ECE 340 Lecture 24
Semiconductor Electronics

Spring 2022
10:00-10:50am
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2062 ECE Building

Today's Discussion

- **The p-n junction out of equilibrium - 3**

Ideal diode current equation

$$I = \underbrace{qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)}_{\text{Term dependent on doping and material}}\left[\exp\left(\frac{qV}{k_B T}\right) - 1\right]$$

$$\frac{D_p}{\sqrt{D_p\tau_p}}p_n = \sqrt{\frac{D_p}{\tau_p}}\,p_n$$

$$\frac{D_n}{\sqrt{D_n\tau_n}}n_p = \sqrt{\frac{D_n}{\tau_n}}\,n_p$$

If $\sqrt{\frac{D_p}{\tau_p}}\,p_n \gg \sqrt{\frac{D_n}{\tau_n}}\,n_p$

holes dominate current

If $\sqrt{\frac{D_n}{\tau_n}}\,n_p \gg \sqrt{\frac{D_p}{\tau_p}}\,p_n$

electrons dominate current

Reverse saturation current

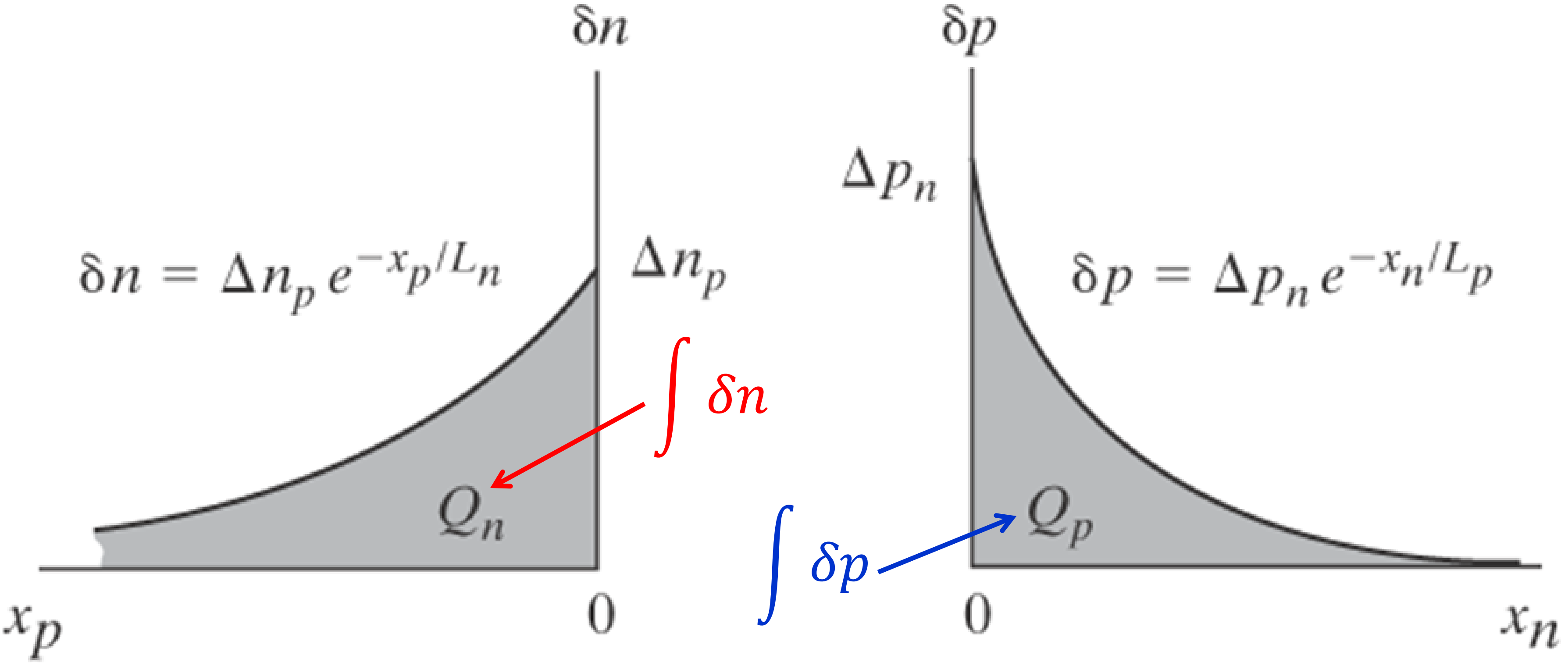
Reverse bias $V = -V_r$

$$I = I_0\left[\exp\left(-\frac{qV_r}{k_B T}\right) - 1\right]$$

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

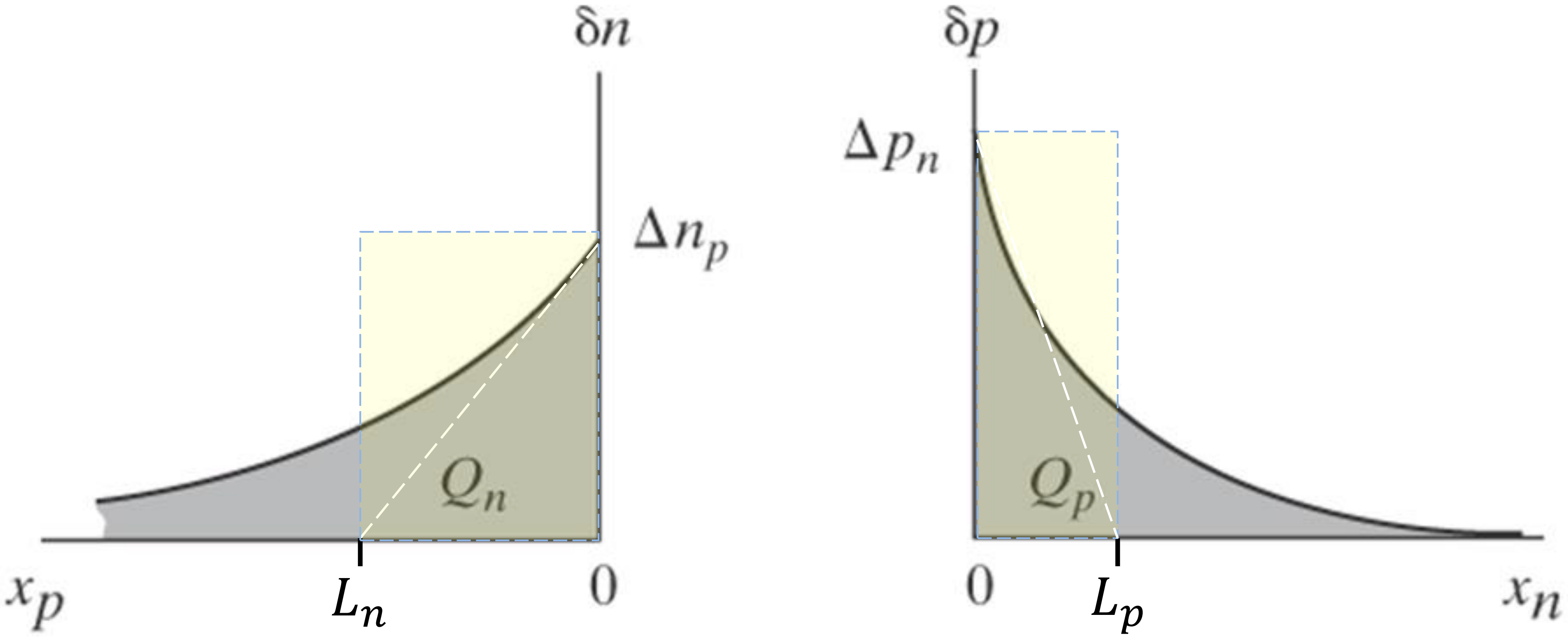
Charge Control Approximation

Another way to calculate current



$$Q_n = -qA\int_0^\infty \delta n \, dx_p \qquad Q_p = qA\int_0^\infty \delta p \, dx_n$$

We found earlier this result



$$Q_n = -qA\, L_n\, \Delta n_p \qquad Q_p = qA\, L_p\, \Delta p_n$$

$$L_n^2 = D_n \tau_n \qquad L_p^2 = D_p \tau_p$$

Charge Control Approximation

Current is *Charge/Time.* For each species we approximate

Current = (Stored Excess Charge) / (Average Lifetime)

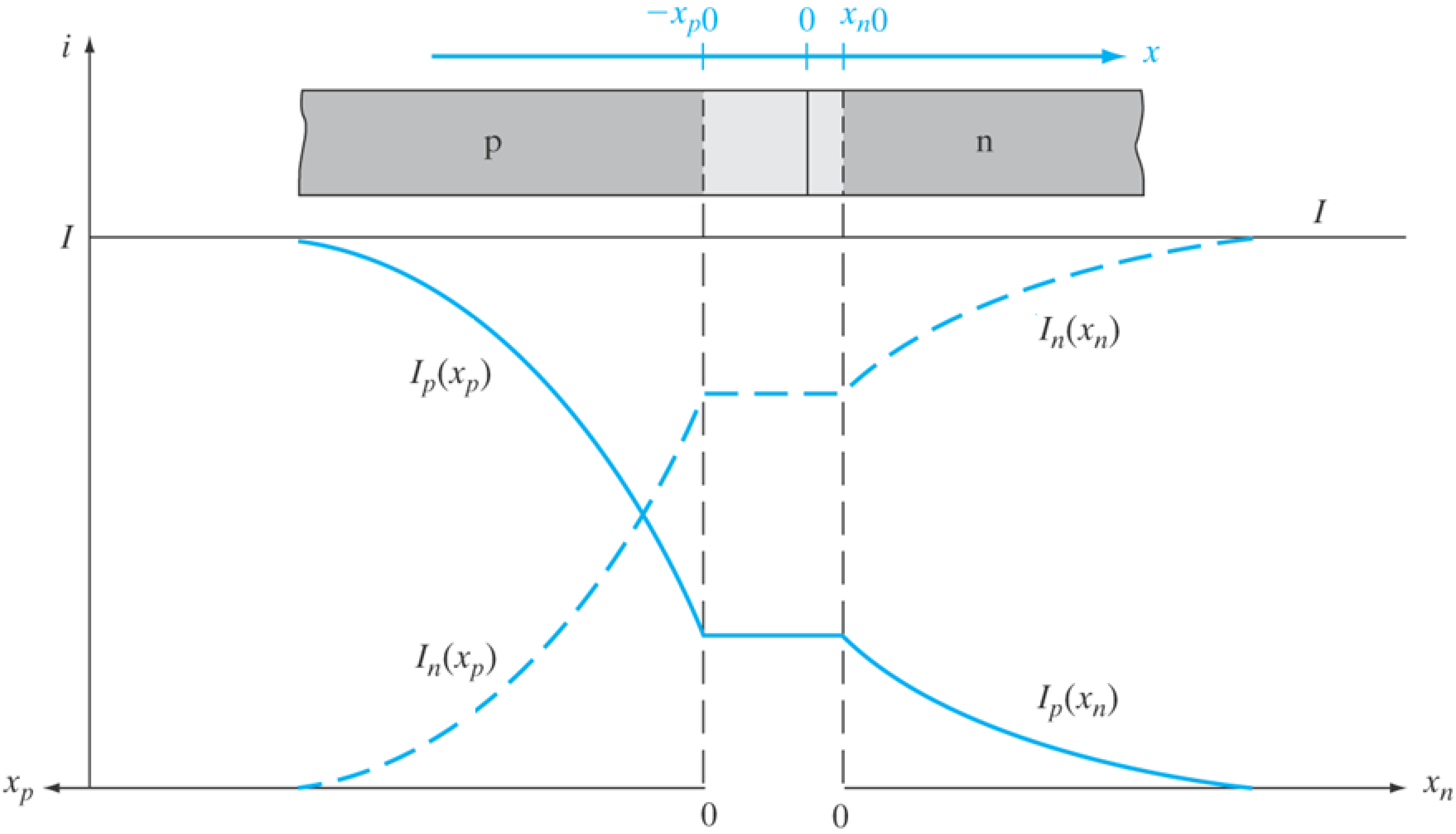
$$Q_n = -qA\,L_n\,\Delta n_p \qquad L_n^2 = D_n\tau_n$$

$$I_n(x_p = 0) = \frac{Q_n}{\tau_n} = -qA\frac{L_n}{\tau_n}\Delta n_p = -qA\frac{D_n}{L_n}\Delta n_p$$

$$Q_p = qA\,L_p\,\Delta p_n \qquad L_p^2 = D_p\tau_p$$

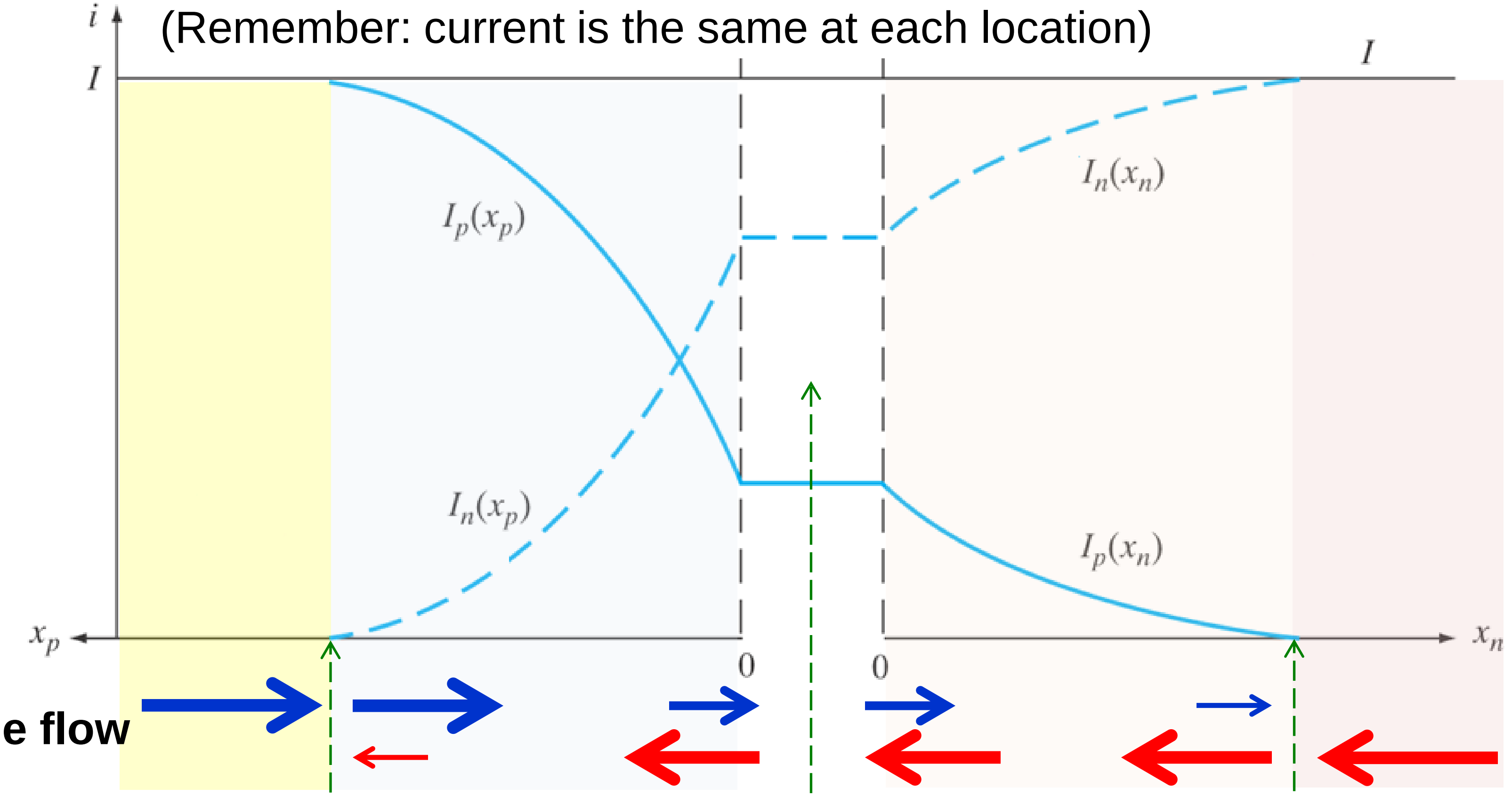
$$I_p(x_n = 0) = \frac{Q_p}{\tau_p} = qA\frac{L_p}{\tau_p}\Delta p_n = qA\frac{D_p}{L_p}\Delta p_n$$

Complete picture of current $(N_D > N_A)$



Note: The book does not have this diagram for the case it considers. This Figure has been recreated to look like the one for $(N_A > N_D)$ in the textbook. Examine the differences.

Details of particle flows ($N_D > N_A$)



(Remember: current is the same at each location)

Particle flow

Current consists only of majority holes

Current consists of majority holes and minority electrons with recombination occurring

Current consists of majority electrons and minority holes with recombination occurring

Current consists only of majority electrons

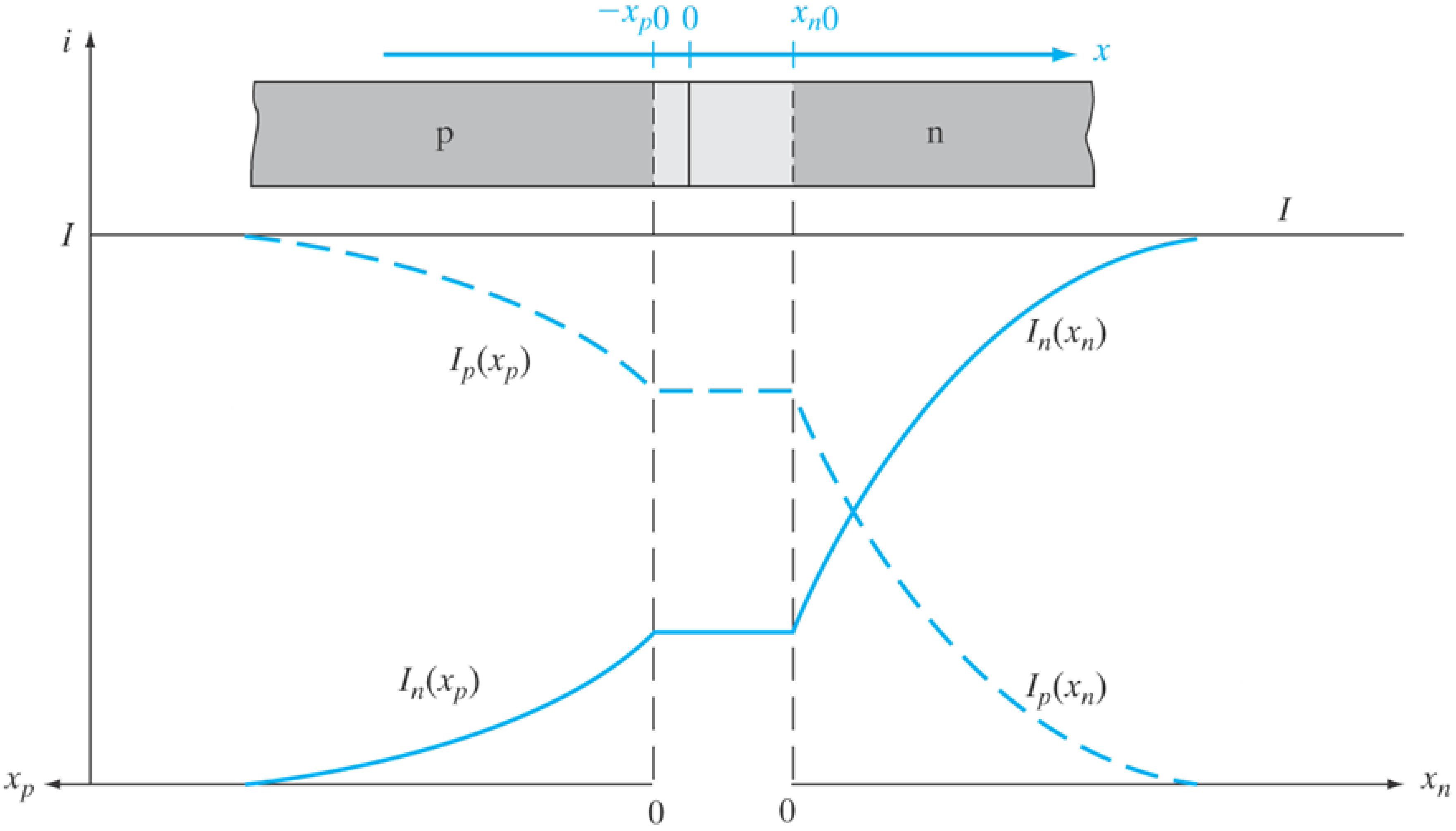
Practically all excess minority electrons have recombined

Assumption of no recombination

Practically all excess minority holes have recombined

Complete picture of current $(N_A > N_D)$

This is the Figure in the text book



From *Solid State Electronic Devices,* Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.
ISBN 0-13-149726-X.

Finding the majority current (e.g., *n*-side)

Total current

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right]$$

Hole minority current at any point on n-side

$$I_p(x_n) = qA\frac{D_p}{L_p}p_n\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right]\exp\left(-\frac{x_n}{L_p}\right)$$

$$I_n(x_n) = I - I_p(x_n) =$$
$$= qA\left[\frac{D_p}{L_p}p_n\left(1 - \exp\left(-\frac{x_n}{L_p}\right)\right) + \frac{D_n}{L_n}n_p\right]\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right]$$

Reverse saturation current

Reverse bias $V = -V_r$

$$I = I_0 \left[\exp\left(-\frac{qV_r}{k_B T} \right) - 1 \right]$$

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

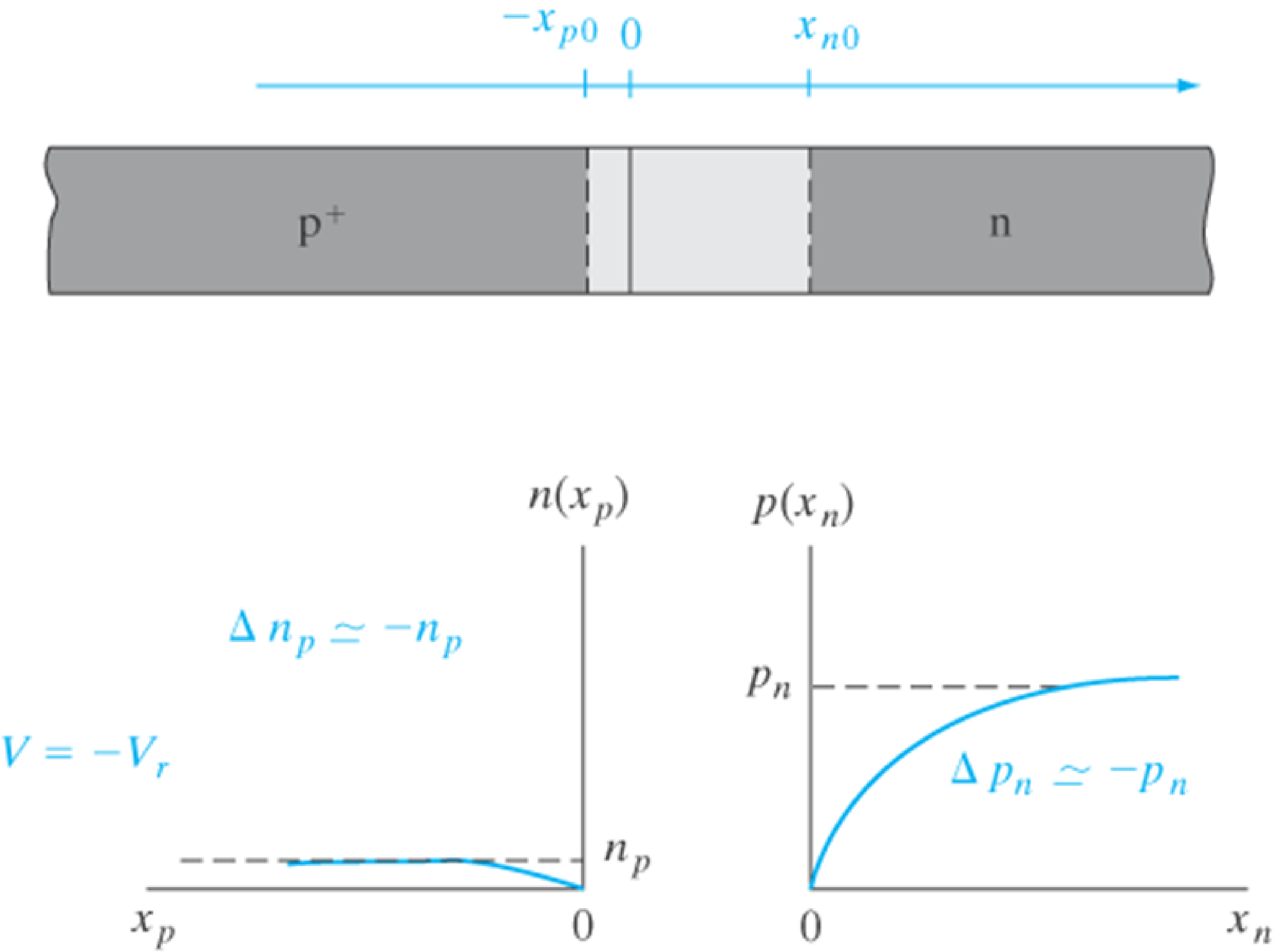
Reverse saturation current

Reverse bias $V = -V_r \quad \text{with} \quad V_r \gg k_B T/q$

$$\Delta p_n = p_n \left[\exp\left(-\frac{qV_r}{k_B T}\right) - 1\right] \approx -p_n$$

$$\Delta n_p = n_p \left[\exp\left(-\frac{qV_r}{k_B T}\right) - 1\right] \approx -n_p$$

Reverse bias minority carriers



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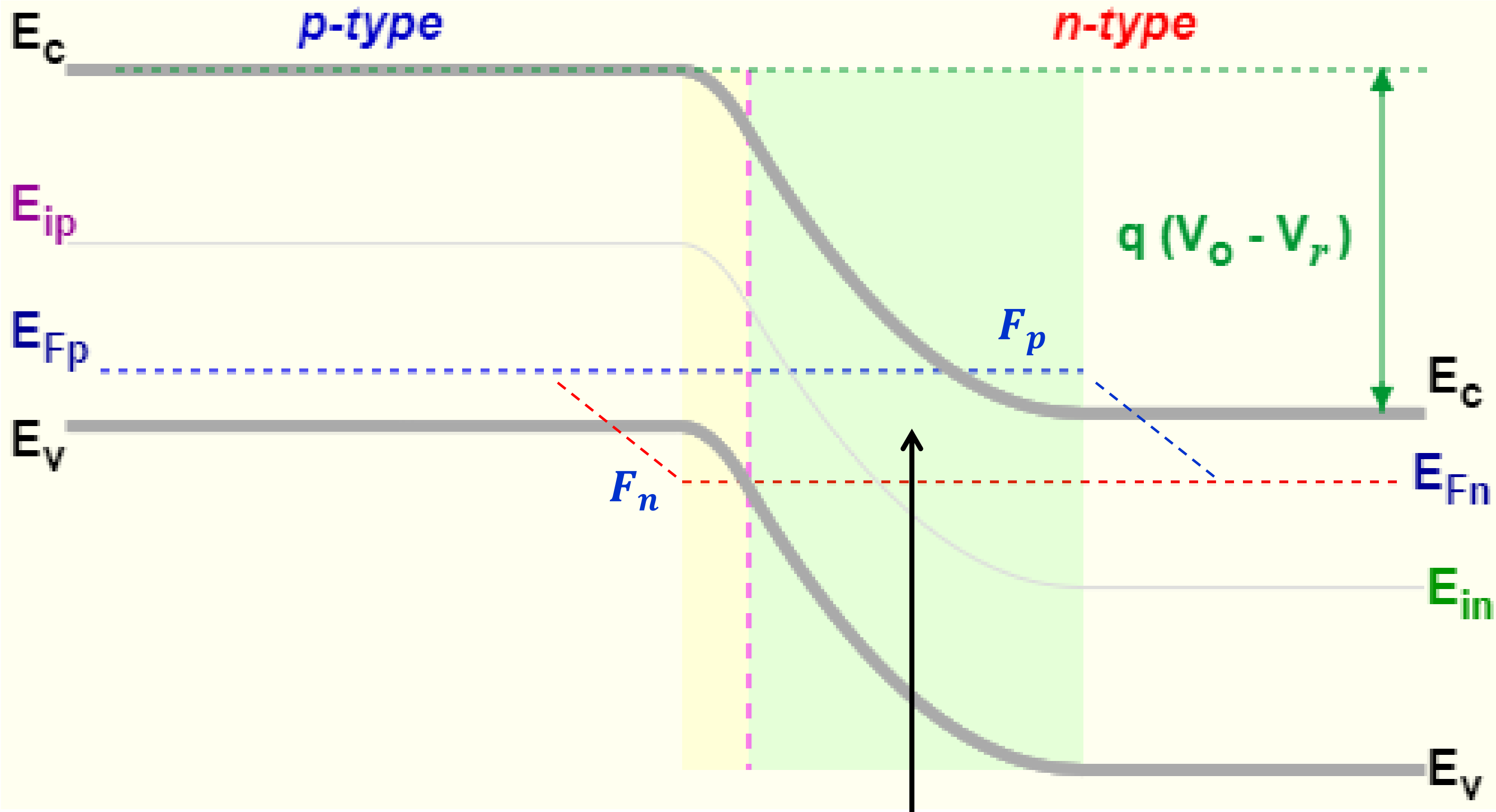
Quasi-Fermi level reminder

$$n = n_i \exp\left(\frac{F_n - E_i}{k_B T}\right)$$

$$p = n_i \exp\left(\frac{E_i - F_p}{k_B T}\right)$$

$$pn = n_i^2 \exp\left(\frac{F_n - E_i + E_i - F_p}{k_B T}\right)$$
$$= n_i^2 \exp\left(\frac{F_n - F_p}{k_B T}\right)$$

Reverse bias minority carriers



$$pn = n_i^2 \exp\left(\frac{F_n - F_p}{k_B T}\right) \approx 0$$

Pictorial summary of a p+/n junction

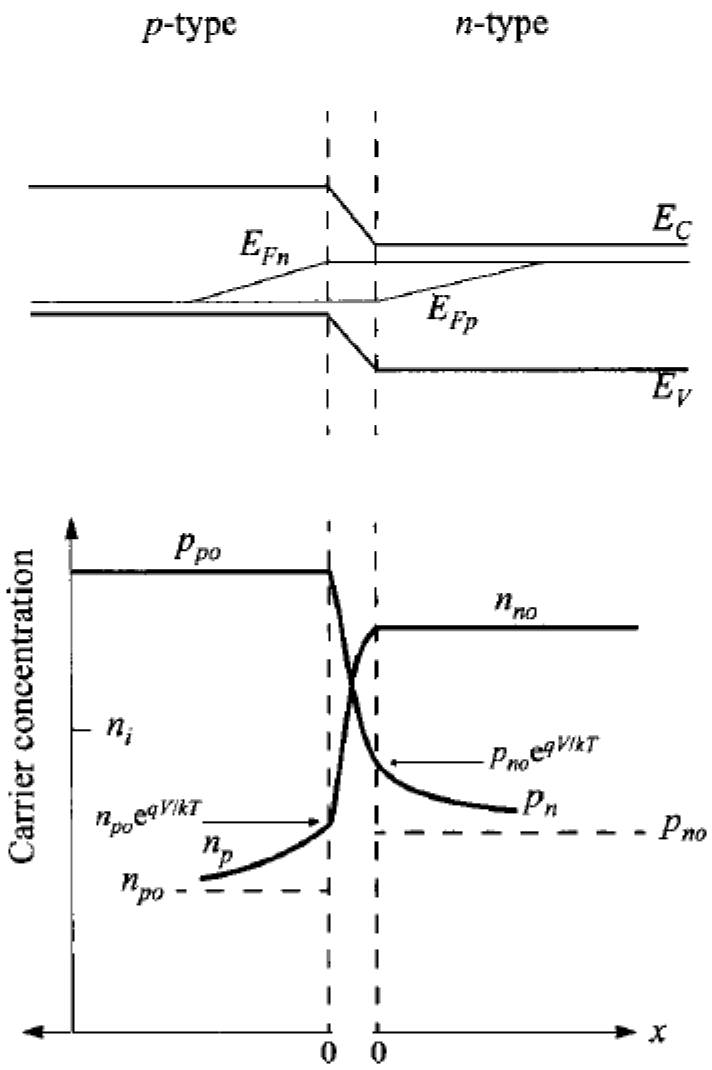
The following summary slides are adapted from the most recent edition (2006) of a classic comprehensive book on semiconductor devices. This book can be downloaded through the University Library:

S.M. Sze and K.K. Ng “Physics of Semiconductor Devices”

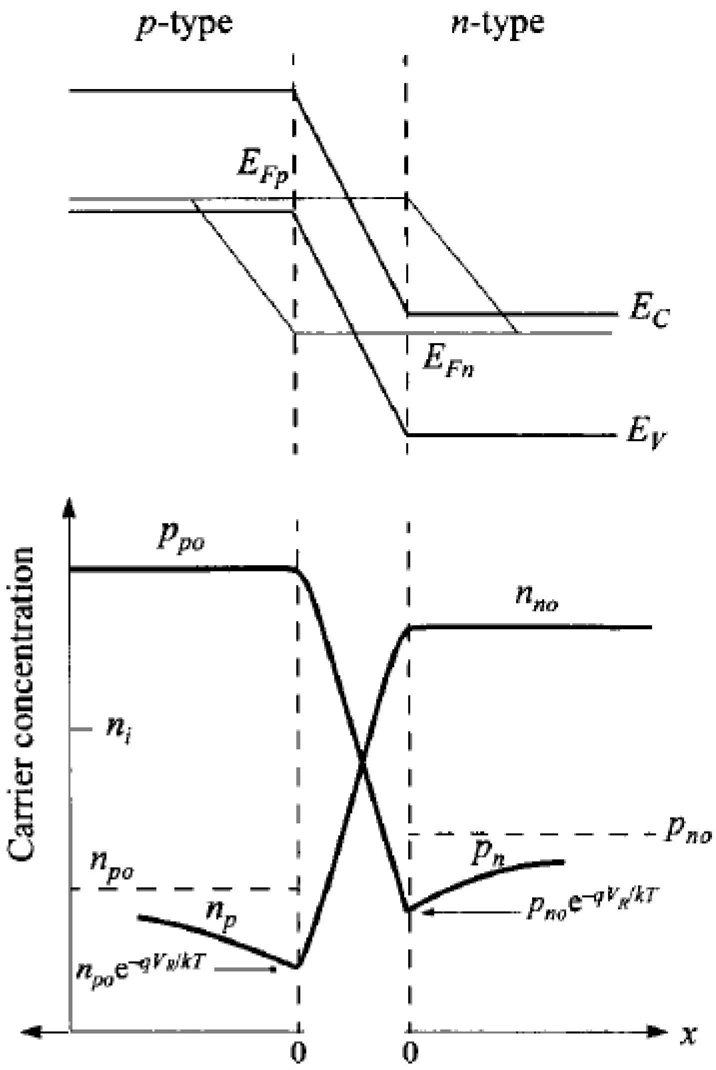
https://vufind.carli.illinois.edu/vf-uiu/Record/uiu_6805644

from the Wiley Online Library. For students who are interested in continuing with semiconductors or who simply want to have the standard reference which most professionals have used since the 1970’s, this is highly recommended.

Forward bias



Reverse bias



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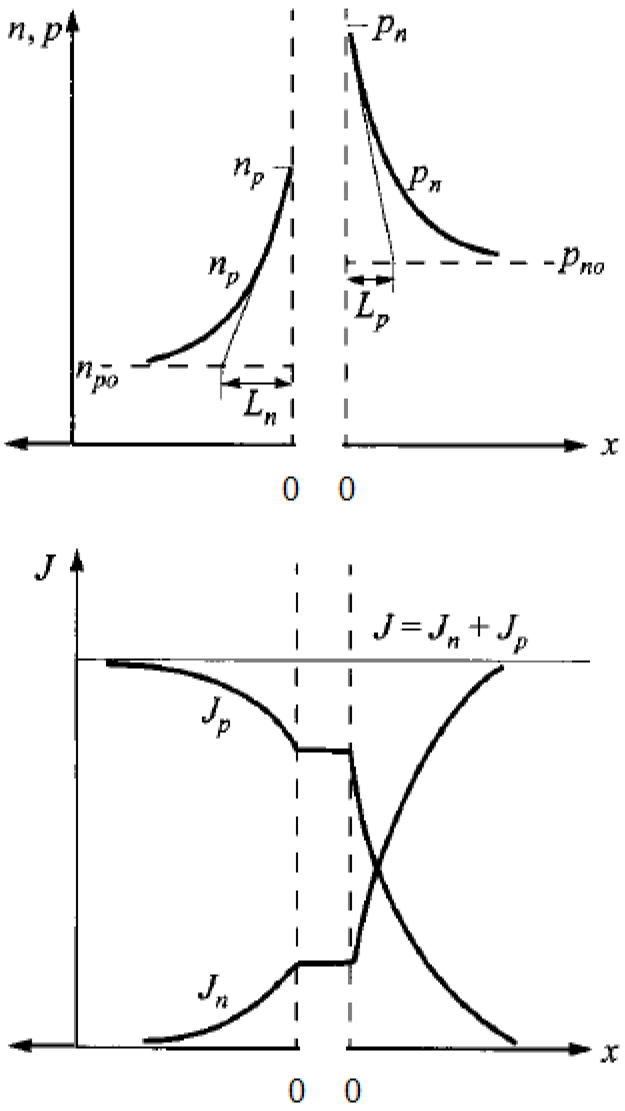
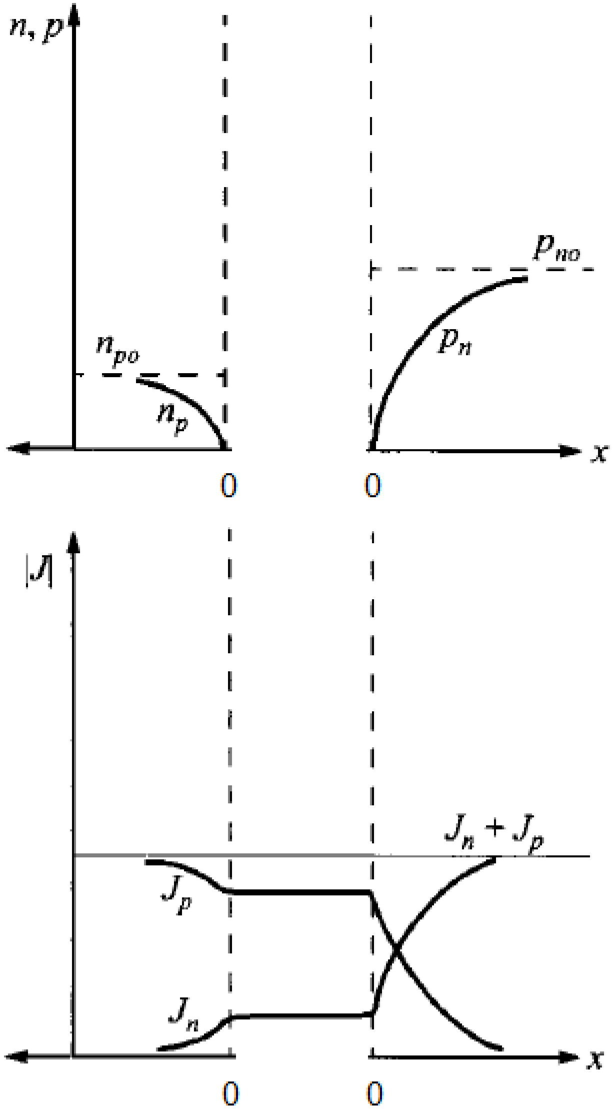
Forward bias



Reverse bias



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