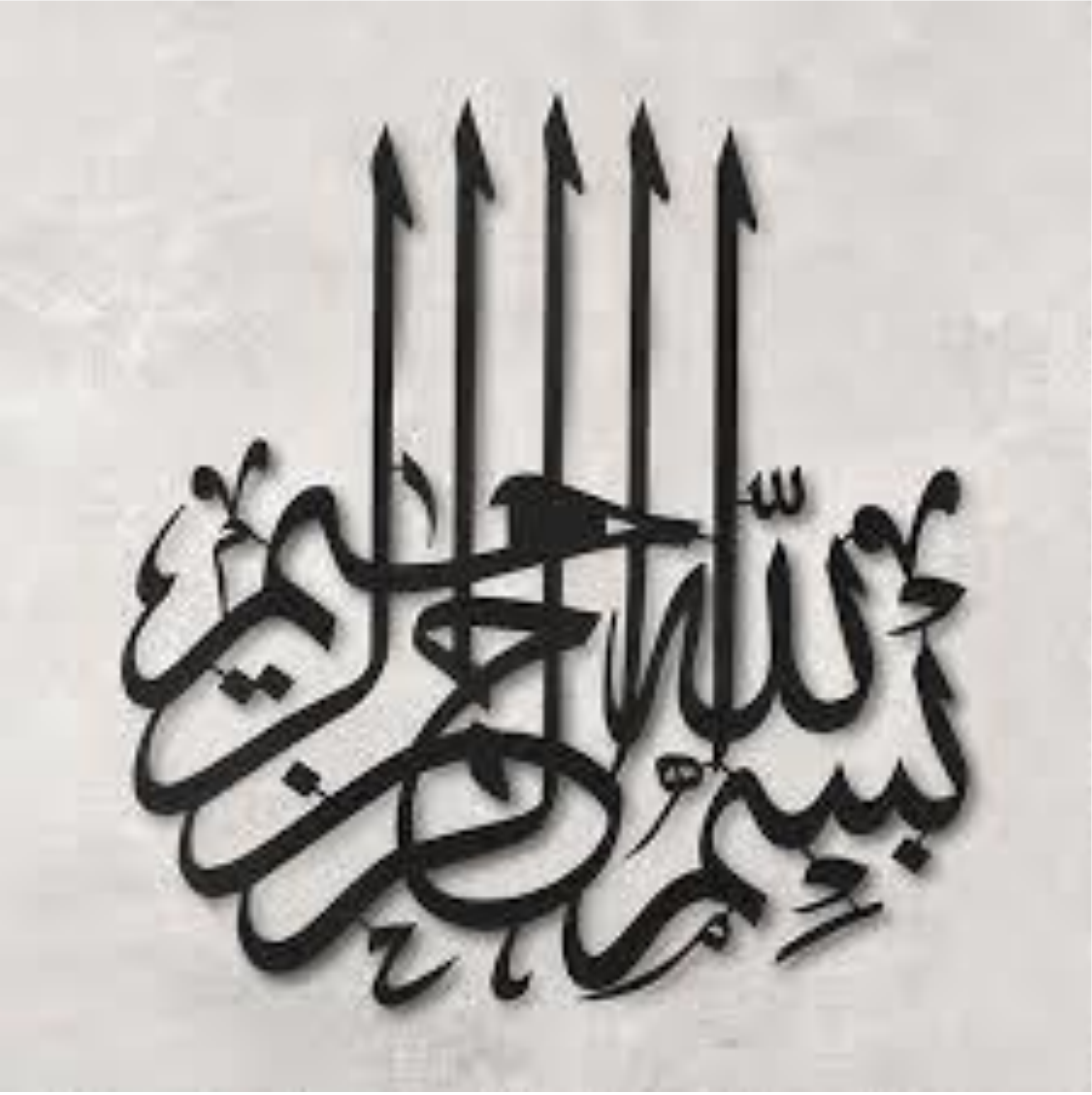
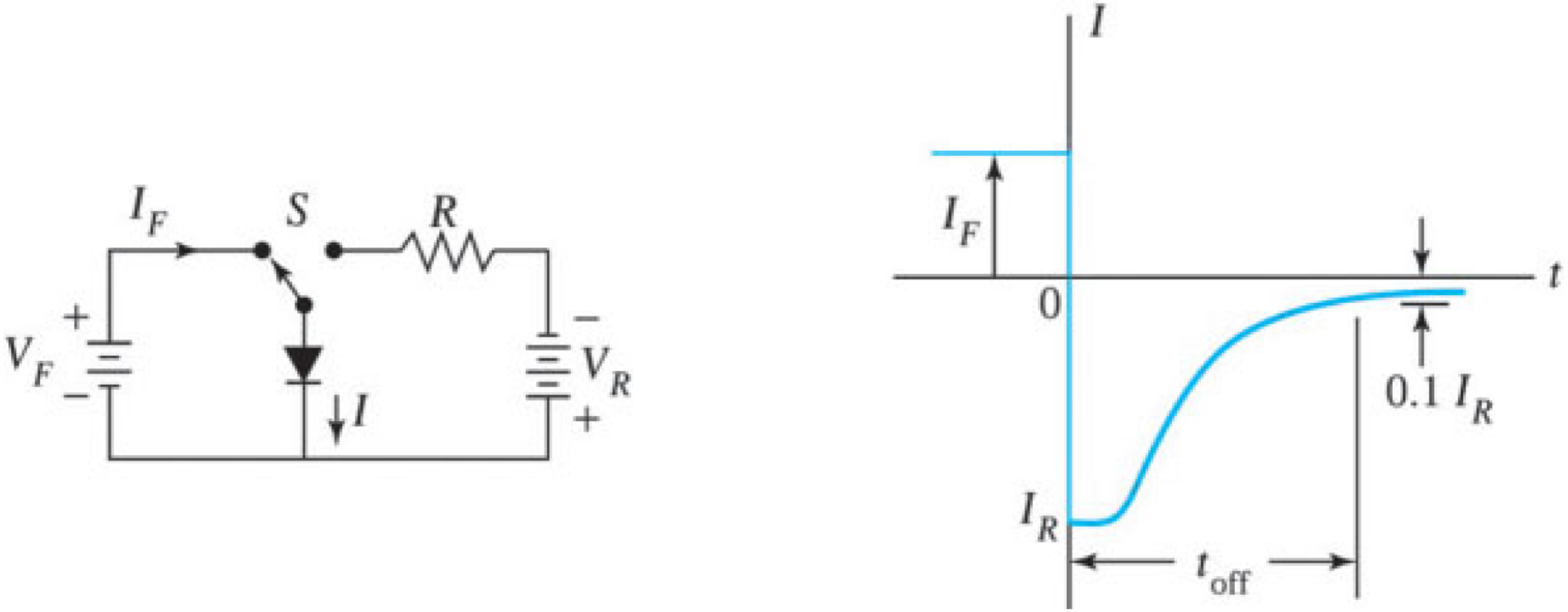

بسم الله الرحمن الرحيم

## CHAPTER 3

# *p*–*n* Junction

### 3.5.3 Transient Behavior(رفتار گذرا)

- For switching applications, the forward-to-reverse-bias transition must be nearly abrupt and the transient time should be short.
- Figure 20a shows a simple circuit where a forward current $I_F$ flows through a *p–n* junction.
- At time $t = 0$, switch *S* is suddenly thrown to the right and an initial reverse current $I_R \cong V/R$ flows.



(a) (b)

**Fig. 20** Transient behavior of a *p–n* junction. (*a*) Basic switching circuit. (*b*) Transient response of the current switched from forward bias to reverse bias.

- The transient time $t_{off}$, plotted in Fig. 20b, is the time required for the current to reach 10% of the initial reverse current *IR*.

- The transient time may be estimated as follows.

- Under the forward-bias condition, the stored minority carriers in the *n*-region for a $p^+$–*n* junction is given by Eq. 76:

$$\boxed{Q_p = \frac{L_p^{\ 2}}{D_p} J_p(x_n) = \tau_p J_p(x_n).} \tag{76}$$

$$Q_p = \tau_p J_p = \tau_p \frac{I_F}{A}, \tag{79}$$

- where $I_F$ is the total forward current and $A$ is the device area.

- If the average current flowing during the turn-off period is $I_{R,ave}$, the turn-off time is the length of time required to remove the total stored charge $Q_p$:

$I_{R,ave}$ میانگین جریان معکوس
مطابق شکل ۲۰ بین جریان
ماکزیمم $IR$ و 10% $IR$ می باشد

$$t_{off} \cong \frac{Q_p A}{I_{R,\text{ave}}} = \tau_p \left( \frac{I_F}{I_{R,\text{ave}}} \right). \tag{80}$$

- Thus the turn-off time depends on both the ratio of forward to reverse currents and the lifetime of the minority carriers.

- The result of a more precise turn-off time calculation taking into account the time-dependent minority-carrier diffusion problem is shown in Fig. 21.
- For fast-switching devices, we must reduce the lifetime of the minority carriers.
- Therefore, we usually introduce recombination-generation centers that have energy levels located near mid-bandgap, such as gold in silicon.

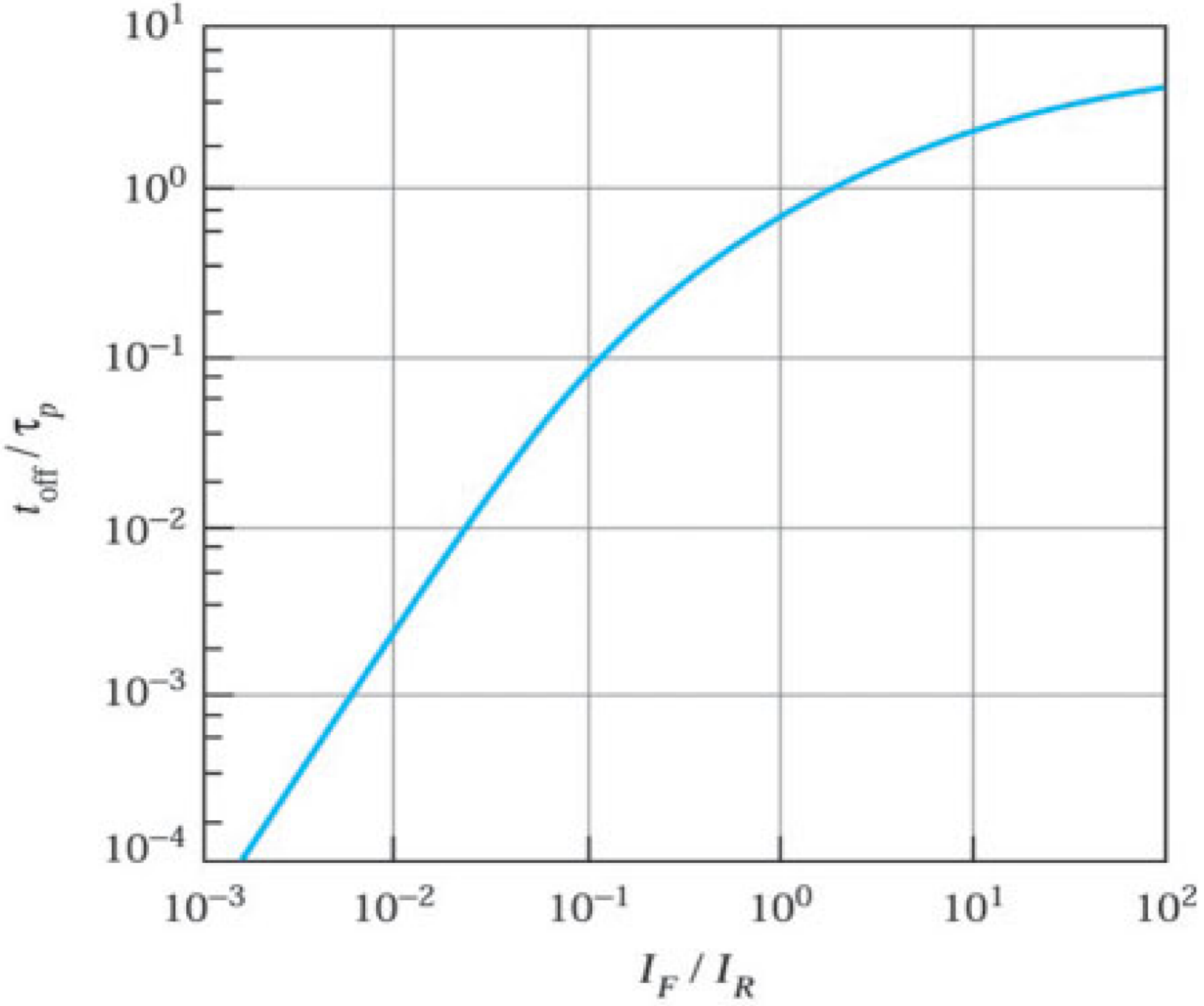


Fig. 21 **Normalized transient time versus the ratio of forward current to reverse current.**

## 3.6 JUNCTION BREAKDOWN

- When a sufficiently large reverse voltage is applied to a p–n junction, the junction breaks down and conducts a very large current.

- Although the breakdown process is not inherently(ذاتاً) destructive(مخرب), the maximum current must be limited by an external circuit to avoid excessive( بیش از اندازه) junction heating.

- Two important breakdown mechanisms are the tunneling effect and avalanche multiplication(تکثیر بهمنی).

- We consider the first mechanism briefly and then discuss avalanche multiplication in detail, because avalanche breakdown imposes an upper limit on the reverse bias for most diodes.

- Avalanche breakdown also limits the collector voltage of a bipolar transistor (Chapter 4) and the drain voltage of a MOSFET (Chapters 5 and 6).

- In addition, the avalanche multiplication mechanisms can generate microwave power, as in an IMPATT diode (Chapter 8), and detect optical signals, as in an avalanche photodetector (Chapter 10).

### 3.6.1 Tunneling Effect

- When a high electric field is applied to a *p*–*n* junction in the reverse direction, a valence electron can make a transition from the valence band to the conduction band, as shown in Fig. 22a.
- This process, in which an electron penetrates through the energy bandgap, is called tunneling.

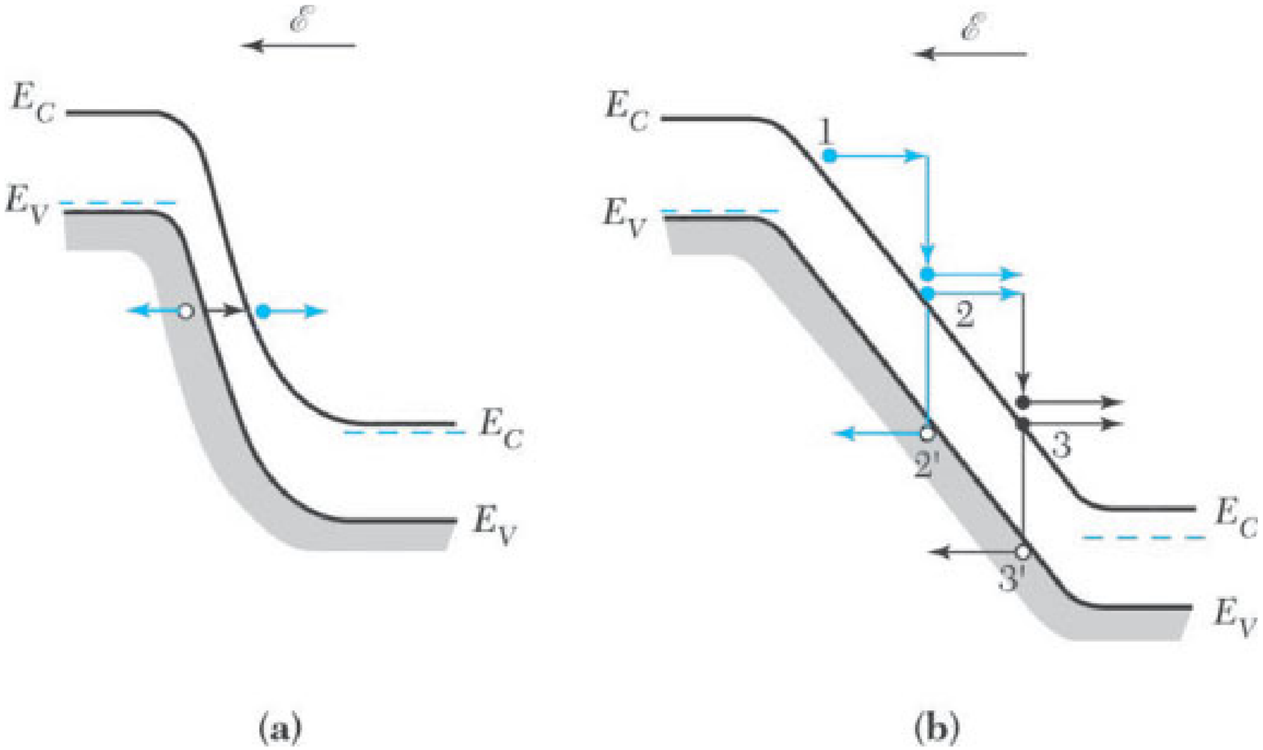


Fig. 22 **Energy band diagrams under junction-breakdown conditions. (*a*) Tunneling effect. (*b*) Avalanche multiplication.**

- Tunneling occurs only if the electric field is very high.

- The typical field for silicon and gallium arsenide is about $10^6$ *V/cm* or higher.

- To achieve such a high field, the doping concentrations for both *p*- and *n*-regions must be quite high ($> 5 \times 10^{17}$ $cm^{-3}$).

- The breakdown mechanisms for silicon and gallium arsenide junctions with breakdown voltages of less than about $4E_g/q$, where $E_g$ is the bandgap, are the result of the tunneling effect.

- For junctions with breakdown voltages in excess of $6E_g/q$, the breakdown mechanism is the result of avalanche multiplication.

- At voltages between *4* and $6E_g/q$, the breakdown is due to a mixture of both avalanche multiplication and tunneling.

### 3.6.2 Avalanche Multiplication

- The avalanche multiplication process is illustrated in Fig. 22b.
- The p–n junction, such as a $p^+$–$n$ one-sided abrupt junction with a doping concentration of $N_D \cong 10^{17}\ cm^{-3}$ or less, is under reverse bias.
- A thermally generated electron in the depletion region (designated by 1) gains kinetic energy from the electric field.

- If the field is sufficiently high, the electron can gain enough kinetic energy that on collision with an atom, it can break the lattice bonds, creating an electron-hole pair (2 and 2′).

- The newly created electron and hole both acquire kinetic energy from the field and create additional electron-hole pairs (e.g., 3 and 3′).

- These in turn continue the process, creating other electron-hole pairs.

- This process is therefore called avalanche multiplication.