
بسم الله الرحمن الرحيم

CHAPTER 3

p–*n* Junction

- 3.1 THERMAL EQUILIBRIUM CONDITION
- 3.2 DEPLETION REGION
- 3.3 DEPLETION CAPACITANCE
- ➡ 3.4 CURRENT-VOLTAGE CHARACTERISTICS
- 3.5 CHARGE STORAGE AND TRANSIENT BEHAVIOR
- 3.6 JUNCTION BREAKDOWN
- 3.7 HETEROJUNCTION
- SUMMARY

3.4.1 Ideal Characteristics

- We now derive the ideal current-voltage characteristics based on the following assumptions:
- (a) the depletion region has abrupt boundaries and, outside the boundaries, the semiconductor is assumed to be neutral;
- (b) the carrier densities at the boundaries are related by the electrostatic potential difference across the junction;

- (c) the low-injection condition, that is, the injected minority carrier densities are small compared with the majority carrier densities (in other words, the majority carrier densities are changed negligibly(ناچیز) at the boundaries of neutral regions by the applied bias);

- (d) neither generation nor recombination current exists in the depletion region and the electron and hole currents are constant throughout the depletion region.

- Departures from these idealized assumptions are considered in the next section.

- At thermal equilibrium, the majority carrier density in the neutral regions is essentially equal to the doping concentration.

- We use the subscripts *n* and *p* to denote the semiconductor type and the subscript *o* to specify the condition of thermal equilibrium.

- Hence, n_{no} and n_{po} are the equilibrium electron densities in the *n*- and *p*-sides, respectively.

- The expression for the built-in potential in Eq. 12 can be rewritten as

$$\boxed{V_{bi} = \psi_n - \psi_p = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right).} \qquad (12)$$

$$V_{bi} = \frac{kT}{q}\ln\frac{p_{po}n_{no}}{n_i^2} = \frac{kT}{q}\ln\frac{n_{no}}{n_{po}}, \qquad (44)$$

- where the mass action law $p_{po}n_{po} = ni^2$ has been used. Rearranging Eq. 44 gives

$$n_{no} = n_{po}e^{qV_{bi}/kT}. \qquad (45)$$

- Similarly, we have

$$p_{po} = p_{no}e^{qV_{bi}/kT}. \qquad (46)$$

- We note from Eqs. 45 and 46 that the electron density and the hole density at the two boundaries of the depletion region are related through the electrostatic potential difference V_{bi} at thermal equilibrium.

- From our second assumption we expect that the same relation holds when the electrostatic potential difference is changed by an applied voltage.

- When a forward bias is applied, the electrostatic potential difference is reduced to $V_{bi} - V_F$; but when a reverse bias is applied, the electrostatic potential difference is increased to $V_{bi} + V_R$.

- Thus, Eq. 45 is modified to

$$n_n = n_p e^{q(V_{bi} - V)/kT} , \tag{47}$$

- where n_n and n_p are the nonequilibrium electron densities at the boundaries of the depletion region in the *n*- and *p*-sides, respectively, with V positive for forward bias and negative for reverse bias.

- For the low-injection condition, the injected minority carrier density is much smaller than the majority carrier density; therefore, $n_n \cong n_{no}$.

- Substituting this condition and Eq. 45 into Eq. 47 yields the electron density at the boundary of the depletion region on the p-side ($x = -x_p$):

وقتی فرض تیز بودن چگالی در ابتدای این
جلسه لحاظ شده است یعنی چگالی در مرز با
سایر ناحیه خنثی یکی است.

$$n_p = n_{po} e^{qV/kT} \tag{48}$$

اثبات این روابط در اسلاید بعدی

or

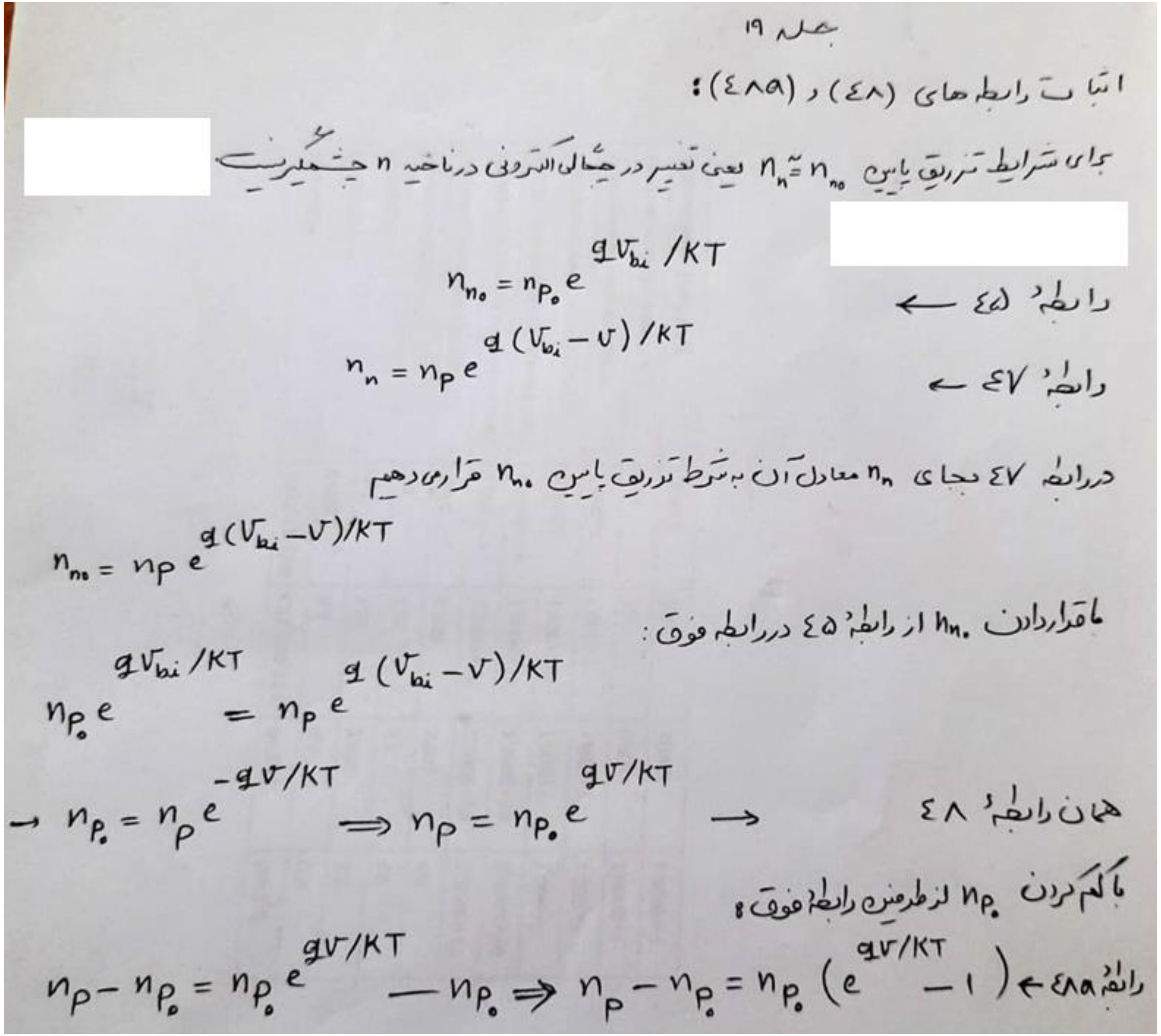
$$n_p - n_{po} = n_{po} \left(e^{qV/kT} - 1 \right). \tag{48a}$$

Similarly, we have

$$p_n = p_{no} e^{qV/kT} \tag{49}$$

or

$$p_n - p_{no} = p_{no} \left(e^{qV/kT} - 1 \right) \tag{49a}$$



جلسه ۱۹

اثبات رابطه های (۴۸) و (۴۸a) :

[redacted] بجای شرایط تزریق پایین $n_n \simeq n_{n_0}$ یعنی تغییر در چگالی الکترونی در ناحیه n چشمگیر نیست

[redacted]

$$n_{n_0} = n_{p_0} e^{qV_{bi}/KT} \quad \leftarrow \text{رابطه ۴۵}$$

$$n_n = n_p e^{q(V_{bi}-V)/KT} \quad \leftarrow \text{رابطه ۴۷}$$

در رابطه ۴۷ بجای n_n معادل آن به شرط تزریق پایین n_{n_0} قرار می دهیم

$$n_{n_0} = n_p e^{q(V_{bi}-V)/KT}$$

با قرار دادن n_{n_0} از رابطه ۴۵ در رابطه فوق :

$$n_{p_0} e^{qV_{bi}/KT} = n_p e^{q(V_{bi}-V)/KT}$$

$$\rightarrow n_{p_0} = n_p e^{-qV/KT} \Longrightarrow n_p = n_{p_0} e^{qV/KT} \longrightarrow \text{همان رابطه ۴۸}$$

با کم کردن n_{p_0} از طرفین رابطه فوق :

$$n_p - n_{p_0} = n_{p_0} e^{qV/KT} - n_{p_0} \Rightarrow n_p - n_{p_0} = n_{p_0}\left(e^{qV/KT} - 1\right) \leftarrow \text{رابطه ۴۸a}$$

at $x = x_n$ for the n-type boundary.

- Figure 14 shows band diagrams and carrier concentrations in a *p–n* junction under forward-bias and reverse-bias conditions.
- Note that the minority carrier densities at the boundaries ($-x_p$ and x_n) increase substantially above their equilibrium values under forward bias, whereas they ↓ decrease below their equilibrium values under reverse bias.
- Equations 48 and 49 define the minority carrier densities at the boundaries of depletion region.

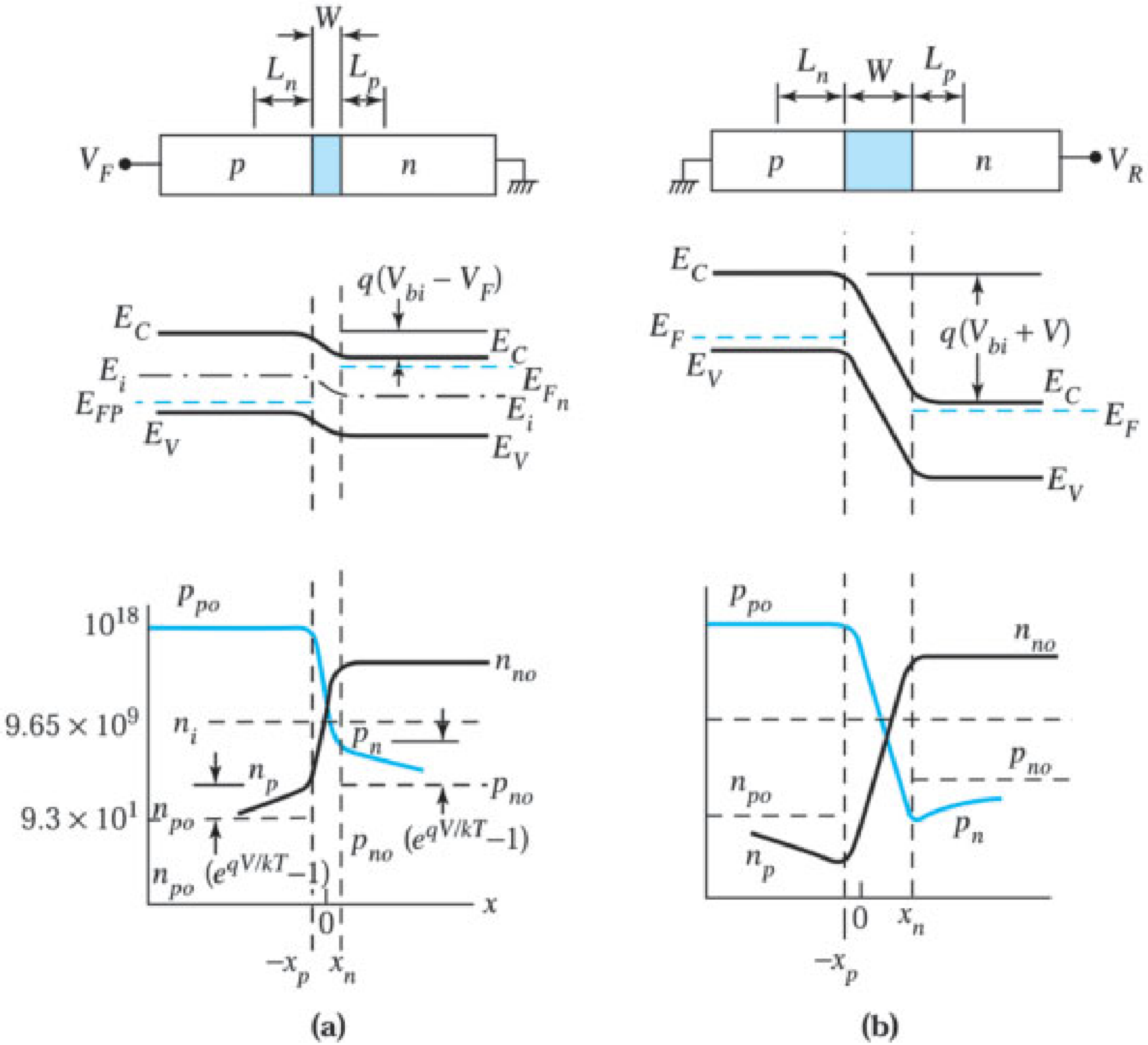


Fig. 14 **Depletion region, energy band diagram and carrier distribution. (*a*) Forward bias. (*b*) Reverse bias.**

- These equations are the most important boundary conditions for the ideal current-voltage characteristics.
- In the depletion region, the slopes of carrier distributions decrease with the forward bias, as shown in Fig. 14.
- This comes from the fast sweep of the carriers across the narrower depletion width.
- Under our idealized assumptions, no current is generated within the depletion region; all currents come from the neutral regions.

- In the neutral n-region, there is no electric field, thus the steady-state continuity equation reduces to

$$\frac{d^2 p_n}{dx^2} - \frac{p_n - p_{no}}{D_p \tau_p} = 0. \tag{50}$$

رابطه بالایی از معادله پیوستگی زیر (از فصل قبلی) بدست می آید (با فرض اینکه حالت ایستا ست یعنی تغییرات چگالی نسبت به زمان صفر بوده و همچنین میدان در ناحیه خنثی صفر فرض می شود و آهنگ تولید هم صفر در نظر گرفته می شود)

$$\boxed{\frac{\partial p_n}{\partial t} = -p_n \mu_p \frac{\partial \mathscr{E}}{\partial x} - \mu_p \mathscr{E} \frac{\partial p_n}{\partial x} + D_p \frac{\partial^2 p_n}{\partial x^2} + G_p - \frac{p_n - p_{no}}{\tau_p}.} \tag{60}$$

- The solution of Eq. 50 with the boundary conditions of Eq. 49 and $p_n\,(x = \infty) = p_{no}$

gives

تفاوت این رابطه با رابطه ۴۹ در این است که
رابطه ۴۹ برای ناحیه تخلیه و این رابطه برای ناحیه
خنثی است

$$p_n - p_{no} = -p_{no}\left(e^{qV/kT} - 1\right)e^{(x-x_n)/L_p}, \qquad (51)$$

این رابطه را باید بعنوان تکلیف ثابت کنید

where L_p, which is equal to $\sqrt{D_p\tau_p}$, is the diffusion length of holes (minority carriers) in the n-region. At $x = x_n$,

$$J_p(x_n) = -qD_p\left.\frac{dp_n}{dx}\right|_{x_n} = -\frac{qD_p p_{no}}{L_p}\left(e^{qV/kT} - 1\right). \qquad (52)$$

بخش اول رابطه فوق همان رابطه ۲. ۷. ۲۷ مربوط به جلسه ۱۲ فصل قبلی است.

به راحتی با مشتق گیری از رابطه ۵۱ و قرار دادن $x=x_n$ رابطه ۵۲ بدست می آید.

Similarly, we obtain for the neutral p-region

$$n_p - n_{po} = n_{po}\left(e^{qV/kT} - 1\right)e^{(x+x_p)/L_n} \qquad (53)$$

and

$$J_n(\ \ x_p) = qD_n \left.\frac{dn_p}{dx}\right|_{x_p} = \frac{qD_n n_{po}}{L_n}\left(e^{qV/kT} - 1\right), \qquad (54)$$

where L_n, which is equal to $\sqrt{D_n\tau_n}$, is the diffusion length of electrons. The minority carrier densities (Eqs. 51 and 53) are shown in the middle of Fig. 15.

بخش اول رابطه ۵۴ همان رابطه ۲. ۷. ۲۶ مربوط به جلسه ۱۲ فصل قبلی است.

- The graphs illustrate that the injected minority carriers recombine with the majority carriers as the minority carriers move away from the boundaries.
- The electron and hole currents are shown at the bottom of Fig. 15.

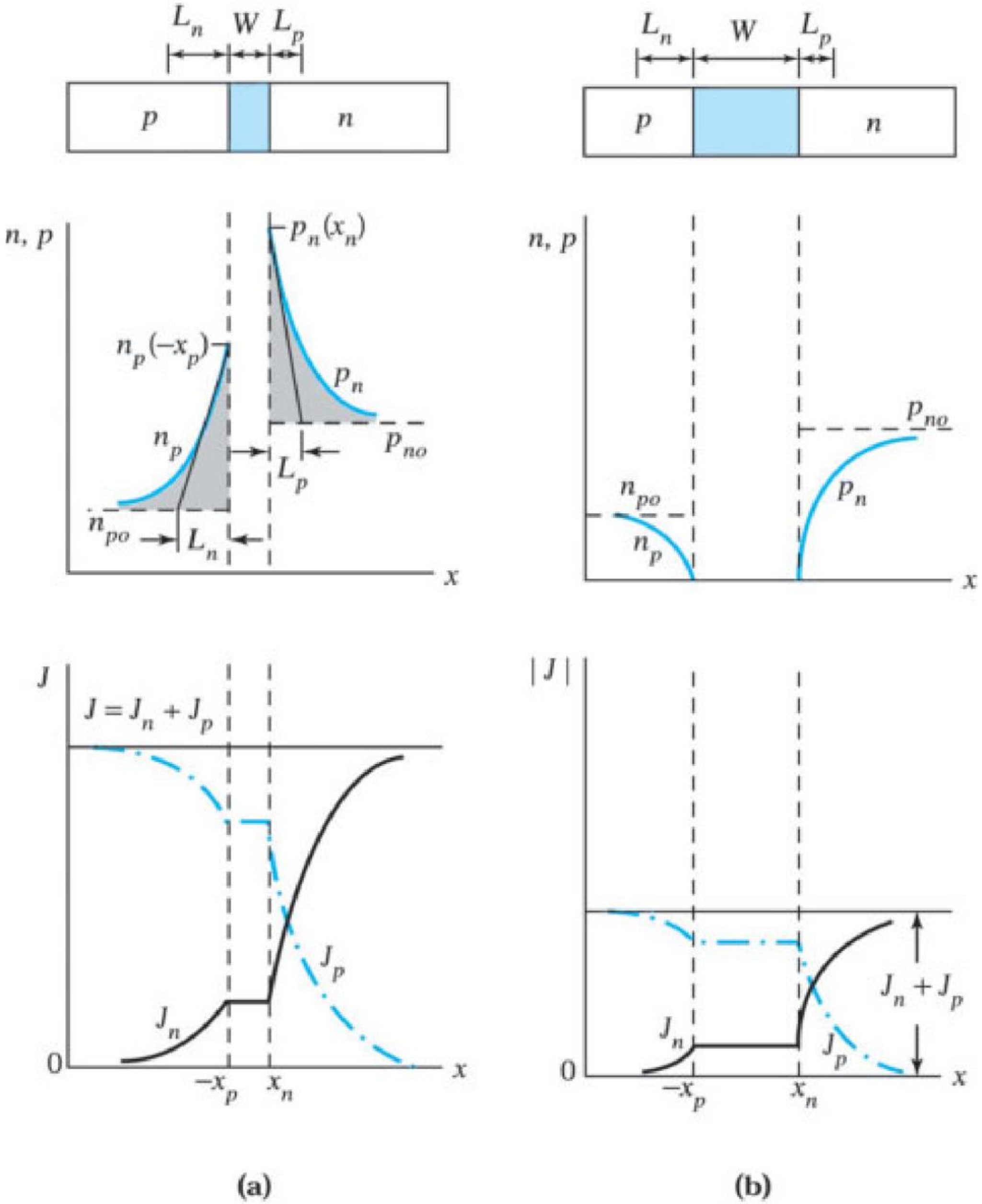


Fig. 15 **Injected minority carrier distribution and electron and hole currents. (*a*) Forward bias. (*b*) Reverse bias. The figure illustrates idealized currents. In practical devices, the currents are not constant across the space charge layer.**

- The hole and electron currents at the boundaries are given by Eqs. 52 and 54, respectively.

- The hole diffusion current will decay exponentially in the *n*-region with diffusion length L_p, and the electron diffusion current will decay exponentially in the *p*-region with diffusion length L_n.

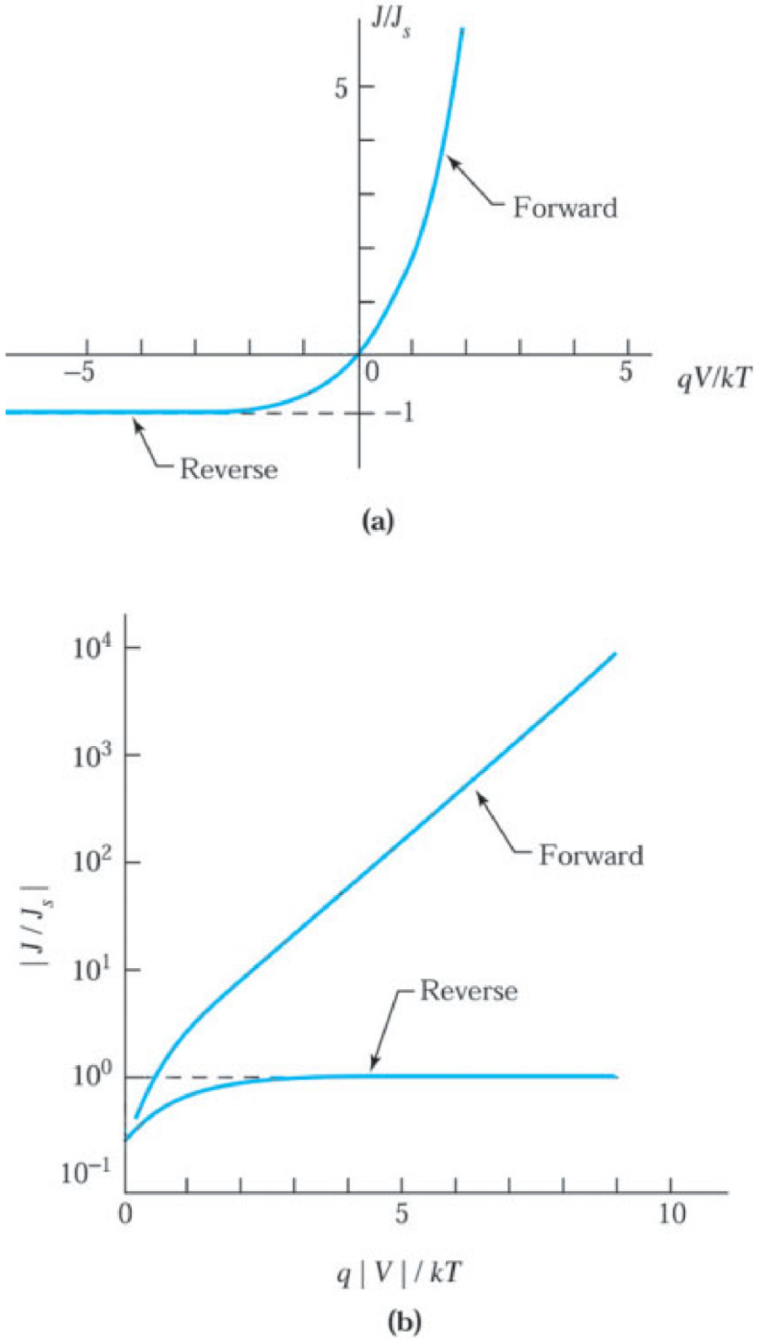
- The total current is constant throughout the device and is the sum of Eqs. 52 and 54:

در واقع جریان ناشی از دیفیوژن الکترونها و حفره هاست. وقتی در اسلایدهای قبلی ملاحظه می شود تاکید روی تغییرات اقلیت است به این معنی است که مثلاً الکترونها از سمت N به سمت P دیفیوژ می شوند(بدلیل اختلاف چگالی) ولی وقتی وارد P می شوند اینجا حامل اقلیت می شوند چون حفره ها در P اکثریت اند، لذا محاسبه چگالی جریان بر حسب تغییرات حاملهای اقلیت منطقی بنظر می رسد(روابط ۵۲ و ۵۴)

$$\boxed{J = J_p(x_n) + J_n(-x_p) = J_s\left(e^{qV/kT} - 1\right),} \tag{55}$$

$$\boxed{J_s \equiv \frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n},} \tag{55a}$$

- where J_s is the saturation current density.
- Equation 55 is the ideal diode equation.
- The ideal current-voltage characteristic is shown in Figs. 16a and 16b in Cartesian and semilog plots, respectively.



(a)

(b)

Fig. 16 **Ideal current-voltage characteristics. (*a*) Cartesian plot. (*b*) Semilog plot.**

In science and engineering, a **semilog plot**, or **semi-log graph** (or **semi-logarithmic plot/graph**), has one axis on a logarithmic scale, the other on a linear scale. It is useful for data with exponential relationships, where one variable covers a large range of values

- In the forward direction with positive bias on the p-side, for $V \geq 3kT/q$, the rate of current increase is constant, as shown in Fig. 16b.

یعنی به ازای 3<(qV/KT) مطابق شکل 16b یا
V>(3KT/q) ملاحظه می شود آهنگ تغییرات چگالی جریان
ثابت و نمودار تقریباً خطی است

- In the reverse direction, the current density saturates at $-J_s$.

- The total current for p^+-n junction is

$$J = \frac{qD_p p_{no}}{L_p}\left(e^{qV/kT} - 1\right) = \frac{qD_p}{L_p} N_V \left(e^{[qV-(E_F-E_V)]/kT} - 1\right) \qquad (55b)$$

در حالت p^+-n منظور پیوند یکطرفه است که دراینجا مثل سابق فرض شده است که چگالی در ناحیه P از ناحیه N خیلی بالاتر است در این حالت می توان تصور کرد که در ناحیه N طول پخش یعنی L_n خیلی بزرگ و متمایل به بینهایت باشد که در رابطه 55a جمله دوم صفر و فقط جمله اول باقی می ماند.

در رابطه بالا بجای p_{n0} از رابطه زیر که در فصل اول بدست آمد استفاده شده است.

$$\boxed{p = N_V \exp\left[\,(-E_F + E_V)/kT\right],} \qquad (14)$$

- The current is small if the forward bias is less than $(E_F - E_V)/q$. ↓ یعنی توان بخش نمایی رابطه 55b منفی باشد

- The current increases rapidly if the forward bias is slightly higher than $(E_F - E_V)/q$.

یعنی توان بخش نمایی رابطه 55b مثبت باشد

- This is the cut-in voltage, which is slightly less than the bandgap value in electron volts.

- Basically, the cut-in voltage increases with the bandgap.

EXAMPLE 5

Calculate the ideal reverse saturation current in a Si *p–n* junction diode with a cross-sectional area of 2 × 10^{-4} cm^2.

The parameters of the diode are

$$N_A = 5 \times 10^{16}\ \text{cm}^{-3}, \qquad N_D = 10^{16}\ \text{cm}^{-3}, \qquad n_i = 9.65 \times 10^{9}\ \text{cm}^{-3}$$
$$D_n = 21\ \text{cm}^2/\text{s}, \qquad D_p = 10\ \text{cm}^2/\text{s}, \qquad \tau_p = \tau_n = 5 \times 10^{-7}\ \text{s}.$$

با استفاده از روابط زیر مساله قابل حل است

$$\boxed{J_s \equiv \frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n},} \qquad (55a)$$

$$p_{po} n_{po} = n_i^2 \qquad p_{no}\, n_{no} = n_i^2 \qquad n_{no} = N_D \qquad p_{po} = N_A \qquad I_s = A \times J_s$$