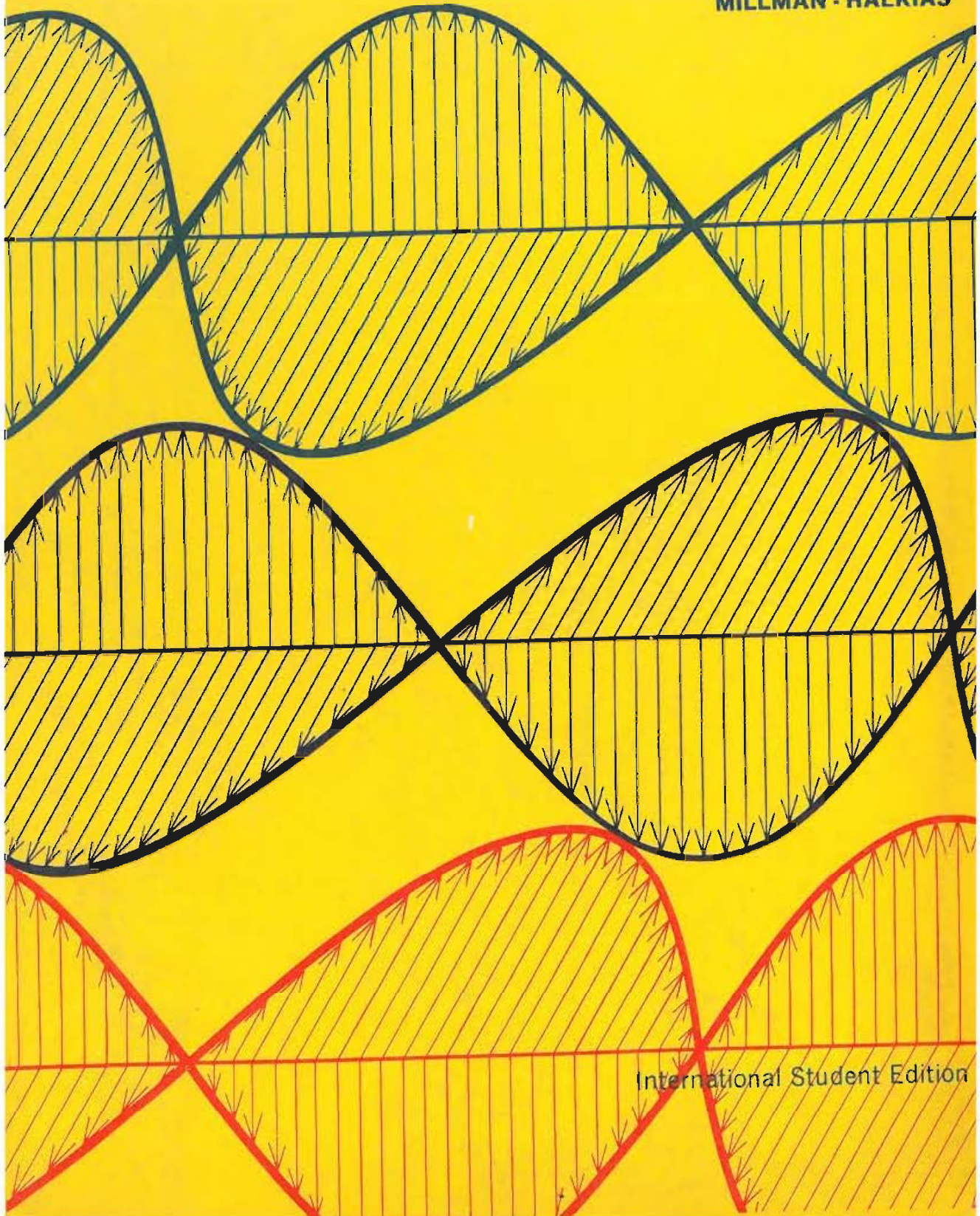


INTEGRATED ELECTRONICS

MILLMAN - HALKIAS



International Student Edition

INTEGRATED ELECTRONICS: ANALOG AND
DIGITAL CIRCUITS AND SYSTEMS

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Library of Congress Catalog Card Number 79-172657

07-042315-6

10 11 12 13 K P K P 7 9 8 7 6

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than, but almost equal to, unity, the magnitude of the collector current is (slightly) less than that of the emitter current.

Saturation Region The region to the left of the ordinate, $V_{CB} = 0$, and above the $I_E = 0$ characteristics, in which *both emitter and collector junctions are forward-biased*, is called the *saturation region*. We say that "bottoming" has taken place because the voltage has fallen near the bottom of the characteristic where $V_{CB} \approx 0$. Actually, V_{CB} is slightly positive (for a $p-n-p$ transistor) in this region, and this forward biasing of the collector accounts for the large change in collector current with small changes in collector voltage. For a forward bias, I_C increases exponentially with voltage according to the diode relationship [Eq. (3-9)]. A forward bias means that the collector p material is made positive with respect to the base n side, and hence that hole current flows from the p side across the collector junction to the n material. This hole flow corresponds to a positive change in collector current. Hence the collector current increases rapidly, and as indicated in Fig. 5-6, I_C may even become positive if the forward bias is sufficiently large.

Cutoff Region The characteristic for $I_E = 0$ passes through the origin, but is otherwise similar to the other characteristics. This characteristic is not coincident with the voltage axis, though the separation is difficult to show because I_{CO} is only a few nanoamperes or microamperes. The region below the $I_E = 0$ characteristic, for which the *emitter and collector junctions are both reverse-biased*, is referred to as the *cutoff region*. The temperature characteristics of I_{CO} are discussed in Sec. 5-7.

5-6 THE COMMON-EMITTER CONFIGURATION

Most transistor circuits have the emitter, rather than the base, as the terminal common to both input and output. Such a *common-emitter* (CE), or *grounded-emitter*, configuration is indicated in Fig. 5-9. In the common-emitter (as in the common-base) configuration, the input current and the output voltage are taken as the independent variables, whereas the input voltage and output

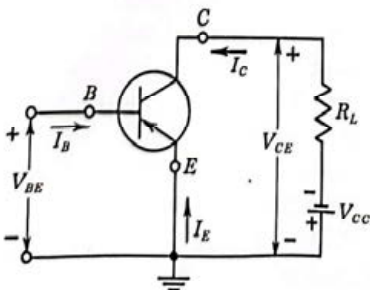


Fig. 5-9 A transistor common-emitter configuration. The symbol V_{CC} is a positive number representing the magnitude of the supply voltage.

current are the dependent variables. We may write

$$V_{BE} = f_1(V_{CE}, I_B) \quad (5-11)$$

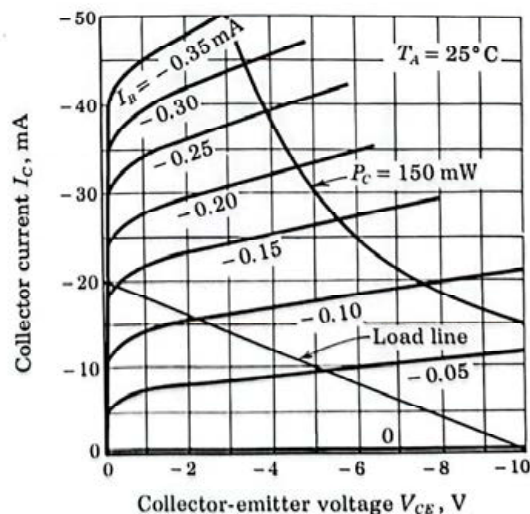
$$I_C = f_2(V_{CE}, I_B) \quad (5-12)$$

Equation (5-11) describes the family of input characteristic curves, and Eq. (5-12) describes the family of output characteristic curves. Typical output and input characteristic curves for a $p-n-p$ junction germanium transistor are given in Figs. 5-10 and 5-11, respectively. In Fig. 5-10 the abscissa is the collector-to-emitter voltage V_{CE} , the ordinate is the collector current I_C , and the curves are given for various values of base current I_B . For a fixed value of I_B , the collector current is not a very sensitive value of V_{CE} . However, the slopes of the curves of Fig. 5-10 are larger than in the common-base characteristics of Fig. 5-6. Observe also that the base current is much smaller than the emitter current.

The locus of all points at which the collector dissipation is 150 mW is indicated in Fig. 5-10 by a solid line $P_C = 150$ mW. This curve is the hyperbola $P_C = V_{CE}I_C \approx V_{CE}I_C = \text{constant}$. To the right of this curve the rated collector dissipation is exceeded. In Fig. 5-10 we have selected $R_L = 500 \Omega$ and a supply $V_{CC} = 10$ V and have superimposed the corresponding load line on the output characteristics. The method of constructing a load line is identical with that explained in Sec. 4-2 in connection with a diode.

The Input Characteristics In Fig. 5-11 the abscissa is the base current I_B , the ordinate is the base-to-emitter voltage V_{BE} , and the curves are given for various values of collector-to-emitter voltage V_{CE} . We observe that, with the collector shorted to the emitter and the emitter forward-biased, the input characteristic is essentially that of a forward-biased diode. If V_{BE} becomes zero, then I_B will be zero, since under these conditions both emitter and collector junctions will be short-circuited. In general, increasing $|V_{CE}|$ with constant

Fig. 5-10 Typical common-emitter output characteristics of a $p-n-p$ germanium junction transistor. A load line corresponding to $V_{CC} = 10$ V and $R_L = 500 \Omega$ is superimposed. (Courtesy of Texas Instruments, Inc.)



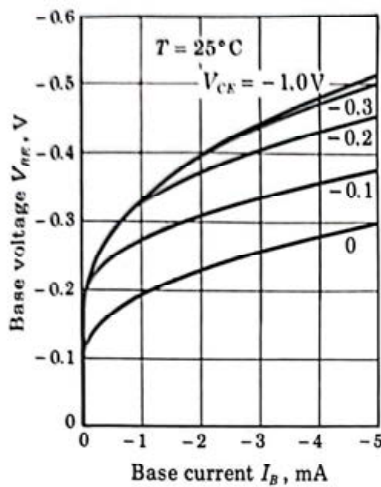


Fig. 5-11 Typical common-emitter input characteristics of the p - n - p germanium junction transistor of Fig. 5-10.

V_{BE} causes a decrease in base width W'_B (Fig. 5-8) and results in a decreasing recombination base current. These considerations account for the shape of input characteristics shown in Fig. 5-11.

The input characteristics for silicon transistors are similar in form to those in Fig. 5-11. The only notable difference in the case of silicon is that the curves break away from zero current in the range 0.5 to 0.6 V, rather than in the range 0.1 to 0.2 V as for germanium.

The Output Characteristics This family of curves may be divided into three regions, just as was done for the CB configuration. The first of these, the *active region*, is discussed here, and the *cutoff* and *saturation regions* are considered in the next two sections.

In the active region the collector junction is reverse-biased and the emitter junction is forward-biased. In Fig. 5-10 the active region is the area to the right of the ordinate $V_{CE} =$ a few tenths of a volt and above $I_B = 0$. In this region the transistor output current responds most sensitively to an input signal. If the transistor is to be used as an amplifying device without appreciable distortion, it must be restricted to operate in this region.

The common-emitter characteristics in the active region are readily understood qualitatively on the basis of our earlier discussion of the common-base configuration. From Kirchhoff's current law (KCL) applied to Fig. 5-9, the base current is

$$I_B = -(I_C + I_E) \quad (5-13)$$

Combining this equation with Eq. (5-3), we find

$$I_C = \frac{I_{C0}}{1 - \alpha} + \frac{\alpha I_B}{1 - \alpha} \quad (5-14)$$

If we define β by

$$\beta = \frac{\alpha}{1 - \alpha} \quad (5-15)$$

then Eq. (5-14) becomes

$$I_C = (1 + \beta)I_{CO} + \beta I_B \quad (5-16)$$

Note that usually $I_B \gg I_{CO}$, and hence $I_C \approx \beta I_B$ in the active region.

If α were truly constant, then, according to Eq. (5-14), I_C would be independent of V_{CE} and the curves of Fig. 5-10 would be horizontal. Assume that, because of the Early effect, α increases by only one-half of 1 percent, from 0.98 to 0.985, as $|V_{CE}|$ increases from a few volts to 10 V. Then the value of β increases from $0.98/(1 - 0.98) = 49$ to $0.985/(1 - 0.985) = 66$, or about 34 percent. This numerical example illustrates that a very small change (0.5 percent) in α is reflected in a very large change (34 percent) in the value of β . It should also be clear that a slight change in α has a large effect on β , and hence upon the common-emitter curves. Therefore the common-emitter characteristics are normally subject to a wide variation even among transistors of a given type. This variability is caused by the fact that I_B is the difference between large and nearly equal currents, I_E and I_C .

EXAMPLE (a) Find the transistor currents in the circuit of Fig. 5-12a. A silicon transistor with $\beta = 100$ and $I_{CO} = 20 \text{ nA} = 2 \times 10^{-5} \text{ mA}$ is under consideration. (b) Repeat part a if a 2-K emitter resistor is added to the circuit, as in Fig. 5-12b.

Solution a. Since the base is forward-biased, the transistor is not cut off. Hence it must be either in its active region or in saturation. Assume that the transistor operates in the active region. From KVL applied to the base circuit of Fig.

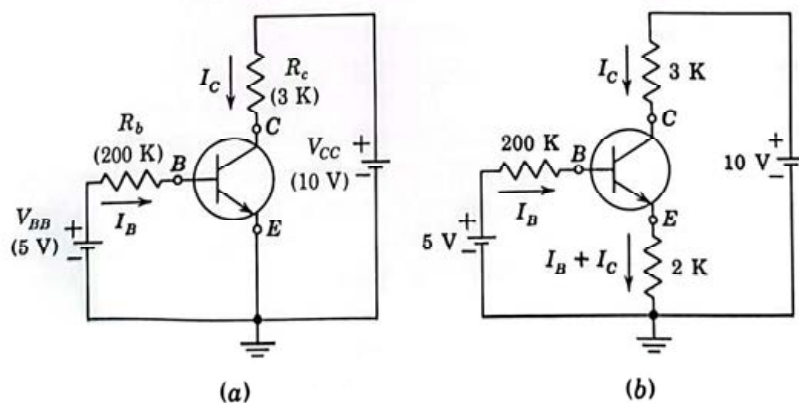


Fig. 5-12 An example illustrating how to determine whether or not a transistor is operating in the active region.

5-12a (with I_B expressed in milliamperes), we have

$$-5 + 200 I_B + V_{BE} = 0$$

As noted in Table 5-1, a reasonable value for V_{BE} is 0.7 V in the active region.

Hence

$$I_B = \frac{5 - 0.7}{200} = 0.0215 \text{ mA}$$

Since $I_{CO} \ll I_B$, then $I_C \approx \beta I_B = 2.15 \text{ mA}$.

We must now justify our assumption that the transistor is in the active region, by verifying that the collector junction is reverse-biased. From KVL applied to the collector circuit we obtain

$$-10 + 3 I_C + V_{CB} + V_{BE} = 0$$

or

$$V_{CB} = -(3)(2.15) + 10 - 0.7 = +2.85 \text{ V}$$

For an $n-p-n$ device a positive value of V_{CB} represents a reverse-biased collector junction, and hence the transistor is indeed in its active region.

Note that I_B and I_C in the active region are independent of the collector circuit resistance R_c . Hence, if R_c is increased sufficiently above 3 K, then V_{CB} changes from a positive to a negative value, indicating that the transistor is no longer in its active region. The method of calculating I_B and I_C when the transistor is in saturation is given in Sec. 5-9.

b. The current in the emitter resistor of Fig. 5-12b is

$$I_B + I_C \approx I_B + \beta I_B = 101 I_B,$$

assuming $I_{CO} \ll I_B$. Applying KVL to the base circuit yields

$$-5 + 200 I_B + 0.7 + (2)(101 I_B) = 0$$

or

$$I_B = 0.0107 \text{ mA} \quad I_C = 100 I_B = 1.07 \text{ mA}$$

Note that $I_{CO} = 2 \times 10^{-6} \text{ mA} \ll I_B$, as assumed.

To check for active circuit operation, we calculate V_{CB} . Thus

$$\begin{aligned} V_{CB} &= -3 I_C + 10 - (2)(101 I_B) - 0.7 \\ &= -(3)(1.07) + 10 - (2)(101)(0.0107) - 0.7 = +3.93 \text{ V} \end{aligned}$$

Since V_{CB} is positive, this ($n-p-n$) transistor is in its active region.

5.7 THE CE CUTOFF REGION

We might be inclined to think that cutoff in Fig. 5-10 occurs at the intersection of the load line with the current $I_B = 0$; however, we now find that appreciable collector current may exist under these conditions. From Eqs.

(5-13) and (5-14), if $I_B = 0$, then $I_E = -I_C$ and

$$I_C = -I_E = \frac{I_{CO}}{1 - \alpha} \equiv I_{CEO} \quad (5-17)$$

The actual collector current with collector junction reverse-biased and base open-circuited is designated by the symbol I_{CEO} . Since, even in the neighborhood of cutoff, α may be as large as 0.9 for germanium, then $I_C \approx 10I_{CO}$ at zero base current. Accordingly, in order to cut off the transistor, it is not enough to reduce I_B to zero. Instead, it is necessary to reverse-bias the emitter junction slightly. We shall define cutoff as the condition where the collector current is equal to the reverse saturation current I_{CO} and the emitter current is zero. It is found (Sec. 19-15) that a reverse-biasing voltage of the order of 0.1 V established across the emitter junction will ordinarily be adequate to cut off a germanium transistor. In silicon, at collector currents of the order of I_{CO} , α is very nearly zero because of recombination^{5,6} in the emitter-junction transition region. Hence, even with $I_B = 0$, we find, from Eq. (5-17), that $I_C = I_{CO} = -I_E$, so that the transistor is still very close to cutoff. We verify in Sec. 19-15 that, in silicon, cutoff occurs at $V_{BE} \approx 0$ V corresponding to a base short-circuited to the emitter. *In summary, cutoff means that $I_E = 0$, $I_C = I_{CO}$, $I_B = -I_C = -I_{CO}$, and V_{BE} is a reverse voltage whose magnitude is of the order of 0.1 V for germanium and 0 V for a silicon transistor.*

The Reverse Collector Saturation Current I_{CBO} The collector current in a physical transistor (a real, nonidealized, or commercial device) when the emitter current is zero is designated by the symbol I_{CBO} . Two factors cooperate to make $|I_{CBO}|$ larger than $|I_{CO}|$. First, there exists a leakage current which flows, not through the junction, but around it and across the surfaces. The leakage current is proportional to the voltage across the junction. The second reason why $|I_{CBO}|$ exceeds $|I_{CO}|$ is that new carriers may be generated by collision in the collector-junction transition region, leading to avalanche multiplication of current and eventual breakdown. But even before breakdown is approached, this *multiplication* component of current may attain considerable proportions.

At 25°C, I_{CBO} for a germanium transistor whose power dissipation is in the range of some hundreds of milliwatts is of the order of microamperes. Under similar conditions a silicon transistor has an I_{CBO} in the range of nanoamperes. The temperature sensitivity of I_{CBO} is the same as that of the reverse saturation current I_0 of a p - n diode (Sec. 3-5). Specifically, it is found⁸ that I_{CBO} approximately doubles for every 10°C increase in temperature for both Ge and Si. However, because of the lower absolute value of I_{CBO} in silicon, these transistors may be used up to about 200°C, whereas germanium transistors are limited to about 100°C.

In addition to the variability of reverse saturation current with temperature, there is also a wide variability of reverse current among samples of a

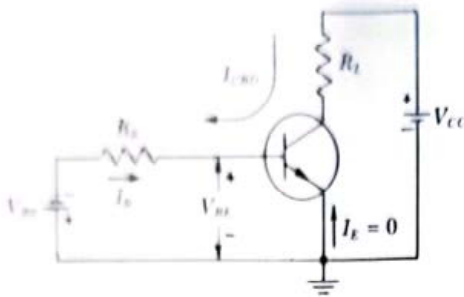


Fig. 5-13 Reverse biasing of the emitter junction to maintain the transistor in cutoff in the presence of the reverse saturation current I_{CBO} through R_B .

given transistor type. For example, the specification sheet for a Texas Instrument type 2N337 grown-diffused silicon switching transistor indicates that this type number includes units with values of I_{CBO} extending over the tremendous range from 0.2 nA to 0.3 μ A. Accordingly, any particular transistor may have an I_{CBO} which differs very considerably from the average characteristic for the type.

Circuit Considerations at Cutoff Because of temperature effects, avalanche multiplication, and the wide variability encountered from sample to sample of a particular transistor type, even silicon may have values of I_{CBO} of the order of many tens of microamperes. Consider the circuit configuration of Fig. 5-13, where V_{BB} represents a biasing voltage intended to keep the transistor cutoff. Assume that the transistor is just at the point of cutoff, with $I_E = 0$, so that $I_B = -I_{CBO}$. If we require that at cutoff $V_{BE} \approx -0.1$ V, then the condition of cutoff requires that

$$V_{BE} = -V_{BB} + R_B I_{CBO} \leq -0.1 \text{ V} \quad (5-18)$$

As an extreme example consider that R_B is, say, as large as 100 K and that we want to allow for the contingency that I_{CBO} may become as large as 100 μ A. Then V_{BB} must be at least 10.1 V. When I_{CBO} is small, the magnitude of the voltage across the base-emitter junction will be 10.1 V. Hence we must use a transistor whose maximum allowable reverse base-to-emitter junction voltage before breakdown exceeds 10 V. It is with this contingency in mind that a manufacturer supplies a rating for the reverse *breakdown voltage* between emitter and base, represented by the symbol BV_{EBO} . The subscript *O* indicates that BV_{EBO} is measured under the condition that the collector current is zero. Breakdown voltages BV_{EBO} may be as high as some tens of volts or as low as 0.5 V. If $BV_{EBO} = 1$ V, then V_{BB} must be chosen to have a maximum value of 1 V.

5-8 THE CE SATURATION REGION

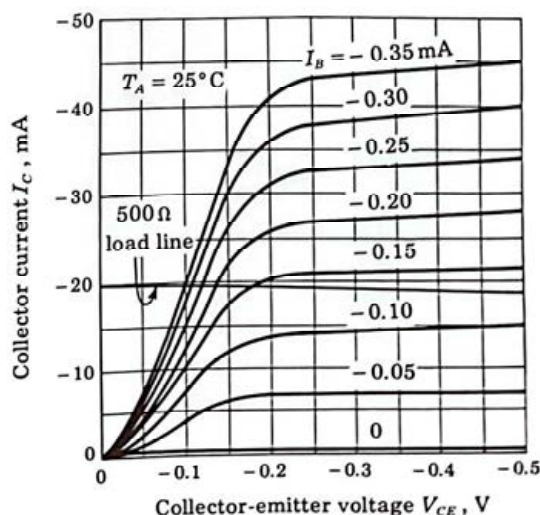
In the saturation region the collector junction (as well as the emitter junction) is forward-biased by at least the cutin voltage. Since the voltage V_{BE} (or V_{BC})

across a forward-biased junction has a magnitude of only a few tenths of a volt, the $V_{CE} = V_{BE} - V_{BC}$ is also only a few tenths of a volt at saturation. Hence, in Fig. 5-10, the saturation region is very close to the zero-voltage axis, where all the curves merge and fall rapidly toward the origin. A load line has been superimposed on the characteristics of Fig. 5-10 corresponding to a resistance $R_L = 500 \Omega$ and a supply voltage of 10 V. We note that in the saturation region the collector current is approximately independent of base current, for given values of V_{CC} and R_L . Hence we may consider that the onset of saturation takes place at the knee of the transistor curves in Fig. 5-10. Saturation occurs for the given load line at a base current of -0.17 mA , and at this point the collector voltage is too small to be read in Fig. 5-10. In saturation, the collector current is nominally V_{CC}/R_L , and since R_L is small, it may well be necessary to keep V_{CC} correspondingly small in order to stay within the limitations imposed by the transistor on maximum current and dissipation.

We are not able to read the collector-to-emitter saturation voltage, $V_{CE,\text{sat}}$, with any precision from the plots of Fig. 5-10. We refer instead to the characteristics shown in Fig. 5-14. In these characteristics the 0- to -0.5-V region of Fig. 5-10 has been expanded, and we have superimposed the same load line as before, corresponding to $R_L = 500 \Omega$. We observe from Figs. 5-10 and 5-14 that V_{CE} and I_C no longer respond appreciably to base current I_B , after the base current has attained the value -0.15 mA . At this current the transistor enters saturation. For $I_B = -0.15 \text{ mA}$, $|V_{CE}| \approx 175 \text{ mV}$. At $I_B = -0.35 \text{ mA}$, $|V_{CE}|$ has dropped to $|V_{CE}| \approx 100 \text{ mV}$. Larger magnitudes of I_B will, of course, decrease $|V_{CE}|$ slightly further.

Saturation Resistance For a transistor operating in the saturation region, a quantity of interest is the ratio $V_{CE,\text{sat}}/I_C$. This parameter is called the *common-emitter saturation resistance*, variously abbreviated R_{CS} , R_{CES} , or $R_{CE,\text{sat}}$. To specify R_{CS} properly, we must indicate the operating

Fig. 5-14 Saturation-region common-emitter characteristics of the type 2N404 germanium transistor. A load line corresponding to $V_{CC} = 10 \text{ V}$ and $R_L = 500 \Omega$ is superimposed. (Courtesy of Texas Instruments, Inc.)



point at which it was determined. For example, from Fig. 5-14, we find that, at $I_C = -20$ mA and $I_B = -0.35$ mA, $R_{CS} \approx -0.1/(-20 \times 10^{-3}) = 5 \Omega$. The usefulness of R_{CS} stems from the fact, as appears in Fig. 5-14, that to the left of the knee each of the plots, for fixed I_B , may be approximated, at least roughly, by a straight line.

The Base-spreading Resistance $r_{bb'}$ Recalling that the base region is very thin (Fig. 5-5), we see that the current which enters the base region across the emitter junction must flow through a long narrow path to reach the base terminal. The cross-sectional area for current flow in the collector (or emitter) is very much larger than in the base. Hence, usually the ohmic resistance of the base is very much larger than that of the collector or emitter. The dc ohmic base resistance, designated by $r_{bb'}$, is called the *base-spreading resistance* and is of the order of magnitude of 100Ω .

The Temperature Coefficient of the Saturation Voltages Since both junctions are forward-biased, a reasonable value for the temperature coefficient of either $V_{BE,sat}$ or $V_{BC,sat}$ is -2.5 mV/ $^{\circ}\text{C}$. In saturation the transistor consists of two forward-biased diodes back to back in series opposing. Hence it is to be anticipated that the temperature-induced voltage change in one junction will be canceled by the change in the other junction. We do indeed find such to be the case for $V_{CE,sat}$, whose temperature coefficient is about one-tenth that of $V_{BE,sat}$.

The DC Current Gain h_{FE} A transistor parameter of interest is the ratio I_C/I_B , where I_C is the collector current and I_B is the base current. This quantity is designated by β_{dc} or h_{FE} , and is known as the (negative of the) *dc beta*, the *dc forward current transfer ratio*, or the *dc current gain*.

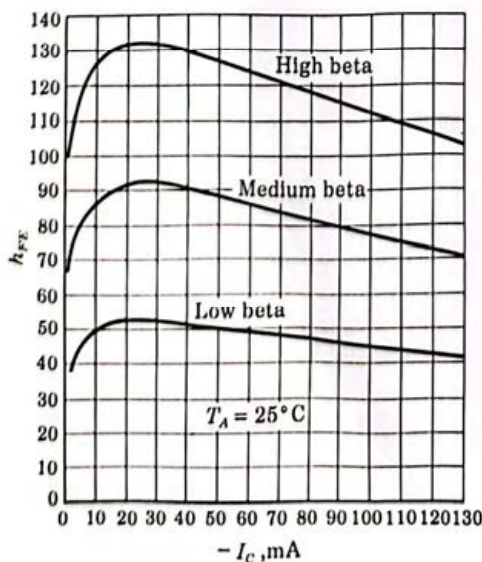


Fig. 5-15 Plots of dc current gain h_{FE} (at $V_{CE} = -0.25$ V) versus collector current for three samples of the type 2N404 germanium transistor. (Courtesy of General Electric Company.)

In the saturation region, the parameter h_{FE} is a useful number and one which is usually supplied by the manufacturer when a switching transistor is involved. We know $|I_C|$, which is given approximately by V_{CC}/R_L , and a knowledge of h_{FE} tells us the minimum base current (I_C/h_{FE}) which will be needed to saturate the transistor. For the type 2N404, the variation of h_{FE} with collector current at a low value of V_{CE} is as given in Fig. 5-15. Note the wide spread (a ratio of 3:1) in the value which may be obtained for h_{FE} even for a transistor of a particular type. Commercially available transistors have values of h_{FE} that cover the range from 10 to 150 at collector currents as small as 5 mA and as large as 30 A.

5-9 TYPICAL TRANSISTOR—JUNCTION VOLTAGE VALUES

The characteristics plotted in Fig. 5-16 of output current I_C as a function of input voltage V_{BE} for n - p - n germanium and silicon transistors are quite instructive and indicate the several regions of operation for a CE transistor circuit. The numerical values indicated are typical values obtained experimentally or from the theoretical equations of the following section. (The calculations are made in Sec. 19-15.) Let us examine the various portions of the transfer curves of Fig. 5-16.

The Cutoff Region *Cutoff* is defined, as in Sec. 5-5, to mean $I_E = 0$ and $I_C = I_{CO}$, and it is found that a reverse bias $V_{BE, \text{cutoff}} = 0.1$ V (0 V) will cut off a germanium (silicon) transistor.

What happens if a larger reverse voltage than $V_{BE, \text{cutoff}}$ is applied? It turns out that if V_{BE} is reverse biased and much larger than V_T , that the collector current falls slightly below I_{CO} and that the emitter current *reverses* but remains small in magnitude (less than I_{CO}).

Short-circuited Base Suppose that, instead of reverse-biasing the emitter junction, we connect the base to the emitter so that $V_E = V_{BE} = 0$. As indicated in Fig. 5-16, $I_C \equiv I_{CES}$ does not increase greatly over its cutoff value I_{CO} .

Open-circuited Base If instead of a shorted base we allow the base to "float" so that $I_B = 0$, we obtain the $I_C \equiv I_{CEO}$ given in Eq. (5-17). At low currents $\alpha \approx 0.9$ (0) for Ge (Si), and hence $I_C \approx 10I_{CO}(I_{CO})$ for Ge (Si). The values of V_{BE} calculated for this open-base condition ($I_C = -I_E$) are a few tens of millivolts of forward bias, as indicated in Fig. 5-16.

The Cutoff Voltage The volt-ampere characteristic between base and emitter at constant collector-to-emitter voltage (Fig. 5-11) is not unlike the volt-ampere characteristic of a simple junction diode. When the emitter junction is reverse-biased, the base current is very small, being of the order of nanoamperes or microamperes, for silicon and germanium, respectively.

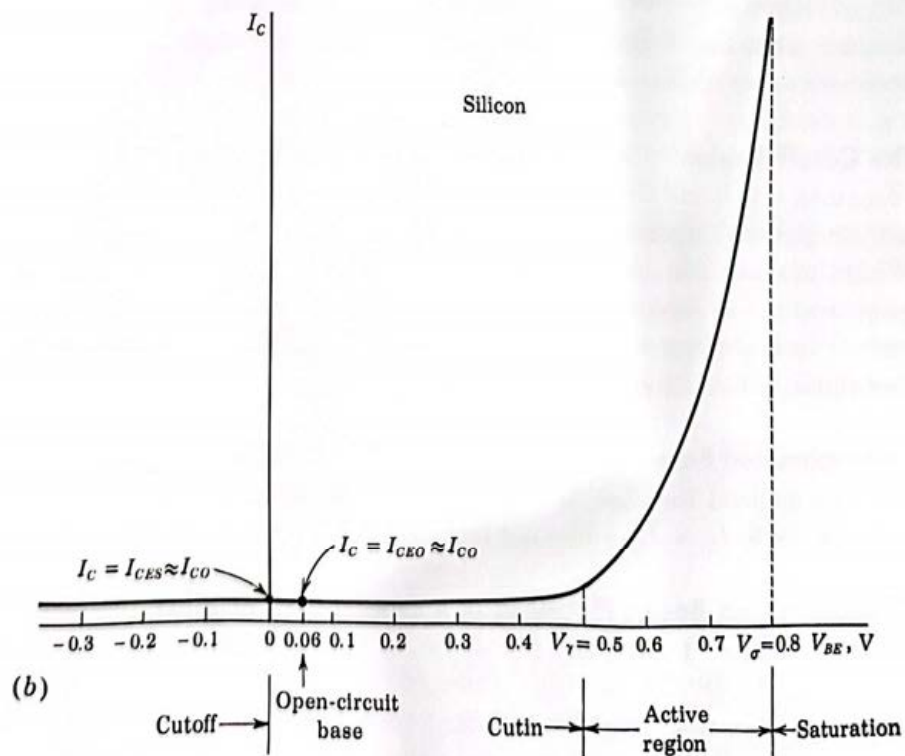
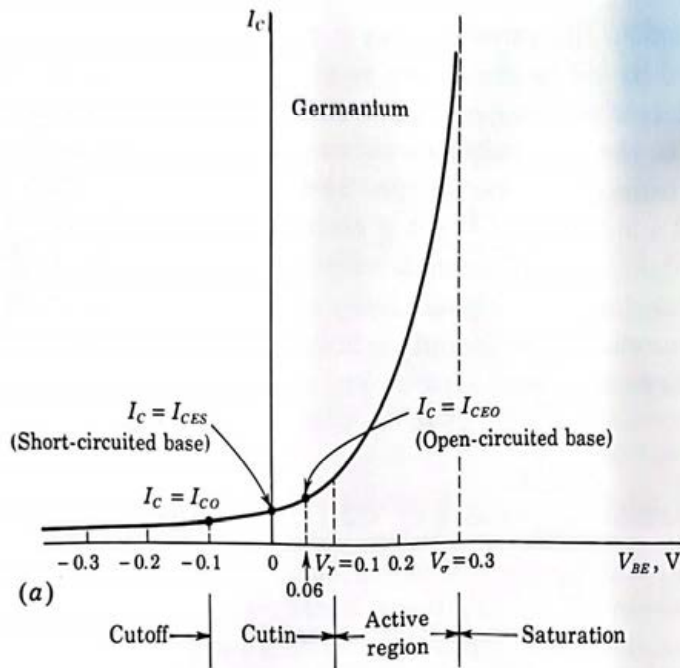


Fig. 5-16 Plots of collector current against base-to-emitter voltage for (a) germanium and (b) silicon *n-p-n* transistors. (I_C is not drawn to scale.)