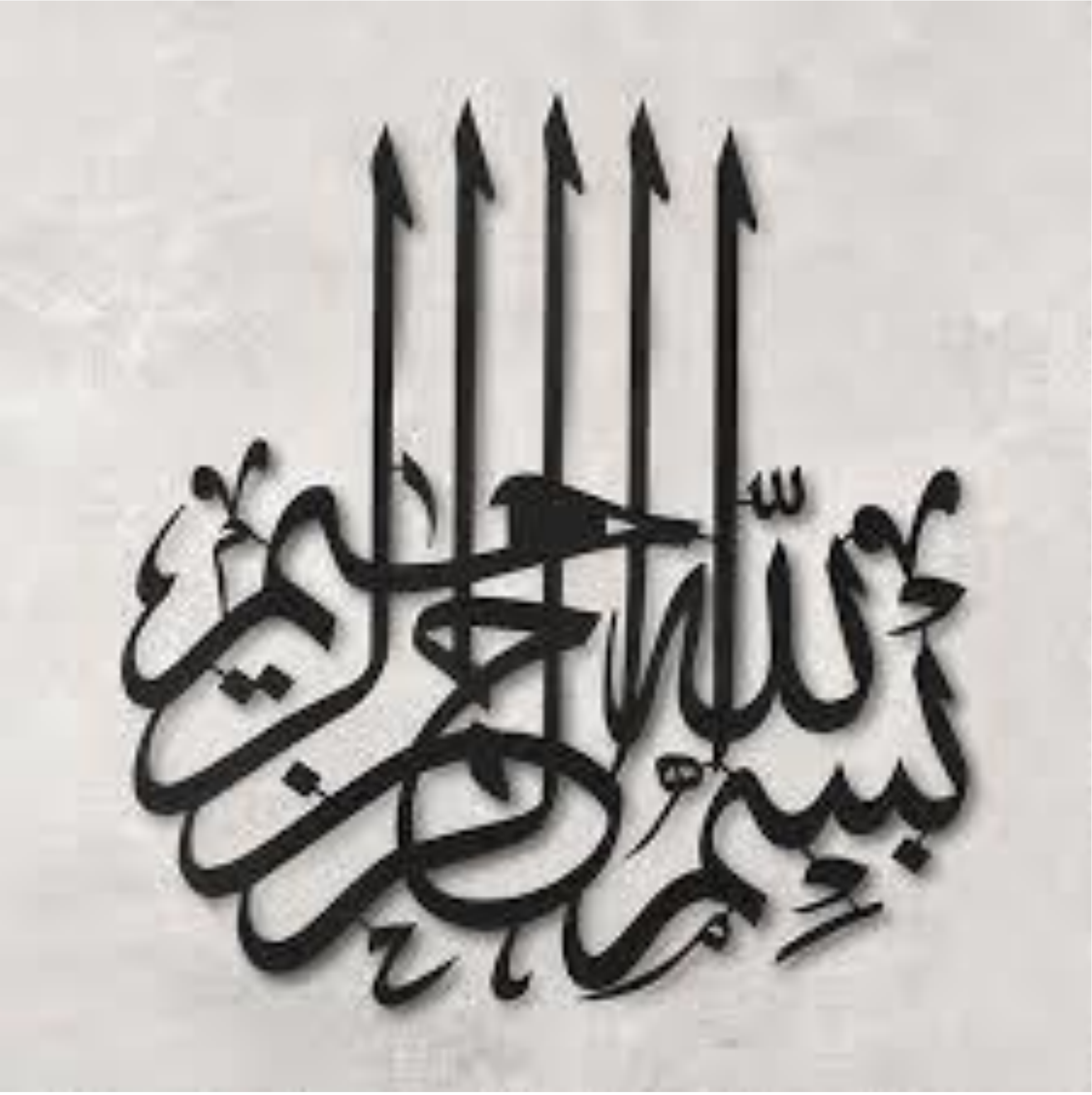
بسم الله الرحمن الرحيم

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

3.3.3 Varactor

- ✓ Many circuit applications employ the voltage-variable properties of reverse-biased p–n junctions.
- ✓ A p–n junction designed for such a purpose is called a varactor, which is a shortened form of variable reactor.
- ✓ As previously derived (Eq. 34 for abrupt and Eq. 38 for linearly graded junctions), the reverse-biased depletion capacitance is given by

$$C_j = \frac{\varepsilon_s}{W} = \sqrt{\frac{q\varepsilon_s N_B}{2(V_{bi} - V)}} \tag{34}$$

$$C_j = \frac{\varepsilon_s}{W} = \left[\frac{qa\varepsilon_s^2}{12\left(V_{bi} - V\right)}\right]^{1/3} \quad \mathrm{F/cm^2}. \tag{38}$$

$$C_j \propto \left(V_{bi} + V_R\right)^{-n} \tag{39}$$

وقتی صحبت از ولتاژ معکوس است بجای V، $-V_R$ قرار داده است.

or

$$C_j \propto \left(V_R\right)^{-n} \quad \text{for} \quad V_R >> V_{bi}, \tag{39a}$$

✓where $n = 1/3$ for a linearly graded junction and $n = 1/2$ for an abrupt junction.

✓ Therefore, the voltage sensitivity of C (i.e., variation of C with V_R) is greater for an abrupt junction than for a linearly graded junction.

✓We can further increase the voltage sensitivity by using a hyperabrupt junction having an exponent n (Eq. 39) greater than $1/2$.

✓Figure 13 shows three $p^+–n$ doping profiles with the donor distribution $N_D(x)$ given by $B(x/x0)^m$, where B and x_0 are constants, $m = 1$ for a linearly graded junction, $m = 0$ for an abrupt junction, and $m = –3/2$ for a hyperabrupt junction.

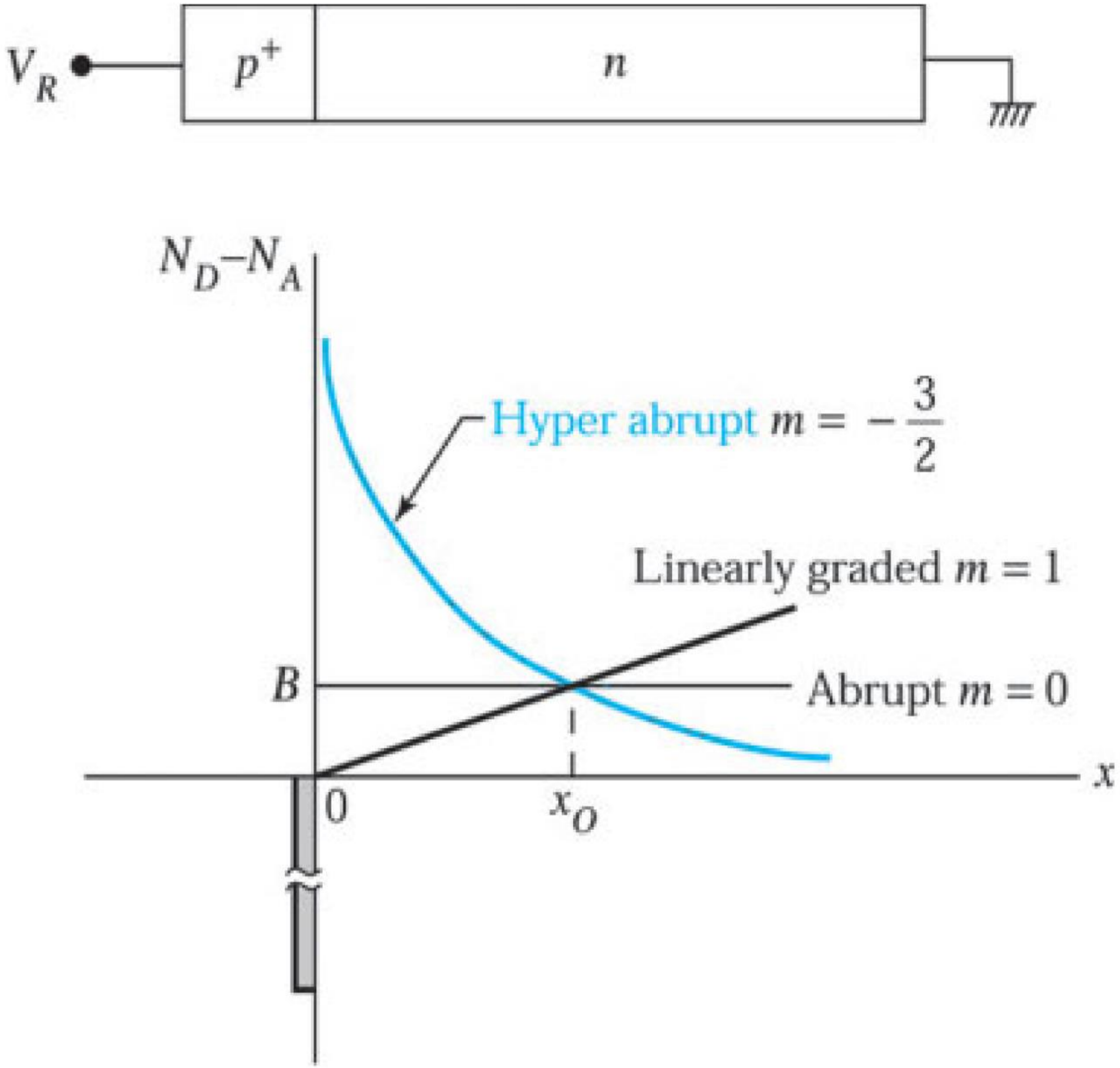

Fig. 13 **Impurity profiles for hyperabrupt, one-sided abrupt, and one-sided linearly graded junctions.**

- ✓The hyperabrupt profile can be achieved by epitaxial growth techniques discussed in Chapter 11.

- ✓To obtain the capacitance-voltage relationship, we solve the equation:

$$\frac{d^2\psi}{dx^2} = -B\left(\frac{x}{x_0}\right)^m . \tag{40}$$

- ✓Integrating Eq. 40 twice with appropriate boundary conditions gives the dependence of the depletion layer width on the reverse bias as derived for abrupt and linearly graded junctions:

$$W \propto \left(V_R\right)^{1/(m+2)}. \tag{41}$$

Therefore

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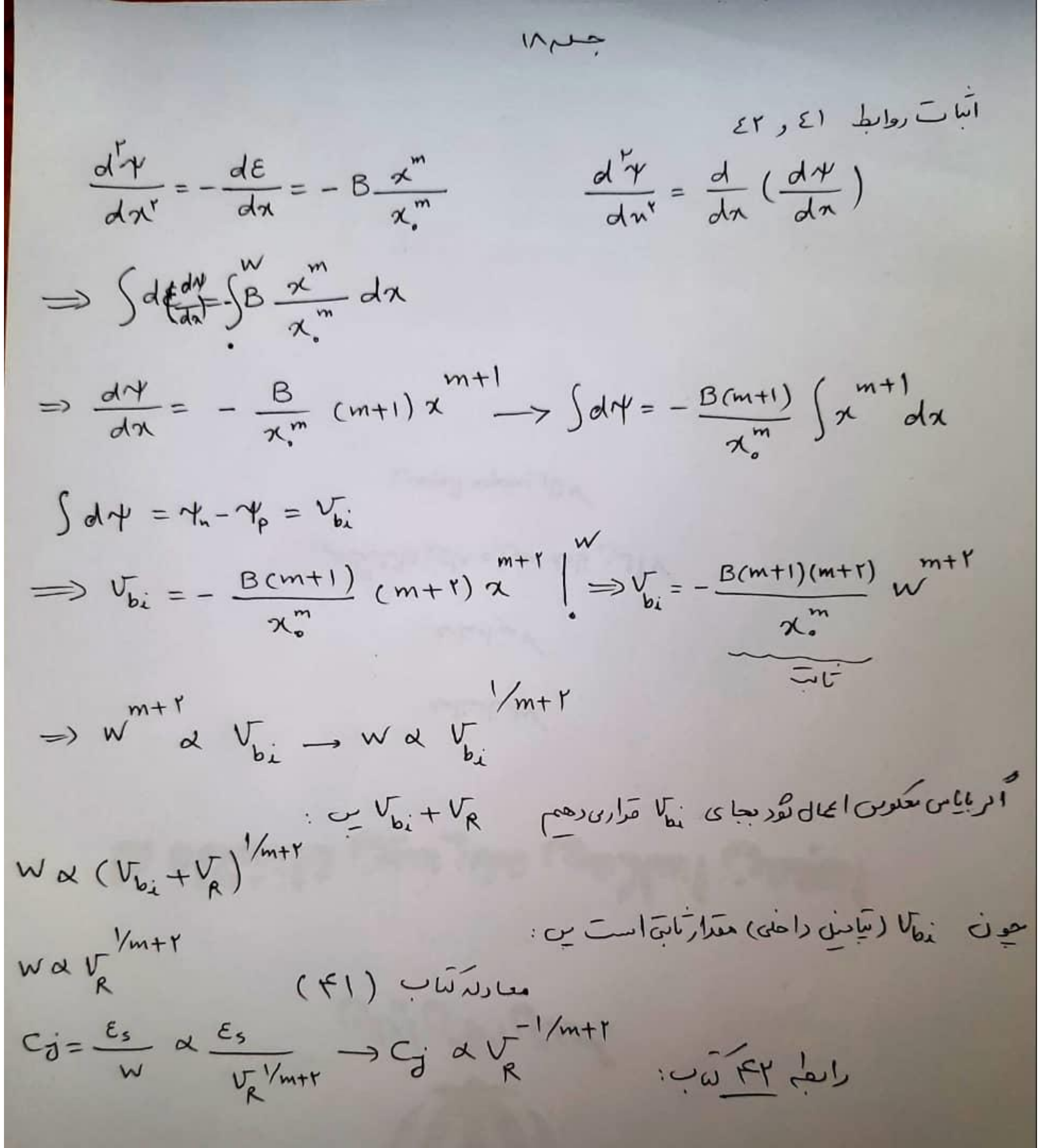
$$C_j = \frac{\varepsilon_s}{W} \propto \left(V_R\right)^{-1/(m+2)}. \tag{42}$$

- ✓Comparing Eq. 42 with Eq. 39a yields $n = l/(m + 2)$.

$$C_j \propto \left(V_R\right)^{-n} \quad \text{for} \quad V_R >> V_{bi}, \tag{39a}$$

- ✓For hyperabrupt junctions with $n > 1/2$, m must be a negative number.
- ✓By choosing different values for m, we can obtain a wide variety of C_j-versus-V_R dependencies for specific applications.



جلسه ۱۸

اثبات روابط ۴۱ و ۴۲

$$\frac{d^2\psi}{dx^2} = \frac{d}{dx}\left(\frac{d\psi}{dx}\right)$$

$$\frac{d^2\psi}{dx^2} = -\frac{d\mathcal{E}}{dx} = -B\frac{x^m}{x_0^m}$$

$$\Rightarrow \int d\left(\frac{d\psi}{dx}\right) = -\int_0^W B\frac{x^m}{x_0^m}\,dx$$

$$\Rightarrow \frac{d\psi}{dx} = -\frac{B}{x_0^m}(m+1)\,x^{m+1} \longrightarrow \int d\psi = -\frac{B(m+1)}{x_0^m}\int x^{m+1}\,dx$$

$$\int d\psi = \psi_n - \psi_p = V_{bi}$$

$$\Longrightarrow V_{bi} = -\frac{B(m+1)}{x_0^m}(m+2)\,x^{m+2}\Big|_0^W \Longrightarrow V_{bi} = -\underbrace{\frac{B(m+1)(m+2)}{x_0^m}}_{\text{ثابت}}\,W^{m+2}$$

$$\Rightarrow W^{m+2} \propto V_{bi} \longrightarrow W \propto V_{bi}^{1/m+2}$$

اگر بایاس معکوس اعمال شود بجای V_{bi} قرار می‌دهیم $V_{bi}+V_R$ پس :

$$W \propto (V_{bi}+V_R)^{1/m+2}$$

چون V_{bi} (پتانسیل داخلی) مقدار ثابتی است پس :

$$W \propto V_R^{1/m+2}$$

معادله کتاب (۴۱)

رابطه ۴۲ کتاب:

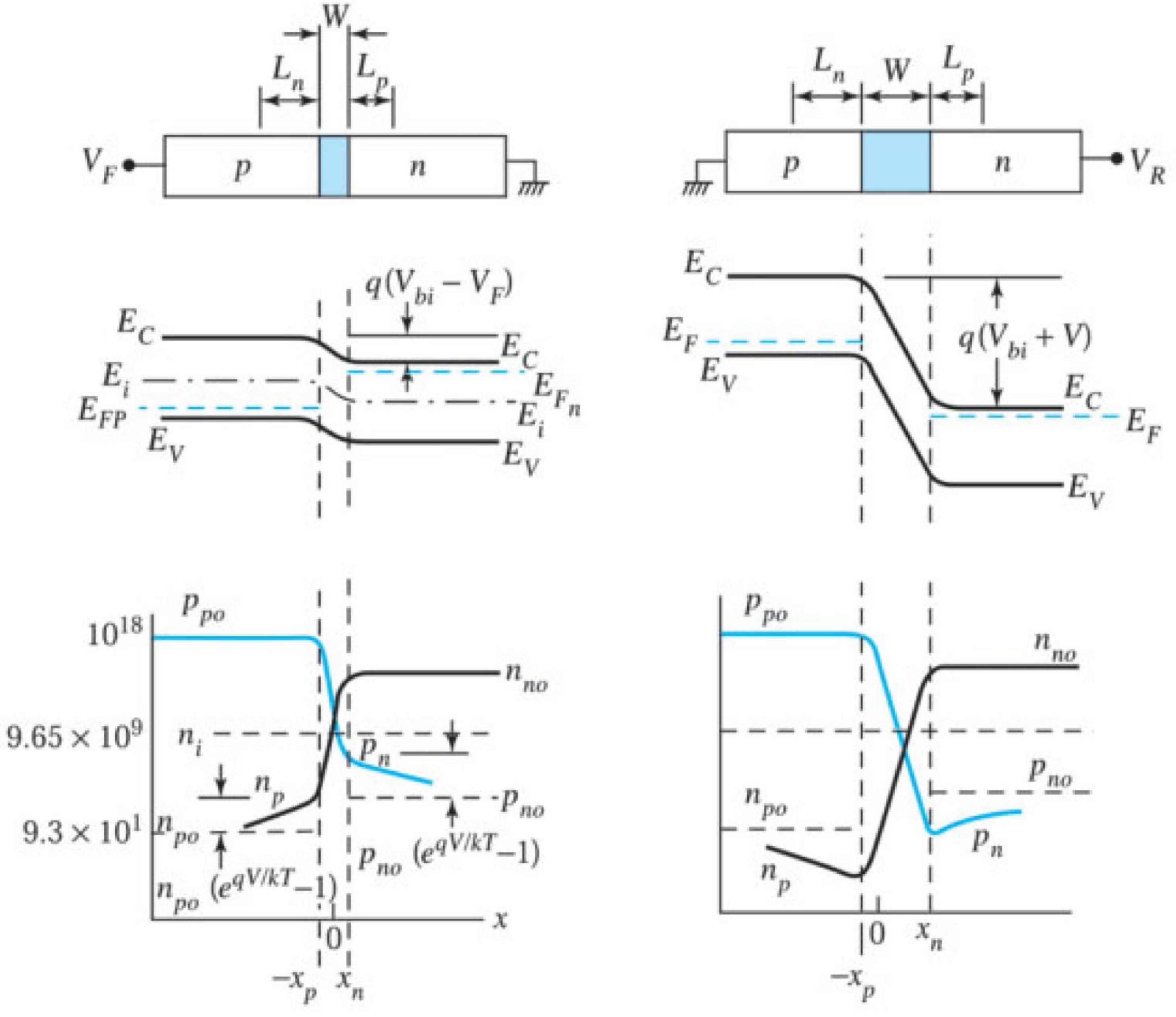
$$C_j = \frac{\varepsilon_s}{W} \propto \frac{\varepsilon_s}{V_R^{1/m+2}} \longrightarrow C_j \propto V_R^{-1/m+2}$$

- ✓One interesting example, shown in Fig. 13, is the case for $m = -3/2$. For this case, $n = 2$.
- ✓When this varactor is connected to an inductor L in a resonant circuit, the resonant frequency varies linearly with the voltage applied to the varactor:

$$\omega_r = \frac{1}{\sqrt{LC_j}} \propto \frac{1}{\sqrt{V_R^{-n}}} = V_R \qquad \text{for n = 2.} \qquad (43)$$

3.4 CURRENT-VOLTAGE CHARACTERISTICS

- ✓A voltage applied to a p-n junction will disturb the precise balance between the diffusion current and drift current of electrons and holes.
- ✓Under forward bias, the applied voltage reduces the electrostatic potential across the depletion region, as shown in the middle of Fig. 14a.
- ✓ More electrons in the high-energy tail of the n-side conduction band shown in Fig. 22d in Chapter 1 have enough energy to surmount(غلبه کردن) the smaller barrier and diffuse from the n-side to p-side.



(a) (b)

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

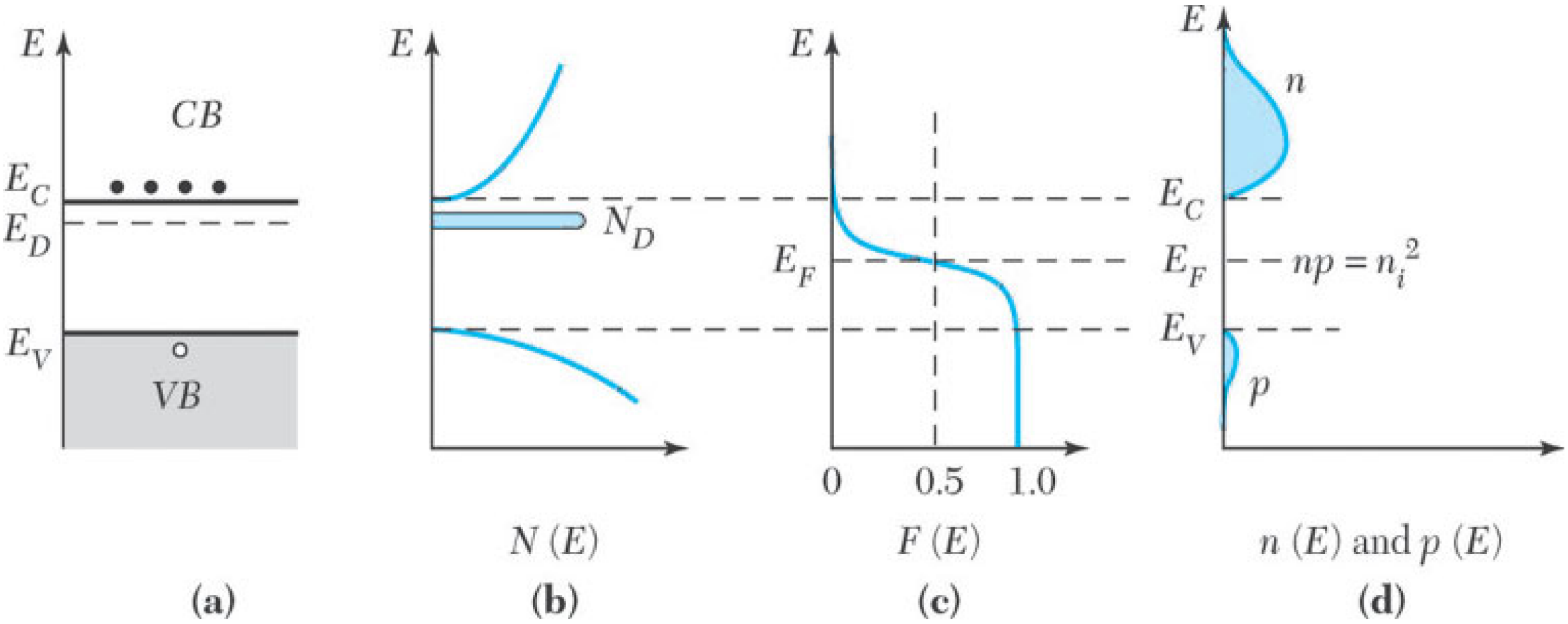


Fig. 22 ***n*-Type semiconductor. (*a*) Schematic band diagram. (*b*) Density of states. (*c*) Fermi distribution function. (*d*) Carrier concentration. Note that $np = n_i^2$.**

- ✓ Similarly, holes in the p-side valence band diffuse to the n-side over the smaller barrier.

- ✓ Therefore, minority carrier injections occur, that is, electrons are injected into the p-side, whereas holes are injected into the n-side.

- ✓ Under reverse bias, the applied voltage increases the electrostatic potential across the depletion region, as shown in the middle of Fig. 14b.

- ✓ This greatly reduces the diffusion currents.

- ✓ For the drift current, it is almost the same despite(با وجود) the barrier change.

- ✓Because a low concentration of minority electrons or holes in the *p* or *n* side that wander(منحرف شدن) into the transition region will drift into the n or p side.
- ✓The drift current depends mainly on the number of minority carriers, which travel at almost their saturation velocity.
- ✓The drift current and the diffusion current coexist in the depletion region and make it more difficult to derive the current equations. Therefore, we derive the current equations only by the diffusion equations outside the depletion region.
- ✓ In this section, we first consider the ideal current-voltage