TOPIC – Bipolar Junction transistors

Things to cover: **n-p-n and p-n-p Transistors. CB and CE Configurations. Current gains α and β. Relations between α and β. Physical Mechanism of Current Flow.**

1. n-p-n and p-n-p Transistors

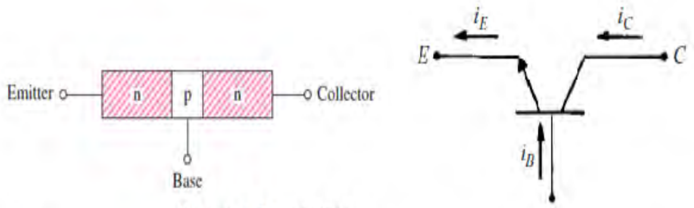
- The **bipolar junction transistor (BJT)** has three separately doped regions and contains two pn junctions. A single pn junction has two modes of operation—forward bias and reverse bias. The bipolar transistor, with two pn junctions, therefore has four possible modes of operation, depending on the bias condition of each pn junction, which is one reason for the versatility of the device
- With three separately doped regions, the bipolar transistor is a three-terminal device. The basic transistor principle is that *the voltage between two terminals controls the current through the third terminal*.
- Current in the transistor is due to the flow of both electrons and holes, hence the name **bipolar.** If only one carrier is employed (electron or hole), it is considered a unipolar device. The Schottky diode is such a device.

Co-inventors of the first transistor at Bell Laboratories: Dr. William Shockley (seated); Dr. John Bardeen (left); Dr. Walter H. Brattain. (Courtesy of AT&T Archives.)

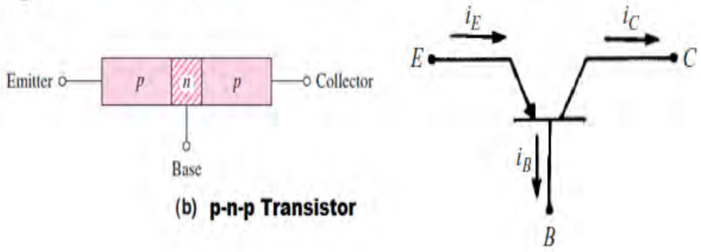
Dr. Shockley	Born: London, England, 1910 PhD Harvard, 1936
Dr. Bardeen	Born: Madison, Wisconsin, 1908 PhD Princeton, 1936
Dr. Brattain	Born: Amoy, China, 1902 PhD University of Minnesota, 1928

All shared the Nobel Prize in 1956 for this contribution.

Fig. 1



(a) n-p-n Transistor



(b) p-n-p Transistor

- Fig. 1 shows simplified block diagrams of the basic structure of the two types of bipolar transistor: npn and pnp. The **npn bipolar transistor** contains a thin p-region between two n-regions. In contrast, the **pnp bipolar transistor** contains a thin n region sandwiched between two p-regions. The three regions and their terminal connections are called the **emitter (E), base (B),** and **collector(C).** The operation of the device depends on the two pn junctions being in close proximity, so the width of the base must be very narrow, normally in the range of tenths of a micrometer $(10^{-6}\,\mathrm{m})$.
- The arrow on the emitter specifies the direction of current flow when E-B junction is forward biased. Emitter is heavily doped so as to inject a large number of charge carriers into base. Base is lightly doped and very thin. It passes most of the injected charge carriers from emitter into the collector. Collector is moderately doped.

2. Operation and Transistor Currents

- Fig. 2 shows an idealized npn bipolar transistor biased in the forward-active mode. Since the B–E junction is forward biased, electrons from the emitter are injected across the B–E junction into the base, creating an excess minority carrier concentration in the base. Since the B–C junction is reverse biased, the electron concentration at the edge of that junction is approximately zero.
- The base region is very narrow so that, in the ideal case, the injected electrons will not recombine with any of the majority carrier holes in the base. Because of the large gradient in this concentration, electrons that are injected, or *emitted,* from the emitter region diffuse across the base, are swept across the base–collector space-charge region by the electric field, and are *collected* in the collector region creating the collector current.

To minimize recombination effects, the width of the neutral base region must be small compared to the minority carrier diffusion length.

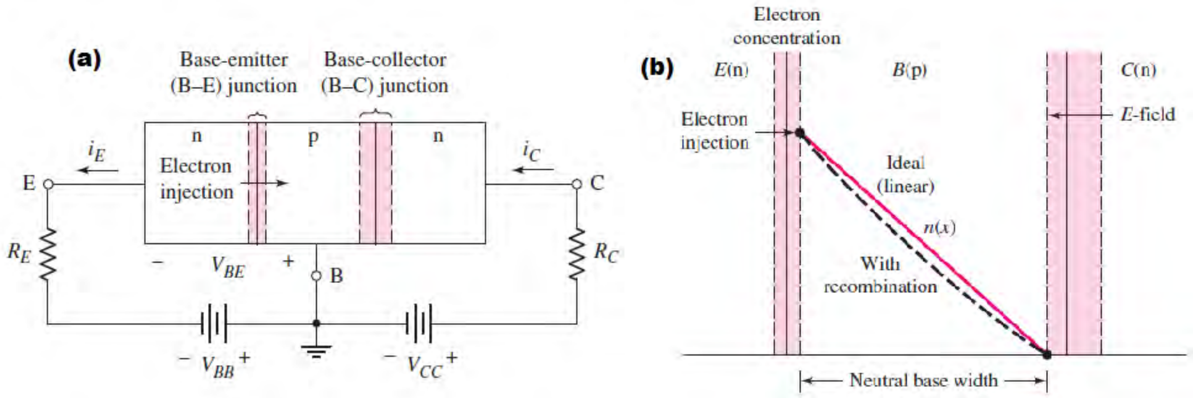


Fig. 2 (a) npn bipolar transistor biased in the forward-active mode. (b) Minority carrier electron concentration across the base region of an npn bipolar transistor biased in the forward-active mode. Minority carrier concentration is a linear function versus distance for an ideal transistor (no carrier recombination), and is a nonlinear function versus distance for a real device (with carrier recombination).

Applying Kirchhoff's current law to the transistor of Fig. 2 as if it were a single node, we obtain

$$I_E = I_C + I_B$$

and find that the emitter current is the sum of the collector and base currents. The collector current, however, is comprised of two components—the majority and minority carriers as indicated in Fig. 3.5. The minority-current component is called the *leakage current* and is given the symbol I_{CO} (I_C current with emitter terminal Open). The collector current, therefore, is determined in total by

$$I_C = I_{C_{\text{majority}}} + I_{CO_{\text{minority}}}$$

LET'S TRY – Draw pnp transistor current in the forward-active mode.

3. Transistor Configurations

A transistor can be connected in a circuit in the following three ways:

- ***(i)*** common base connection
- ***(ii)*** common emitter connection
- ***(iii)*** common collector connection

(i) Common base configuration-

The common-base terminology is derived from the fact that the base is common to both the input and output sides of the configuration. In addition, the base is usually the terminal closest to, or at, ground potential. **Configuration given in Fig. 2**

Emitter Current: Since the B–E junction is forward biased, we expect the current through this junction to be an exponential function of B–E voltage. $i_E = I_{EO}[e^{v_{BE}/V_T} - 1] \cong I_{EO}e^{v_{BE}/V_T}$

Neglecting the (-1) term is usually valid since $v_{BE} >> V_T$ in most cases. The parameter V_T is the usual thermal voltage. Typical values of I_{EO} are in the range of 10^{-12} to 10^{-16} A.

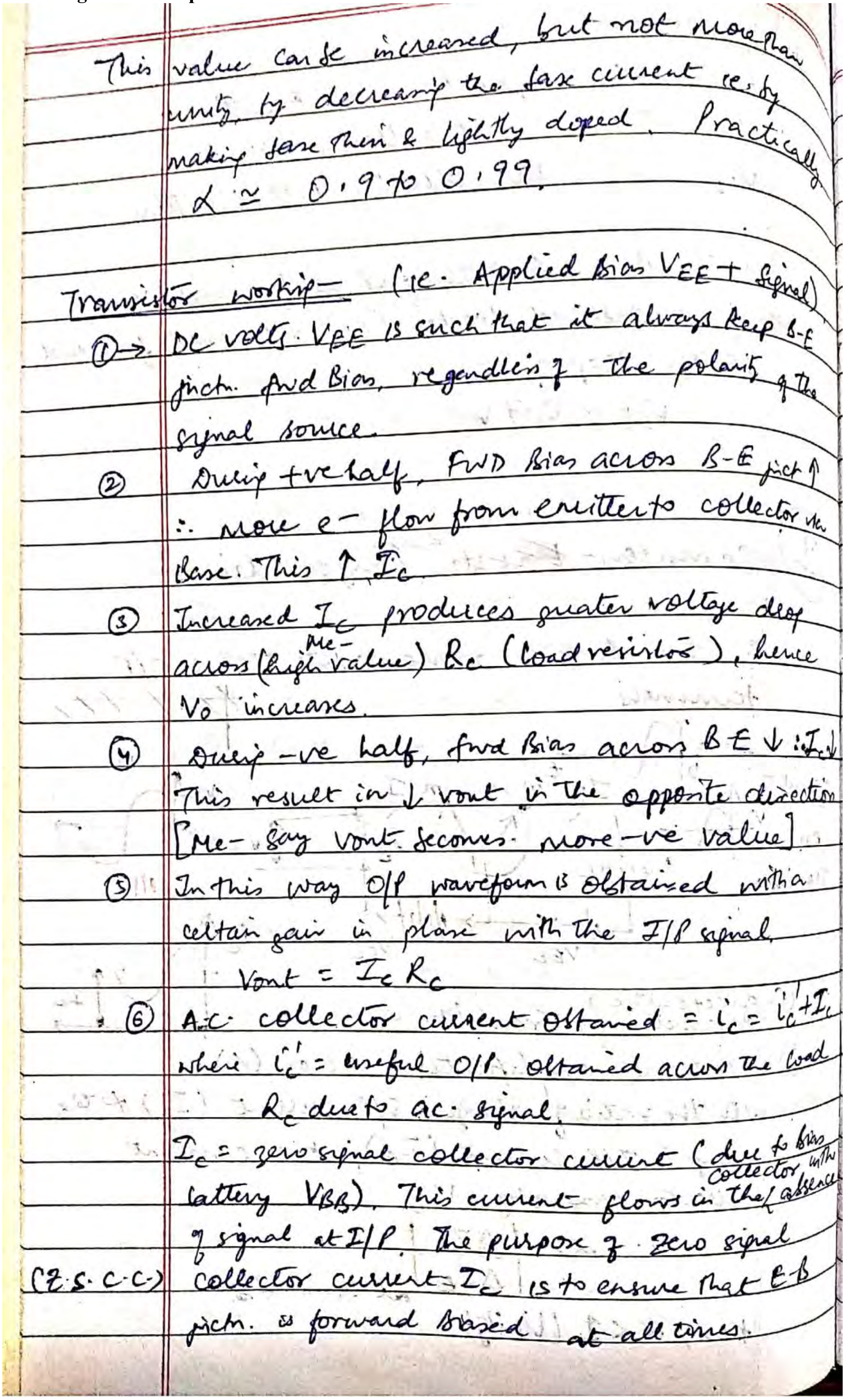
Collector Current: Since the doping concentration in the emitter is much larger than that in the base region, the number of electrons reaching the collector per unit time is proportional to the number of electrons injected into the base, which in turn is a function of the B–E voltage. To a first approximation, the collector current is proportional to *exp*(v_{BE}/V_T) and is independent of the reverse-biased B–C voltage. The device therefore looks like a **constant-current source.** The collector current is controlled by the B–E voltage; in other words, the current at one terminal (the collector) is controlled by the voltage across the other two terminals. *This control is the basic transistor action*

$$i_C = I_S e^{v_{BE}/V_T}$$

The emitter and collector currents are related by $i_C = \alpha i_E$. We can also relate the coefficients by $I_S = \alpha I_{EO}$. The parameter α is called the **common-base current gain** whose value is always slightly less than unity.

Base Current: The total base current is the sum of the two components (forward-biased B–E junction as well as recombination current) $i_B \propto e^{v_{BE}/V_T}$

Current gain value alpha



This value can be increased, but not more than unity, by decreasing the base current i.e. by making base thin & lightly doped. Practically

$\alpha \simeq 0.9$ to 0.99.

Transistor working— (i.e. Applied Bias V_{EE} + Signal)

①→ DC volts. V_{EE} is such that it always keep B-E junctn. fwd Bias, regardless of the polarity of the signal source.

② During +ve half, FWD Bias across B-E junct ↑ ∴ more e– flow from emitter to collector via Base. This ↑ I_c

③ Increased I_c produces greater voltage drop across (high $\overset{\text{Me-}}{\text{value}}$) R_c (Load resistor), hence V_o increases.

④ During –ve half, fwd Bias across B E ↓ ∴ I_c ↓ This result in ↓ vout in the opposite direction [Me- say vout becomes more –ve value].

⑤ In this way O/P waveform is obtained with a certain gain in phase with the I/P signal.

$V_{out} = I_c R_c$

⑥ A.C. collector current obtained $= i_c = i_c' + I_c$

where i_c' = useful O/P obtained across the load R_c due to ac signal.

I_c = zero signal collector current (due to bias battery V_{BB}). This current flows in the collector with absence of signal at I/P. The purpose of zero signal

(Z.S.C.C.) collector current I_c is to ensure that E-B junctn. is forward biased at all times.

Expression for collector current -

① Whole of I_E does not reach the collector due to e^--hole recombination occuring in the base area. & giving base current, I_B.

② As C-B junct is reverse biased ∴ some leakage current flows due to minority carriers ∴ Total
Total collector current consist of —

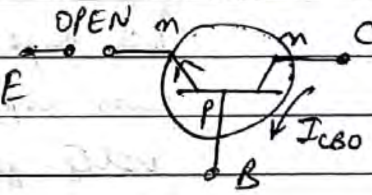
i) A part of I_E that reaches the collector terminal i.e. (αI_E)

ii) The leakage current due to reverse bias, due to movement of minority carriers across the rev. biased junct. (CB)

$I_{leakage} << \alpha I_E$.

③ ∴ Total $I_c = \alpha I_E + I_{leakage}$

④ If $I_E = 0$ (i.e emitter circuit is open) small leakage current still flows in the collector circuit
This, $I_{leak} = I_{CBO}$ i.e. Collector Base current with emitter open.



$\therefore I_c = \alpha I_E + I_{CBO}$

As $I_E = I_B + I_C$

$\therefore I_c = \alpha(I_B + I_c) + I_{CBO}$

or

$$I_c(1-\alpha) = \alpha I_B + I_{CBO}$$

or

$$\boxed{I_c = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{(1-\alpha)}} \quad — Ⓐ$$

2) Collector current of Transistor can be controlled by either the emitter or base current.

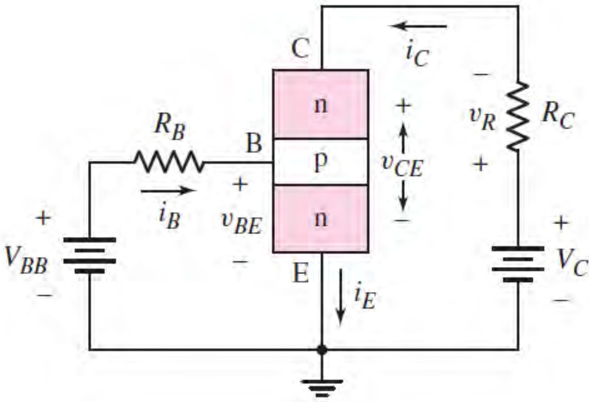
(ii) Common emitter configuration

- Because the emitter is the common connection, this circuit is referred to as a **common-emitter configuration.** When the transistor is biased in the forward-active mode, the B–E junction is forward biased and the B–C junction is reverse biased. We assume that the B–E voltage is equal to V_{BE}(on), the junction turn on voltage. Since $V_{CC} = v_{CE} + i_C R_C$, the power supply voltage must be sufficiently large to keep the B–C junction reverse biased. The base current is established by V_{BB} and R_B, and the resulting collector current is $i_C = \beta i_B$
- If we set $V_{BB} = 0$, the B–E junction will have zero applied volts; therefore, $i_B = 0$, which implies that $i_C = 0$. This condition is called **cutoff.**
- In the transistor, the rate of flow of electrons and the resulting collector current are an exponential function of the B–E voltage, as is the resulting base current. This means that the collector current and the base current are linearly related. Therefore, we can write

$$\frac{i_C}{i_B} = \beta$$

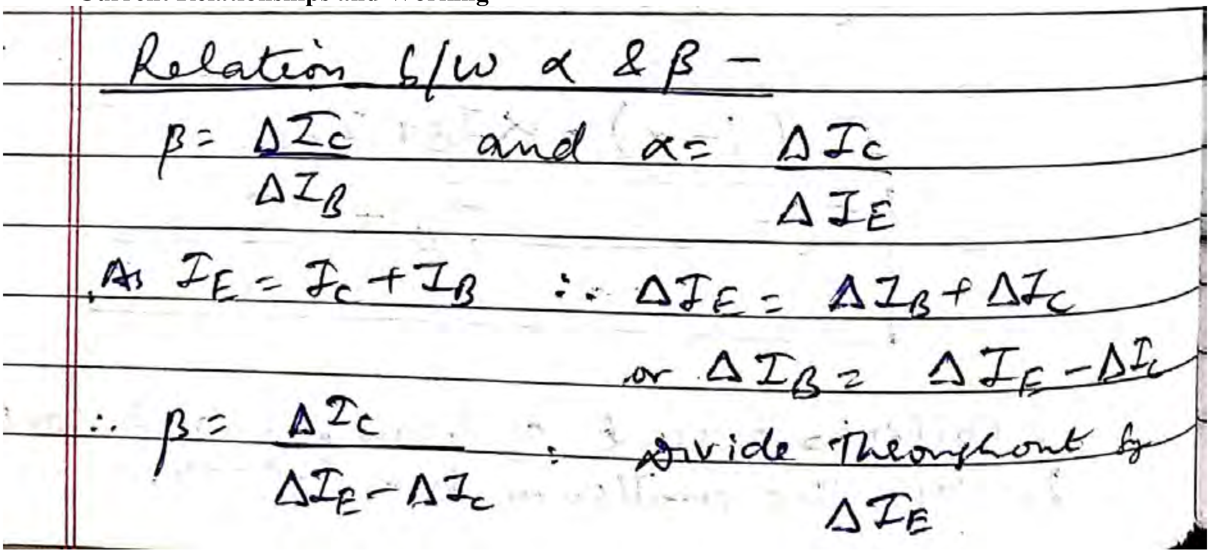
or

$$i_B = I_{BO} e^{v_{BE}/V_T} = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T}$$



- The parameter β is the **common-emitter current gain**[4] and is a key parameter of the bipolar transistor. In this idealized situation, β is considered to be a constant for any given transistor. The value of β is usually in the range of $50 < \beta < 300$, but it can be smaller or larger for special devices.

Current Relationships and Working



Relation b/w α & β –

$\beta = \frac{\Delta I_C}{\Delta I_B}$ and $\alpha = \frac{\Delta I_C}{\Delta I_E}$

As $I_E = I_C + I_B$ $\therefore \Delta I_E = \Delta I_B + \Delta I_C$

or $\Delta I_B = \Delta I_E - \Delta I_C$

$\therefore \beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$: divide throughout by ΔI_E

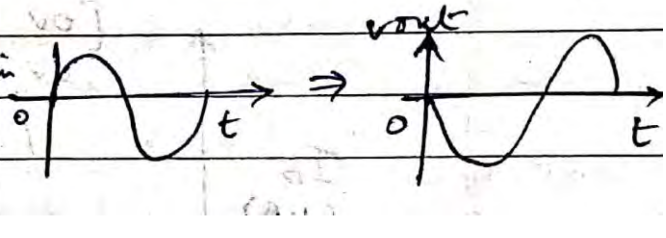
$$\beta = \frac{\Delta I_c / \Delta I_E}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_c}{\Delta I_E}} = \frac{\alpha}{1-\alpha}$$

∴ As α approaches unity, β approaches infinity
⇒ current gain in CE config is very high.
Hence, this arrangement is used in 90–95% applications.

Transistor working –

I/P signal applied to base ⇒ I_B ↑. As a result collector current $= I_C = \beta I_B$ will rise and so the drop across the collector resistor. However, Vout in this case ⇒ $V_{out} = V_{CC} - I_C R_c$

⇒ ↑ I_c or (volt across collector resistor) causes a fall in O/P volt ⇒ for a rise in I/P signal, we see a fall in the O/P signal V_o. ⇒ A phase diff of 180° is introduced b/w I/P & O/P.



THE SCHOTTKY BARRIER DIODE: METAL–SEMICONDUCTOR JUNCTION

7.6

One of the first practical semiconductor devices used in the early 1900s was the metal-semiconductor diode. This diode, also called a *point contact diode* was made by touching a metallic whisker to an exposed semiconductor surface. These metal–semiconductor diodes were not easily reproduced or mechanically reliable and were replaced by the *pn* junction in the 1950s. However, semiconductor and vacuum technology is now used to fabricate reproducible and reliable metal–semiconductor contacts. In this section, we will consider the metal-semiconductor rectifying contact, or Schottky barrier diode. In most cases, the rectifying contacts are made on *n*-type semiconductors; for this reason we will concentrate on this type of diode.

7.6.1 Qualitative Characteristics

The ideal energy-band diagram for a particular metal and *n*-type semiconductor before making contact is shown in Fig. 7.31(a). The vacuum level is used as a reference level. The parameter ϕ_m is the metal work function (measured in volts), ϕ_s is the semiconductor work function, and χ is known as the *electron affinity.* The work functions of various metals are given in Table 7.2 and the electron affinities of several semiconductors are given in Table 7.3. In Fig. 7.31(a), we have assumed that $\phi_m > \phi_s$. The ideal thermal-equilibrium

This barrier is known as the *Schottky barrier* and is given, ideally, by

$$\boxed{\phi_{B0} = (\phi_m - \chi)} \tag{7.79}$$

On the semiconductor side, V_{bi} is the built-in potential barrier. This barrier, similar to the case of the *pn* junction, is the barrier seen by electrons in the conduction band trying to move into the metal. The built-in potential barrier is given by

$$\boxed{V_{bi} = \phi_{B0} - \phi_n} \tag{7.80}$$

which makes V_{bi} a slight function of the semiconductor doping, as was the case in a *pn* junction.

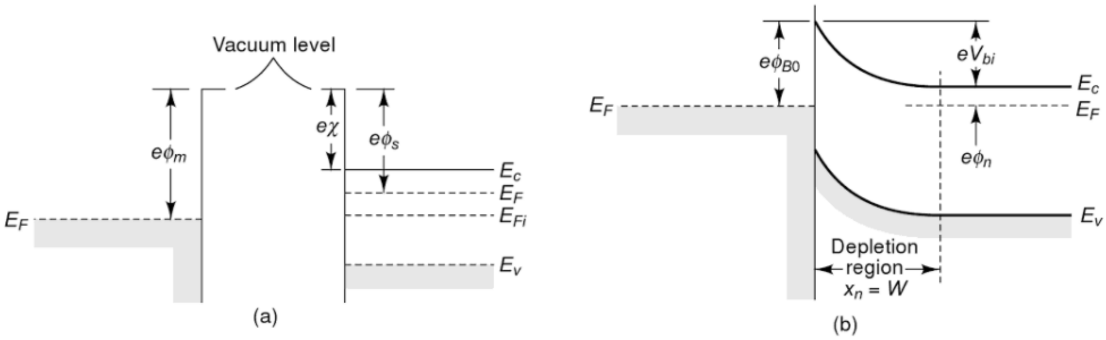


Fig. 7.31 *(a) Energy-band diagram of a metal and semiconductor before contact (b) Ideal energy-band diagram of a metal-n-semiconductor junction for $\phi_m > \phi_s$*

If we apply a positive voltage to the semiconductor with respect to the metal, the semiconductor-to-metal barrier height increases, while ϕ_{B0} remains constant in this idealized case. This bias condition is the reverse bias. If a positive voltage is applied to the metal with respect to the semiconductor, the semiconductor-to-metal barrier V_{bi} is reduced while ϕ_{B0} again remains essentially constant. In this situation, electrons can more easily flow from the semiconductor into the metal since the barrier has been reduced. This bias condition is the forward bias. The energy-band diagrams for the reverse and forward bias are shown in Figs 7.32(a) and 7.32(b), where V_R is the magnitude of the reverse-bias voltage and V_a is the magnitude of the forward-bias voltage.

The energy-band diagrams versus voltage for the metal-semiconductor junction shown in Fig. 7.32 are very similar to those of the *pn* junction given in the last chapter. Because of the similarity, we expect the current–voltage characteristics of the Schottky barrier junction to be similar to the exponential behavior of the *pn* junction diode. The current mechanism here, however, is due to the flow of majority carrier electrons. In forward bias, the barrier seen by the electrons in the semiconductor is reduced, so majority carrier electrons flow more easily from the semiconductor into the metal. The forward-bias current is in the direction from metal to semiconductor; it is an exponential function of the forward-bias voltage V_a.

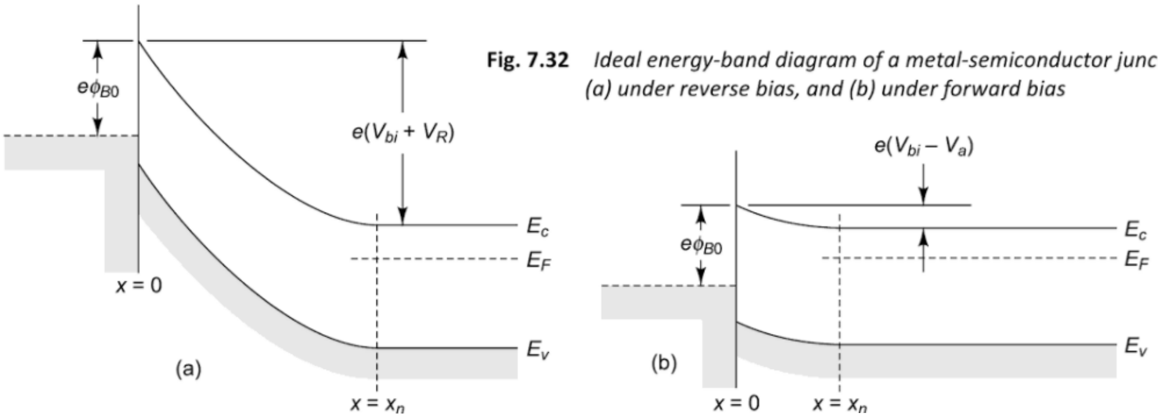


Fig. 7.32 *Ideal energy-band diagram of a metal-semiconductor junction (a) under reverse bias, and (b) under forward bias*

7.6.5 Comparison of the Schottky Barrier Diode and the *pn* Junction Diode

Although the ideal current–voltage relationship of the Schottky barrier diode given by Eq. (7.103) is of the same form as that of the *pn* junction diode, there are two important differences between a Schottky diode and a *pn* junction diode: The first is in the magnitudes of the reverse-saturation current densities, and the second is in the switching characteristics.

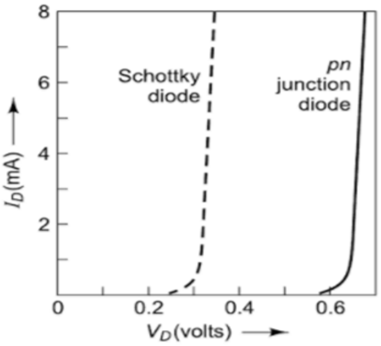


Fig. 7.39(b) *Comparison of forward-bias I-V characteristics between a Schottky diode and a pn junction diode*

The actual difference between the turn-on voltages will be a function of the barrier height of the metal–semiconductor contact and the doping concentrations in the *pn* junction.

References

1. D.A. Neamen - Semiconductor Devices
2. Floyd – Electronic Circuits
3. R. Boylestad – Electronic Devices and circuits
4. Salivahanan and Kumar – Electronic Devices