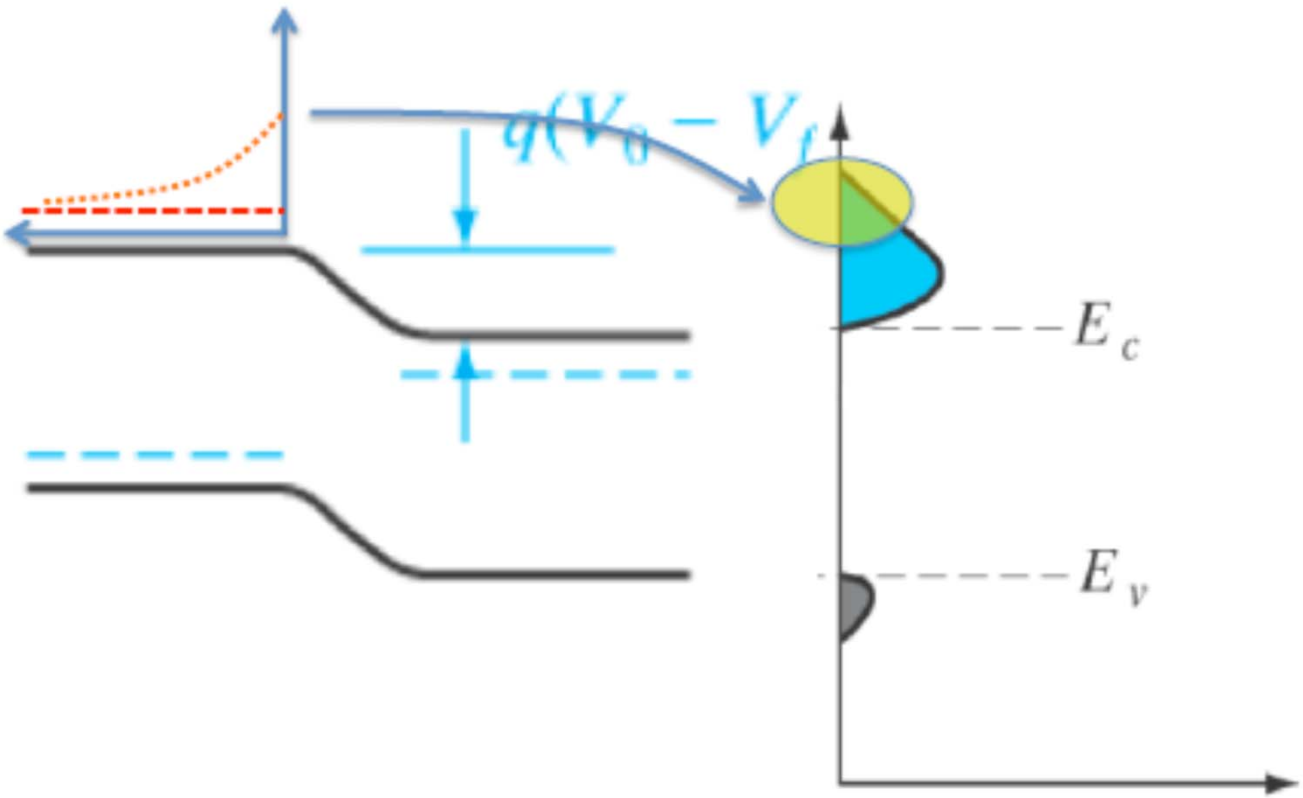
Majority-minority carrier balance



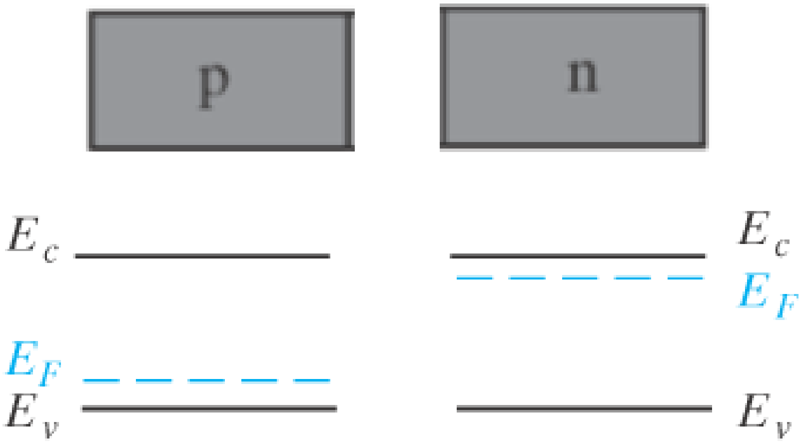
Equilibrium case

Majority-minority carrier injection



Forward bias

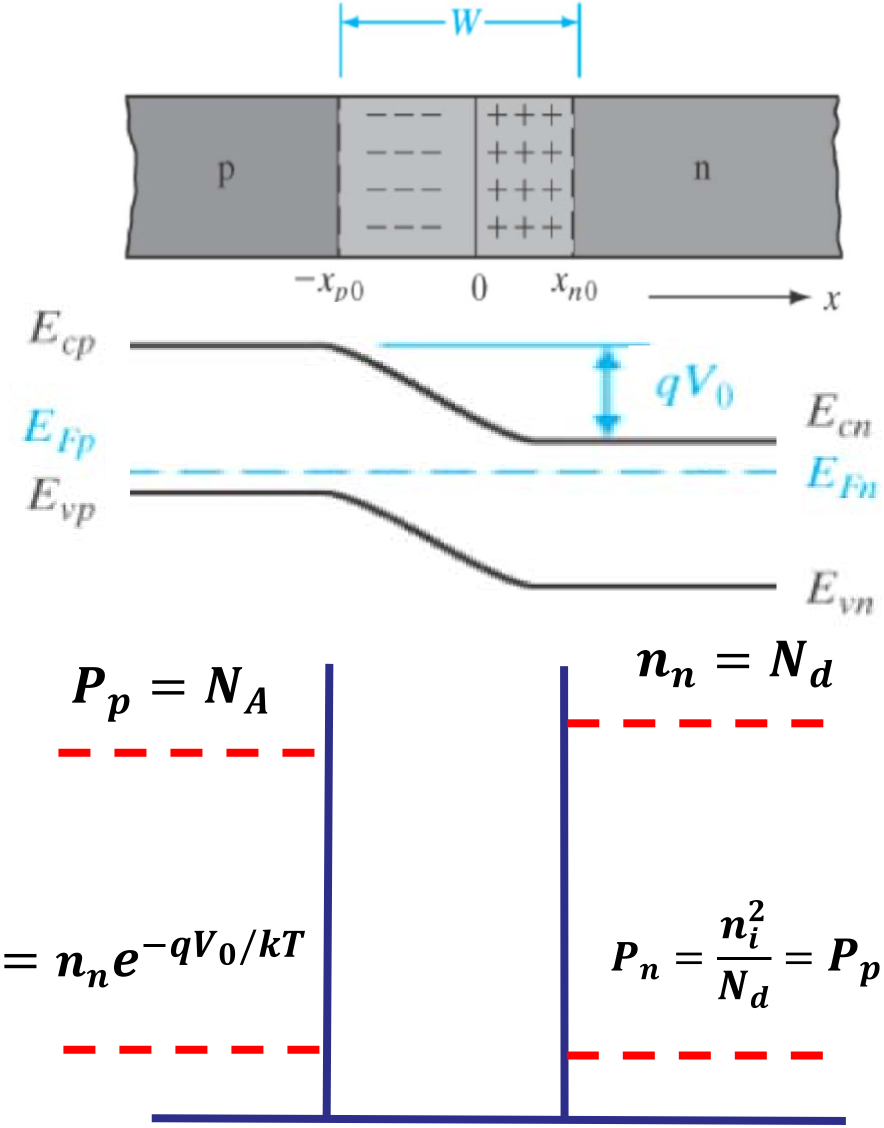
P and n region before contact



Majority carrier: Hole $P_p = N_A$; $n_n = N_d$ Electron

Minority carrier: Electron $n_p = \frac{n_i^2}{N_A}$; $P_n = \frac{n_i^2}{N_d}$ Hole

PN junction at equilibrium



$$P_p = N_A$$

$$n_n = N_d$$

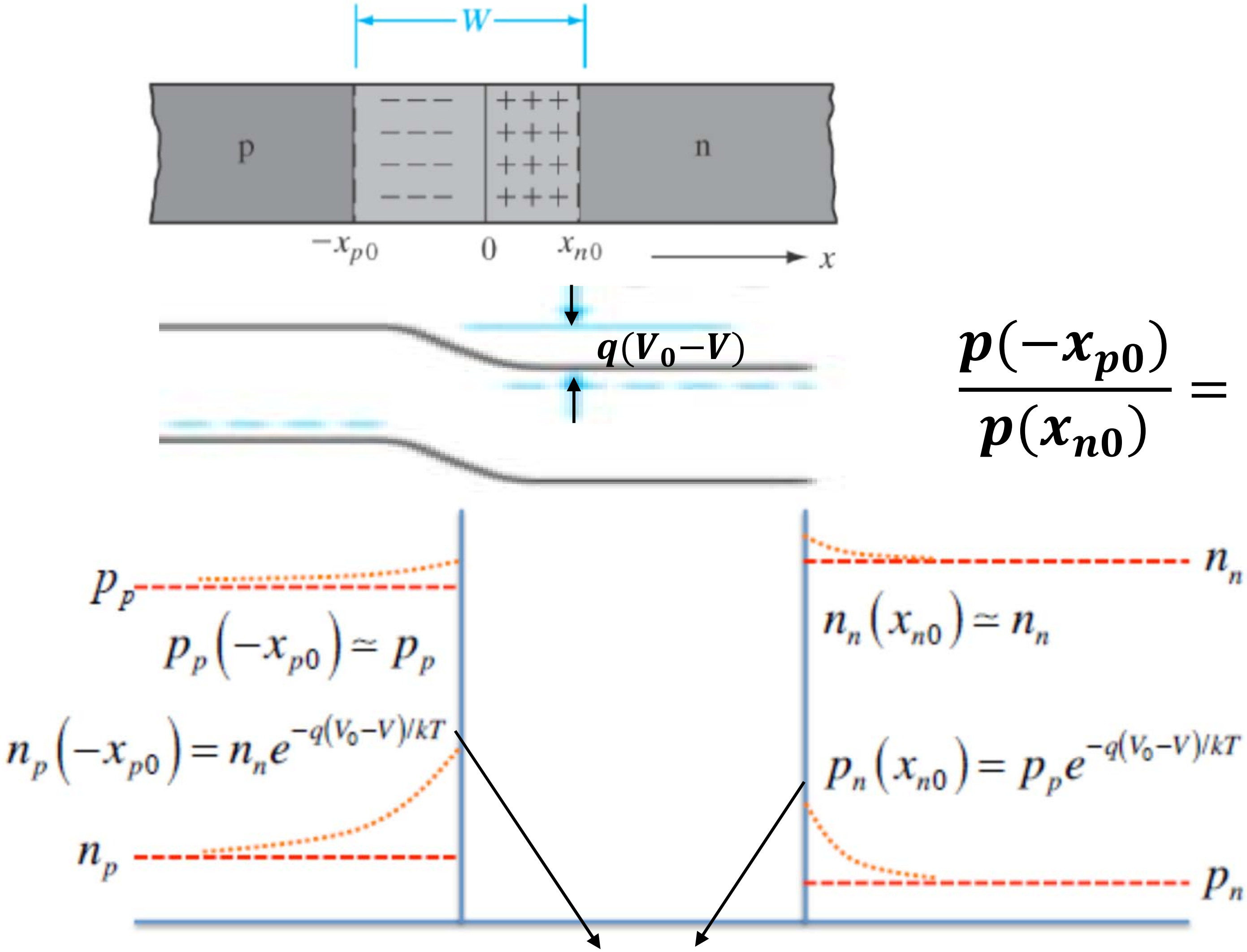
$$n_p = \frac{n_i^2}{N_A} = n_n e^{-qV_0/kT}$$

$$P_n = \frac{n_i^2}{N_d} = P_p e^{-qV_0/kT}$$

$$V_0 = \frac{kT}{q} ln\left(\frac{P_p}{P_n}\right)$$

$$\frac{P_p}{P_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$$

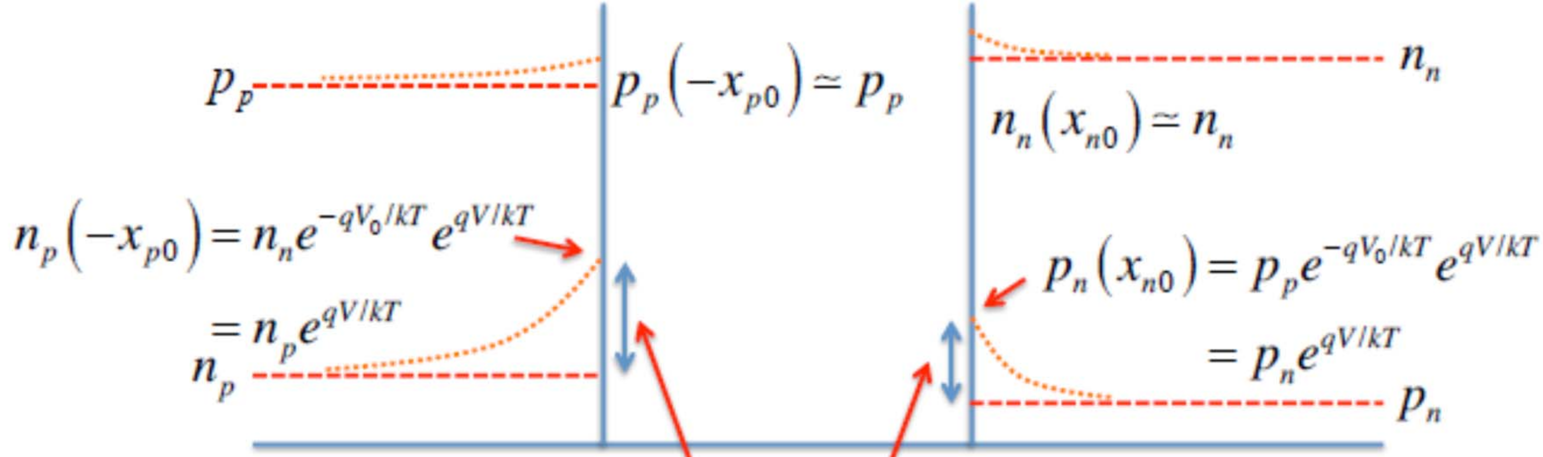
Forward bias
---carrier concentration at edge of transition



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

carrier concentration at the edge of transition region

Forward bias
--- excess carrier concentration



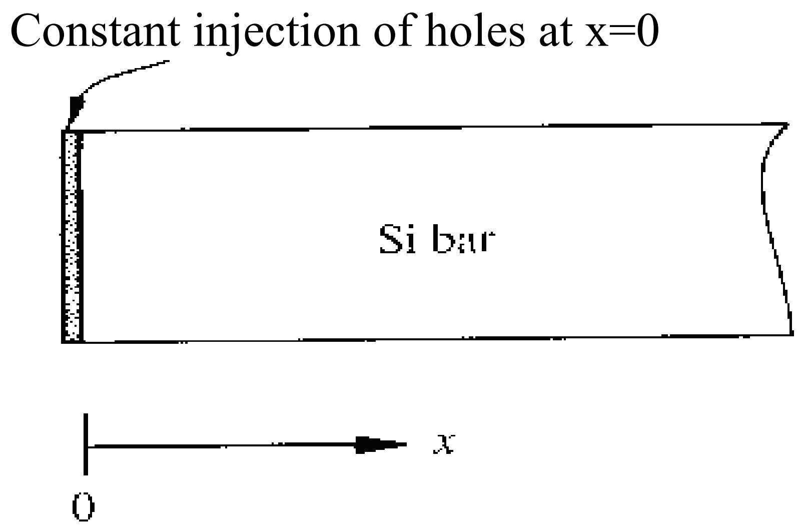
$$\begin{aligned} n_p(-x_{p0}) - n_p(-\infty) &= \Delta n \\ n_p e^{qV/kT} - n_p &= \\ n_p\left(e^{qV/kT} - 1\right) &= \end{aligned}$$

$$\begin{aligned} \Delta p &= p_n(x_{n0}) - p_n(\infty) \\ &= p_n e^{qV/kT} - p_n \\ &= p_n\left(e^{qV/kT} - 1\right) \end{aligned}$$

Space Charge Neutrality, Low - Level Injection :

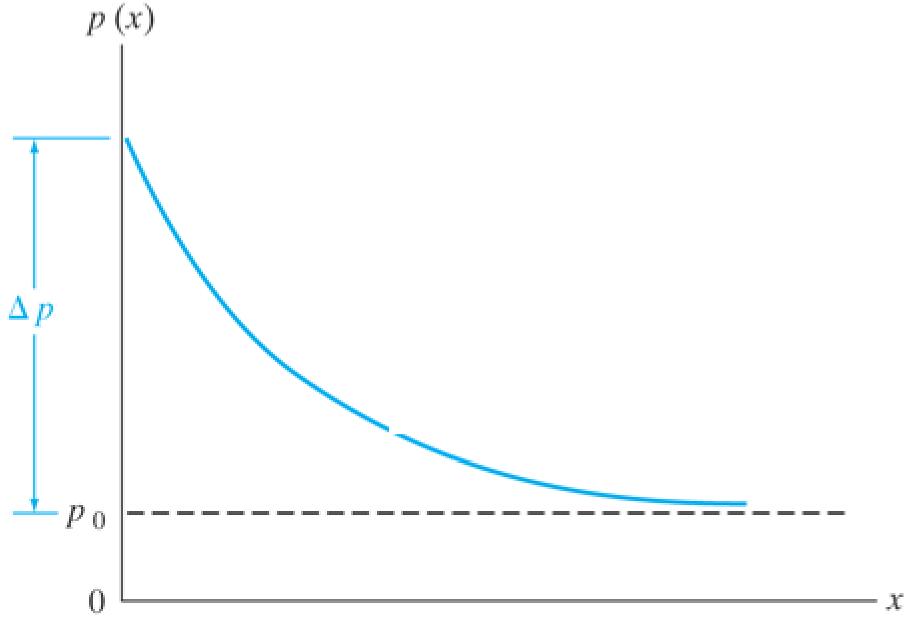
$$p_p(-x_{p0}) = p_p(-\infty) + \Delta n = p_p + n_p\left(e^{qV/kT} - 1\right) \simeq p_p$$

Recap: Hole Diffusion



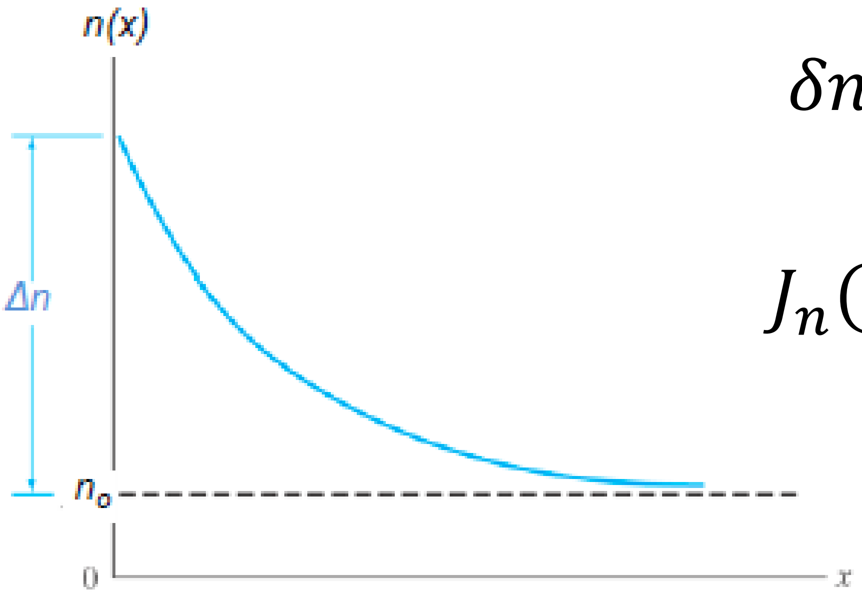
$$\delta p(x) = \Delta p e^{-x/L_p}$$

$$J_p(x) = -qD_p \frac{dp}{dx} = q\frac{D_p}{L_p}\delta p(x)$$



Recap: Electron Diffusion

Electron diffuse in x direction:

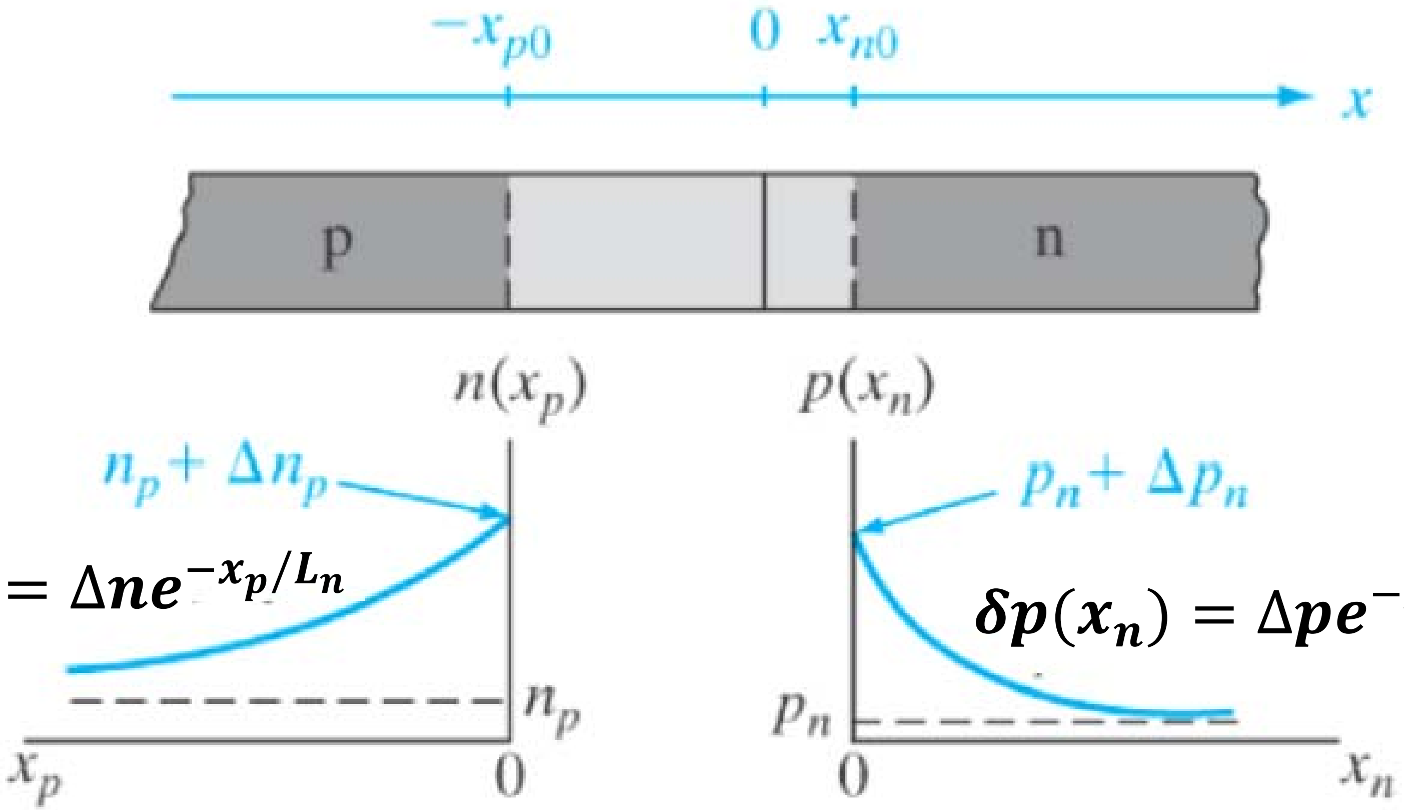


$$\delta n(x) = \Delta n e^{-x/L_n}$$

$$J_n(x) = qD_n \frac{dn}{dx} = -q \frac{D_n}{L_n} \delta n(x)$$

x

Forward bias, minority carrier diffusion



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

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

- New coordinate system referenced to edges of the depletion region:

$$x_n = x - x_{n0} \qquad x_p = -x - x_{p0}$$

x_{n0} and x_{p0} are the n and p side depletion width

Diffusion current

- Hole diffusion current:

$$I_p(\boldsymbol{x_n}) = -qAD_p \frac{\boldsymbol{d\delta p(x_n)}}{d\boldsymbol{x_n}} = qA\frac{D_p}{L_p}\delta p(\boldsymbol{x_n})$$

- Hole diffusion current at $\boldsymbol{x_n} = \mathbf{0}$:

$$I_p(\boldsymbol{x_n} = 0) = qA\frac{D_p}{L_p}\Delta\boldsymbol{p_n} = qA\frac{D_p}{L_p}\boldsymbol{p_n}(\boldsymbol{e^{qV/kT}} - \mathbf{1})$$

- Electron diffusion current at $\boldsymbol{x_p} = \mathbf{0}$

$$I_n(\boldsymbol{x_p} = 0) = qA\frac{D_n}{L_n}\Delta\boldsymbol{n_p} = -qA\frac{D_n}{L_n}\boldsymbol{n_p}(\boldsymbol{e^{qV/kT}} - \mathbf{1})$$

** relative to transformed coordinate, $\boldsymbol{x_p}$ axis pointing to –x direction

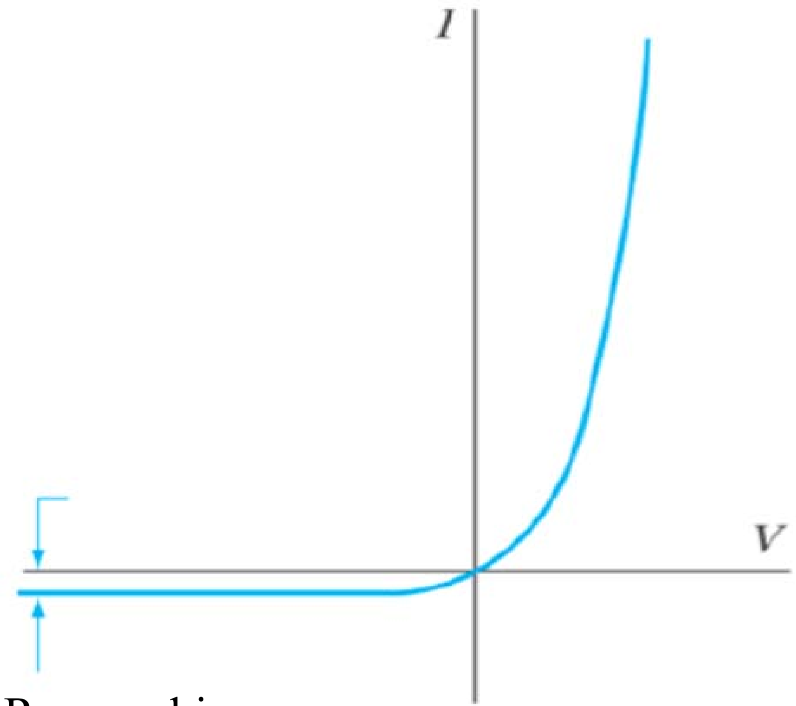
Total diode current

$$I = I_p(\boldsymbol{x_n} = 0) - I_n(\boldsymbol{x_p} = 0)$$
$$= qA\left(\frac{D_p}{L_p}\boldsymbol{p_n} + \frac{D_n}{L_n}\boldsymbol{n_p}\right)\left(e^{\boldsymbol{qV/kT}} - \mathbf{1}\right) = \boldsymbol{I_0}\ \left(\boldsymbol{e^{qV/kT}} - \mathbf{1}\right)$$

n side current **p side current**

- **The dominant current contribution comes from injection from the more heavily doped side into the more lightly doped side**
- **Reducing the doping level on either side of the junction increases the minority carrier concentrations pn and np which would tend to increase the current for a given voltage**

Diode equation: various scenarios



Reverse bias

$$V = -V_r$$

$$I \approx -\boldsymbol{I_0}$$

$$I = \boldsymbol{I_0}\left(\boldsymbol{e^{qV/kT}} - \boldsymbol{1}\right)$$

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

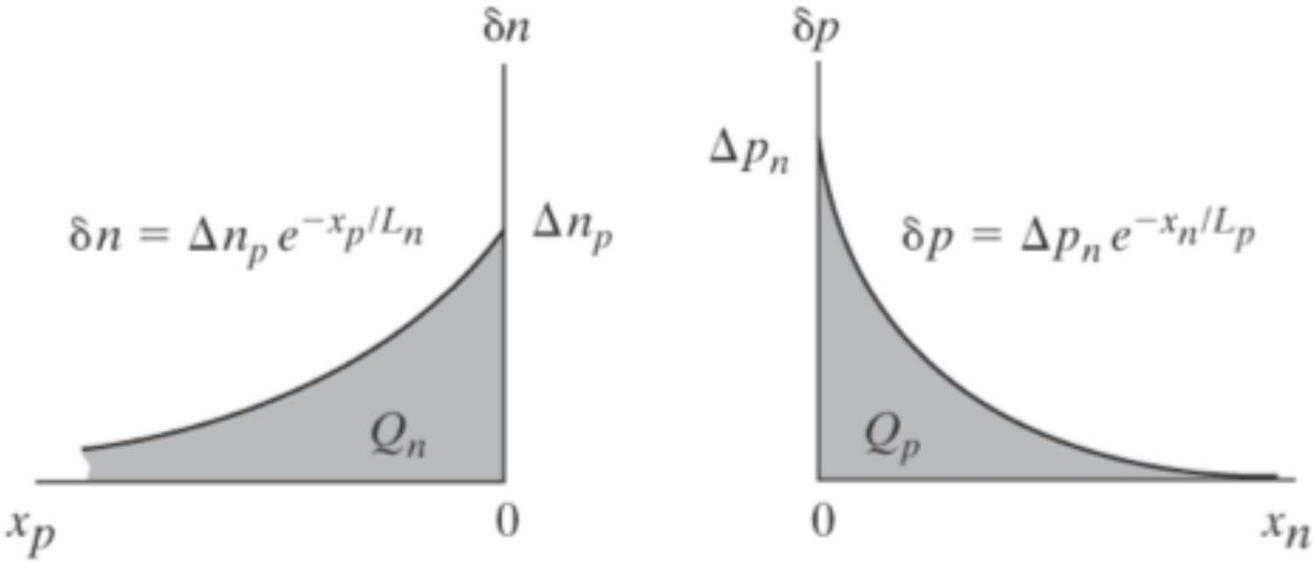
(a) p+-n junction: $\boldsymbol{p_n} \gg \boldsymbol{n_p}$

$$I_0 = qA\frac{D_p}{L_p}\boldsymbol{p_n}$$

(b) p-n+ junction: $\boldsymbol{p_n} \ll \boldsymbol{n_p}$

$$I_0 = qA\frac{D_n}{L_n}\boldsymbol{n_p}$$

Charge control approximation, the alternative way to calculate current



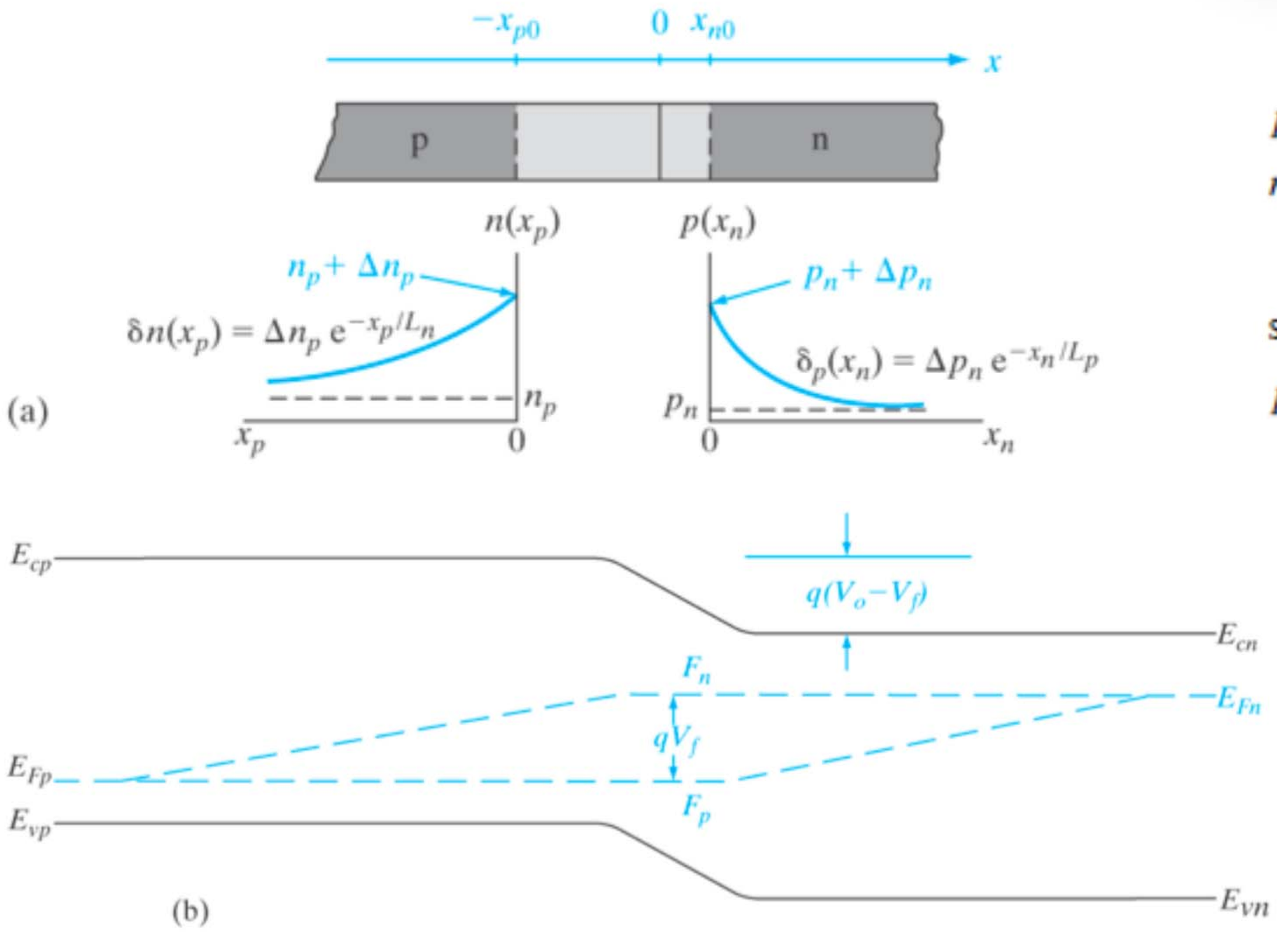
Total positive charge stored in the excess carrier distribution:

$$Q_p = qA\int_0^{\infty} \delta p(x_n)dx_n = qA\Delta p_n \int_0^{\infty} e^{-x_n/L_p}dx_n = qAL_p\Delta p_n$$

Injected hole current at $x_n = 0$:

$$I_p(x_n = 0) = \frac{Q_p}{\tau_p} = \frac{qAL_p}{\tau_p}\Delta p_n = \frac{qAD_p}{L_p}\Delta p_n$$

Quasi-Fermi level at forward bias



$$p(x_p = 0) \sim p_p(x_p = \infty) = p_p$$

$$n(x_p = 0) = n_p(x_p = \infty) + \Delta n$$

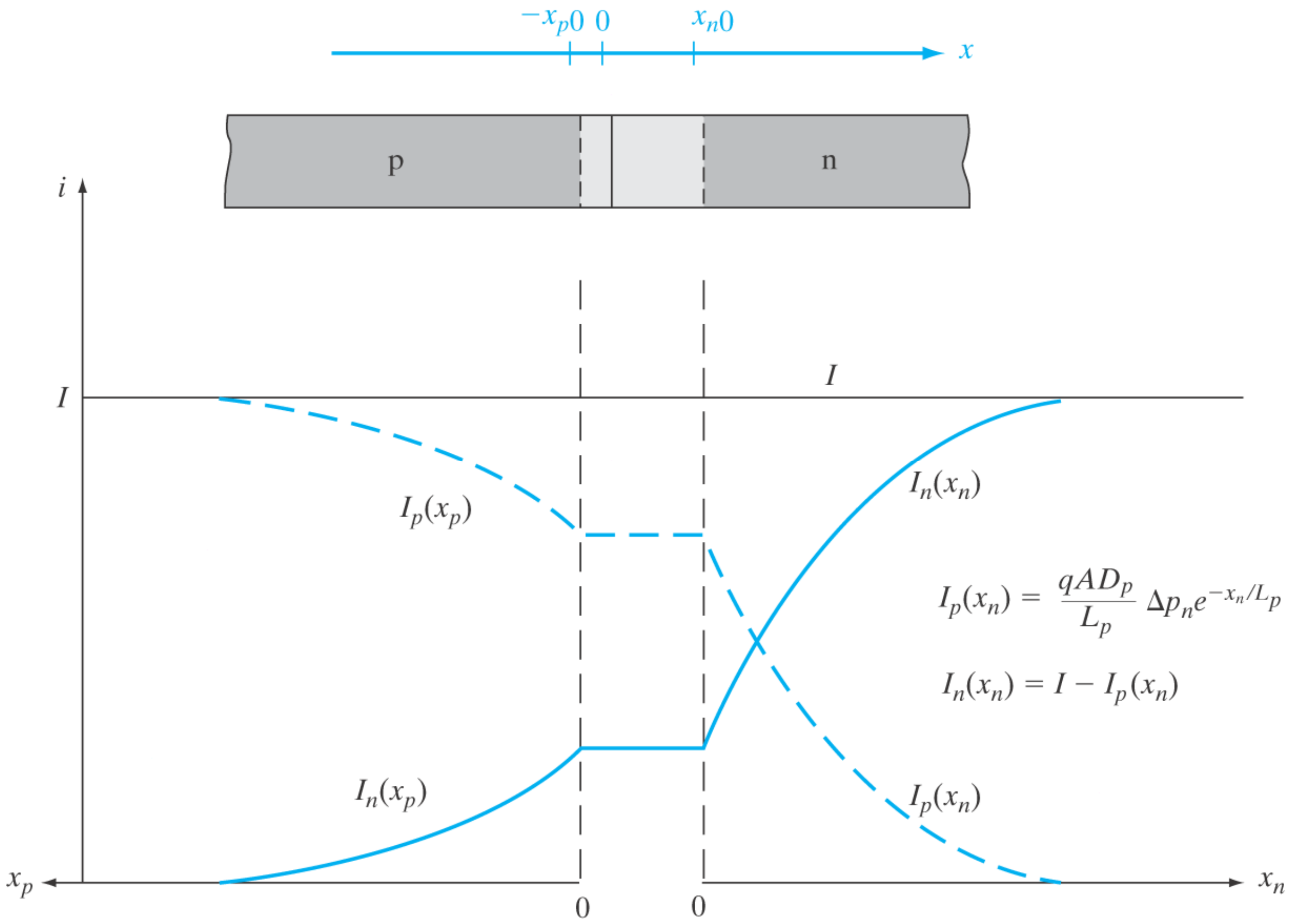
$$= n_p\left(e^{qV/kT} - 1\right) \sim n_p e^{qV/kT}$$

so:

$$pn(x_p = 0) = p_p n_p e^{qV/kT} = n_i^2 e^{qV/kT}$$

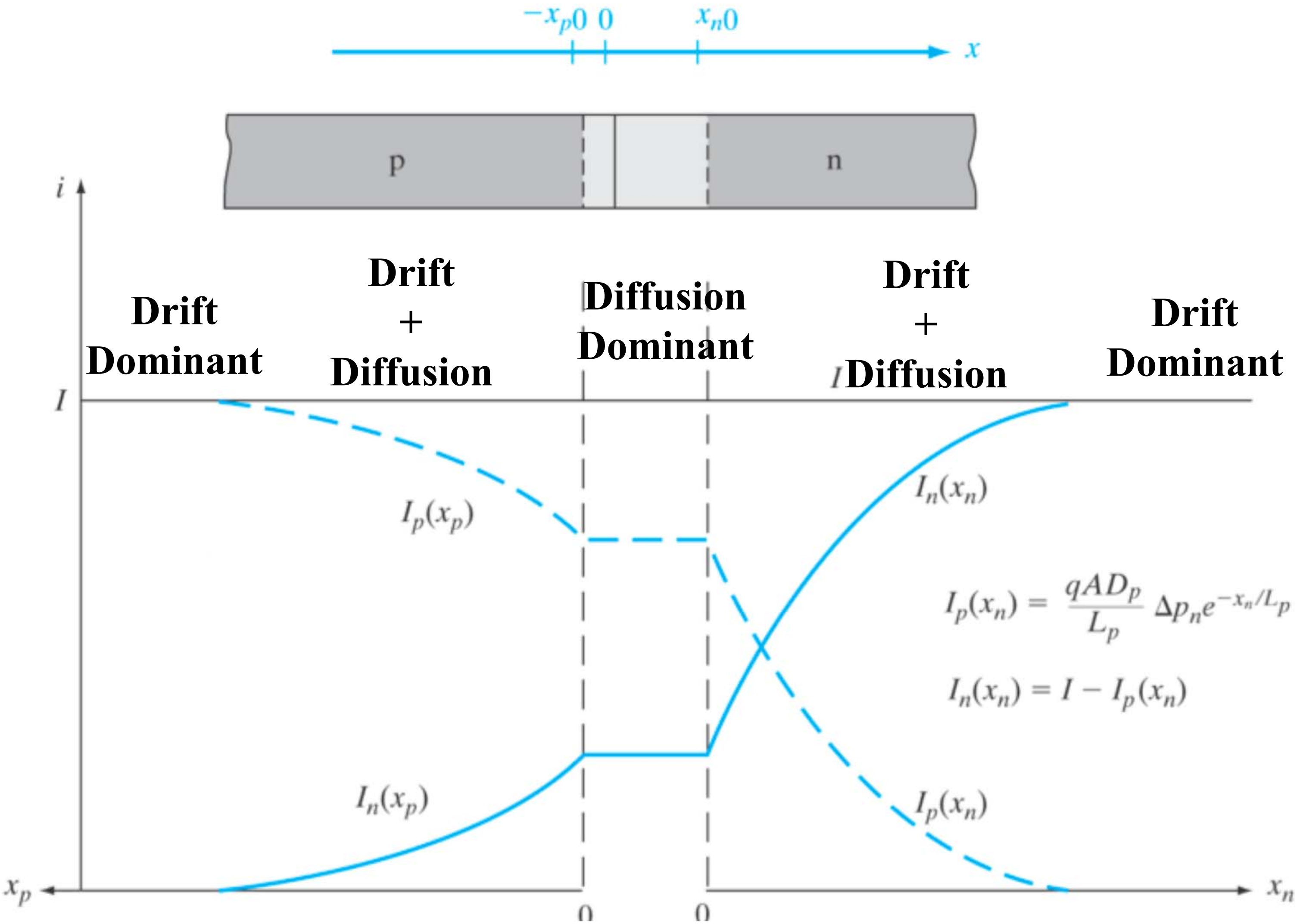
$$pn = n_i^2 e^{(F_n - F_p)/kT} = n_i^2 e^{(qV/kT)}$$

Electron and hole current at forward bias



- Current continuity along junction length, J_{TOT} = const.
- Away from the junction, current is carried by majority carriers

Drift and diffusion in forward bias



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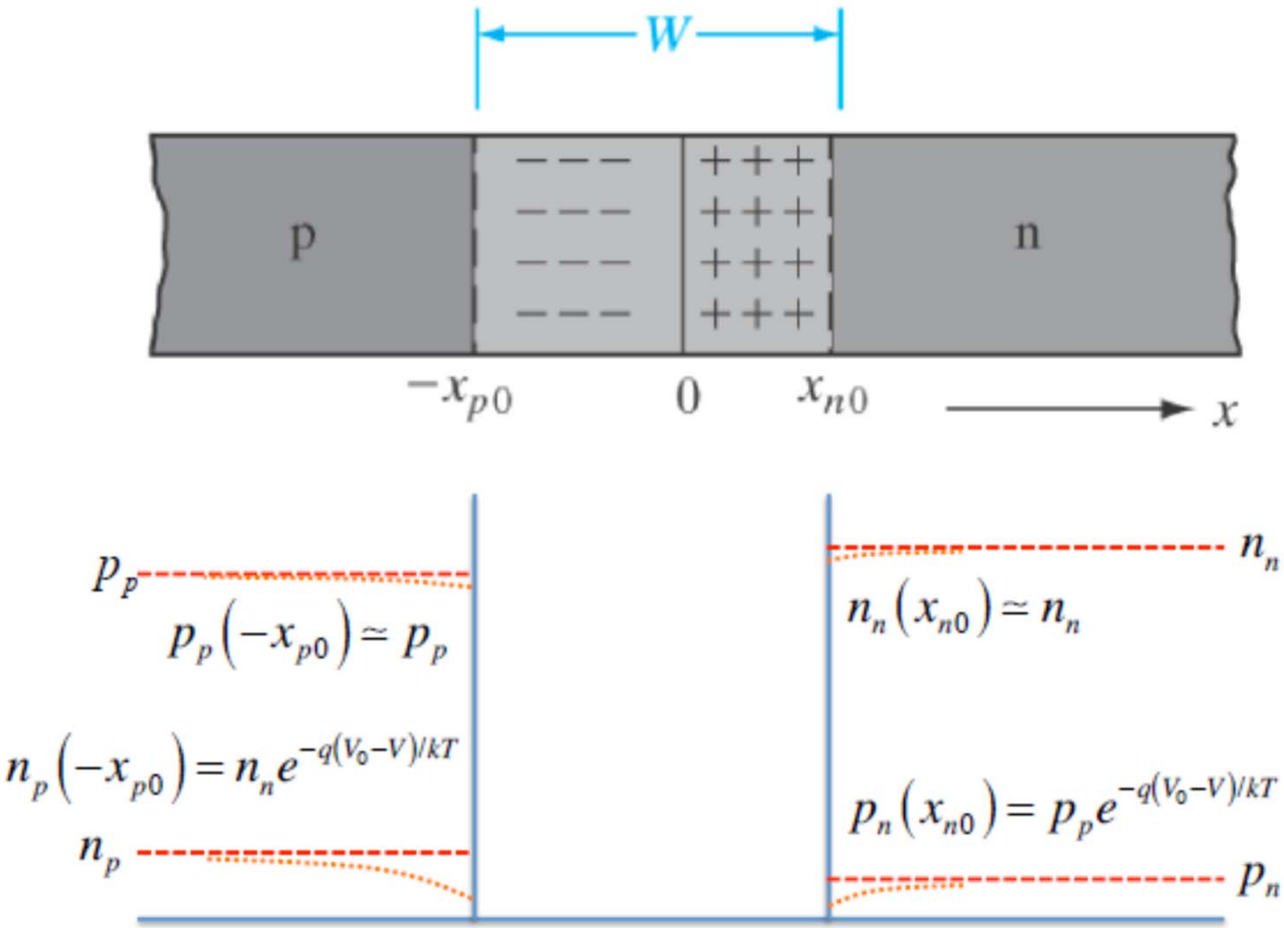
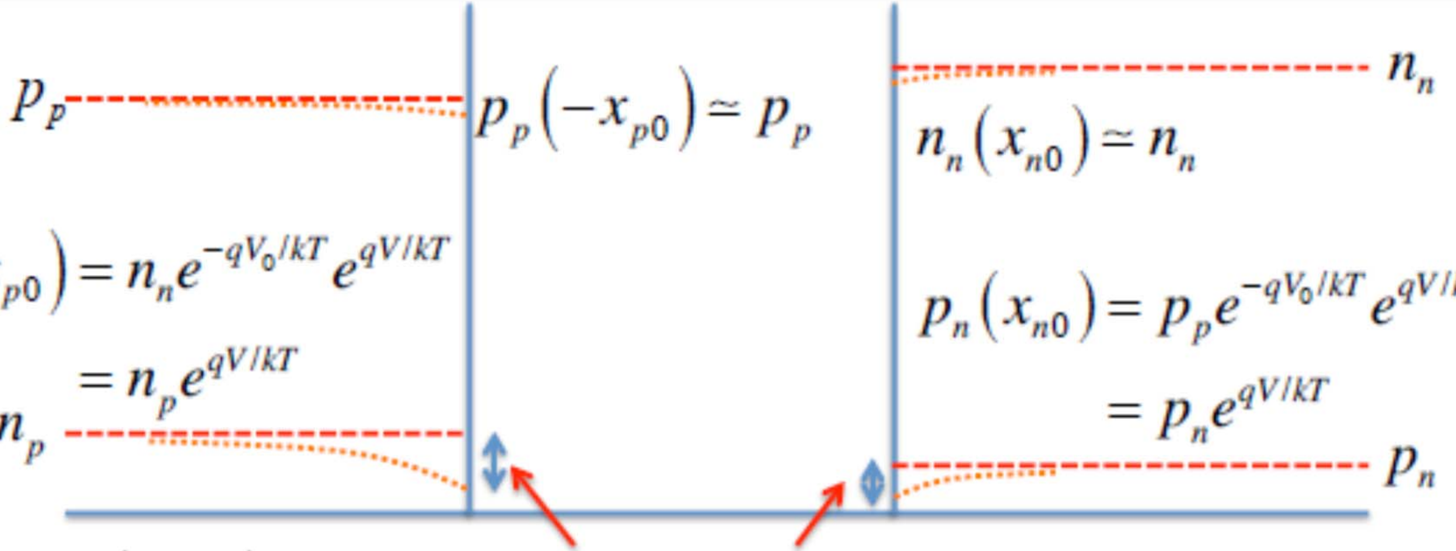
Reverse Bias

---carrier concentration at edge of transition region



Reverse Bias

--- excess carrier concentration



$$p_p(-x_{p0}) \simeq p_p$$

$$n_n(x_{n0}) \simeq n_n$$

$$n_p(-x_{p0}) = n_n e^{-qV_0/kT} e^{qV/kT}$$
$$= n_p e^{qV/kT}$$

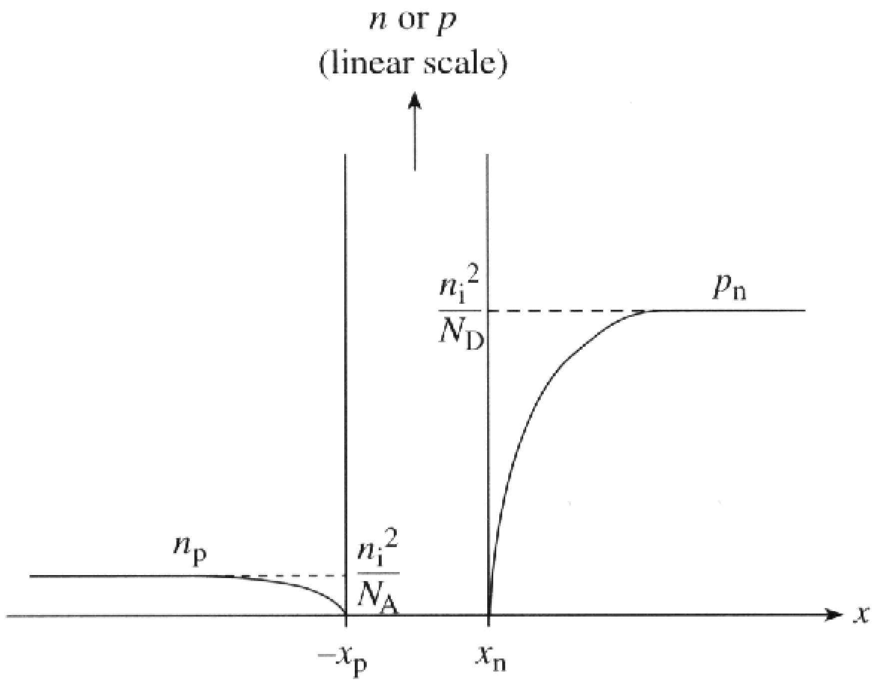
$$p_n(x_{n0}) = p_p e^{-qV_0/kT} e^{qV/kT}$$
$$= p_n e^{qV/kT}$$

$$n_p(-x_{p0}) - n_p(-\infty) = \Delta n$$
$$n_p e^{qV/kT} - n_p =$$
$$n_p\left(e^{qV/kT} - 1\right) =$$
$$-n_p \simeq$$

$$\Delta p = p_n(x_{n0}) - p_n(\infty)$$
$$= p_n e^{qV/kT} - p_n$$
$$= p_n\left(e^{qV/kT} - 1\right)$$
$$\simeq -p_n$$

Reverse bias

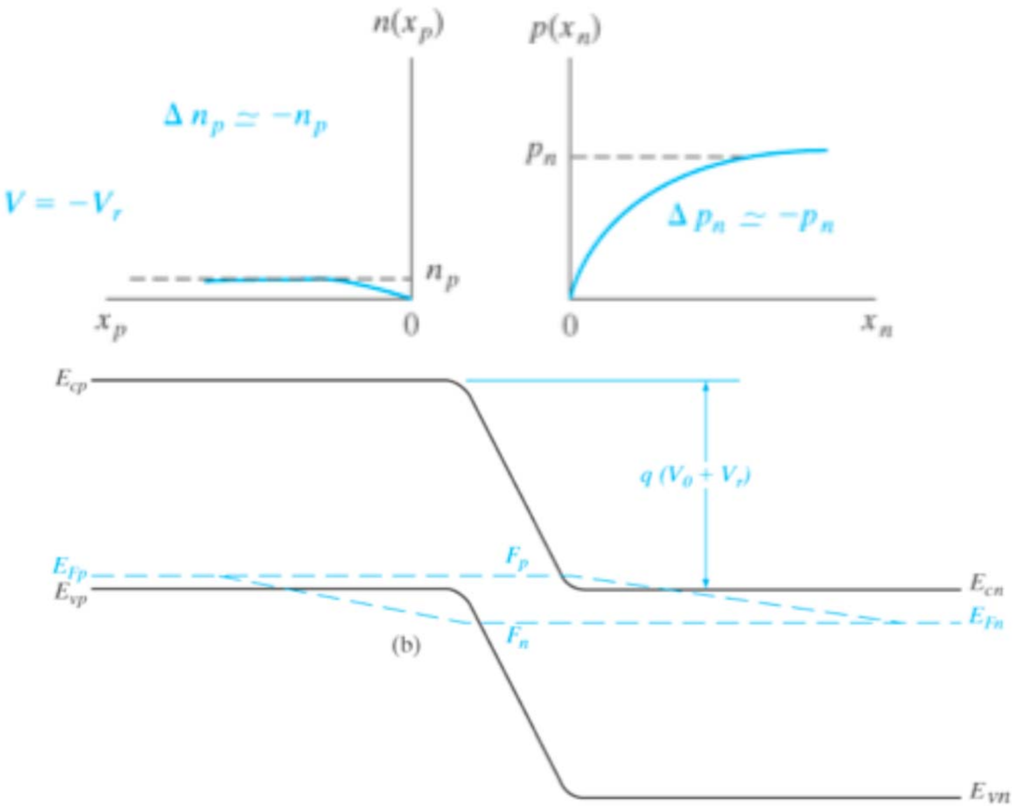
- Depletion region widens
- E-field across depletion region ___________________
- Current is due only to minority carrier ________________ across the junction
- Current is supplied by EHP generation in or within a diffusion length of the ____________________ (what if I change the temperature or turn on the light?)
- Recall, I_0 =



$$\Delta p = p_n(e^{q(-V_r)/kT} - 1) \approx -p_n$$

$$\Delta n \approx -n_p$$

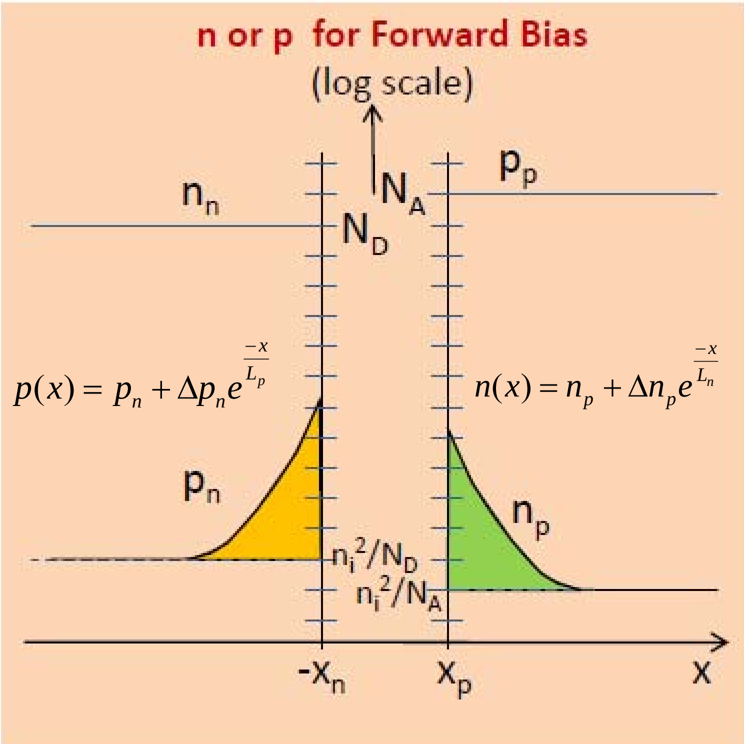
Reverse bias quasi-Fermi level

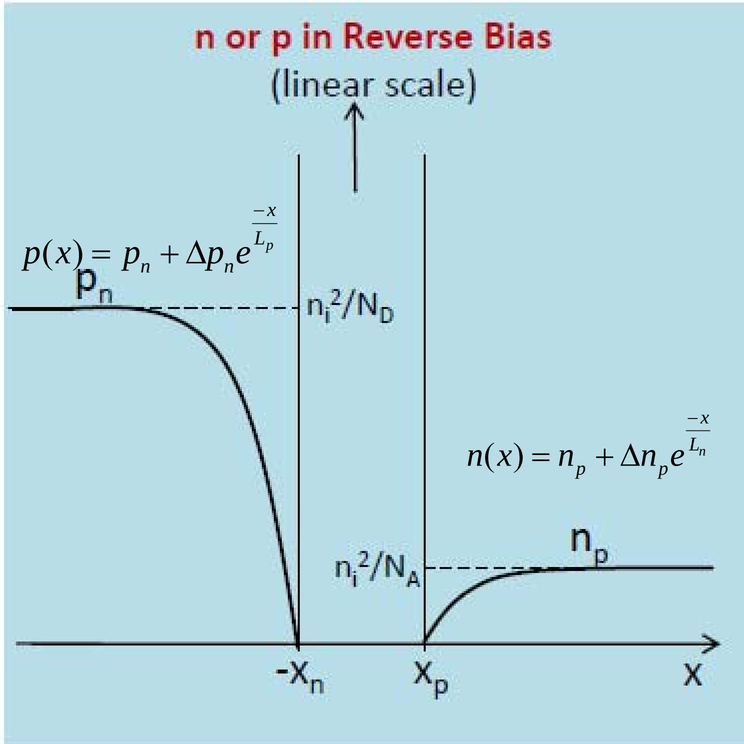


$$pn = n_i^2 e^{(F_n - F_p)/kT} \approx 0$$

- F_n moves farther away from E_c toward E_v because in reverse bias we have fewer carriers than in equilibrium.
- Quasi-Fermi levels here go inside the bands but we need to remember that F_p is a measure of the hole concentration and is correlated with Ev and not Ec
- This just tell us we have very few holes (smaller than in equilibrium)

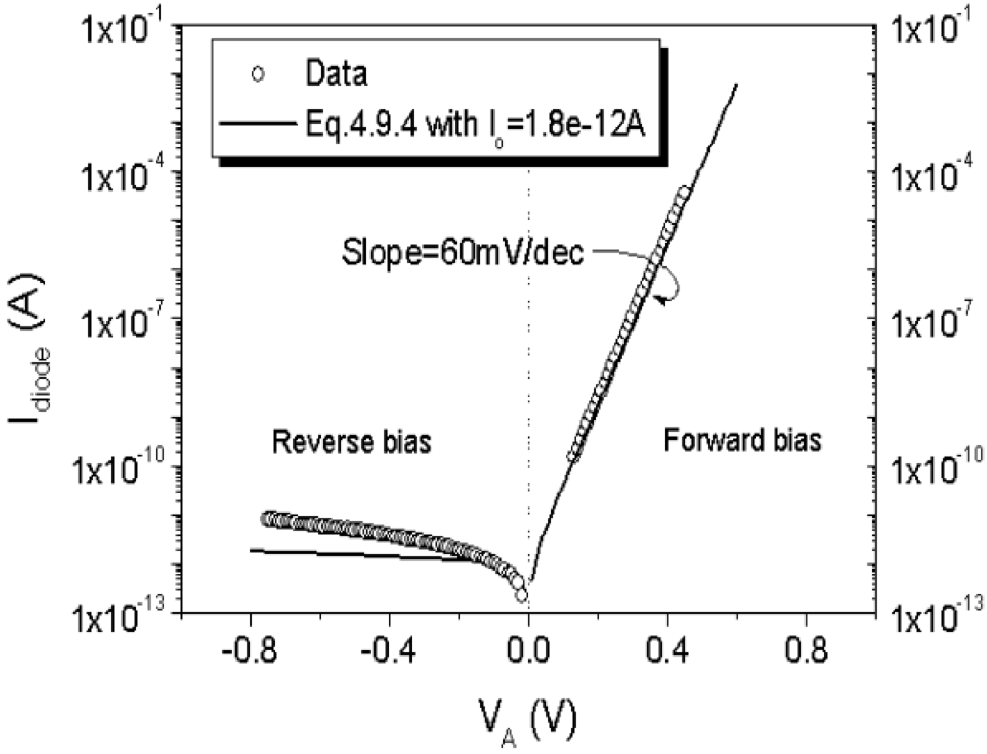
Minority Carrier Distribution





$$\boxed{\Delta n_p = \frac{n_i^2}{N_A}\left(e^{\frac{qV_{APP}}{kT}} - 1\right)} \qquad \boxed{\Delta p_n = \frac{n_i^2}{N_D}\left(e^{\frac{qV_{APP}}{kT}} - 1\right)}$$

IV Characteristic



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

$$I_0 = Aqn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)$$

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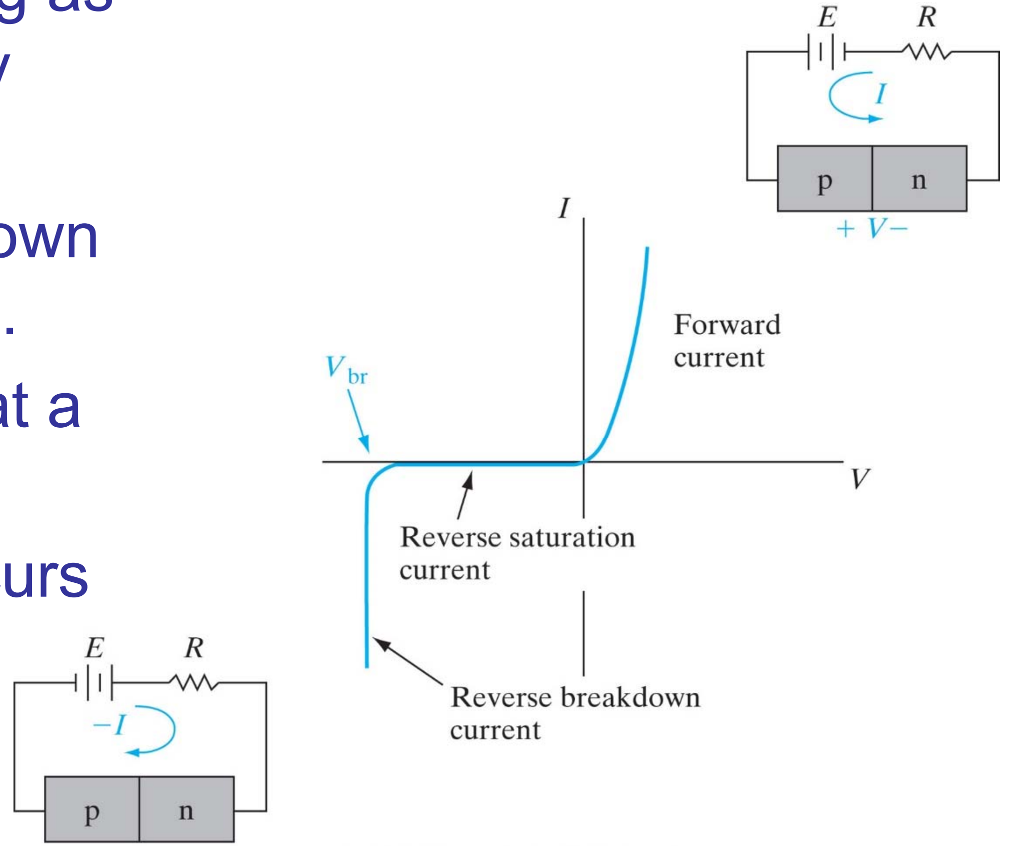
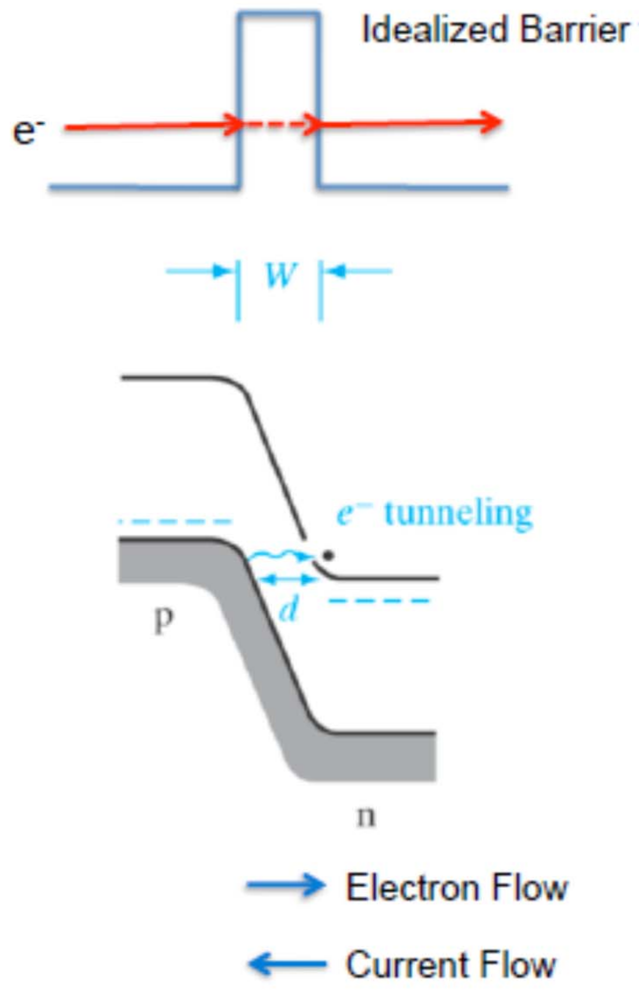
Reverse breakdown

- Reverse "breakdown" is not a destructive process as long as current is limited externally
- There are two types of breakdown: Zener breakdown and avalanche breakdown.
- Zener breakdown occurs at a few volts
- Avalanche breakdown occurs at higher voltages.



Tunneling: a quantum effect

- In classical mechanics, a particle can only overcome a potential barrier if it has higher energy than the barrier
- In quantum mechanics, a particle can tunnel through a barrier
- Tunneling probability is enhanced if the barrier is thin, or under certain resonant conditions
- The Zener effect is a tunneling phenomenon



Zener effect and Zener breakdown

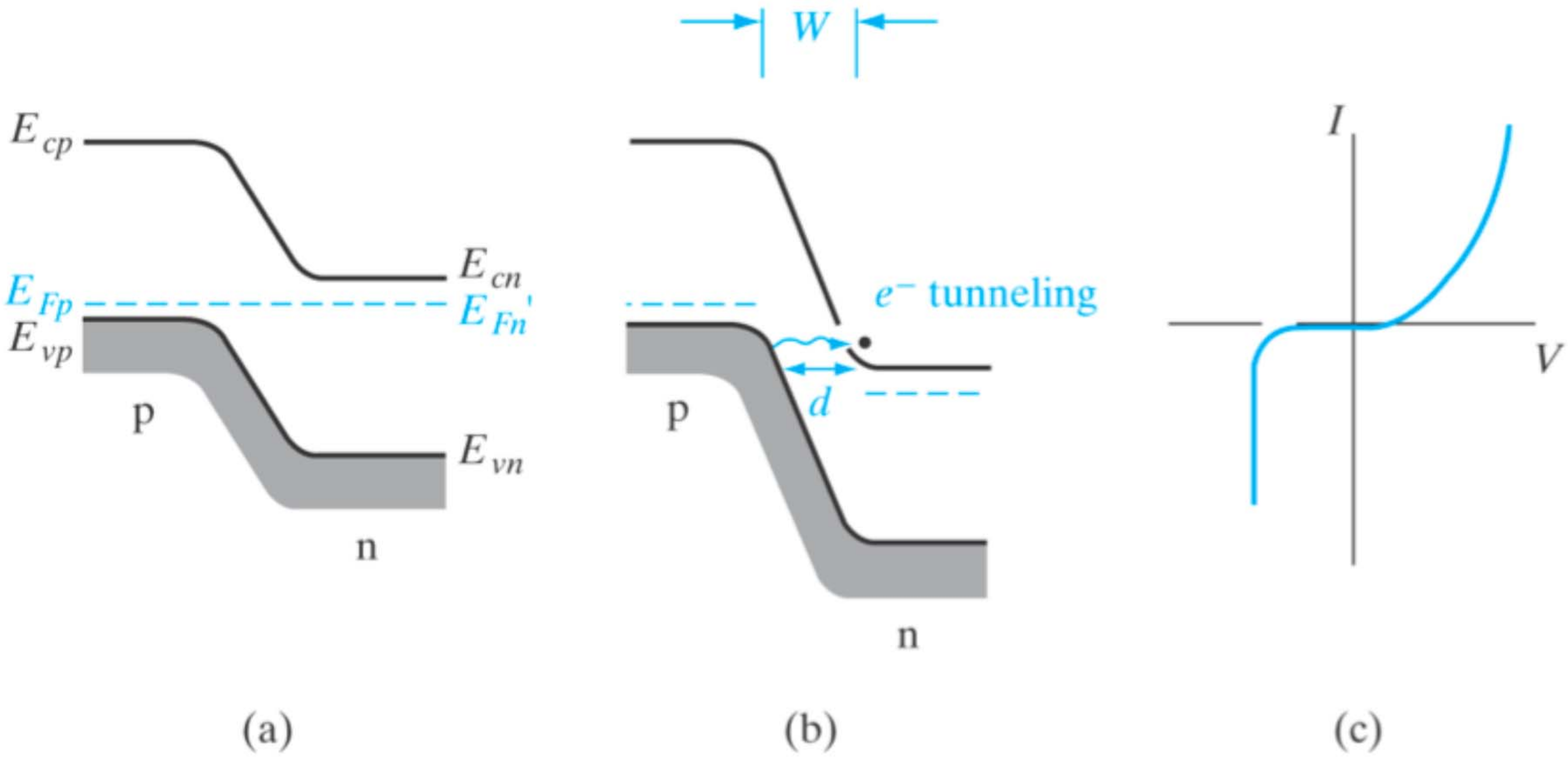


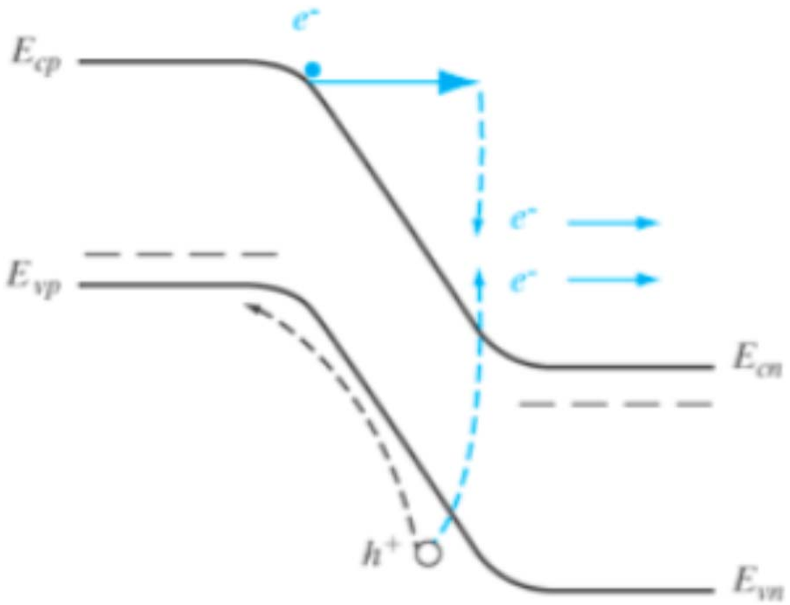
Figure 5.20

The Zener effect: (a) heavily doped junction at equilibrium; (b) reverse bias with electron tunneling from p to n; (c) I–V characteristic.

Zener effect comments

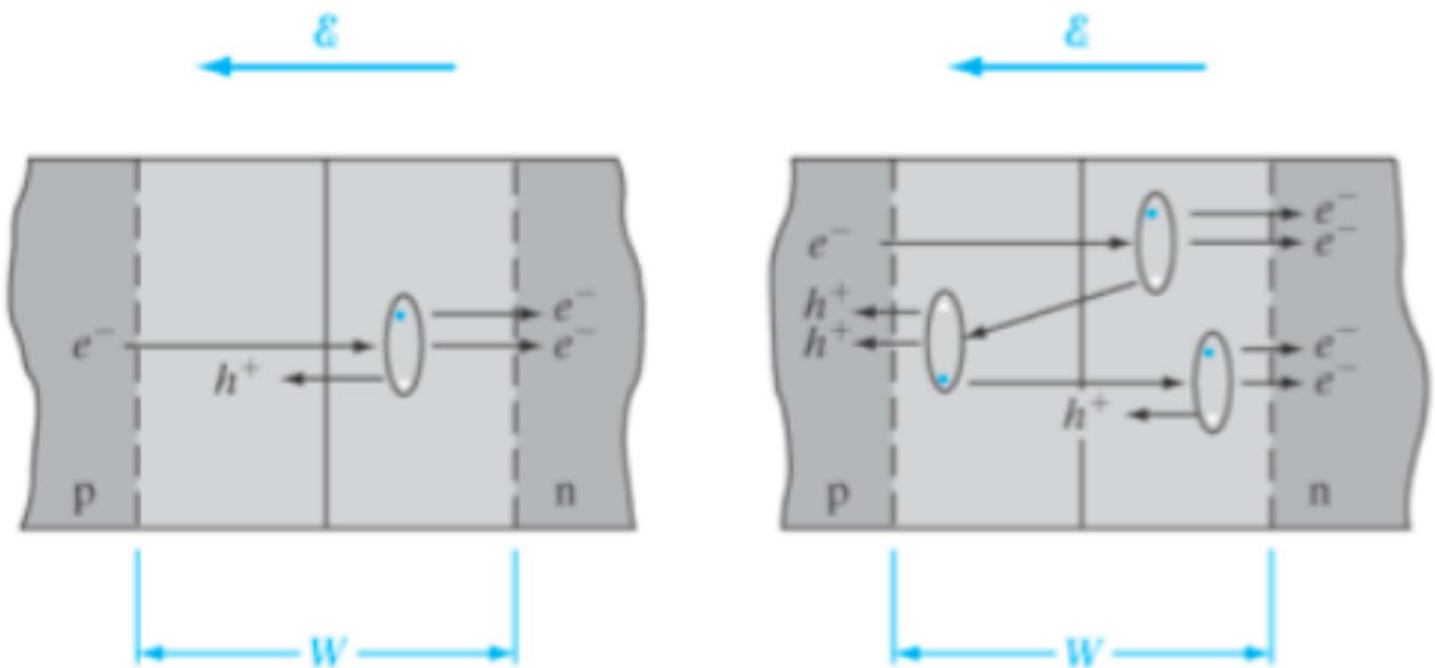
- Tunneling currents can be established when a large number of electrons are separated from a large number of empty states by a narrow barrier of finite height;
- The junction must be sharp, and the doping is high (small transition region);
- increasing voltage will produce steeper bands, decreasing the tunneling distance;

Impact ionization and Avalanche breakdown



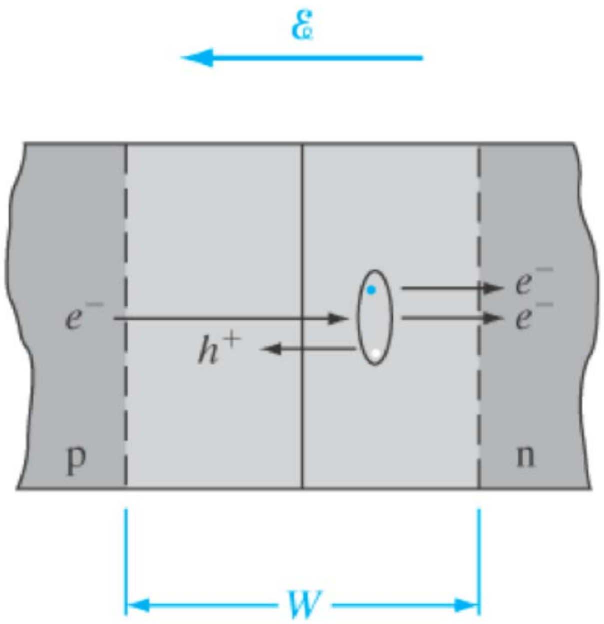
- An electron entering the depletion region is accelerated under high field;
- If enough energy is gained, an ionizing collision with lattice can produce an electron-hole pair (impact ionization)
- Carrier multiplication occurs (1e→2e+1h)

Impact ionization and avalanche breakdown



- impact ionization can also occur for the electron or hole created by the first impact ionization event
- This is an avalanche process- a single carrier can produce a large number of electron-hole pairs

Avalanche Breakdown: Mathematical Treatment



Assume either carrier type has a probability "P" of having an ionizing collision over a distance "W":
1) For n_{in}electrons entering, Pn_{in} electrons will be created and
the total number of electrons exiting will be n_{in} + Pn_{in}
2) Each created EHP travels a combined distance of "W"
3) The probability of an ionizing collision for secondary carriers is therefore still "P" - for Pn_{in} secondary pairs there will be $P(Pn_{in})$ collisions and P^2n_{in} tertiary pairs,

$$n_{out} = n_{in}(1 + P + P^2 + P^3 + \cdots)$$

Avalanche Breakdown: Mathematical Treatment

- **The electron multiplication is**

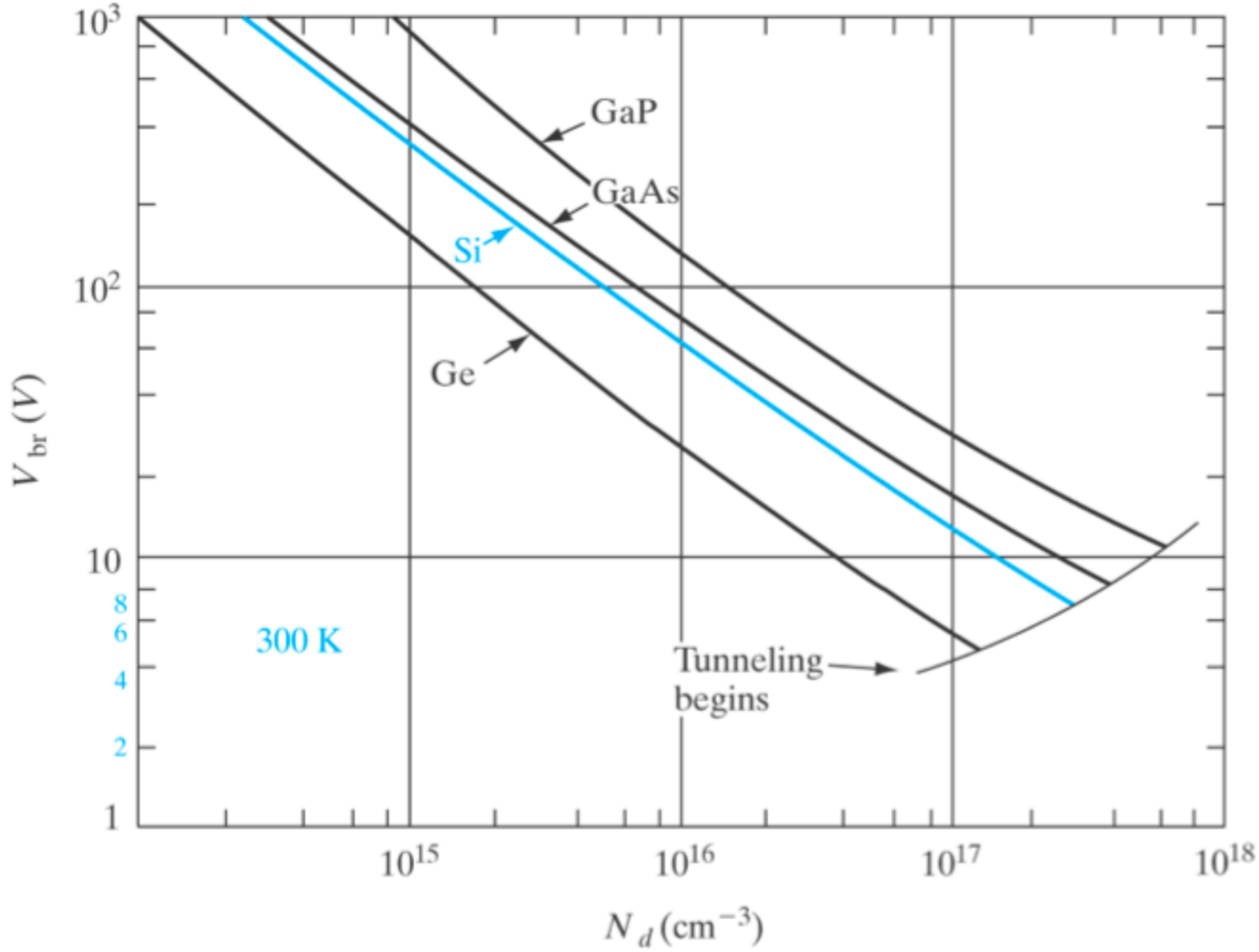
$$M = \frac{n_{out}}{n_{in}} = 1 + P + P^2 + P^3 + \cdots = \frac{1}{1-P}$$

The empirical relationship between M, applied voltage V, and breakdown voltage V_{br} is:

$$M = \frac{1}{1 - (\frac{V}{V_{br}})^n}$$

where n typically varies from 3 to 6

Variation of breakdown voltage with Material and Doping



- V_{br} **increases with increasing bandgap**
- V_{br} **decreases with increasing doping,(peak electric field in depletion region is higher)**

Breakdown diode

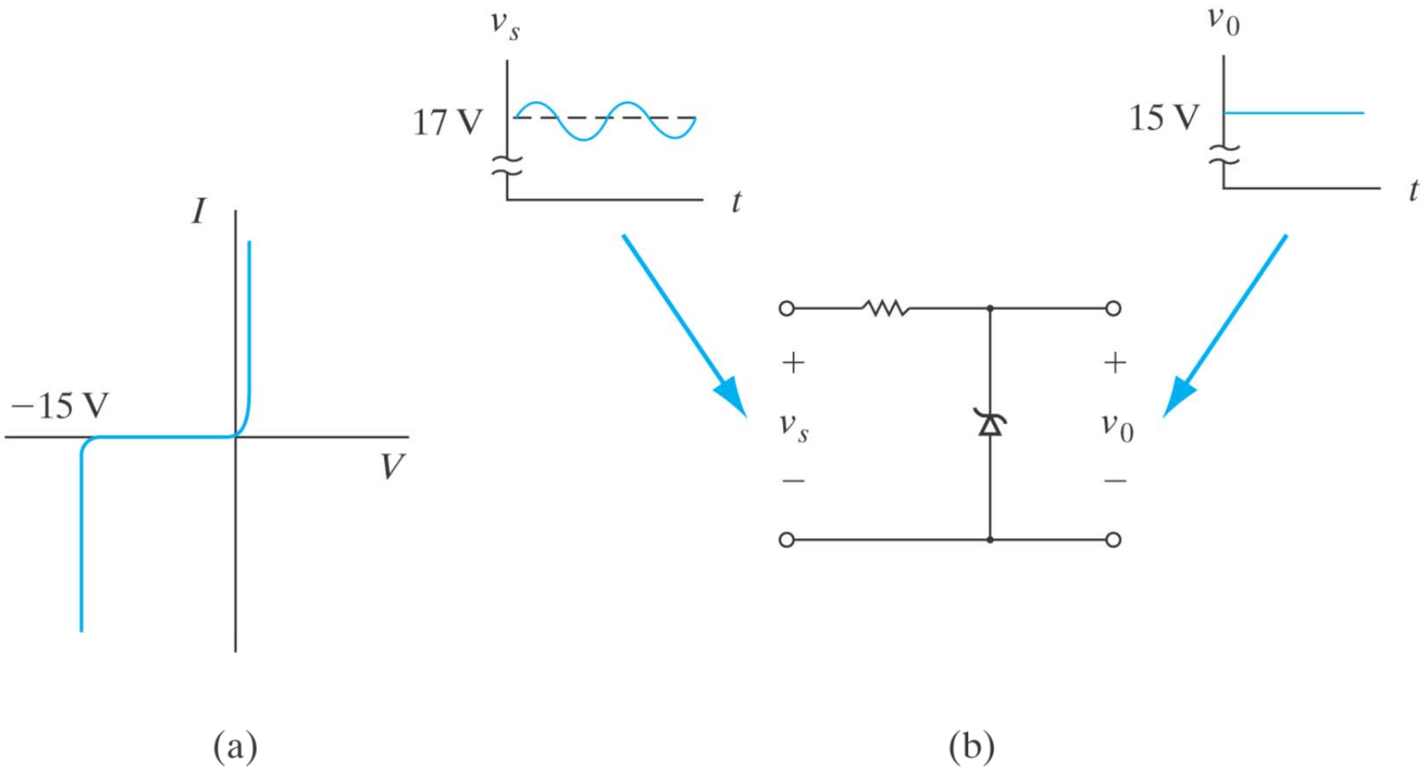


Figure 5.26

A breakdown diode: (a) *I–V* characteristic; (b) application as a voltage regulator.