Transistors.

Presented by
Doctor PhD, assistant-professor
Asset Akhmadiya

Introduction

This lecture introduces the transistor. Transistors are solid-state devices similar in some ways to the diodes you have studied. Transistors are more complex and can be used in many more ways. The most important feature of transistors is their ability to amplify signals and act as switches. Amplification can make a weak signal strong enough to be useful in an electronic application. For example, an audio amplifier can be used to supply a strong signal to a loudspeaker.

Amplification

Amplification is one of the most basic ideas in electronics. Amplifiers make sounds louder and signal levels greater and, in general, provide a function called ***gain***. Figure 5-1 shows the general function of an ***amplifier***. Note that the amplifier must be provided two things: ***dc power*** and the **input signal**. The signal is the electrical quantity that is too small in its present form to be usable. With gain, it becomes usable. As shown in Fig. 5-1, the output signal is greater because of the gain provided by the amplifier.

Amplification (1)

Gain can be measured in several ways. If an oscilloscope is used to measure the amplifier input signal voltage and the output signal voltage, then the ***voltage gain*** can be determined. If an ammeter is used to measure amplifier input and output currents, then the ***current gain*** can be obtained. If the voltage gain and the current gain are both known, then the **power gain** can be established.

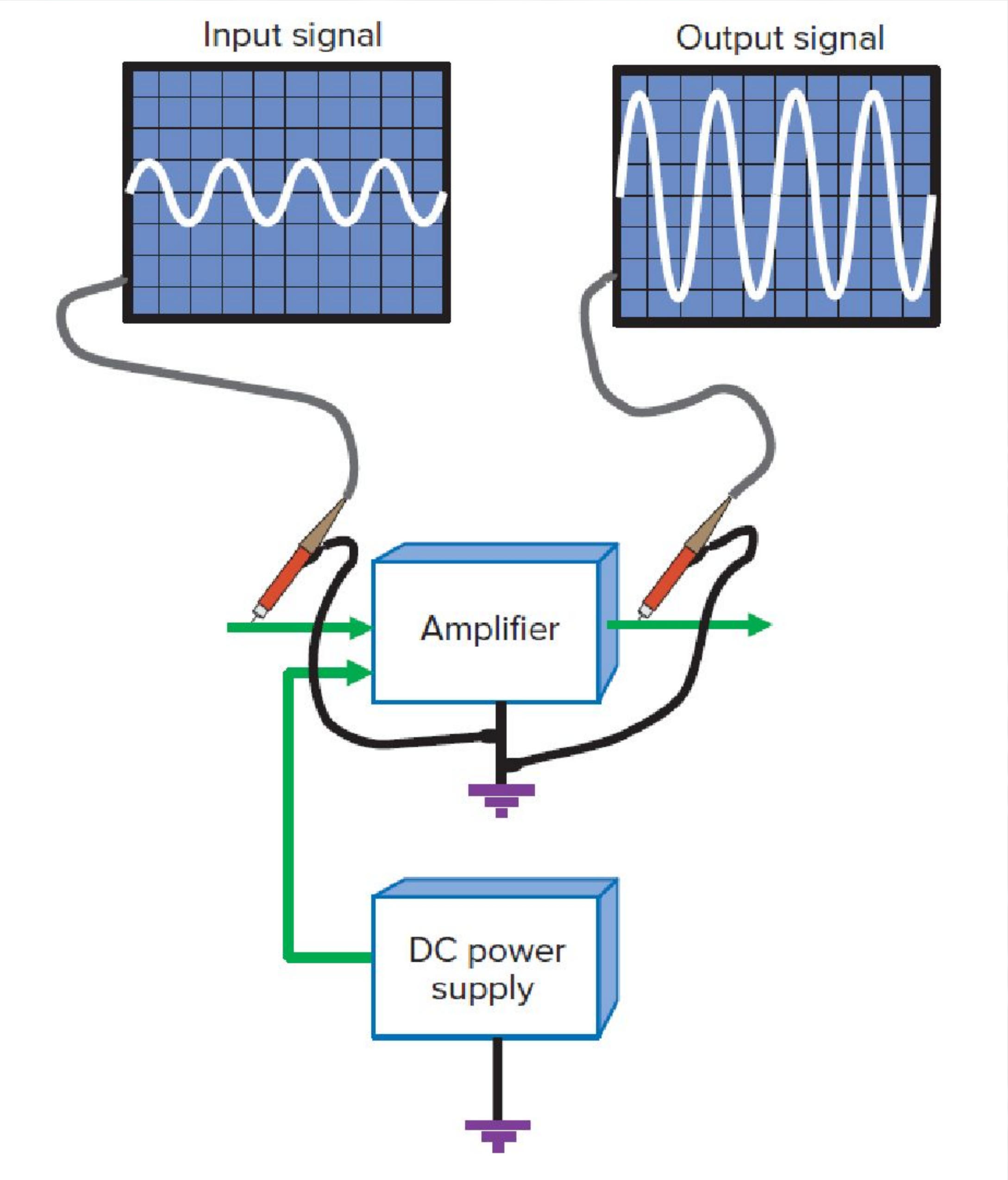
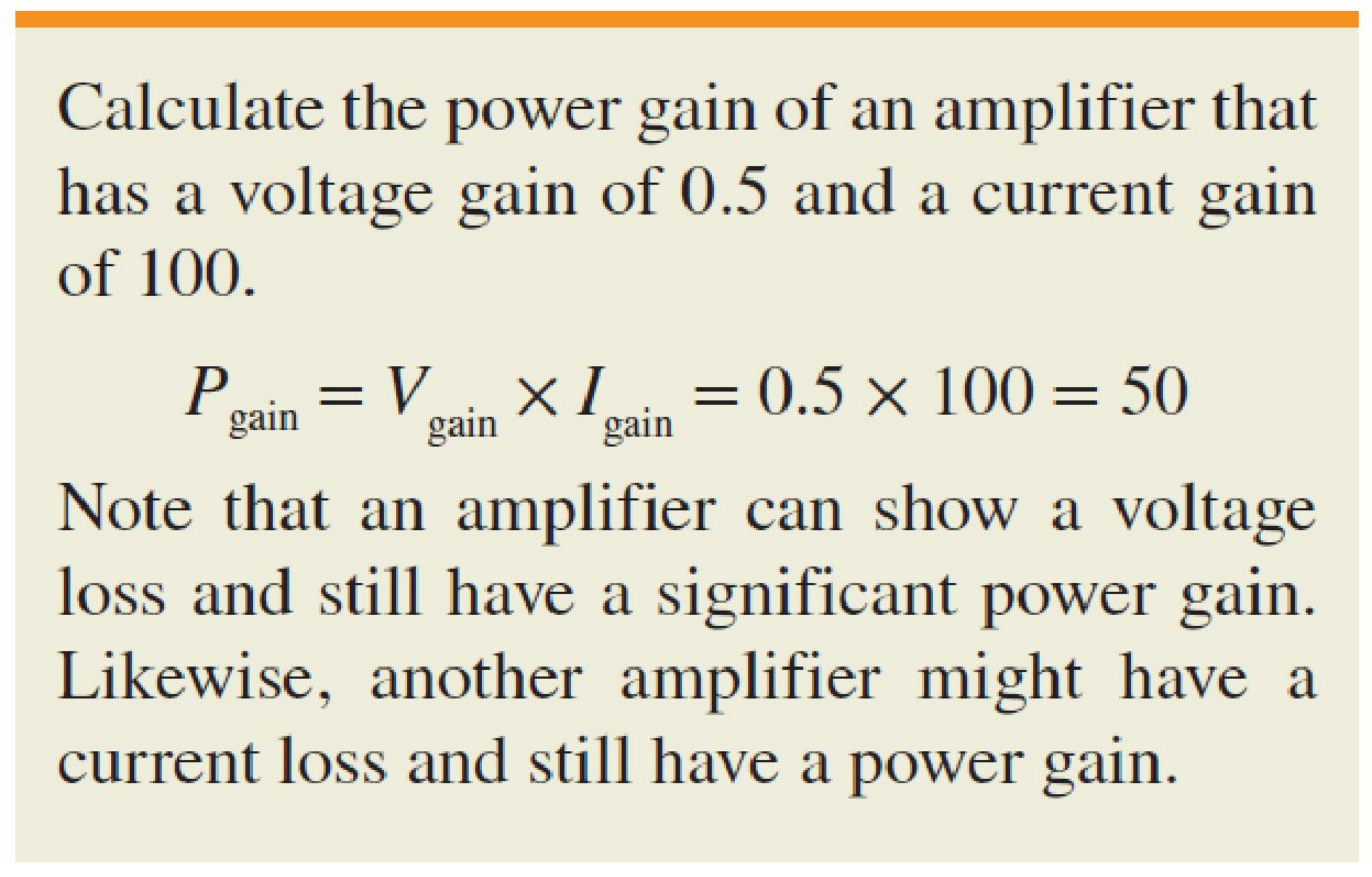


Fig. 5-1 Amplifiers provide gain.

Calculation of the power gain



Calculate the power gain of an amplifier that has a voltage gain of 0.5 and a current gain of 100.

$$P_{\text{gain}} = V_{\text{gain}} \times I_{\text{gain}} = 0.5 \times 100 = 50$$

Note that an amplifier can show a voltage loss and still have a significant power gain. Likewise, another amplifier might have a current loss and still have a power gain.

Power gain

Only amplifiers provide a power gain. Other devices might give a voltage gain or a current gain, but not both. A step-up transformer provides voltage gain but is **not** an amplifier. A transformer does not provide any power gain. If the transformer steps up the voltage 10 times, then it steps down the current 10 times. The power gain, ignoring loss in the transformer, will be

$$\begin{aligned} P_{\text{gain}} &= V_{\text{gain}} \times I_{\text{gain}} \\ &= 10 \times 0.1 \\ &= 1 \end{aligned}$$

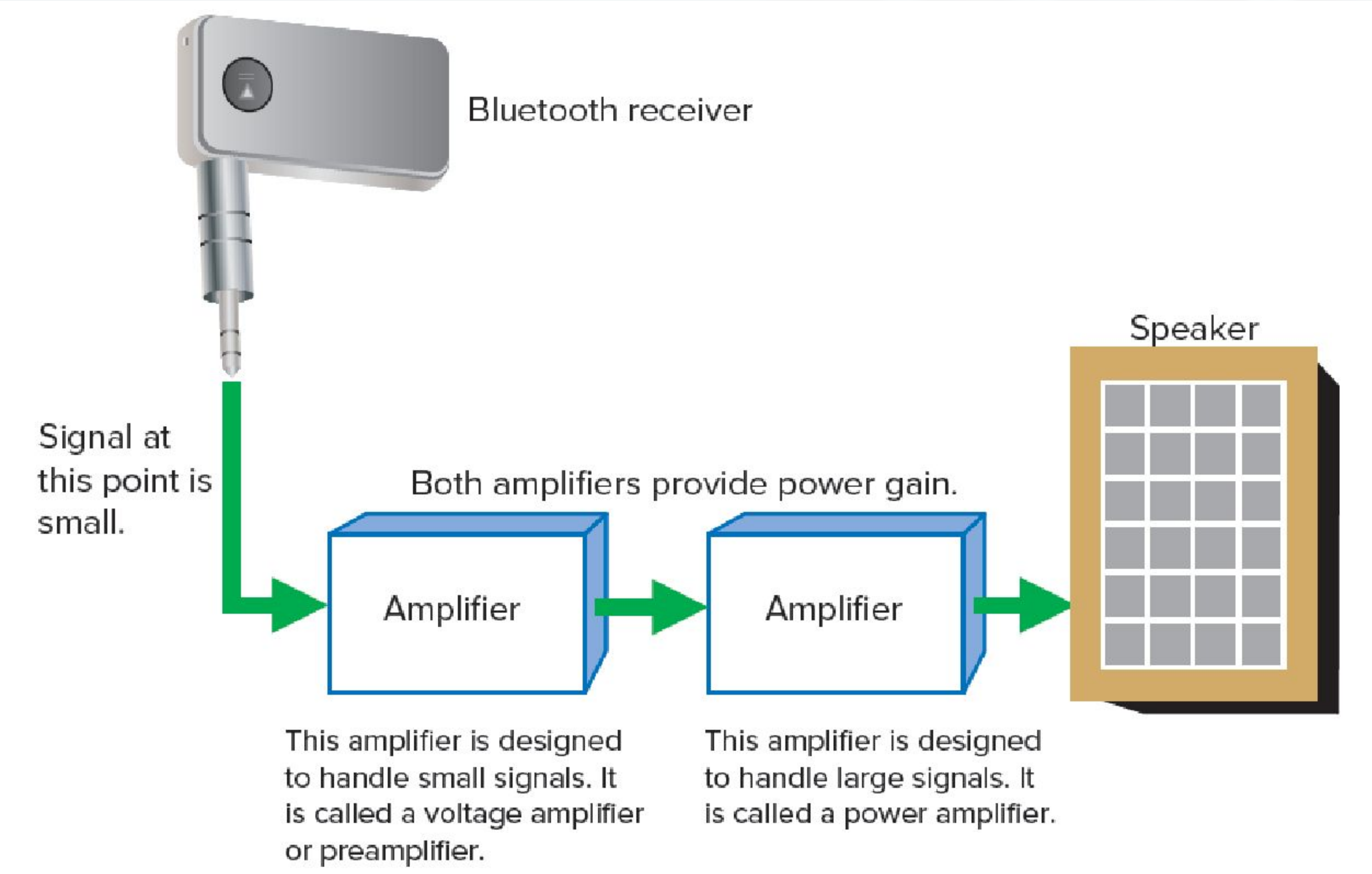
A step-down transformer provides a current gain. It cannot be considered an amplifier. The current gain is offset by a voltage loss, and thus, there is no power gain.

Amplification (2)

Even though power gain seems to be the important idea, some amplifiers are classified as ***voltage amplifiers***. In some circuits, only the voltage gain is mentioned. This is especially true in amplifiers designed to handle ***small signals***. You will run across many voltage amplifiers or ***small-signal amplifiers*** in electronic systems. They provide power gain, too.

The term ***power amplifier*** is generally used to refer to amplifiers that develop a ***large signal***. In the electronic system in Fig. 5-2, the speaker requires several watts for good volume. The signal from the Bluetooth receiver is in the milliwatt (mW) region. A total power gain of hundreds is needed. However, only the final large-signal amplifier is called a power amplifier.

Amplification (3)



Signal at this point is small.

Both amplifiers provide power gain.

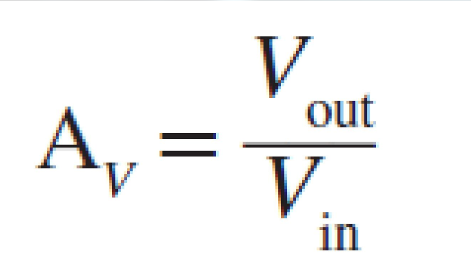
This amplifier is designed to handle small signals. It is called a voltage amplifier or preamplifier.

This amplifier is designed to handle large signals. It is called a power amplifier.

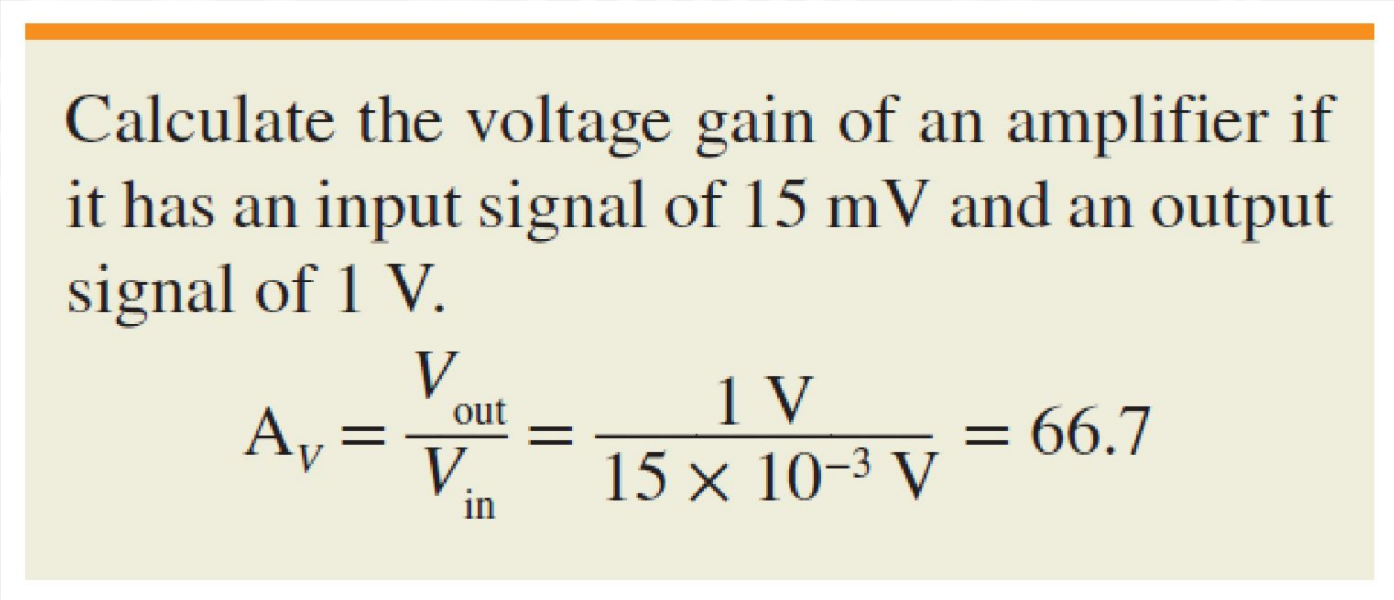
Fig. 5-2 Small-signal and large-signal

Amplification (4)

In electronics, ***gain*** is not expressed in volts, amperes, or watts. If voltage gain is being discussed, it will be a pure number. Gain is the ratio of some output to some input. The letter A is often used as the symbol for gain or amplification. For voltage gain, it is



$$A_V = \frac{V_{out}}{V_{in}}$$



Calculate the voltage gain of an amplifier if it has an input signal of 15 mV and an output signal of 1 V.

$$A_V = \frac{V_{out}}{V_{in}} = \frac{1\ \text{V}}{15 \times 10^{-3}\ \text{V}} = 66.7$$

Transistors

Transistors provide the power gain that is needed for most electronic applications. They also can provide voltage gain and current gain. There are several important types of transistors. The most popular type is the ***bipolar junction transistor*** (BJT). Field-effect transistors are also important. Both types are covered here.

Bipolar junction transistors are similar to junction diodes, but one more junction is included. Figure 5-3 shows one way to make a transistor. A P-type semiconductor region is located between two N-type regions. The polarity of these regions is controlled by the Bipolar junction transistor valence of the materials used in the doping process.

Transistors (1)

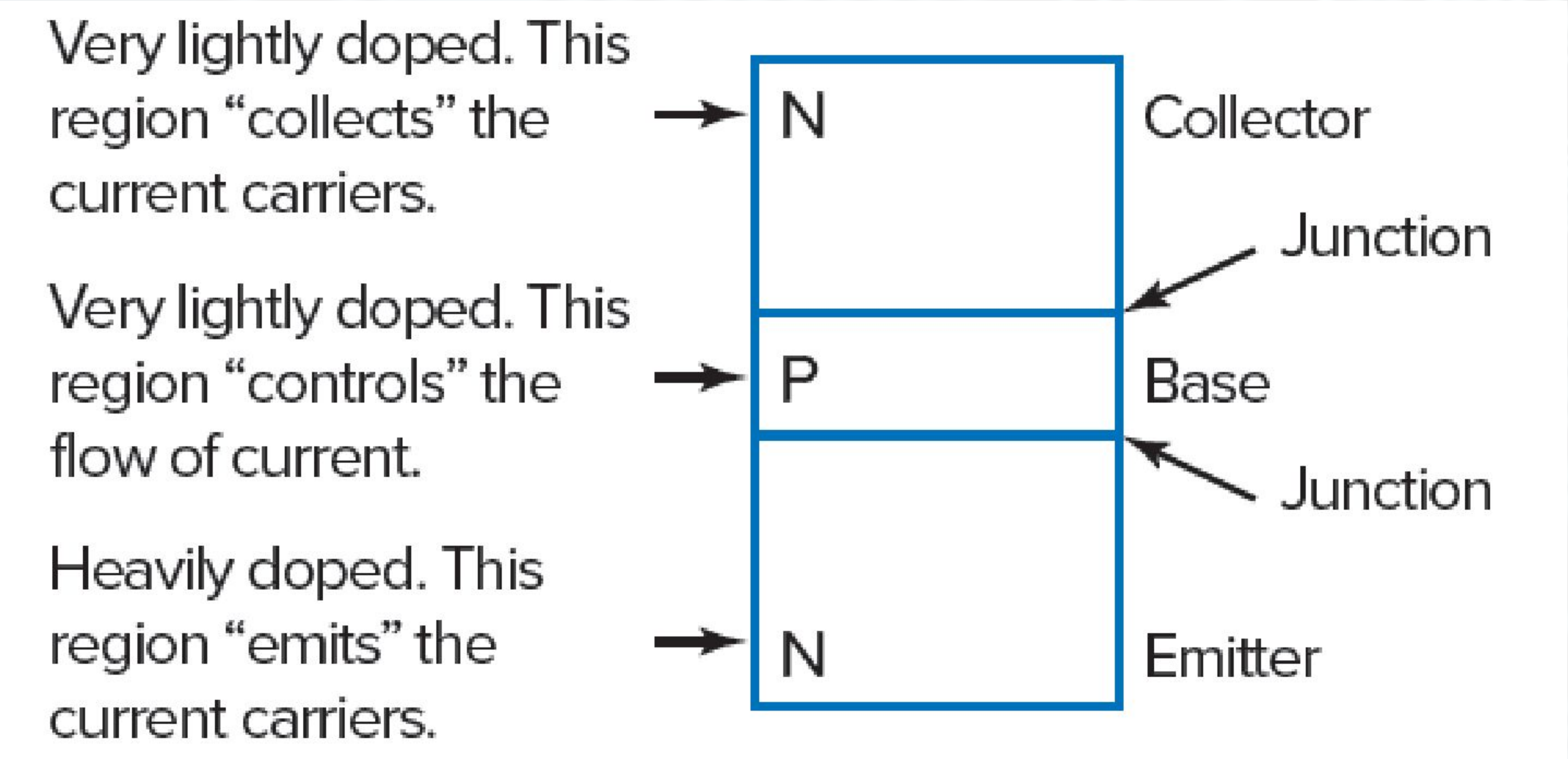


Fig. 5-3 NPN transistor structure.

Transistors (2)

The transistor regions shown in Fig. 5-3 are named ***emitter***, ***collector***, and ***base***. The emitter is very rich in current carriers. Its job is to send its carriers into the base region and then on to the collector. The ***collector*** collects the carriers. The ***emitter*** emits the carriers. The ***base*** acts as the control region. The base can allow none, some, or many of the carriers to flow from the emitter to the collector.

The transistor in Fig. 5-3 is ***bipolar*** because both holes (+) and electrons (−) will take part in the current flow through the device. The N-type regions contain free electrons, which are negative carriers. The P-type region contains free holes, which are positive carriers. Two (bi) polarities of carriers are present. Note that there are also two PN junctions in the transistor. It is a BJT.

Transistors (3)

The transistor shown in Fig. 5-3 would be classified as an ***NPN transistor***. Another way to make a bipolar junction transistor is to make the emitter and collector of P-type material and the base of N-type material. This type would be classified as a ***PNP transistor***. Figure 5-4 shows both possibilities and the schematic symbols for each. You should memorize the symbols. Remember that the emitter lead is always the one with the arrow. Also remember that if the arrow is Not Pointing iN, the transistor is an NPN type.

Transistors (4)

The two transistor junctions must be biased properly. This is why you cannot replace an NPN transistor with a PNP transistor. The polarities would be wrong. Transistor bias is shown in Fig. 5-5. The ***collector-base junction*** must be ***reverse-biased*** for proper operation. In an NPN transistor, the collector will have to be positive with respect to the base. In a PNP transistor, the collector will have to be negative with respect to the base. PNP and NPN transistors are not interchangeable.

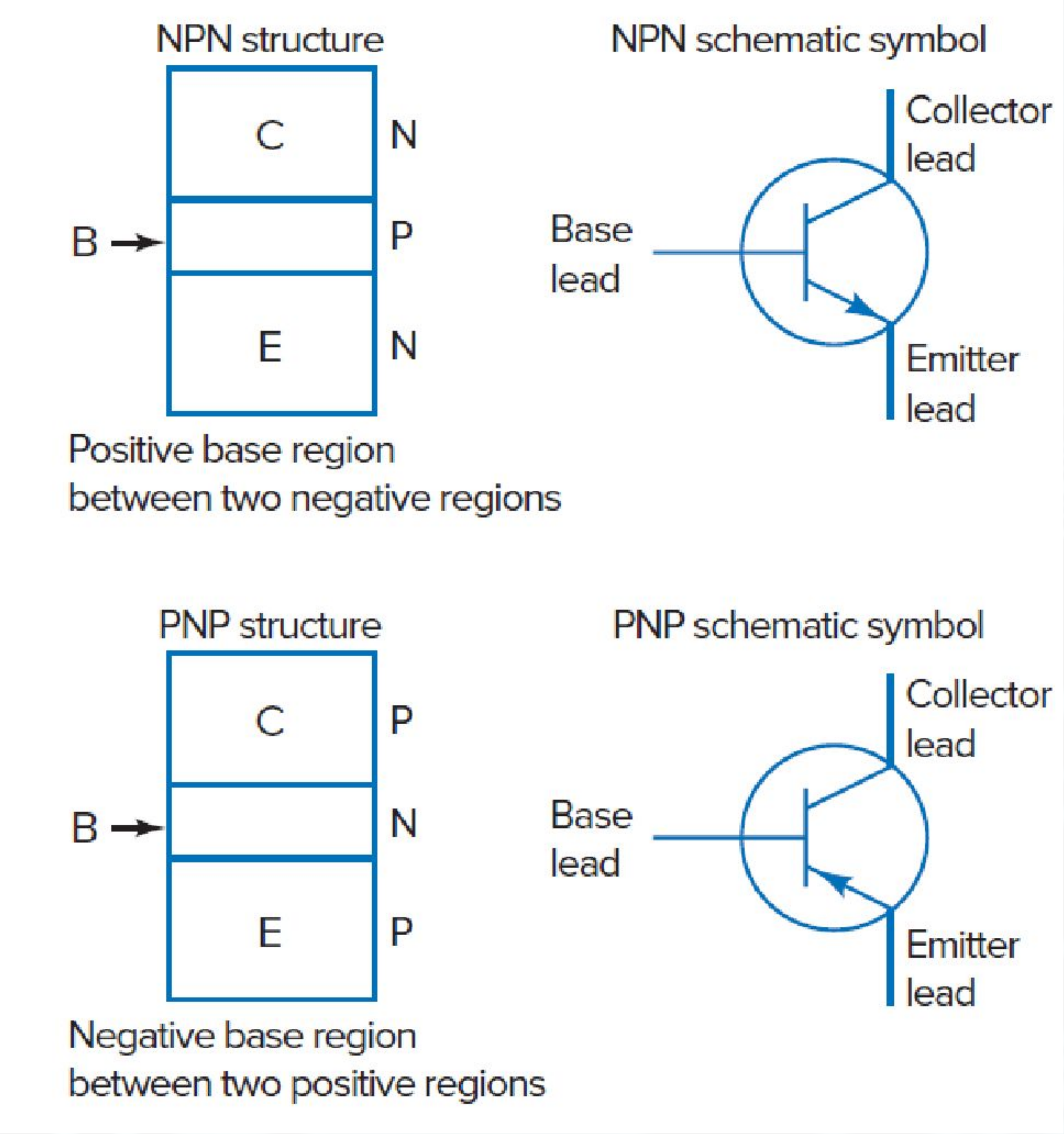


Fig. 5-4 Transistor structures and symbols.

Transistors (5)

The ***base-emitter junction*** must be ***forward-biased*** to turn the transistor on, as shown in Fig. 5-5. This makes the resistance of the base-emitter junction very low as compared with the resistance of the collector-base junction. A forward-biased semiconductor junction has low resistance. A reverse-biased junction has high resistance. Figure 5-6 compares the two junction resistances.

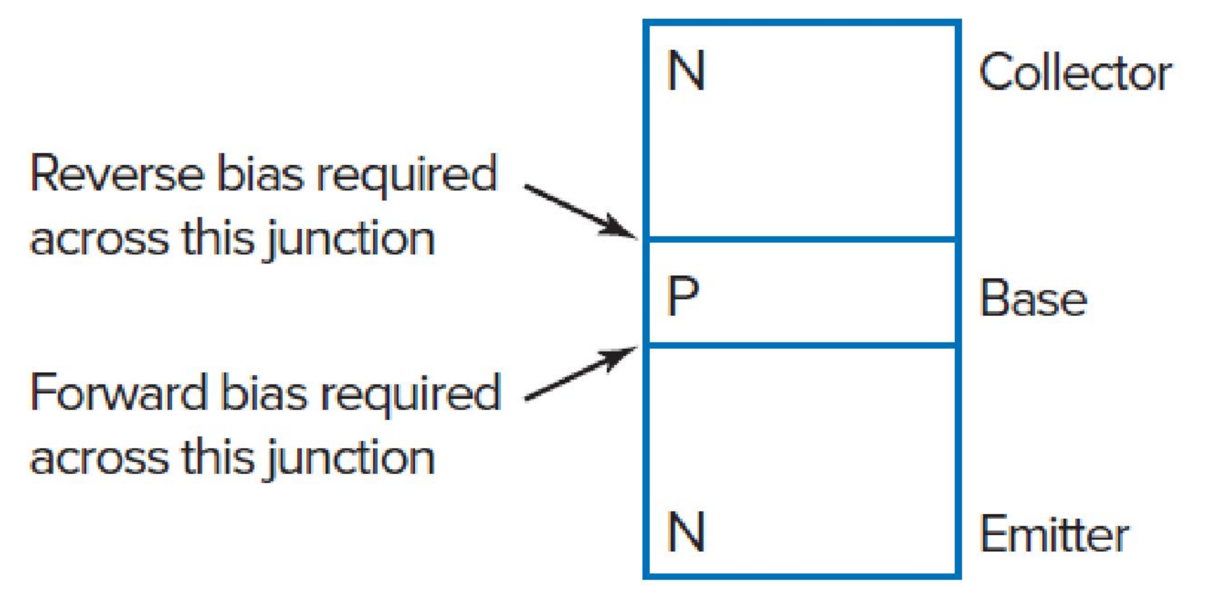


Fig. 5-5 Biasing the transistor junctions.

Transistors (6)

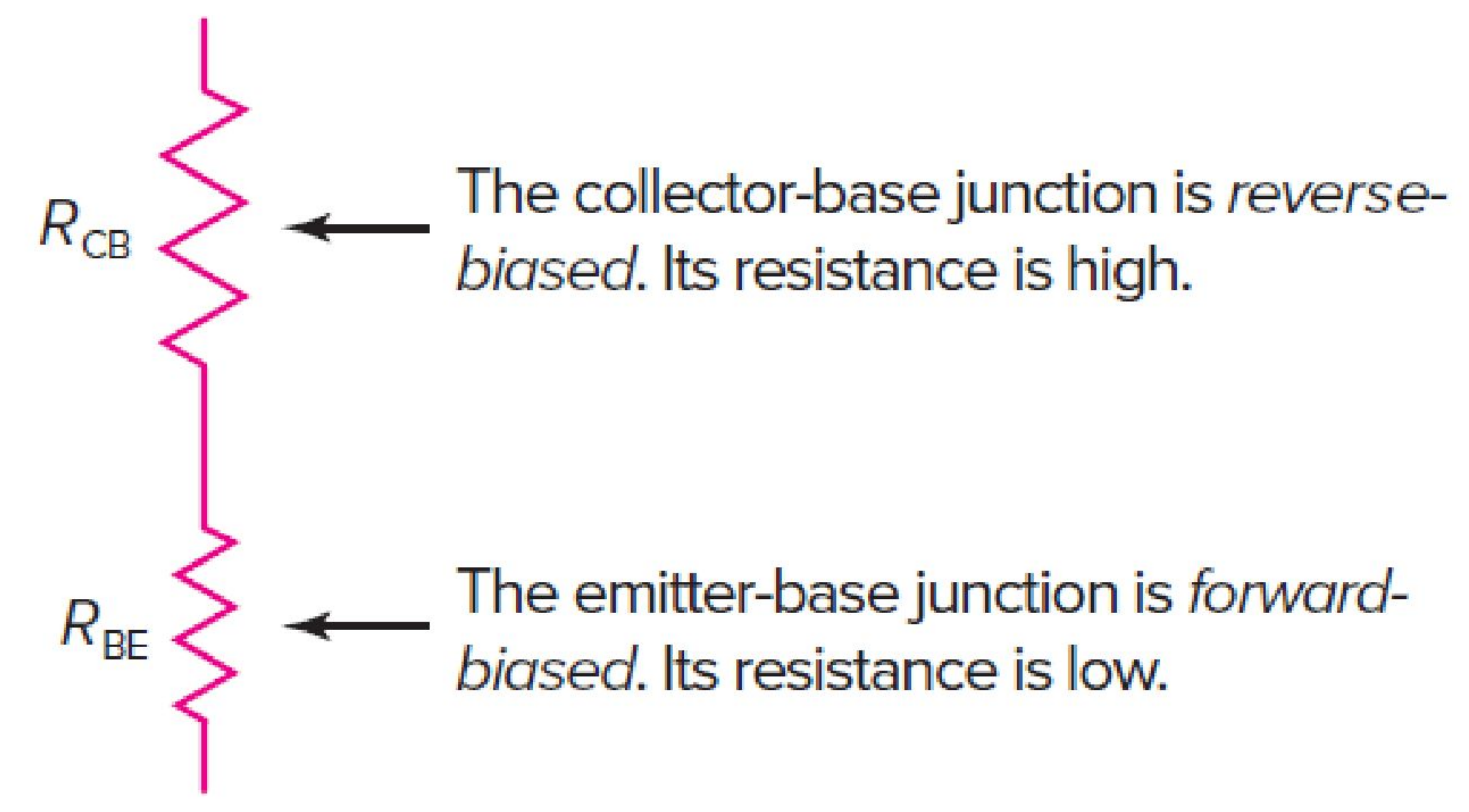
The large difference in junction resistance makes the transistor capable of power gain. Assume that a current is flowing through the two resistances shown in Fig. 5-6. Power can be calculated using

$$P = I^2 \times R$$

The power gain from *R*BE to *R*CB could be established by calculating the power in each and dividing:

$$P_{\text{gain}} = \frac{I^2 \times R_{\text{CB}}}{I^2 \times R_{\text{BE}}}$$

Transistors (7)



The collector-base junction is *reverse-biased*. Its resistance is high.

The emitter-base junction is *forward-biased*. Its resistance is low.

Fig. 5-6 Comparing junction resistances.

Transistors (8)

If the current through R_{CB} happened to be equal to the current through R_{BE}, I^2 would cancel out and the power gain would be

$$P_{\text{gain}} = \frac{R_{\text{CB}}}{R_{\text{BE}}}$$

The currents in transistors are not equal, but they are very close. A typical value for R_{CB} might be 10 kΩ. It is high since the collector-base junction is reverse-biased. A typical value for R_{BE} might be 100 Ω. It is low because the base-emitter junction is forward- biased. The power gain for this typical transistor would be

$$P_{\text{gain}} = \frac{R_{\text{CB}}}{R_{\text{BE}}} = \frac{10 \times 10^3\ \Omega}{100\ \Omega}$$

$$= 100$$

Transistors (9)

Figure 5-7 shows why the collector-base junction current is high. The collector-base voltage V_{CB} produces a reverse bias across the collector-base junction. The base-emitter voltage V_{BE} produces a forward bias across the base-emitter junction. If the transistor were simply two diode junctions, the results would be as follows:

- I_B and I_E would be high.
- I_C would be zero.

The base region of the transistor is very narrow (about 0.0025 cm, or 0.001 in.). The base region is lightly doped. It has only a few free holes. It is not likely that an electron coming from the emitter will find a hole in the base with which to combine.

Transistors (10)

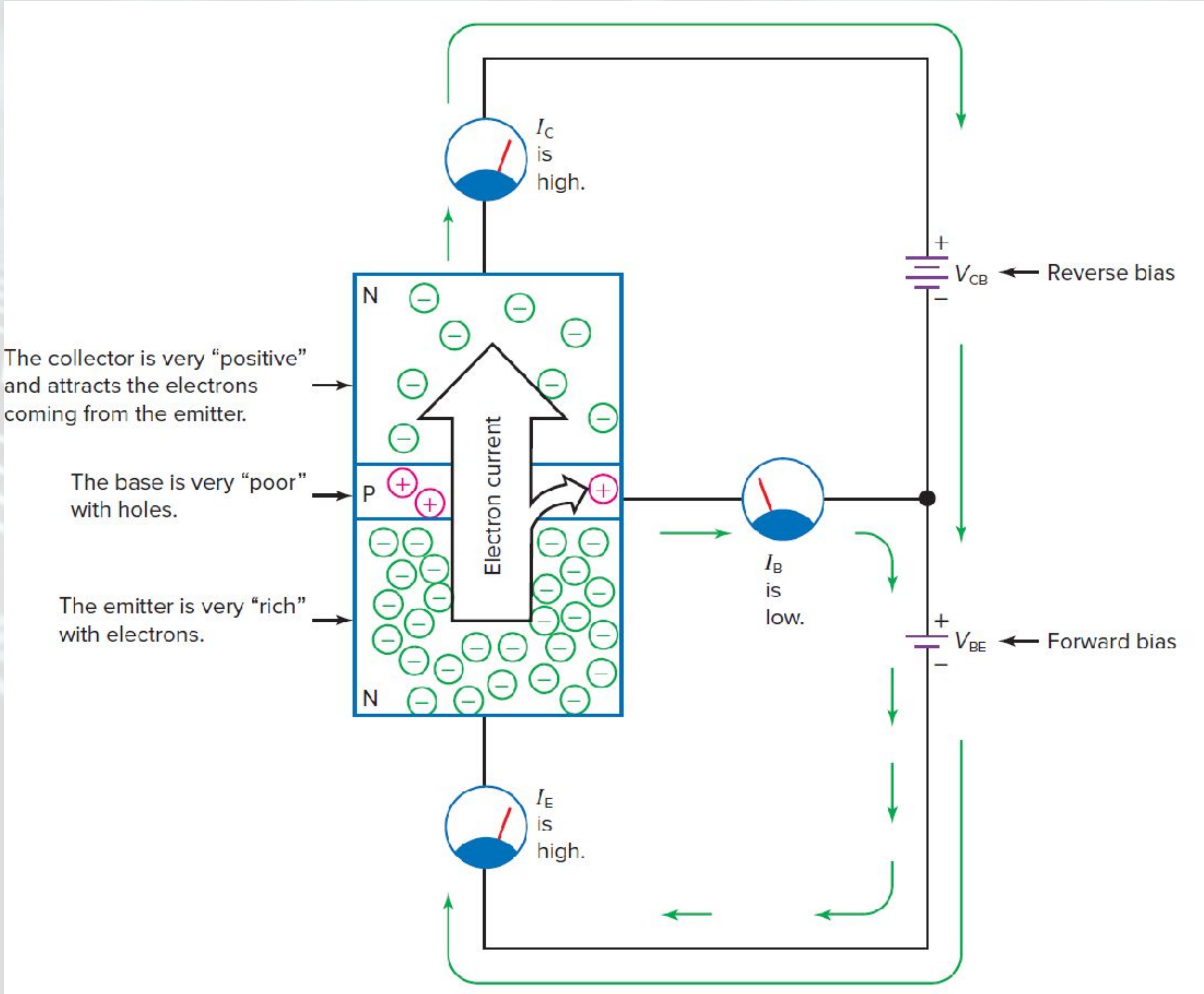


Fig. 5-7 NPN transistor currents.

Transistors (11)

With so few electron-hole combinations in the base region, the base current is very small. The collector is an N-type region but is charged positively by VCB. Since the base is such a narrow region, the positive field of the collector is quite strong, and the great majority of the electrons coming from the emitter are attracted and collected by the collector. Thus,

- I_E and I_C are high.
- I_B is low.

The emitter current in Fig. 5-7 is the highest current in the circuit. The collector current is just a bit less. Typically, about 99 percent of the emitter carriers go on to the collector. About 1 percent of the emitter carriers combine with carriers in the base and become base current.

Transistors (12)

The current equation for Fig. 5-7 is

$$I_E = I_C + I_B$$

By using typical percentages, it can be stated as

$$100\% = 99\% + 1\%$$

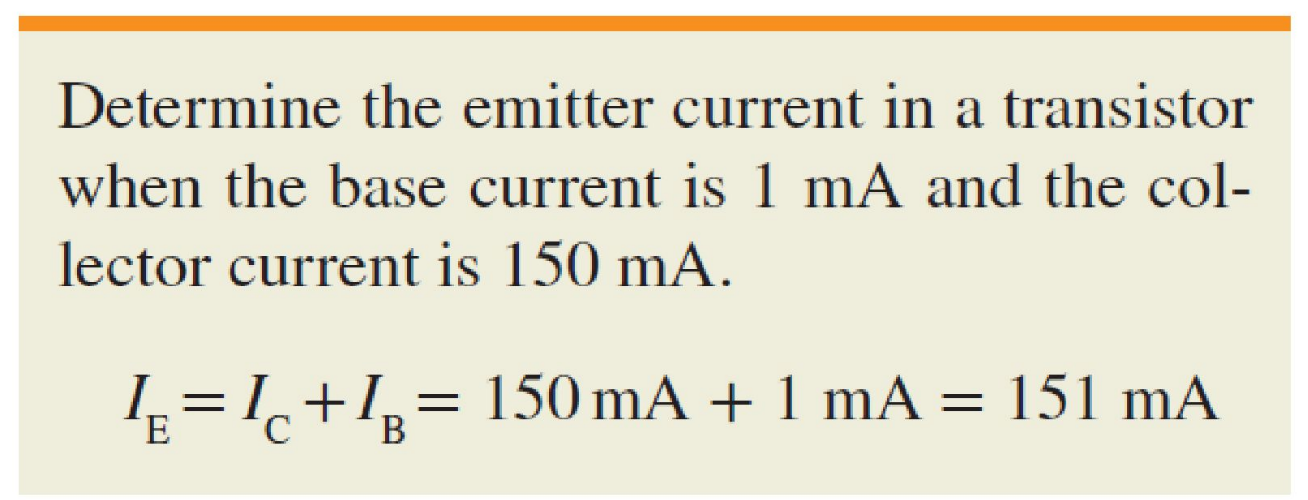
The base current is quite small but ***very*** important. Suppose, for example, that the base lead of the transistor in Fig. 5-7 is opened. With the lead open, there can be no base current. The two voltages V_{CB} and V_{BE} will add in series to make the collector positive with respect to the emitter.

Transistors (13)

Current will continue to flow from the emitter to the collector, but ***it does not. With no base current, there will be no emitter current and no collector current.*** The base-emitter junction ***must*** be forward-biased for the emitter to emit. Opening the base lead removes this forward bias. If the emitter is not emitting, there is nothing for the collector to collect. Even though the base current is very low, it must be present for the transistor to conduct from emitter to collector.

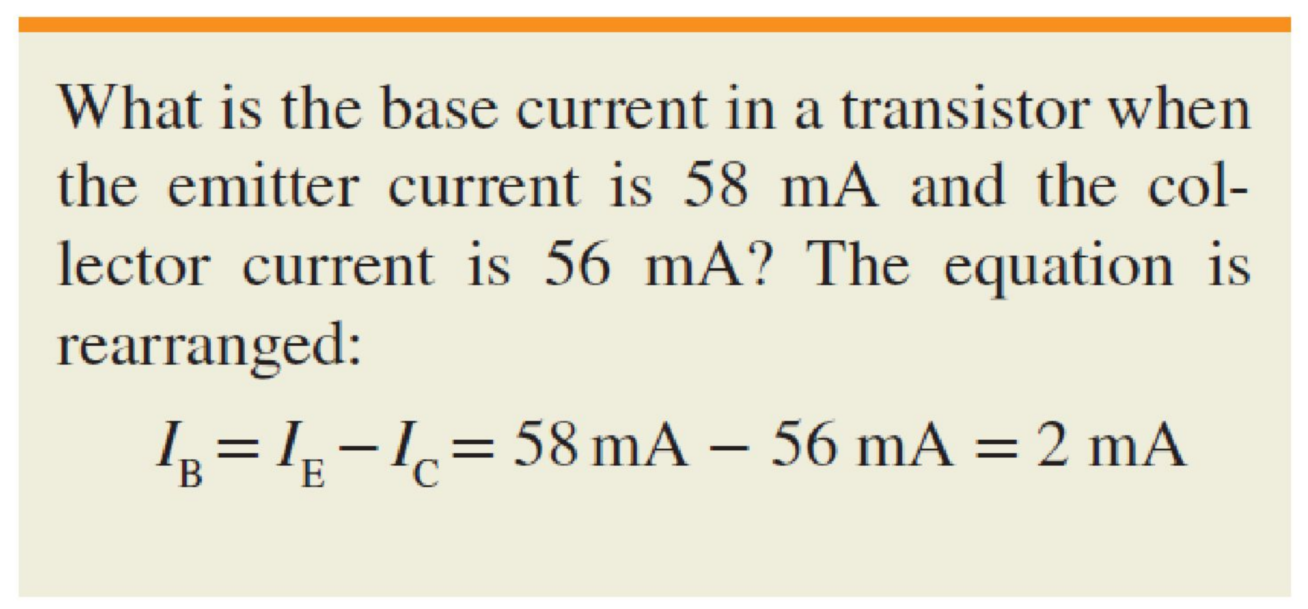
The fact that a low base current controls much higher currents in the emitter and collector is very important. This shows how the transistor is capable of good current gain. Quite often, the current gain from the base terminal to the collector terminal will be specified. This is one of the most important transistor characteristics.

Calculation of transistor’s current



Determine the emitter current in a transistor when the base current is 1 mA and the collector current is 150 mA.

$$I_E = I_C + I_B = 150\,\text{mA} + 1\,\text{mA} = 151\,\text{mA}$$



What is the base current in a transistor when the emitter current is 58 mA and the collector current is 56 mA? The equation is rearranged:

$$I_B = I_E - I_C = 58\,\text{mA} - 56\,\text{mA} = 2\,\text{mA}$$

Transistors (14)

The characteristic is called β (Greek beta), or h_{FE}:

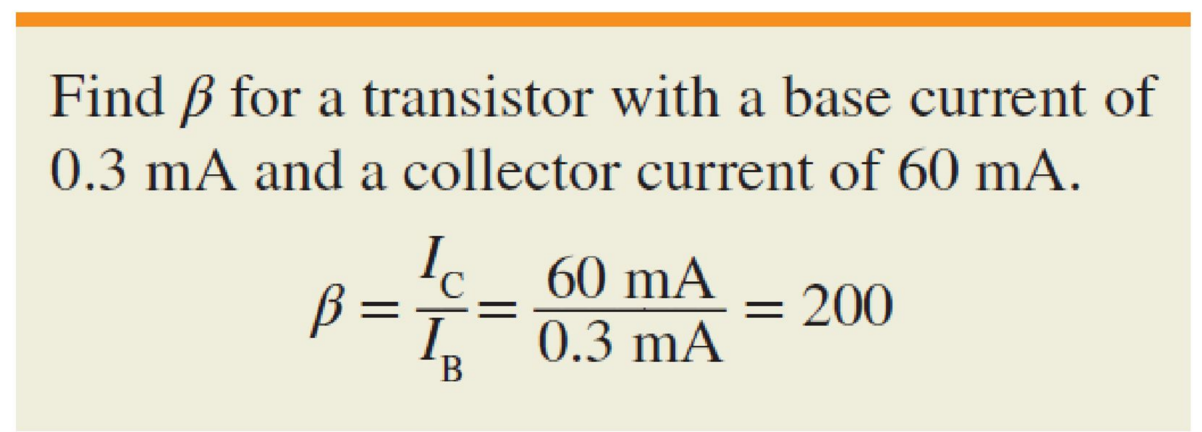
$$\beta = \frac{I_C}{I_B} \qquad \text{or} \qquad h_{FE} = \frac{I_C}{I_B}$$

What is the β of a typical transistor? If the base current is 1 percent and the collector current is 99 percent, then

$$\beta = \frac{99\%}{1\%}$$

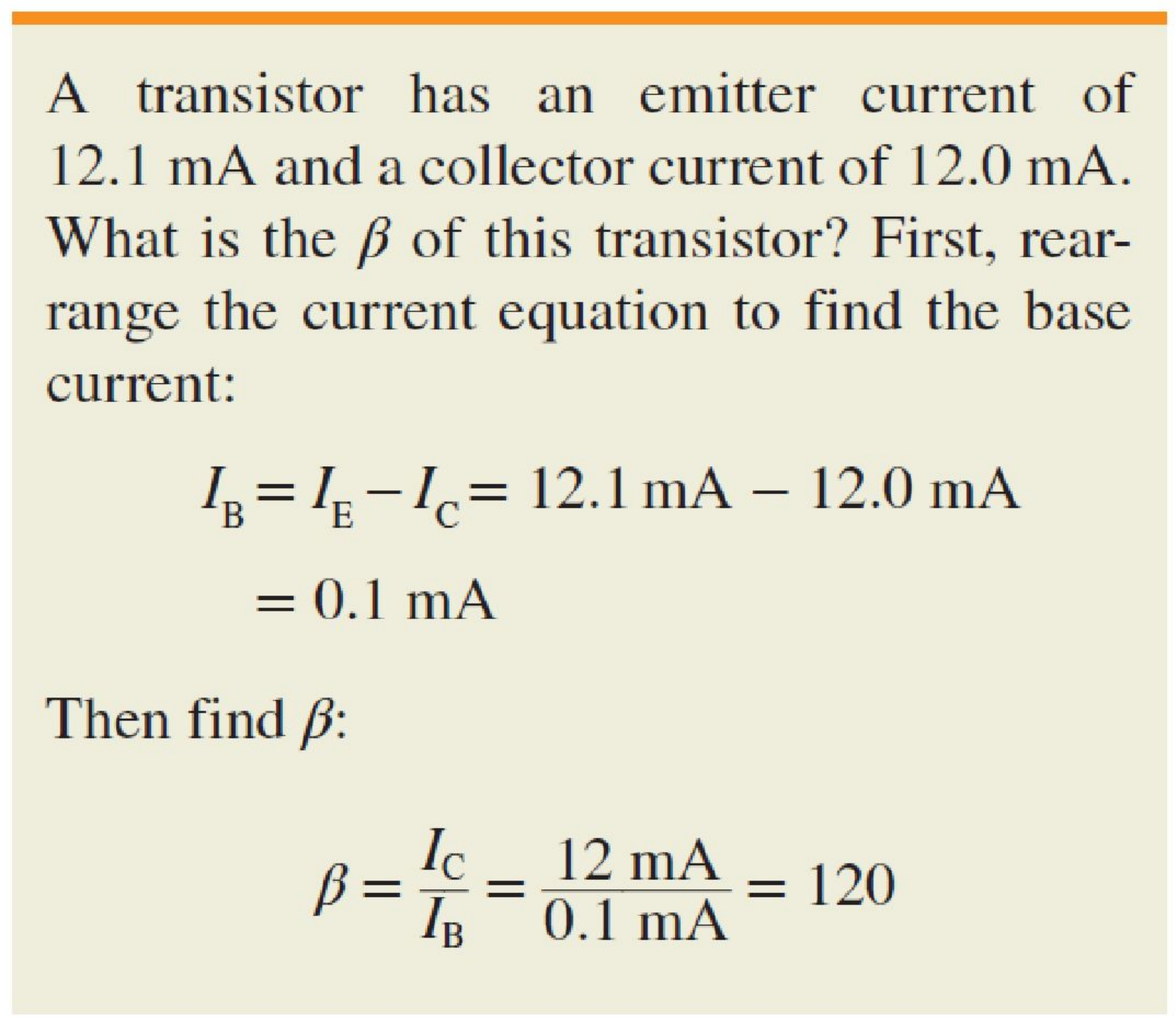
$$= 99$$

Calculation of β



Find β for a transistor with a base current of 0.3 mA and a collector current of 60 mA.

$$\beta = \frac{I_C}{I_B} = \frac{60\text{ mA}}{0.3\text{ mA}} = 200$$



A transistor has an emitter current of 12.1 mA and a collector current of 12.0 mA. What is the β of this transistor? First, rearrange the current equation to find the base current:

$$I_B = I_E - I_C = 12.1\text{ mA} - 12.0\text{ mA}$$

$$= 0.1\text{ mA}$$

Then find β:

$$\beta = \frac{I_C}{I_B} = \frac{12\text{ mA}}{0.1\text{ mA}} = 120$$

Transistors (15)

Figure 5-8 shows the flow from emitter to collector as ***hole current***. In an NPN transistor, it is ***electron current***. The two transistor structures operate about the same in most ways. The emitter is very rich with carriers. The base is quite narrow and has only a few carriers. The collector is charged by the external bias source and attracts the carriers coming from the emitter. The major difference between PNP and NPN transistors is polarity.

The NPN transistor is more widely used than the PNP transistor. Electrons have better mobility than holes; that is, they can move more quickly through the crystal structure. This gives NPN transistors an advantage in high-frequency circuits where things have to happen quickly.

Transistors (16)

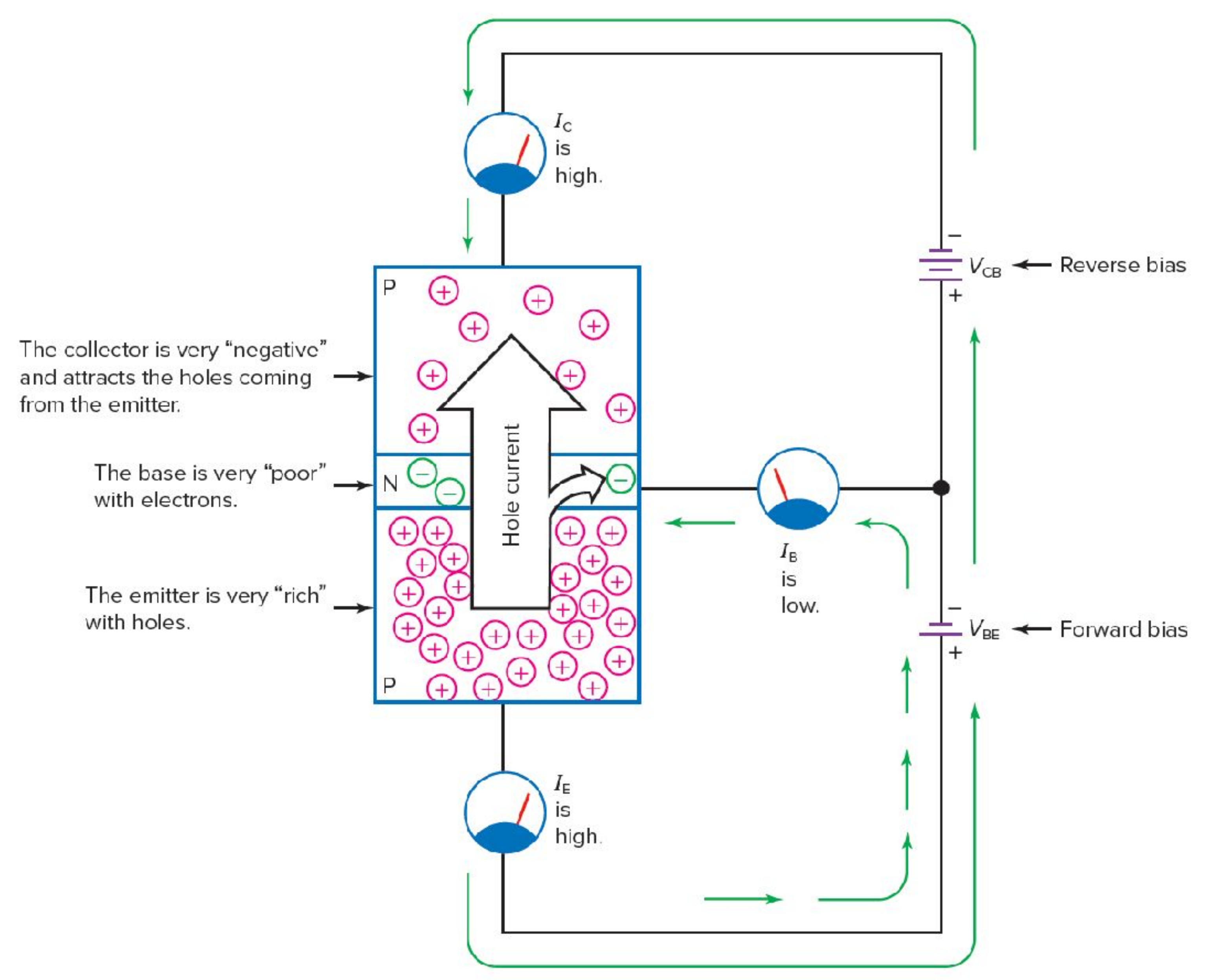
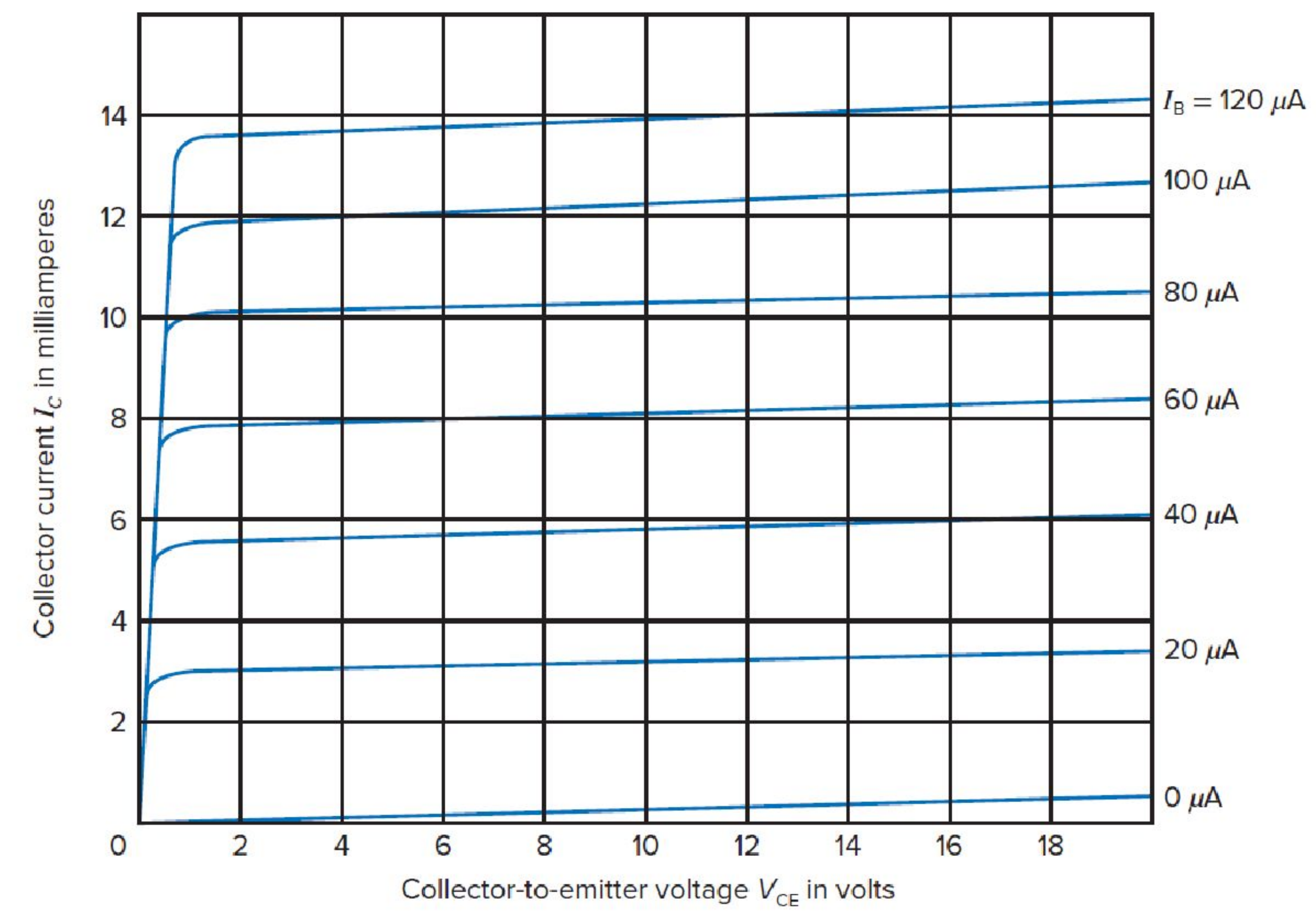


Fig. 5-8 PNP transistor currents.

Characteristic Curves

As with diodes, transistor characteristic curves can provide much information. There are many types of transistor characteristic curves. One of the more popular types is the ***collector family of curves***. An example of this type is shown in Fig. 5-9. The vertical axis shows collector current (I_C) and is calibrated in milliamperes. The horizontal axis shows collector-emitter bias (V_{CE}) and is calibrated in volts. Figure 5-9 is called a collector ***family*** since several voltampere characteristic curves are presented for the same transistor.

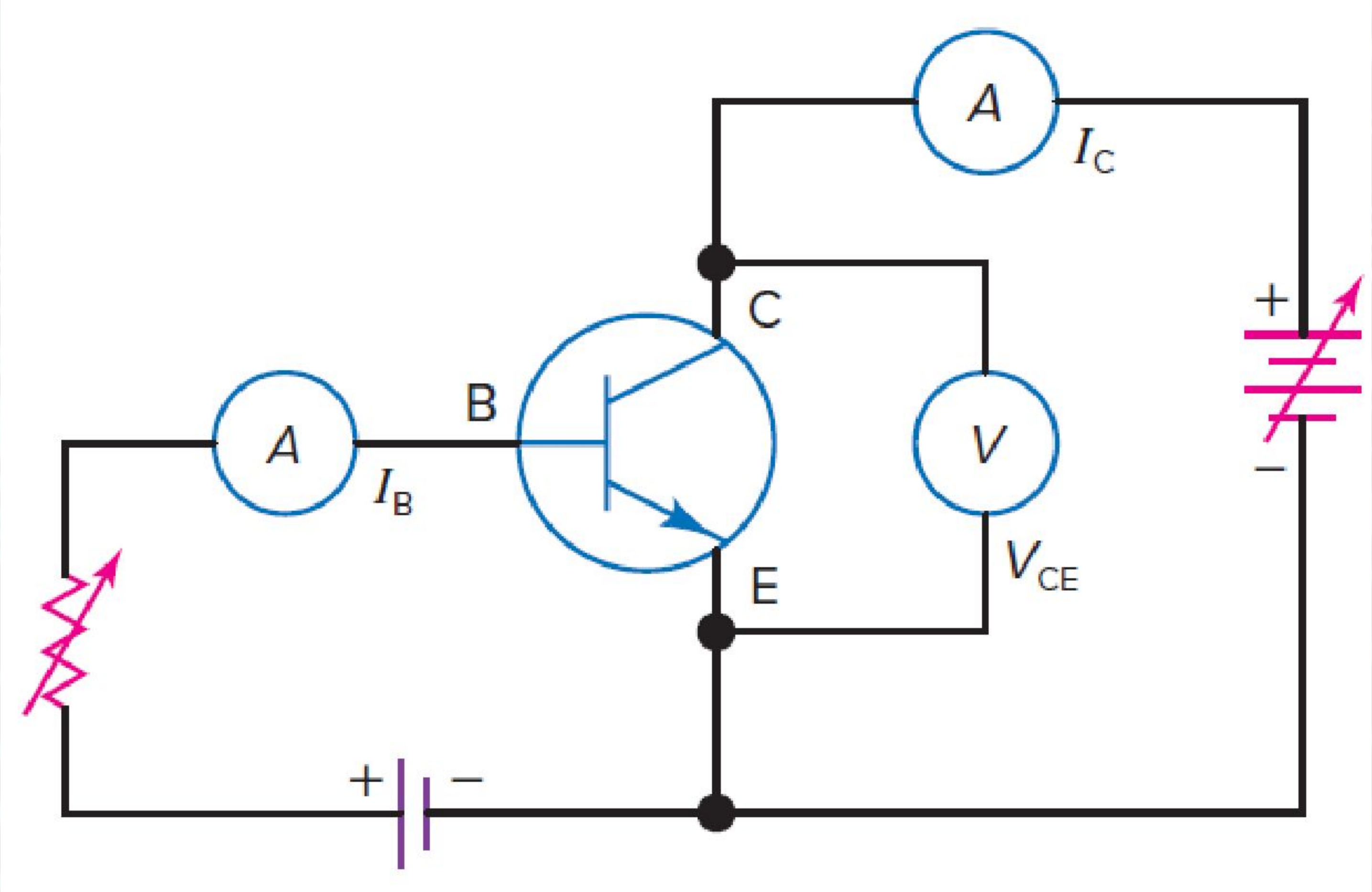
Fig. 5-9 A collector family of curves for an NPN transistor.



Characteristic Curves (1)

Figure 5-10 shows a circuit that can be used to measure the data points for a collector family of curves. Three meters are used to monitor base current I_B, collector current I_C, and collector-emitter voltage V_{CE}. To develop a graph of three values, one value can be held constant as the other two vary. This produces one curve. Then the constant value is set to a new level. Again, the other two values are changed and recorded. This produces the second curve. The process can be repeated as many times as required. For a collector family of curves, the constant value is the base current.

Fig. 5-10 Circuit for collecting transistor data.



Characteristic Curves (2)

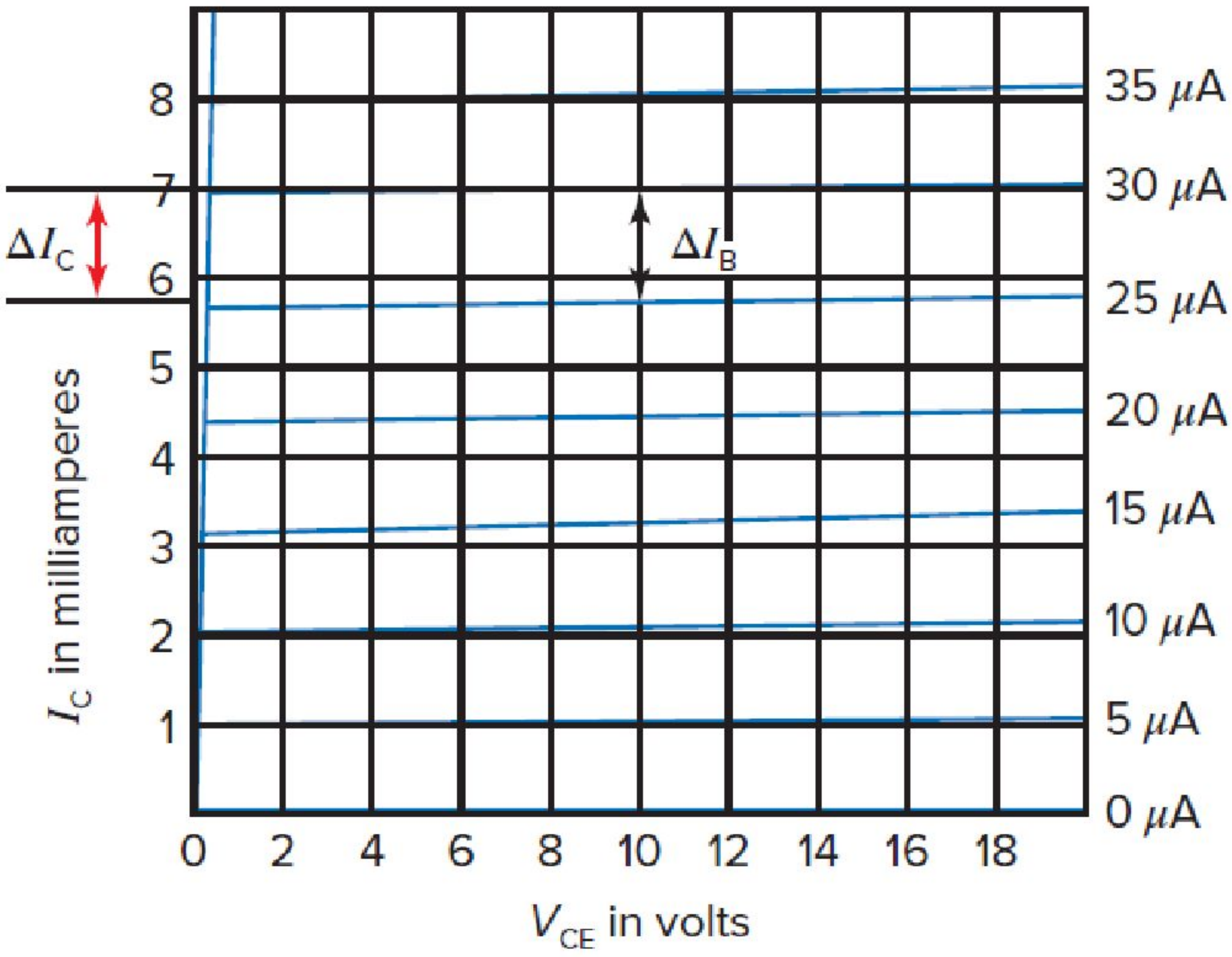
The variable resistor in Fig. 5-10 is adjusted to produce the desired level of base current. Then the adjustable source is set to some value of V_{CE}. The collector current is recorded. Next, V_{CE} is changed to a new value. Again, IC is recorded. These data points are plotted on a graph to produce a volt-ampere characteristic curve of I_C versus V_{CE}. A very accurate curve can be produced by recording many data points. The next curve in the family is produced in exactly the same way but at a new level of base current.

The curves of Fig. 5-9 show some of the important characteristics of junction transistors. Notice that over most of the graph, the collector emitter voltage has little effect on the ***collector current***.

Characteristic Curves (3)

The two prior calculations reveal another act about transistors. ***Not only does β vary from transistor to transistor***, but it also varies with I_C. Later, it will be shown that temperature also affects β.

What happens to a transistor when its base current is relatively large? For example, what about Fig. 5-11 if I_B = 1 mA? This is off the graph! But it can be interpreted. First, this will not damage the transistor unless its maximum collector dissipation rating is exceeded. This subject will be covered a little later in this section. Transistors can be damaged by excess base current, but something important happens before that extreme is reached. The transistor will operate somewhere along the ***steep vertical part*** of the characteristic curves.



$$\beta_{ac} = h_{fe} = \frac{\Delta I_C}{\Delta I_B} = \frac{1.3\text{ mA}}{5\ \mu\text{A}} = 260$$

There is no significant difference between β_{dc} and β_{ac} at low frequencies. This book emphasizes β_{dc}. The beta symbol with no subscript will designate dc current gain. Alternating current gain will be designated by β_{ac}.

Fig. 5-11 Calculating β_{ac} with characteristic curves

Transistors at high frequencies

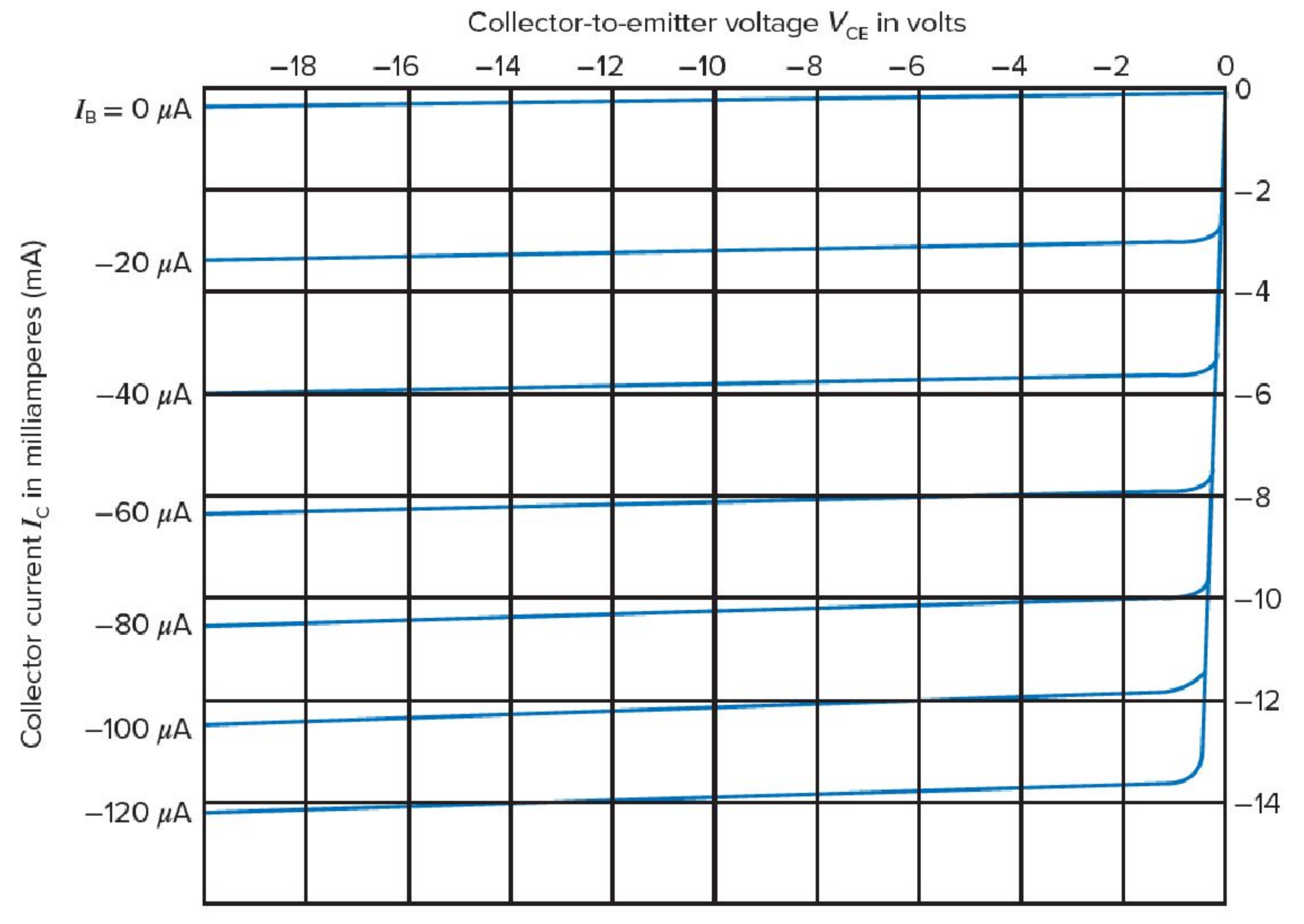
At high frequencies the ac current gain of BJTs starts to fall off. This effect limits the useful frequency range of transistors. The ***gain-bandwidth product*** is the frequency at which the ac current drain drops to 1. The symbol for gain-bandwidth product is f_T . This transistor specification is important in high-frequency applications. For example, the 2N5179 is a radio-frequency transistor and has an fT of 1.4 GHz. The 2N3904 is a general-purpose transistor and has an fT of 300 MHz. Thus, it would not be good practice to substitute a 2N3904 for a 2N5179 in a radiofrequency circuit.

Characteristic Curves (4)

It is standard practice to plot positive values to the right on the horizontal axis and up on the vertical axis. Negative values go to the left and down. A family of curves for a PNP transistor may be plotted on a graph as shown in Fig. 5-12. The collector voltage must be negative in a PNP transistor. Thus, the curves go to the left. The collector current is in the opposite direction, compared with an NPN transistor. Thus, the curves go down. However, curves for PNP transistors are sometimes drawn up and to the right. Either method is equally useful for presenting the collector characteristics.

Some shops and laboratories are equipped with a device called a **curve tracer**. This device draws the characteristic curves on a cathode-ray tube or liquid crystal display (LCD). This is far more convenient than collecting many data points and plotting the curves by hand.

Fig. 5-12 A collector family of curves for a PNP transistor.

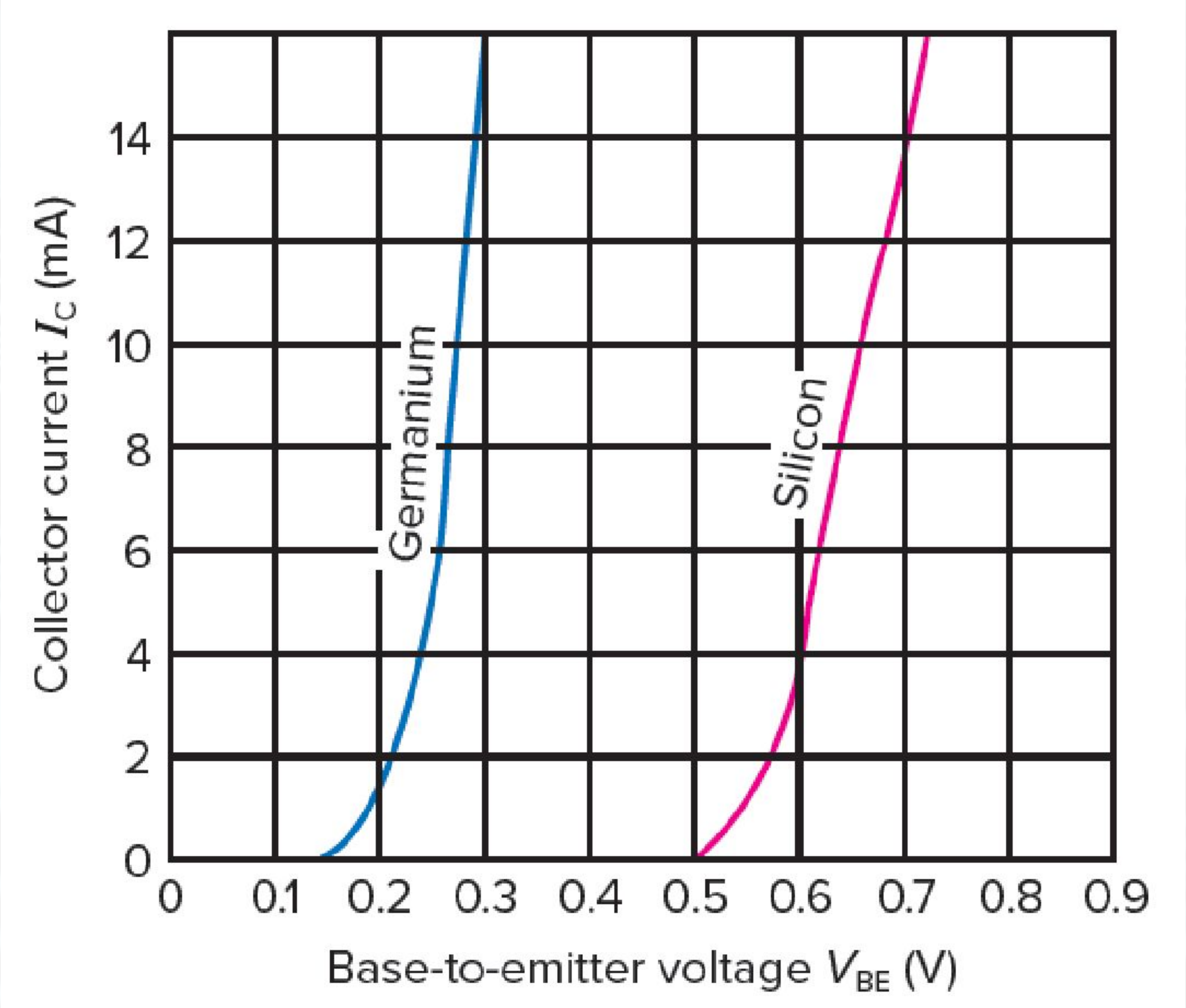


Characteristic Curves (5)

The ***transfer characteristic*** curves shown in Fig. 5-13 are another example of how curves can be used to show the electrical characteristics of a transistor. Curves of this type show how one transistor terminal (the base) affects another (the collector). This is why they are called transfer curves. Because that base current controls collector current. Figure 5-13 shows how base-emitter voltage controls collector current. This is because the base-emitter bias sets the level of base current.

Figure 5-13 also shows one of the important differences between silicon transistors and germanium transistors. Like diodes, germanium transistors turn on at a much lower voltage (approximately 0.2 V). The silicon device turns on near 0.6 V. Germanium transistors are rarely used now. They have been replaced by silicon devices because silicon works better at high temperatures.

Fig. 5-13 Comparing silicon and germanium transistors.



Transistor Data

Transistor manufacturers prepare data sheets that detail the mechanical, thermal, and electrical characteristics of the parts they make. These data sheets are often bound into volumes called ***data manuals***. Table 5-1 is a sample from a data manual. It shows the ***maximum ratings*** and some of the ***characteristics*** for 2N2222A transistors. Data manuals also contain characteristic curves such as those discussed previously.

Technicians usually try to replace a defective transistor with one having the same part number. This is considered an “exact replacement” even when the manufacturer is different. Sometimes it is impossible to find an exact replacement. Data, such as those shown in Table 5-1, are very useful in these cases.

Transistor Data (1)

Comparing two transistors often shows that they are very similar. For example, the specifications of a 2N3904 transistor are strikingly similar to those for a 2N2222A transistor shown in Table 5-1. One difference, not shown in the table, is rise time, which is 25 ns for the 2N2222 and 35 ns for the 2N3904. The 2N2222 is a switching transistor, so it is faster. However, it is possible to substitute one device for the other in most applications.

One way for a technician to learn something about a particular transistor is to use ***substitution*** guides. These guides are not totally accurate, but they do provide a good, general idea about the device of interest. Another good source of information is a ***parts catalog***. Figure 5-14 is a sample of transistor listings from a parts catalog.

Table 5-1 Selected Specifications for the 2N2222A Bipolar Junction Transistor

Parameter	Symbol	Value
Maximum ratings		
Collector-emitter voltage	V_{CEO}	40 V dc
Collector-base voltage	V_{CB}	75 V dc
Emitter-base voltage	V_{EB}	6 V dc
Collector current	I_C	800 mA dc
Total device dissipation (derate above 25°C)	P_D	1.8 W 12 mW/°C
Characteristics		
DC current gain	h_{FE}	100 to 300
AC current gain	h_{fe}	50 to 375
Gain-bandwidth product	f_T	300 MHz
Collector-emitter saturation	$V_{CE(sat)}$	0.3 V dc
Noise figure	NF	4 dB

Type	Case	Material Function	Maximum Ratings			Beta H_{FE}@Ic		f_T MHz
			Dissipation Watts	Coll. to Base Volts	Coll. Curr. mA	Min. Max.	mA	
2N2870/ 2N301	TO-3	GP AP	30C	80	3A	50-165	1A	.200
2N2876	TO-60	SN AV	17.5C	80	2.5A			.200
2N2894	TO-18	SP SH	1.2C	12	200	40-150	30	400
2N2895	TO-18	SN GP	.500	120	1A	60-150	1	120
2N5070	TO-60	SN AP	70C	65	3.3A	10-100	3A	100
2N5071	TO-60	SN AP	70C	65	3.3A	10-100	3A	100
2N5086	TO-92	SP GP	.310	50	50	150-	1	40
2N5087	TO-92	SP GP	.310	50	50	250-	1	40
2N5088	TO-92	SN GP	.310	35	50	350-	1	
2N5172	TO-98	SN GP	.200	25	100	100-	10	
2N5179	TO-72	SN AU	.200	20	50	25-	20	900
2N5180	TO-104	SN AU	.180	30		20-	2	650
2N5183	TO-104	SN GP	.500	18	1A	70-	10	62
2N5184	TO-104	SN GP	.500	120	50	10-	50	50

Material code:	GP	Germanium, PNP
	SN	Silicon, NPN
	SP	Silicon, PNP
Function code:	AP	Amplifier, power
	AV	Amplifier, VHF
	SH	Switch, high speed
	GP	General purpose
	AU	Amplifier, UHF

Fig. 5-14 Transistor catalog listings.

Transistor case styles

There are hundreds of transistor case styles. Most are registered with the Joint Electron Device Engineering Council. The JEDEC website shows transistor cases (Transistor Outlines) from TO-1 to TO-249. Figure 5-15 shows three examples. SOT means small-outline transistor. Transistor data sheets often provide case dimensions and identify the emitter, base, and collector leads.

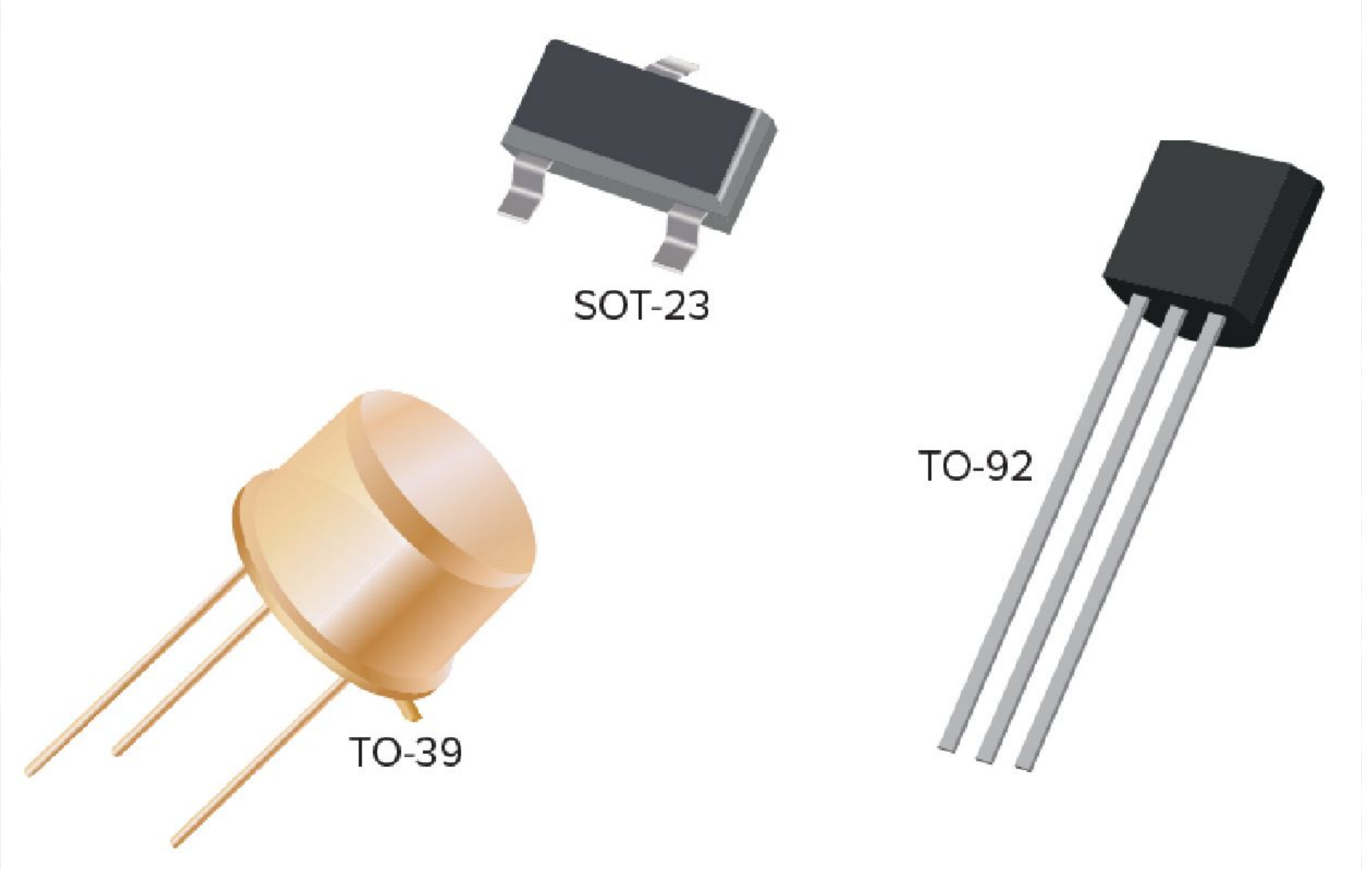


Fig. 5-15 Three transistor case styles.

Transistor replacement

In some cases the part number cannot be found in any of the available guides or on the original transistor. It may be possible to use a general type of unit in these situations. For example, the 2N2222A (or the 2N3904) is a good, general-purpose replacement for small-signal silicon NPN BJTs. Likewise, the 2N2905A (or the 2N3906) is a general-purpose PNP replacement. General-purpose replacements should be avoided in these cases:

- VHF or UHF applications
- High-power applications
- High-voltage applications

Substitute transistors must be of the same material and the same polarity. Also, be sure that size and lead arrangements are compatible. They must be based on the same technology.

Transistor Testing

One way to test transistors is to use a curve tracer. This technique is used by semiconductor manufacturers and by equipment makers to test incoming parts. Curve tracers are also used in design labs. Figure 5-19 at the end of this section shows an affordable curve tracer.

Another technique used at manufacturing and design centers is to place the transistor in a special fixture or test circuit. This is a ***dynamic test*** because it makes the device operate with real voltages and signals. This method of testing is often used for VHF and UHF transistors. Dynamic testing reveals power gain and ***noise figure*** under signal conditions. Noise figure is a measure of a transistor’s ability to amplify weak signals. Some transistors generate enough electrical noise to overpower a weak signal. These transistors are said to have a poor noise figure.

Transistor Testing

Fig. 5-19(a) Atlas DCA Pro curve tracer

Transistor Testing

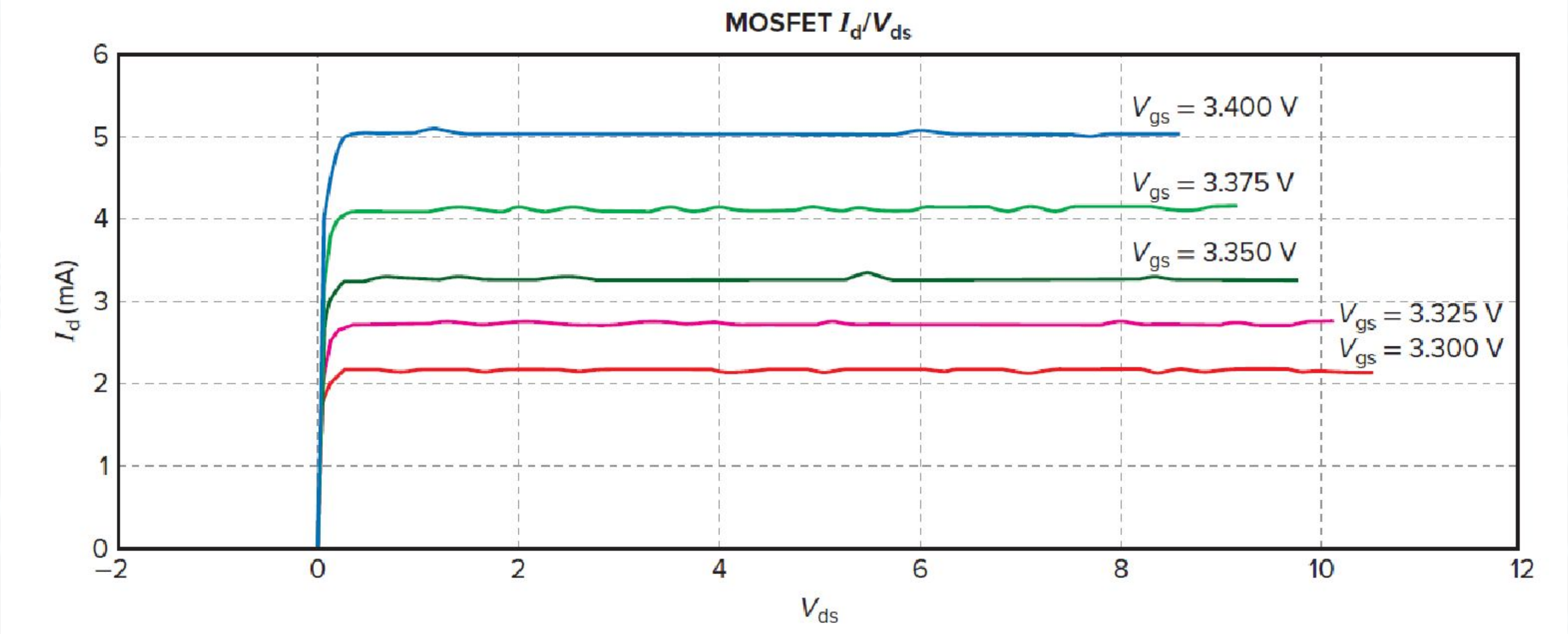


Fig. 5-19(b) Atlas DCA Pro curve analyzer

Transistor Testing (1)

A few transistor types may show a gradual loss of power gain. Radio-frequency power amplifiers, for example, may use overlay-type transistors. These transistors can have over 100 separate emitters. They can suffer base-emitter changes that can gradually degrade power gain. Another problem is moisture, which can enter the transistor package and gradually degrade performance. Even though gradual failures are possible in transistors, they are ***not*** typical.

For the most part, ***transistors fail suddenly and completely***. One or both junctions (the junction is the transition region between P and N) may short-circuit. An internal connection can break loose or burn out from an overload. This type of failure is easy to check. Most bad transistors can be identified with a few ohmmeter tests out-of-circuit or with voltmeter checks in-circuit.

Transistor Testing (2)

A good transistor has two PN junctions. Both can be checked with an ohmmeter. As shown in Fig. 5-16, a PNP transistor is comparable to two diodes with a common cathode connection. The base lead acts as the common cathode. Figure 5-17 shows an NPN transistor as two diodes with a common anode connection. If two good diodes can be verified by ohmmeter tests, the transistor is probably good.

The ohmmeter can also be used to identify the polarity (NPN or PNP) of a transistor and the three leads. This can be helpful when data are not available. Analog ohmmeters should be set to the R × 100 range for testing most transistors. For DMMs, the diode function can be used

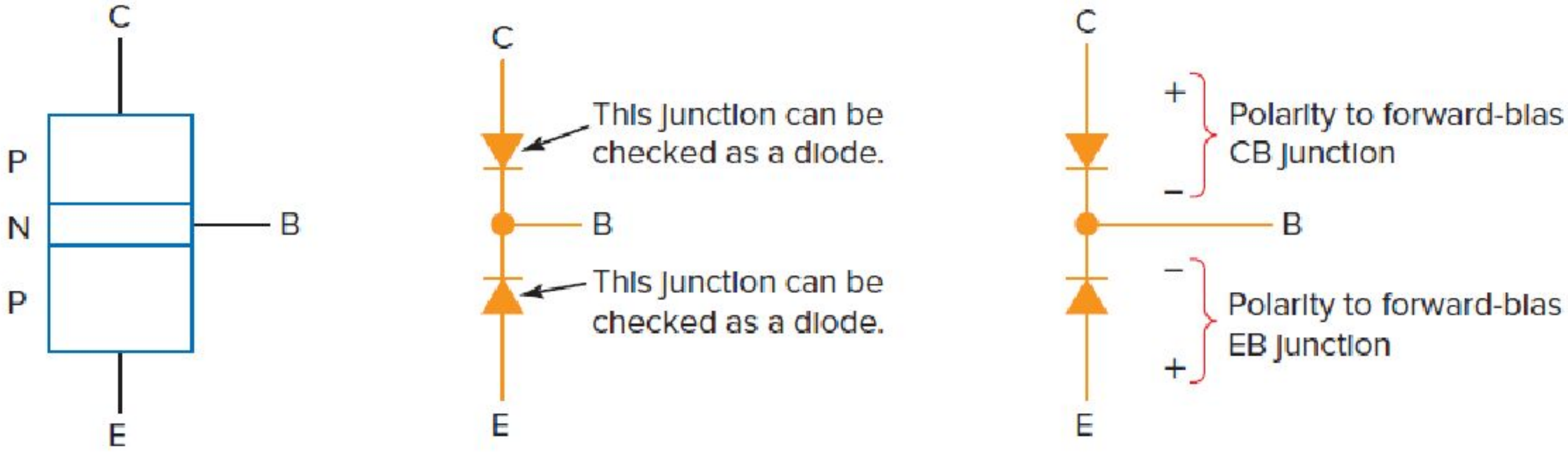


Fig. 5-16 PNP junction polarity.

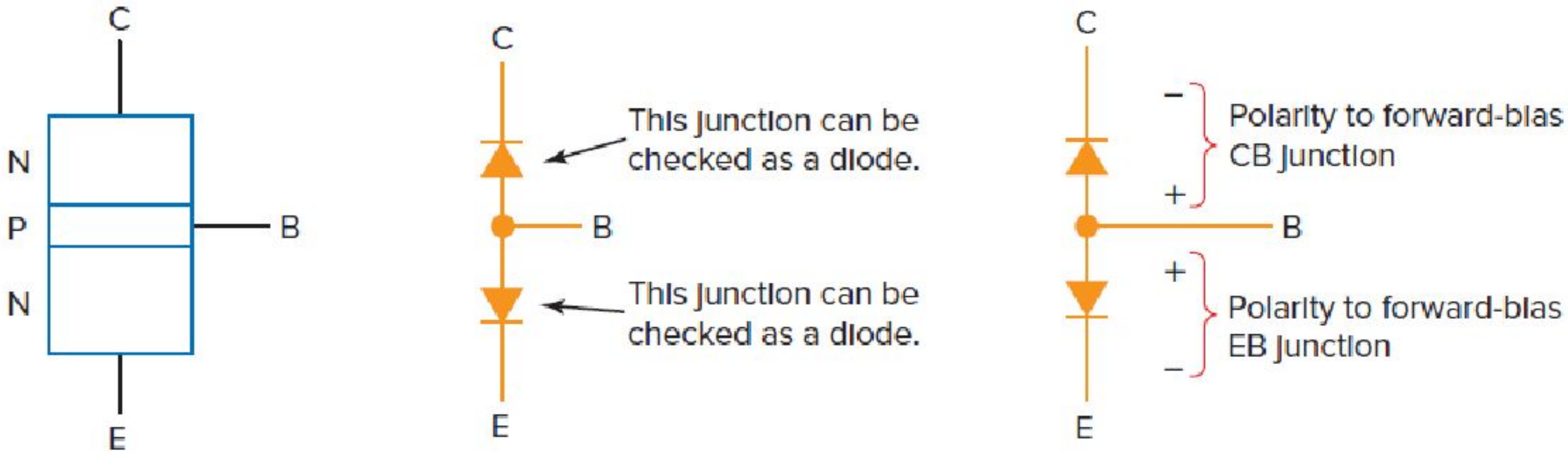


Fig. 5-17 NPN junction polarity.

Transistor Testing (3)

The resistor will be used to provide the transistor with a small amount of base current. If the transistor has good current gain, the collector current will be much greater. The ohmmeter will indicate a resistance much lower than 100,000 Ω, and this proves that the transistor is capable of current gain. This check is made by connecting the ohmmeter across the emitter and collector leads at the same time that the resistor is connected across the collector and base leads. The technique is illustrated for both kinds of meters in Fig. 5-18.

Transistor Testing (4)

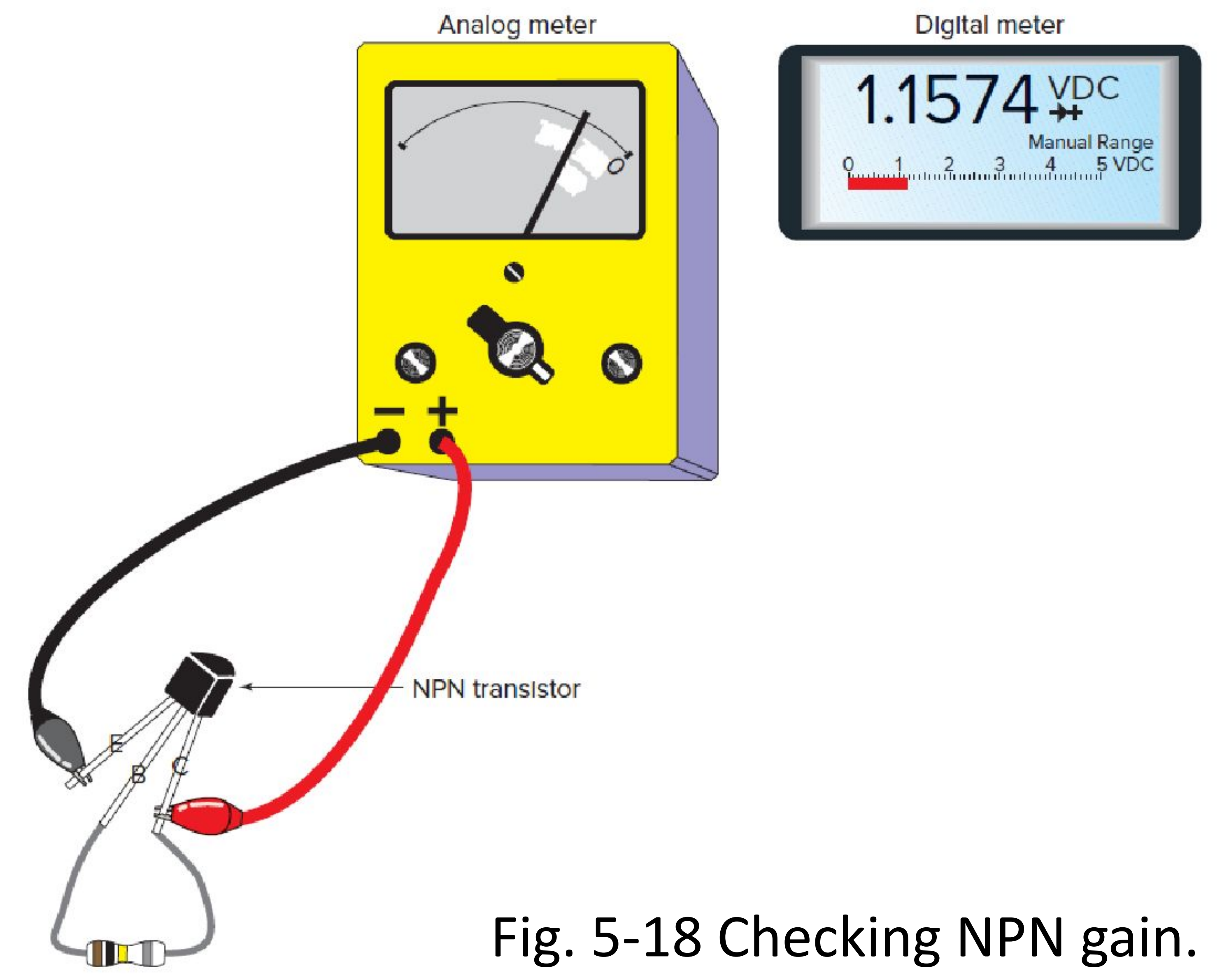


Fig. 5-18 Checking NPN gain.

Transistor Testing (4)

Transistors have some ***leakage current***. This is due to minority carrier action. One leakage current in a transistor is called I_{CBO}. (The symbol I stands for current, CB stands for the collector-base junction, and O tells us the emitter is open.) This is the current that flows across the collector-base junction under conditions of reverse bias and with the emitter lead open. Another transistor leakage current is I_{CEO}. (The symbol I stands for current, CE stands for the collector-emitter terminals, and O tells us that the base terminal is open.) I_{CEO} is the largest leakage current. It is an amplified form of I_{CBO}:

$$I_{\mathrm{CEO}} = \beta \times I_{\mathrm{CBO}}$$

Transistor Testing (5)

With the base terminal open, any current leaking across the reverse-biased collector-base junction will have the same effect on the base-emitter junction as an externally applied base current. With the base terminal open, there is no other place for the leakage current to go. The transistor amplifies this leakage just as it would any base current:

$$I_C = \beta \times I_B$$

Silicon transistors have very low leakage currents. When ohmmeter tests are made, the ohmmeter should show an infinite resistance when the junctions are reverse-biased. Anything less may mean the transistor is defective. Germanium transistors have much greater leakage currents. This will probably show up as a high, but not infinite, reverse resistance.

Other Transistor Types

Bipolar transistors use both holes and electrons as current carriers. A unipolar (one-polarity) transistor uses only one type of current carrier. The ***junction field-effect transistor*** (JFET) is an example of a unipolar transistor. Figure 5-20 shows the structure and schematic symbol for an N-channel JFET. Notice that the leads are named **source**, ***gate***, and ***drain***.

The JFET can be made in two ways. The channel can be N-type material or P-type material. The schematic symbol in Fig. 5-20 is for an N-channel device. The symbol for a ***P-channel device*** will show the arrow on the gate lead pointing out. Remember, pointing iN indicates an ***N-channel device***. In a BJT, both holes and electrons are used to support conduction. In an N-channel JFET, ***only electrons*** are used. In a P-channel JFET, ***only holes*** are used.

Other Transistor Types

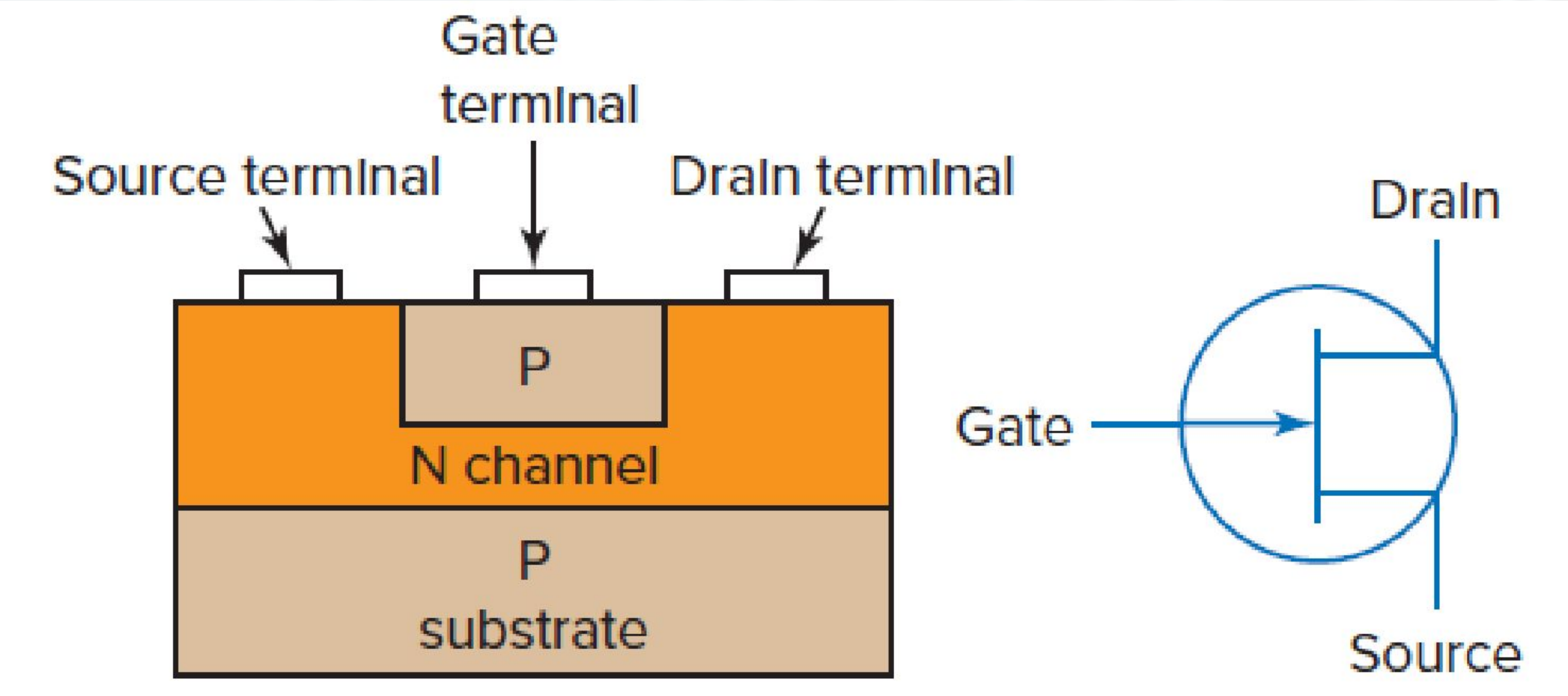


Fig. 5-20 An N-channel JFET.

Other Transistor Types (1)

The JFET operates in the ***depletion mode***. A control voltage at the gate terminal can deplete (remove) the carriers in the channel. For example, the transistor in Fig. 5-20 will normally conduct from the source terminal to the drain terminal. The N channel contains enough free electrons to support the flow of current. If the gate is made negative, the free electrons can be ***pushed out of the channel***. Like charges repel. This leaves the channel with fewer free carriers. The resistance of the channel is now much higher, and this tends to decrease the source and drain currents. In fact, if the gate is made negative enough, the device can be turned off and no current will flow.

Other Transistor Types (2)

Examine the curves of Fig. 5-21. Notice that as the voltage from gate to source ($-V_{GS}$) increases, the drain current ID decreases. The curves in Fig. 5-21 are sometimes divided into three regions: (1) the ohmic region where the current ID increases rapidly from 0 to the bends, (2) the saturation region where the curves are flat, and (3) the cutoff region where the device is off and ID is 0. Compare a JFET with a BJT:

- A BJT is off (there is no collector current) until base current is provided.
- A JFET is on (drain current is flowing) until the gate voltage becomes high enough to remove the carriers from the channel.

Other Transistor Types (3)

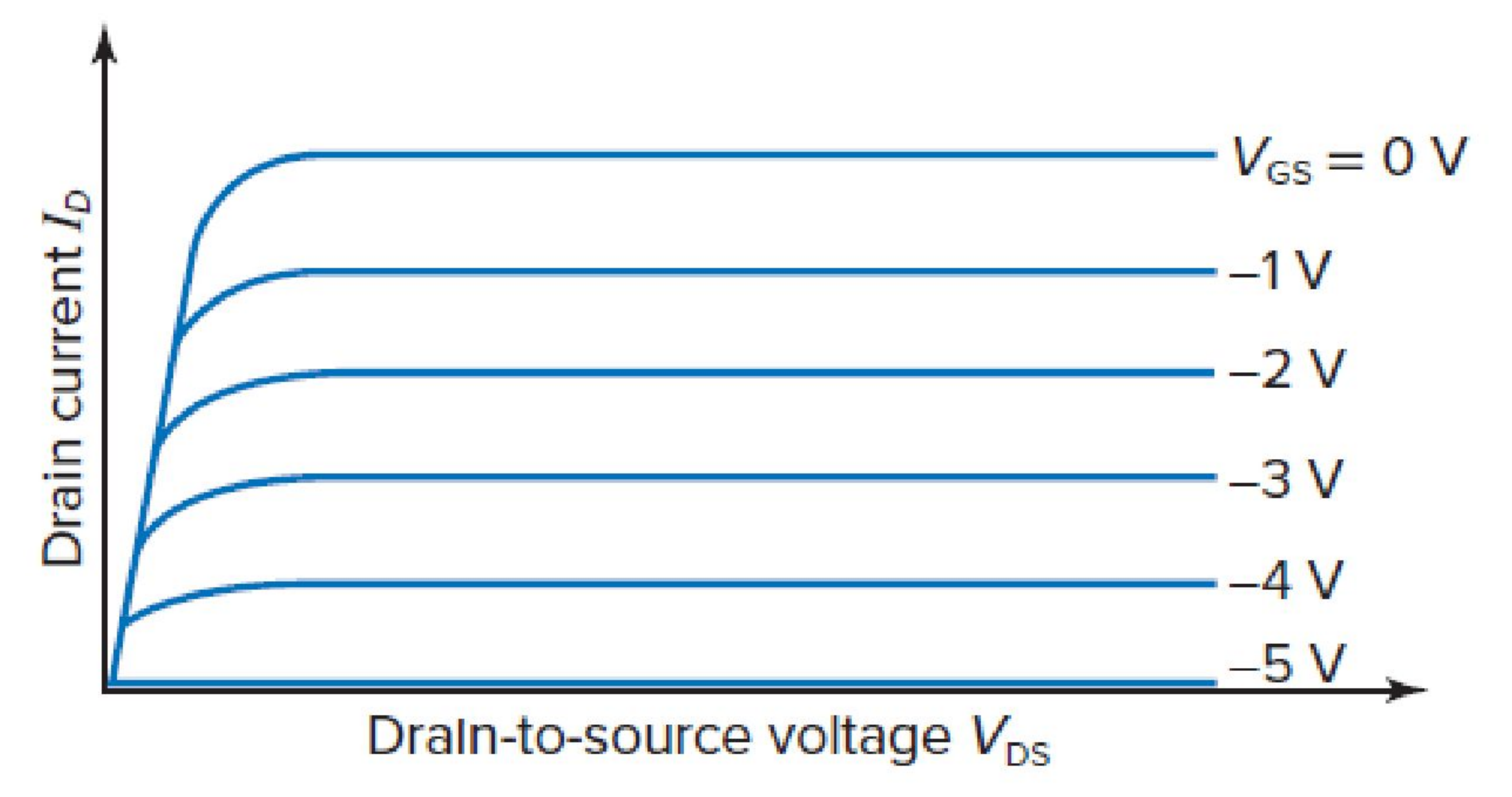


Fig. 5-21 Characteristic curves of a JFET.

Other Transistor Types (4)

These are ***important*** differences: (1) The bipolar device is current-controlled. (2) The unipolar Device is voltage-controlled. (3) The bipolar transistor is normally off. (4) The JFET is normally on.

Will there be any ***gate current*** in the JFET? Check Fig. 5-20. The gate is made of P-type material. To control channel conduction, the gate is made negative. This reverse-biases the gate channel diode. The gate current should be ***zero*** (there may be a very small leakage current).

There are also P-channel JFETs. They use P-type material for the channel and N-type material for the gate. The gate will be made positive to repel the holes in the channel. Again, this reverse-biases the gate-channel diode, and the gate current will be zero if the gate voltage is high. Since the polarities are opposite, N-channel JFETs and P-channel JFETs are not interchangeable.

Other Transistor Types (5)

Field-effect transistors (FETs) do not require any gate current for operation. This means the gate structure can be completely insulated from the channel. Thus, any slight leakage current resulting from minority carrier action is blocked. The gate can be made of metal. The insulation used is an oxide of silicon. This structure is shown in Fig. 5-22. It is called a ***metal oxide semiconductor field-effect transistor*** (MOSFET). The MOSFET can be made with a P channel or an N channel. Again, the arrow pointing iN (toward the center) tells us that the channel is N-type material.

Other Transistor Types (5)

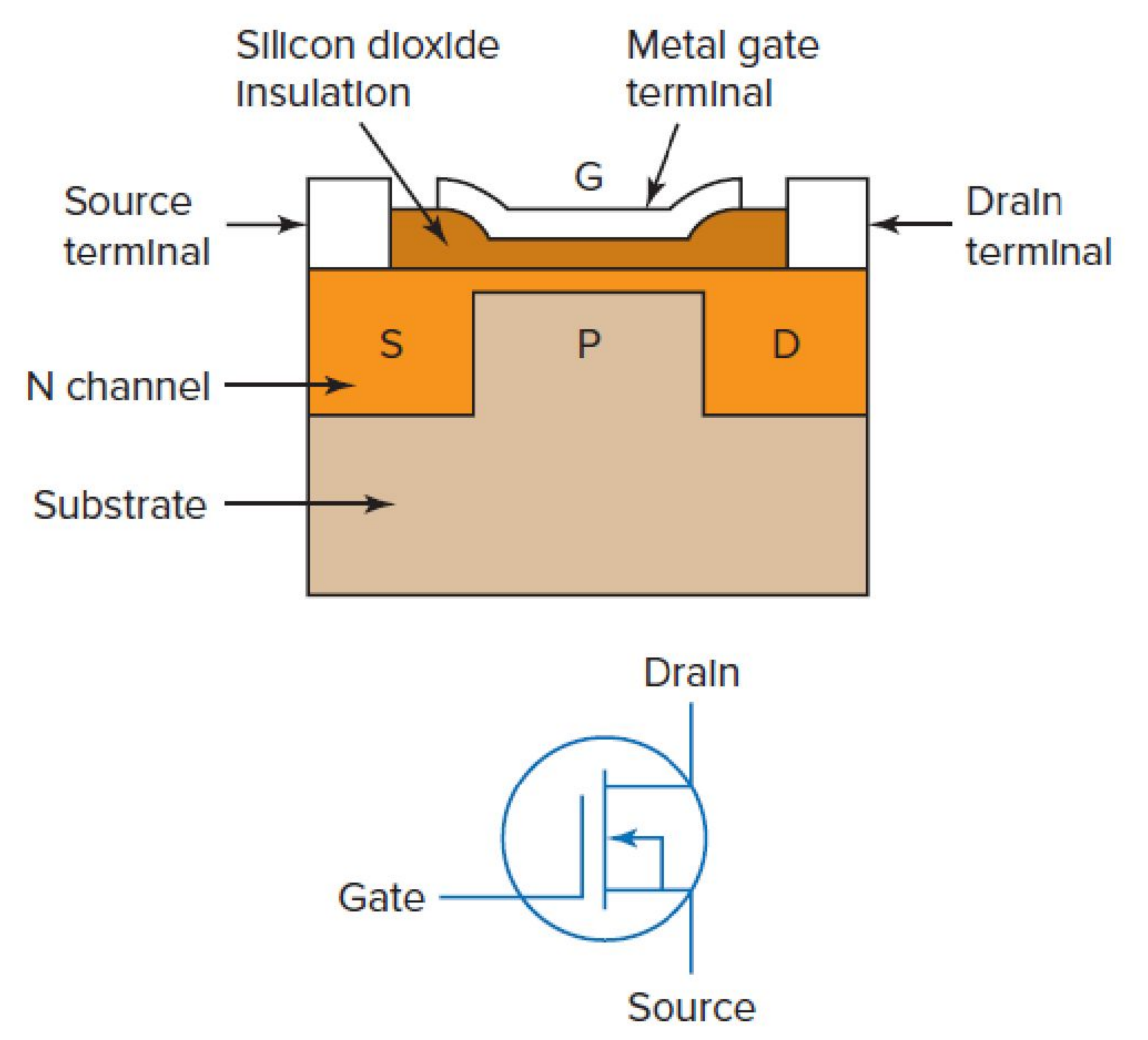


Fig. 5-22 An N-channel MOSFET.

Other Transistor Types (6)

Early MOSFETs were very delicate. The thin oxide insulator was easily damaged by excess voltage. The static charge on a technician’s body could easily break down the gate insulator. These devices had to be handled very carefully. Their leads were kept shorted together until the device was soldered into the circuit. Special precautions were needed to safely make measurements in some MOSFET circuits. Today most MOSFET devices have built-in diodes to protect the gate insulator. If the gate voltage goes too high, the diodes turn on and safely discharge the potential. However, manufacturers still advise careful handling of MOSFET devices.

Other Transistor Types (7)

The gate voltage in a MOSFET circuit can be of either polarity since a diode junction is not used. This makes another mode of operation possible— the ***enhancement mode***. An enhancement- mode device normally has no conductive channel from the source to the drain. It is a normally off device. The proper gate voltage will attract carriers to the gate region and form a conductive channel. The channel is ***enhanced*** (aided by gate voltage).

Other Transistor Types (8)

Figure 5-23 shows a family of curves for an N-channel enhancement-mode device. As the gate is made more positive, more electrons are attracted into the channel area. This enhancement improves channel conduction, and the drain current increases. When $V_{GS} = 0$, the drain current is 0. This is the cutoff region mentioned before. In Fig. 5-23, the cutoff region lies along the V_{DS} axis where I_D is zero. The flat or nearly flat curves are in the saturation region, and the steep vertical section is the ohmic region. A JFET should not be operated in the enhancement mode because the gate diode could become forward-biased, and gate current would flow. Gate current is not desired in any type of FET. Field-effect transistors are normally ***voltage-controlled***.

Other Transistor Types (9)

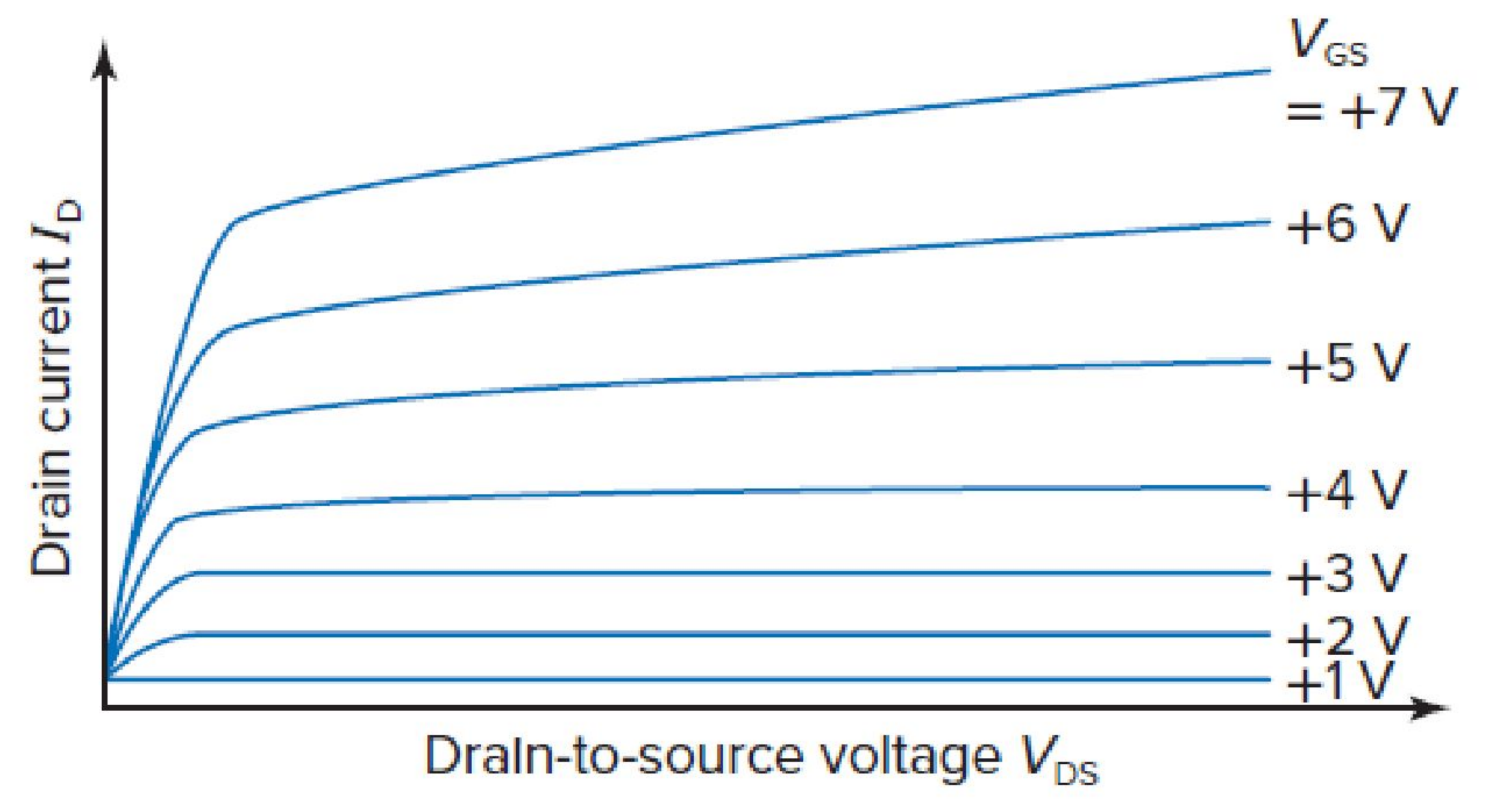


Fig. 5-23 Enhancement-mode characteristic curves.

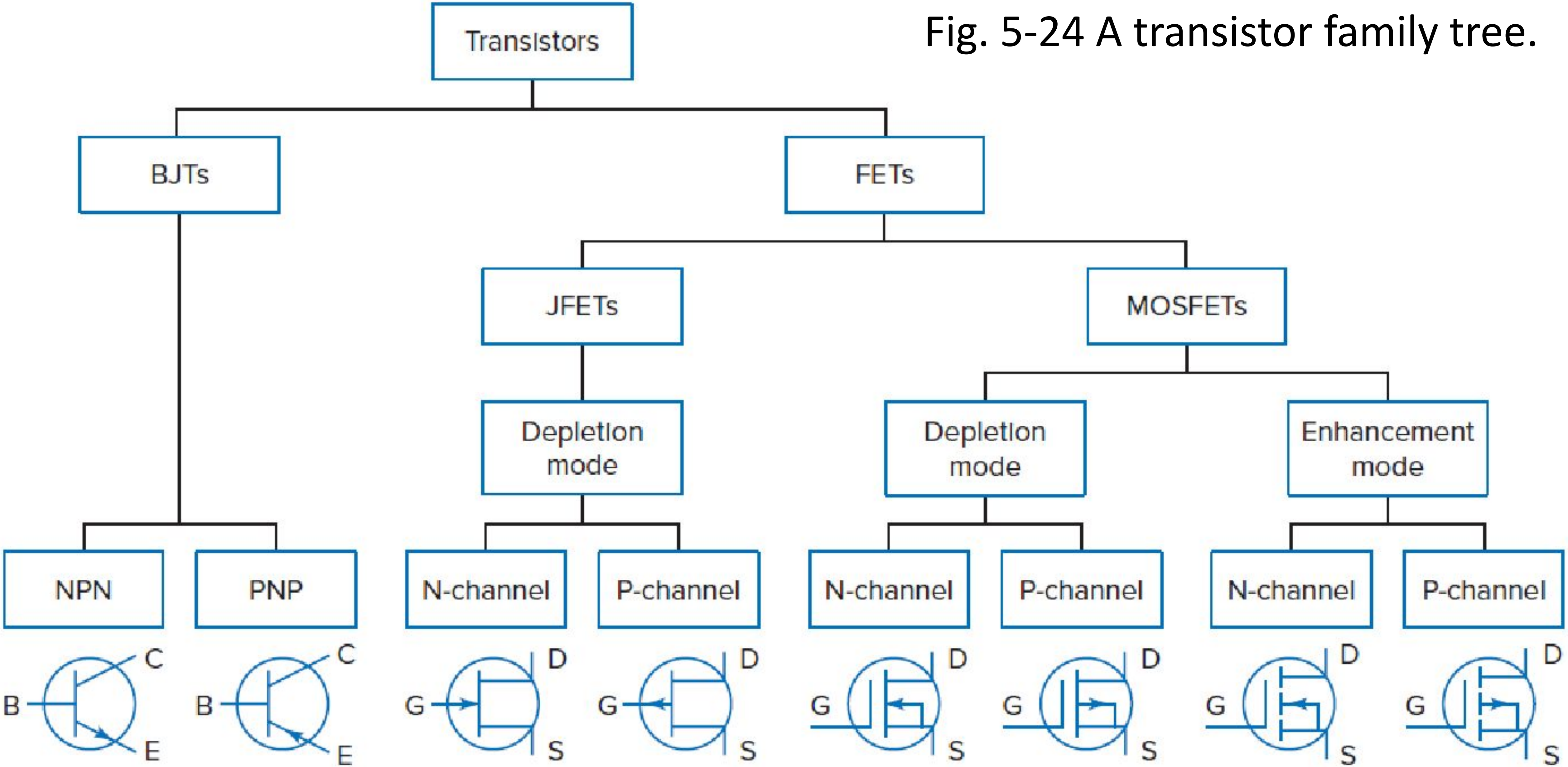
Other Transistor Types (10)

Figure 5-24 shows a transistor family tree. Note that the enhancement-mode symbols use a broken line from the source to the drain. This is because the channel can be created or enhanced by applying the correct gate voltage. Field-effect transistors have some advantages over bipolar transistors that make the former attractive for certain applications. Their gate terminal does not require any current. This is a good feature when an amplifier with high input resistance is needed. This is easy to understand by inspecting Ohm’s law:

$$R = \frac{V}{I}$$

Consider V to be a signal voltage supplied to an amplifier and I the current taken by the amplifier. In this equation, as I decreases, R increases.

Fig. 5-24 A transistor family tree.

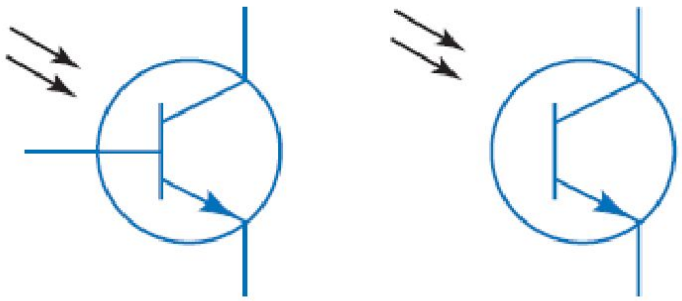


- Transistors
  - BJTs
    - NPN
    - PNP
  - FETs
    - JFETs
      - Depletion mode
        - N-channel
        - P-channel
    - MOSFETs
      - Depletion mode
        - N-channel
        - P-channel
      - Enhancement mode
        - N-channel
        - P-channel

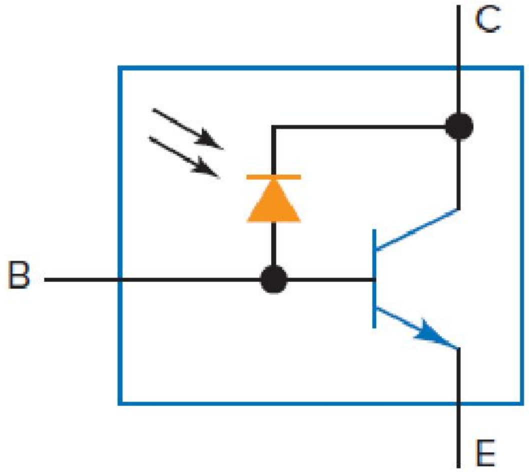
Phototransistors

What if a transistor could be controlled by something else? How about light? One can imagine uses for such a device. It turns out that bipolar junction transistors are ***inherently light-sensitive***, and their packages are designed to eliminate this effect. ***Phototransistors*** are packaged differently to allow light to enter the crystal. Entry of the light energy creates hole-electron pairs in the base region and turns the transistor on. Thus, phototransistors can be controlled by light instead of by base current. In fact, some phototransistors are manufactured without a base lead, as shown by the schematic symbol at the right in Fig. 5-25(a). Figure 5-25(b) shows the equivalent circuit for a phototransistor.

Phototransistors (1)



(a) Schematic symbols



(b) Equivalent circuit

Fig. 5-25
Phototransist

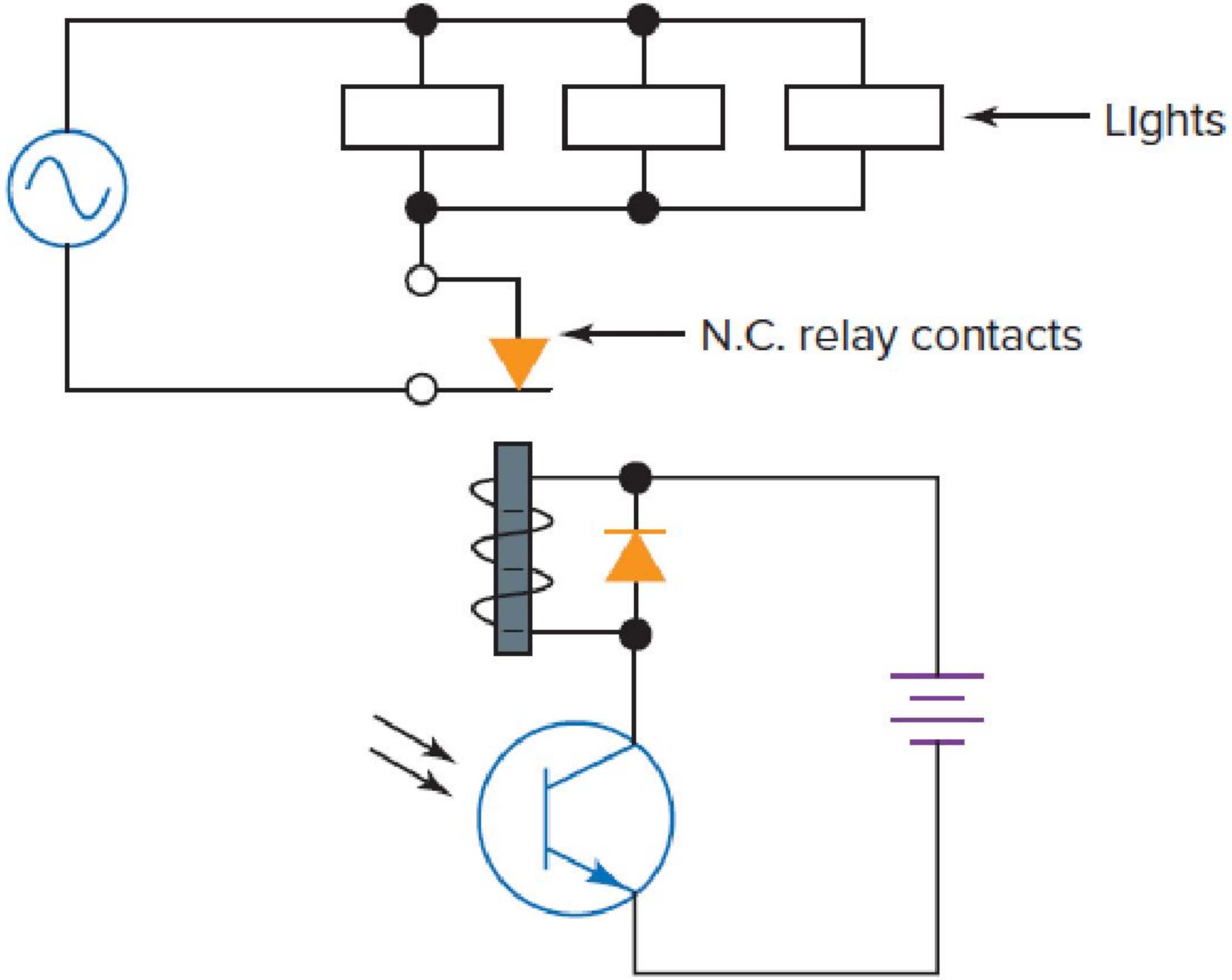


Fig. 5-26 Phototransistor-controlled lighting.

Phototransistors (2)

The collector is several volts positive with respect to the emitter. With no light entering the package, only a small current flows. It is typically on the order of 10 nanoamperes (nA) at room temperature. It is called the ***dark current***. When light does enter, it penetrates the diode depletion region and generates carriers. The diode conducts and provides base current for the phototransistor. The transistor has gain, so we can expect the collector current to be a great deal larger than the current flow in the diode in Fig. 5-25(b). A typical photo transistor might show 5 mA of collector current with a light input of 3 mW per square centimeter.

One possible application for a phototransistor is shown in Fig. 5-26. This circuit provides automatic lighting. With daylight conditions, the transistor conducts and holds the normally closed (NC) contacts of the relay open. This keeps the lights turned off. When night falls, the phototransistor dark current is too small to hold the relay in, and the contacts close and turn on the lights.

Phototransistors (3)

Phototransistors can also be used in ***optoisolators*** (also called optocouplers). Figure 5-27 shows the 4N35 optoisolator package, which houses a gallium arsenide, infrared-emitting diode and an NPN silicon phototransistor. The diode and transistor are optically coupled. Applying forward bias to the diode will cause it to produce infrared light and turn on the transistor. The 4N35 can safely withstand as much as 2,500 V across the input-to-output circuit, so its ability to isolate circuits is good. 4N35s are also (a) Schematic symbols available in SMT packages.

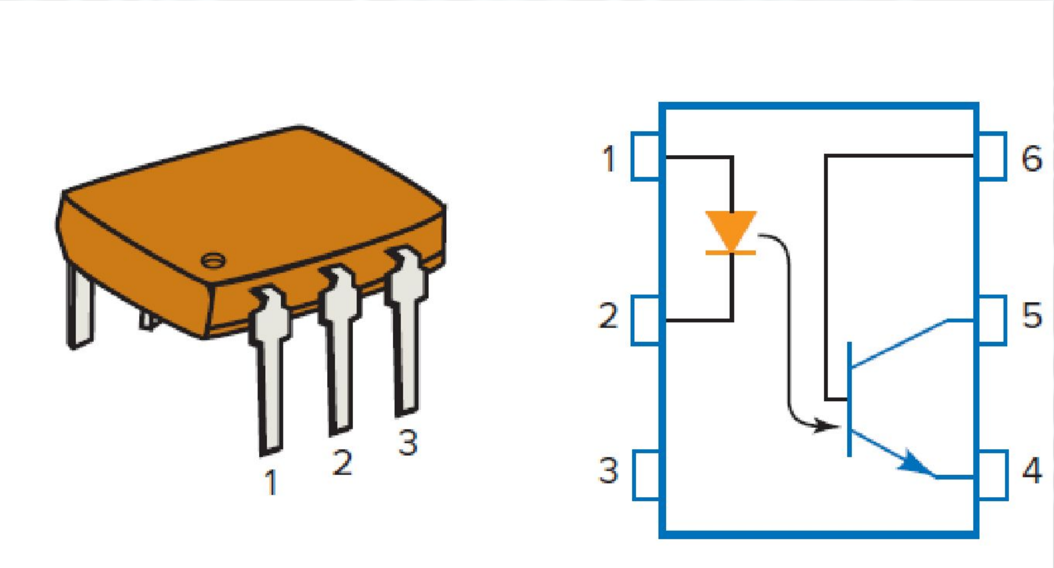


Fig. 5-27 4N35 optoisolator.

Phototransistors (3)

Photo MOSFET transistors are another possibility. Figure 5-28 shows a gallium arsenide, infrared-emitting diode optically coupled to a photo-MOSFET pair in a dual inline package (DIP). These photo relays have higher output current ratings than the BJT phototransistor-type optocouplers. The on resistance of a TLP222A is only 2 Ω, and the maximum current is 500 mA and can be bidirectional: it can flow from pin 3 to pin 4 or from 4 to pin 3. It has a maximum isolation rating of 2,500 V, the same as the 4N35.

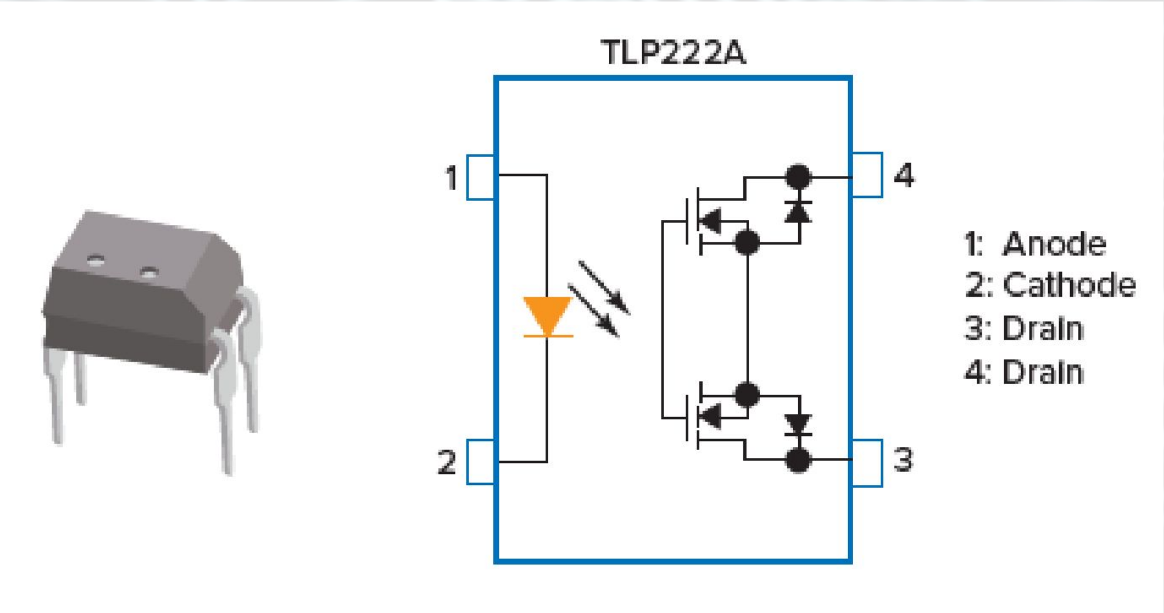


Fig. 5-28 A TLP222A photo relay.

Power Transistors

Transistors can be divided into two broad categories: ***small-signal devices*** and ***power devices***. When they must safely handle more than 1 W, they are in the power category. This is an arbitrary division. Accordingly, in Table 5-1 2N2222A transistor is rated at 1.8 W. However, that rating is for a ***device temperature*** of 25°C. When the ambient temperature is 25°C, the rating is only 625 mW. This is because the transistor will rise in temperature when it is ***dissipating power***.

Power Transistors (1)

A 2N2222A conducting 200 mA and dropping 9 V (that’s 1.8 W) can burn your finger if you touch it. It will be operating well above 25°C and will fail if it operates like that for a period of time (perhaps only seconds). When operated at 625 mW, it will still burn your finger (but not as badly) because it will reach a case temperature of around 90°C. Compare that with a 2N6288 power transistor, which will reach a case temperature of only about 55°C when dissipating 625 mW. Looking at the two cases shown in Fig. 5-29 makes it clear why the power transistor operates cooler. The 2N6288 is packaged in a TO-220 case, while a 2N2222A uses the TO-92.

Power Transistors (2)

Figure 5-29 shows that there is a significant difference in transistor case sizes. It also shows that the power transistor has a metal tab. This tab is often mechanically connected to a heat sink. The heat sink is designed to conduct and transfer heat to the ambient environment, which will prevent the transistor from failing due to overtemperature. A 2N6288 is rated at 40 W maximum dissipation, but that’s only if the heat sink maintains the case temperature at 25°C (77°F). That is not easily done; think of Florida in August. Power transistors are almost never operated at their maximum ratings. Fig. 5-30 shows the power derating curve for the device.

Power Transistors (3)

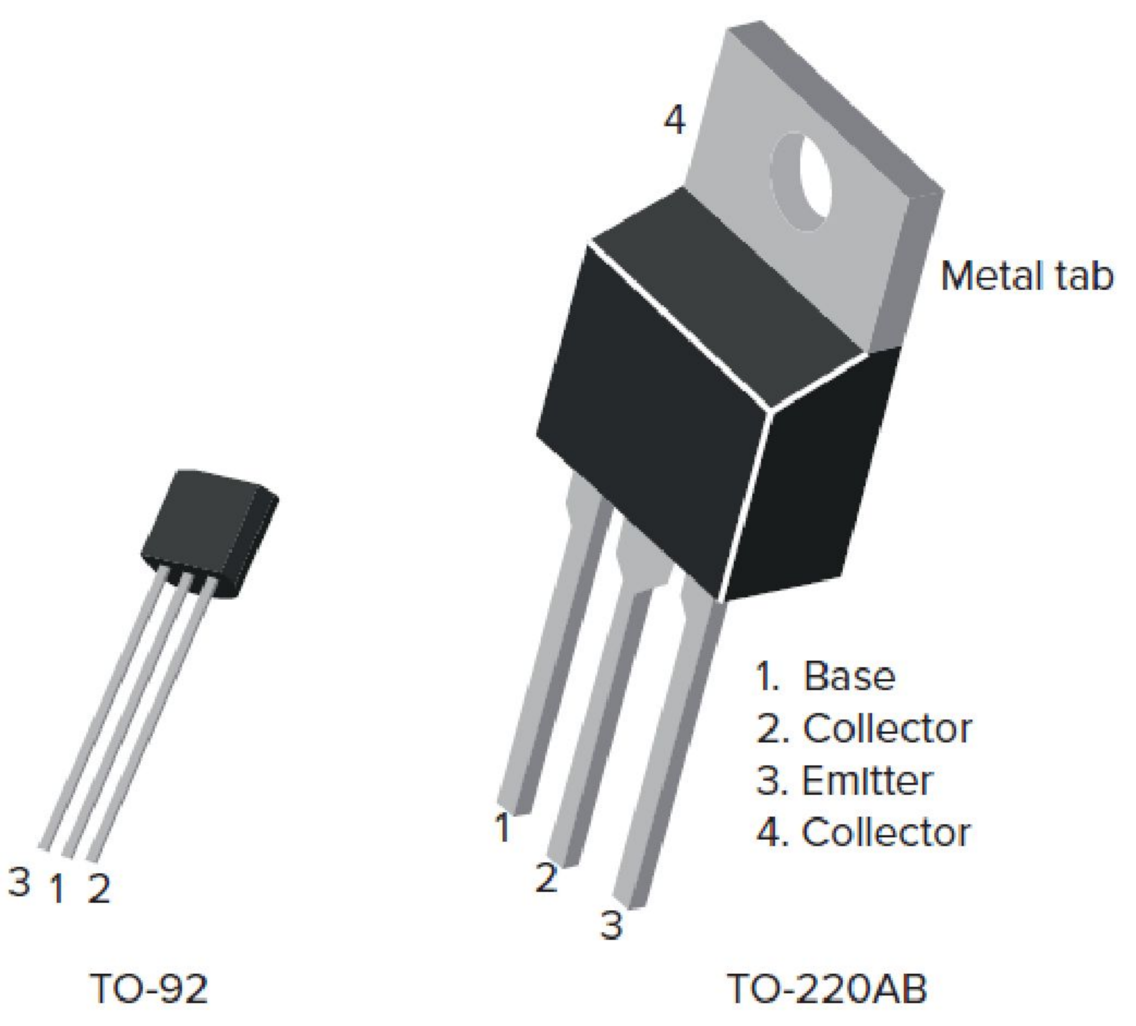


Fig. 5-29 A small-signal transistor and a power transistor.

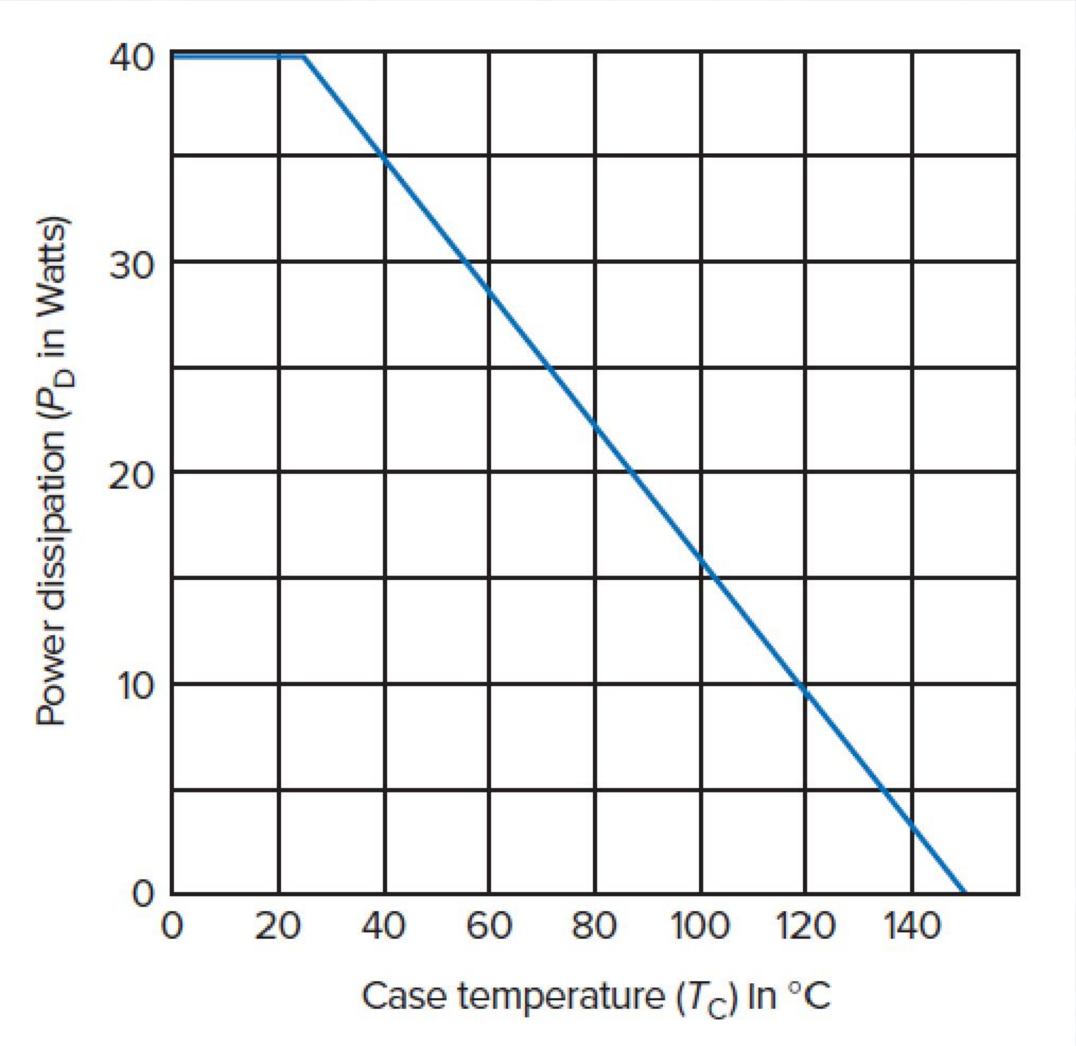


Fig. 5-30 Power derating curve for a 2N6288 transistor.

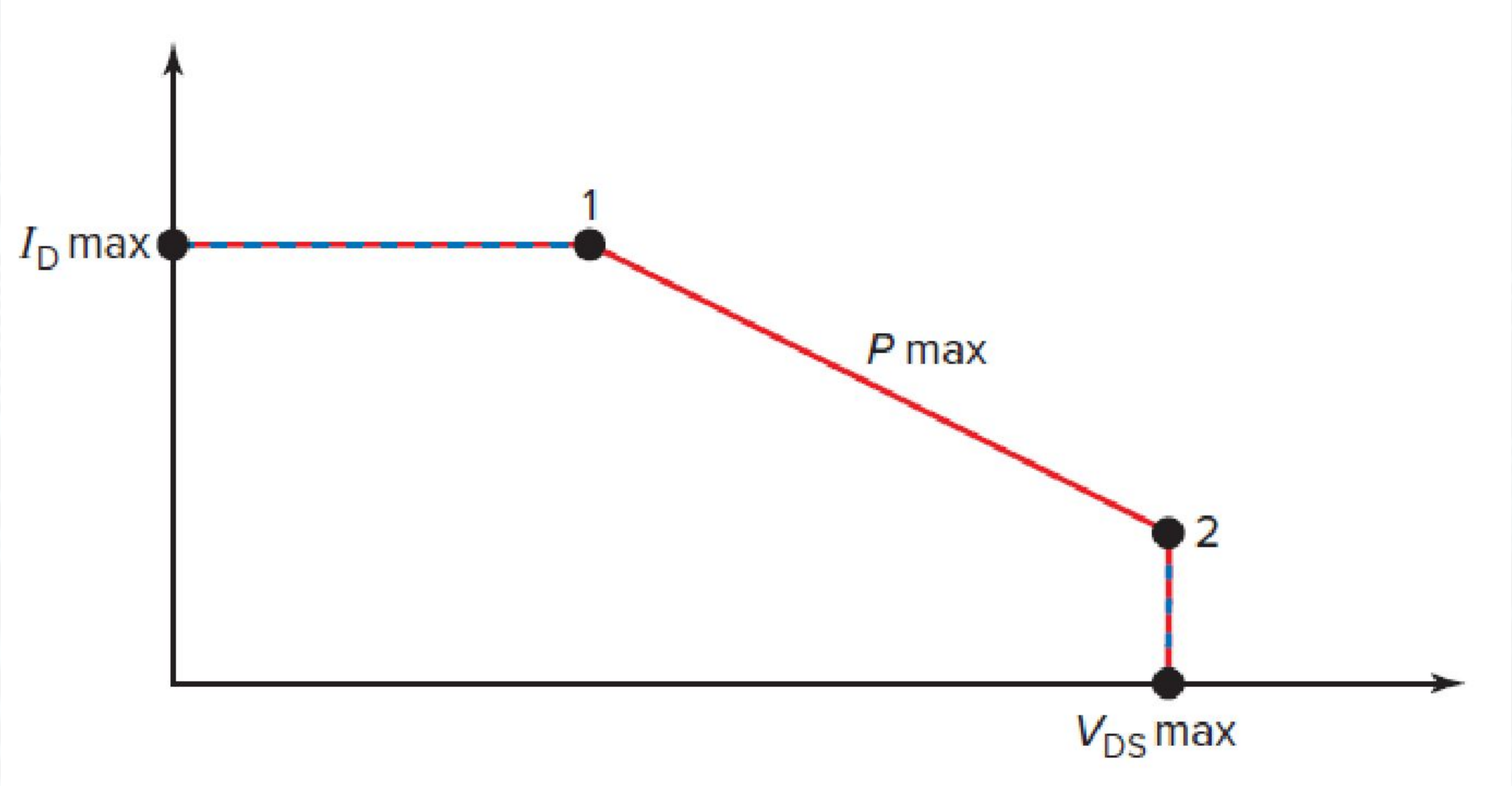
Power Transistors (4)

Heat is one of biggest factors in the failure of electronic devices, and that certainly includes transistors. Most have an upper temperature limit of 150°C, although some are rated at 200°C. Those are junction temperature ratings. If you burn a finger on a transistor, consider that the junction inside the case is a lot hotter! How hot will a transistor get? Power (dissipation) can be determined using

$$P_D = V_{DS} \times I_D \text{ (for FETs) or } P_C = V_{CE} \times I_C \text{ (for BJTs)}$$

Thus, as current and/or voltage increases, so does the power. This implies limits. Look at Fig. 5-31.

Fig. 5-31 Safe limits of FET operation.

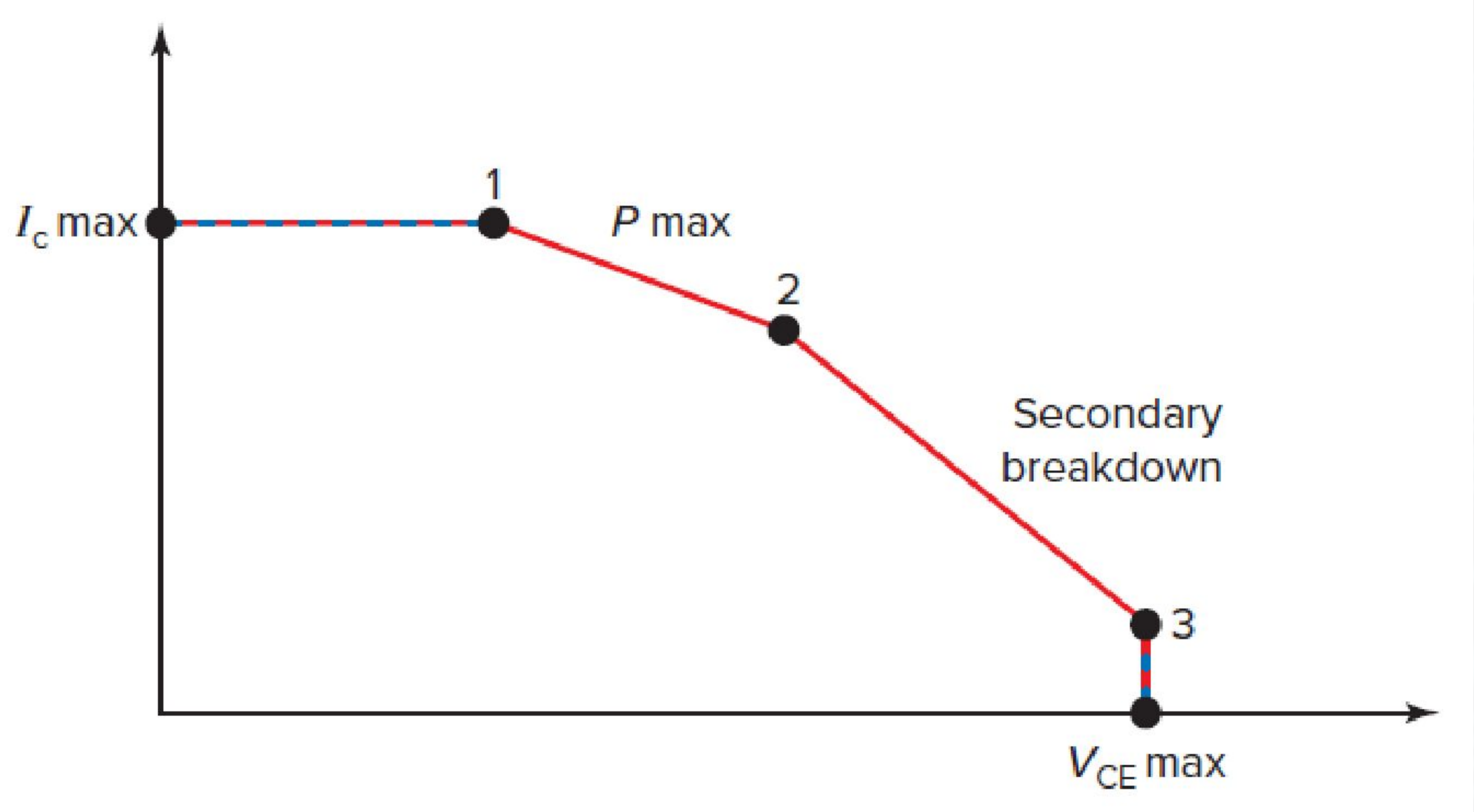


Power Transistors (5)

The most obvious limits are the maximum safe current and the maximum safe voltage. Exceeding either can damage or destroy a transistor. The other limit is set by the product of voltage and current. Thus, as V_{DS} increases, I_D will be less for the same power. The line between points 1 and 2 in Fig. 5-31 represents the maximum power limit for the device.

Bipolar junction transistors have an additional limitation, as shown in Fig. 5-32.

Fig. 5-32 Safe limits of BJT operation.

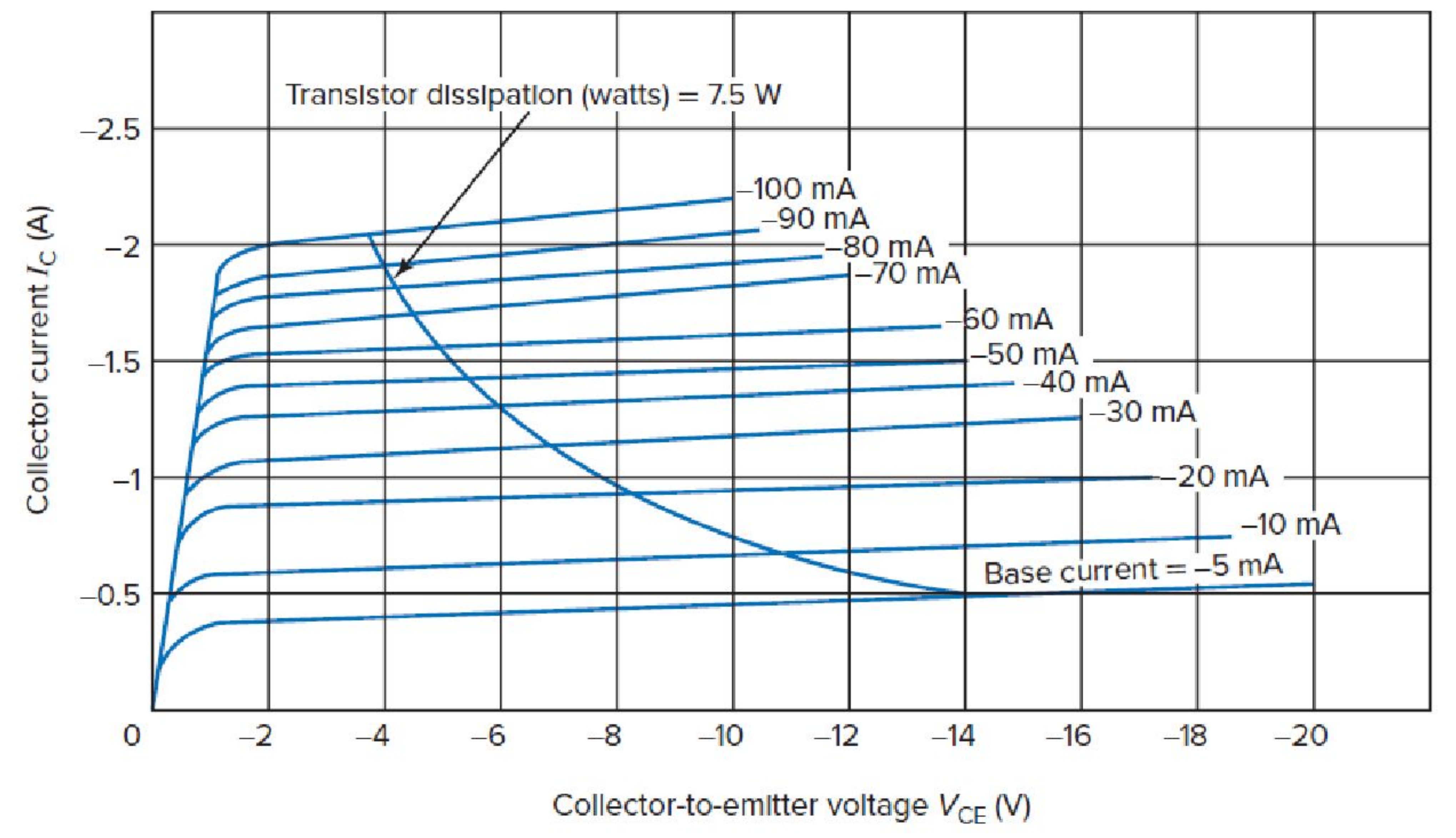


Power Transistors (6)

Notice the curve between points 2 and 3. It has a steeper slope than P_{max}, which implies an additional limit on the maximum safe power. With BJTs, higher currents and voltages can cause current flow to become confined to a small region of the crystal. A hot spot forms, and the crystal is damaged. This phenomenon does not exist with power FETs and is one of the reasons that FETs have become dominant in some applications. There is a related phenomenon called secondary breakdown or second breakdown, but it usually does not cause as many device failures. Although BJTs are often cheaper, power FETs are often more reliable.

Semiconductor manufacturers publish many kinds of graphs for their devices. Fig. 5-33 shows the safe operating area for a PNP transistor. The maximum safe transistor dissipation for this particular transistor happens to be 7.5 W, and no operating point that falls to the right of the power curve would be safe.

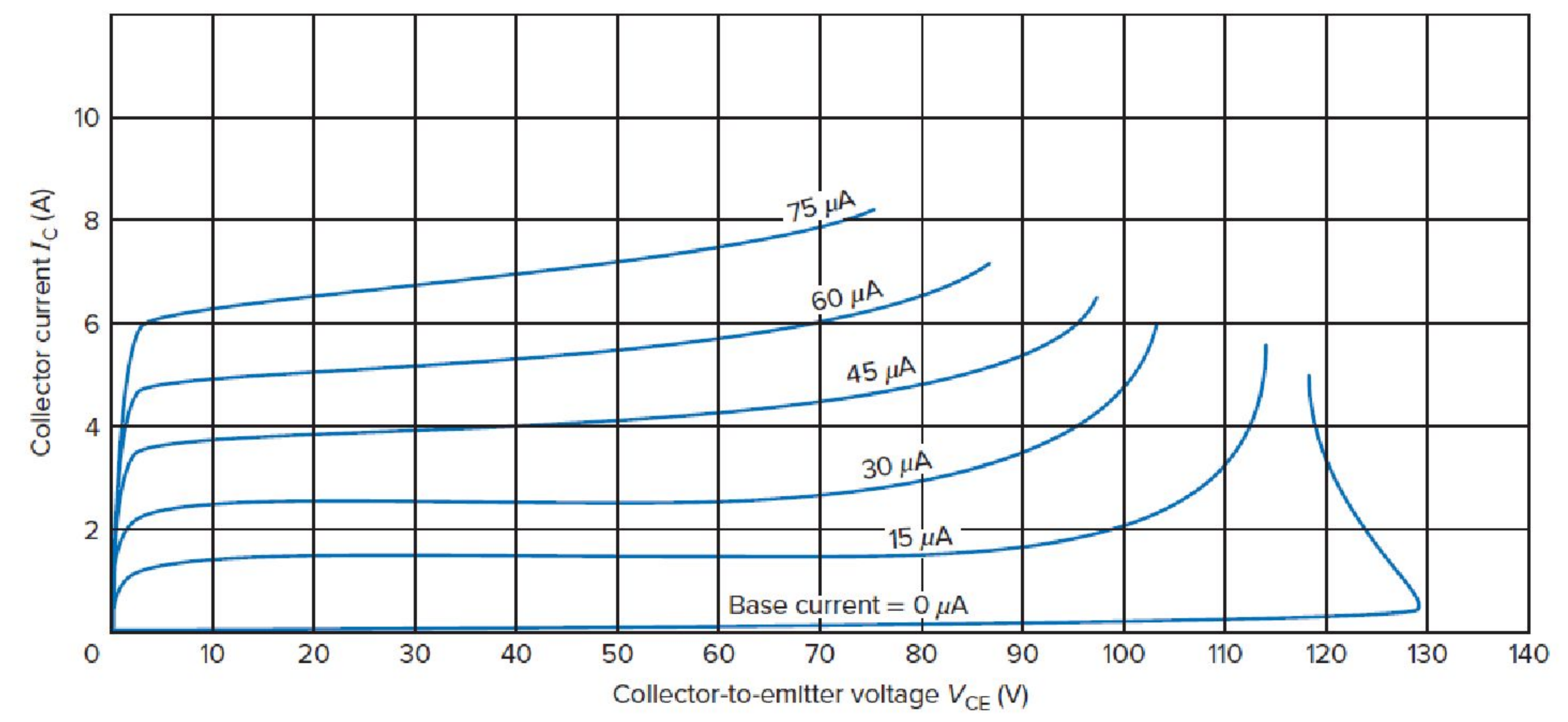
Fig. 5-33 Constant power curve.



Power Transistors (7)

If the collector characteristic curves are extended to include higher voltages, ***collector breakdown*** can be shown. Like diodes, transistors have limits to the amount of reverse bias that can be applied. BJTs have two junctions, and their breakdown ratings are more complicated than those for diodes. Figure 5-34 shows a collector family of curves where the horizontal axis is extended to 140 V. When collector voltage becomes very high, it begins to control collector current, which is not desired. The base current is supposed to control the collector current. Transistors should not be operated near or over their maximum voltage ratings. As can be seen from Fig. 5-34, collector breakdown is not a fixed point as it is with diodes. It varies with the amount of base current. At 15 µA, the collector breakdown point is around 110 V. At 0 µA, it occurs near 130 V.

Fig. 5-34 Collector breakdown.



Power Transistors (8)

Figure 5-35 shows the safe operating area (SOA) curves for a power MOSFET. Both the continuous and peak drain currents are given as a function of drain-source voltage up to the breakdown limit of 55 V. The values are for an initial temperature of 25°C and a ***single current pulse***.

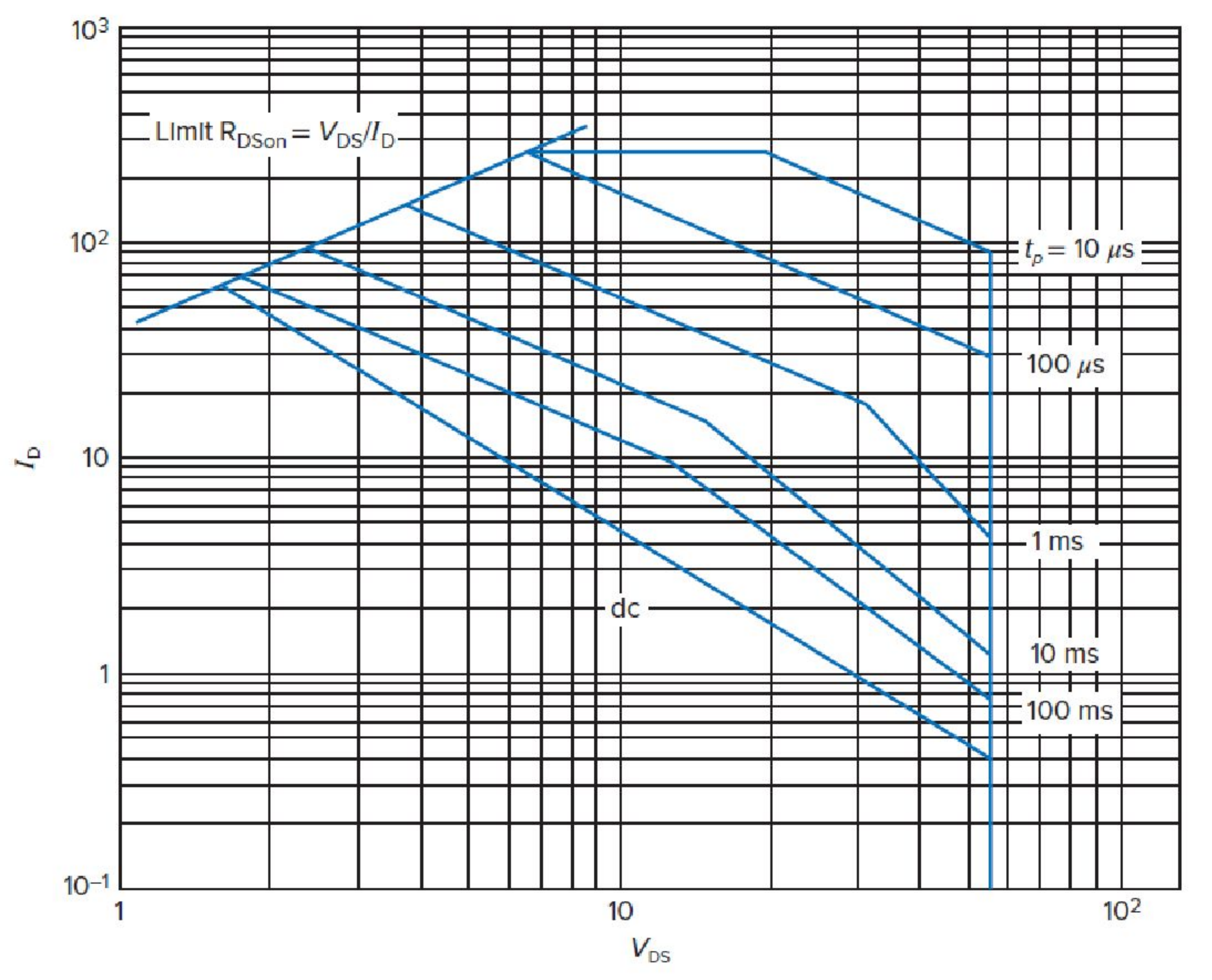


Fig. 5-35 SOA curves for a power MOSFET.

Power Transistors (9)

Figure 5-36 shows the SOA curves for a 2N6284 Darlington power transistor. Pay close attention to the second breakdown region where the curves are solid and are shown at the right. Another factor for safe operation is the ***bonding wire limit***. This occurs for pulse currents in excess of 40 A or a dc current of more than 20 A. A transistor is made of a small slab of semiconductor material called a ***die***. The die is connected to the pins or terminals with small bonding wires. These wires can fuse (fail by open circuiting) at high currents.

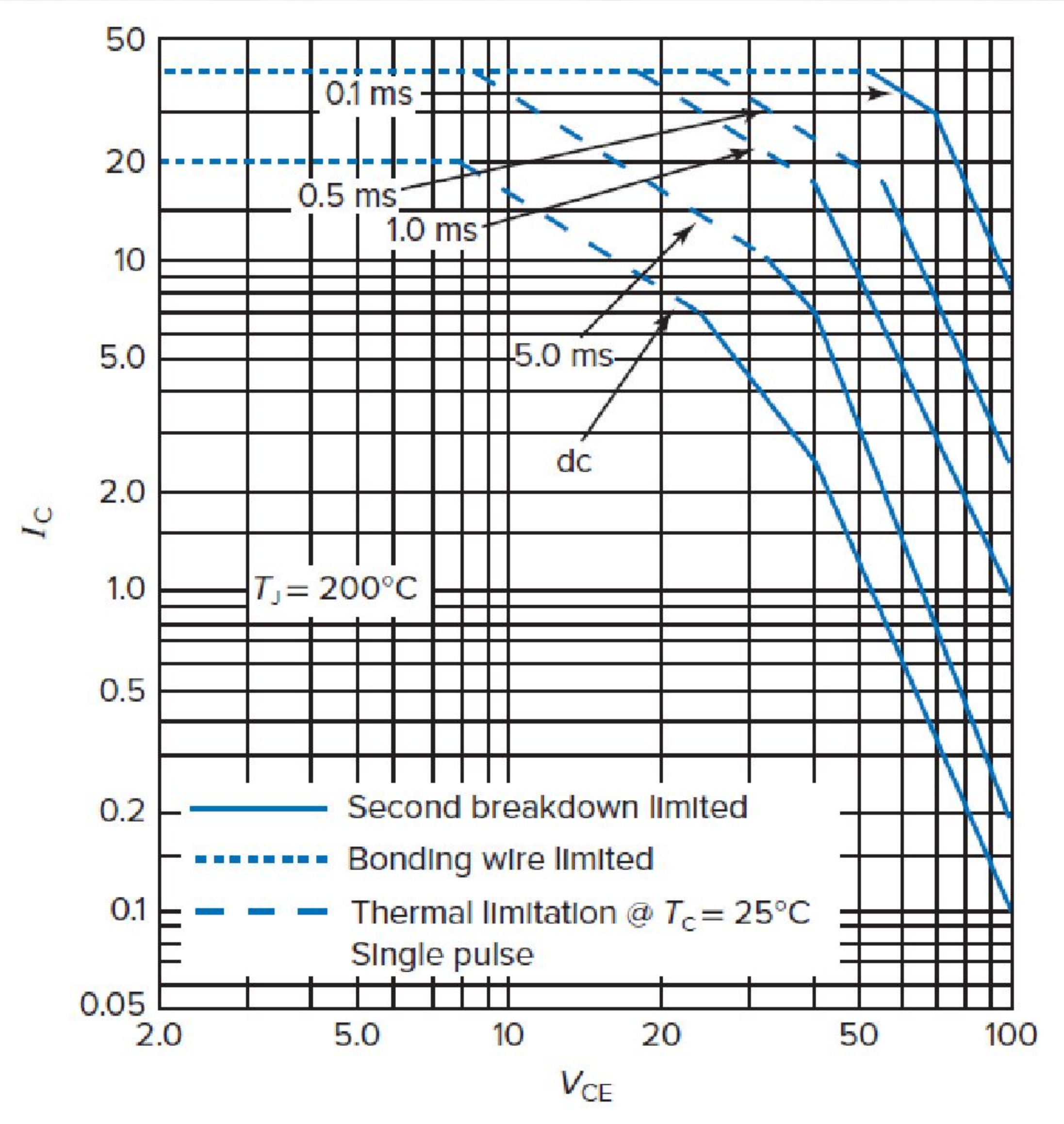


Fig. 5-36 SOA curves for a Darlington power transistor.

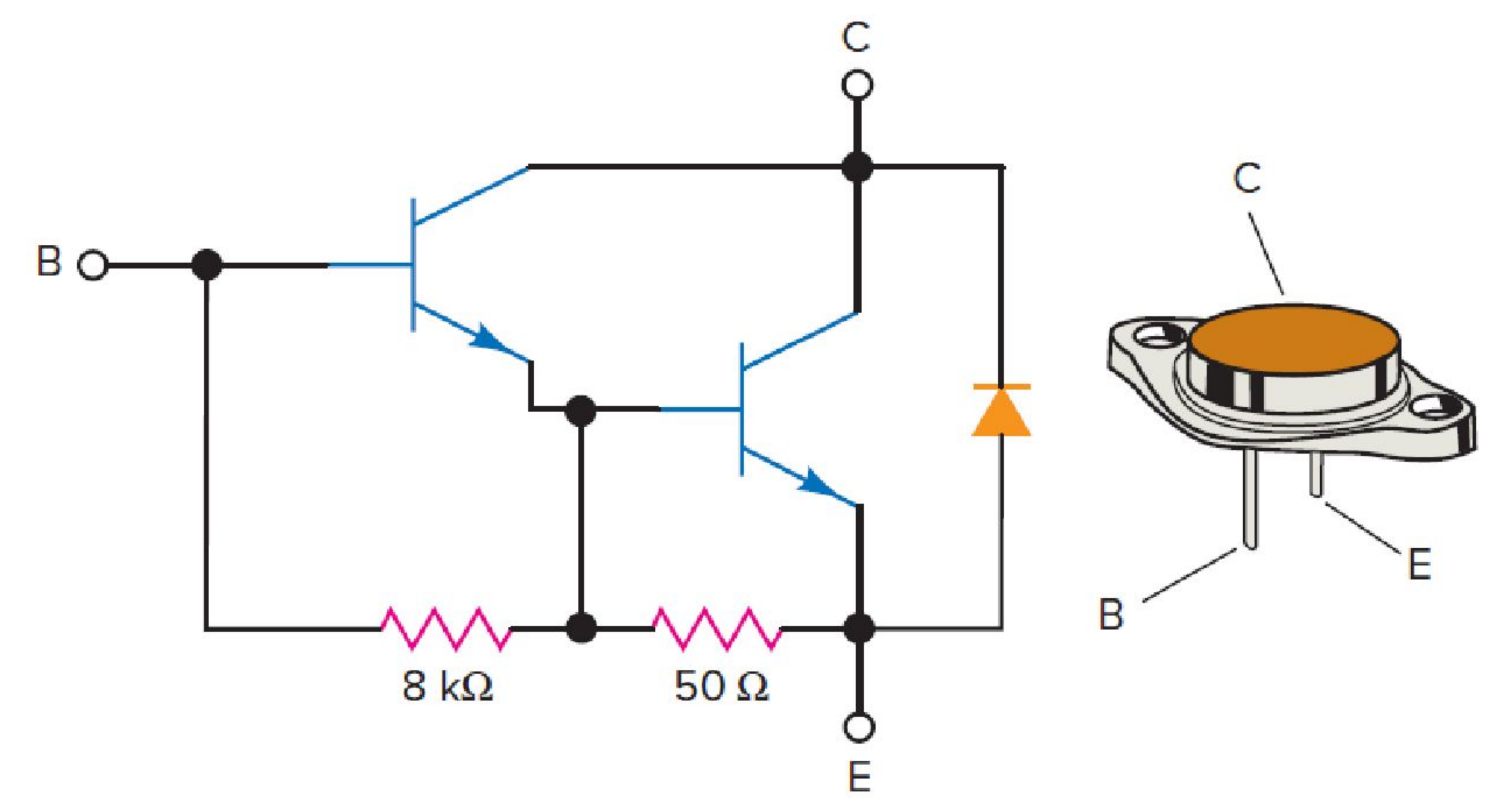
Power Transistors (10)

Figure 5-37 shows the internal circuit for a 2N6284 Darlington power transistor. The case is the TO-3 style, which is similar to the TO-204. Notice that the emitter of the left-hand transistor controls (feeds into) the base of the right-hand transistor. The current gain from the B terminal to the C terminal is approximately equal to the product of both transistor gains. If each transistor has a current gain of 50:

$$h_{FE(both)} = h_{FE(1)} \times h_{FE(2)} = 50 \times 50 = 2{,}500$$

The high current gain of Darlingtons makes them easy to drive. The next section shows how four of them can be used to control a stepper motor.

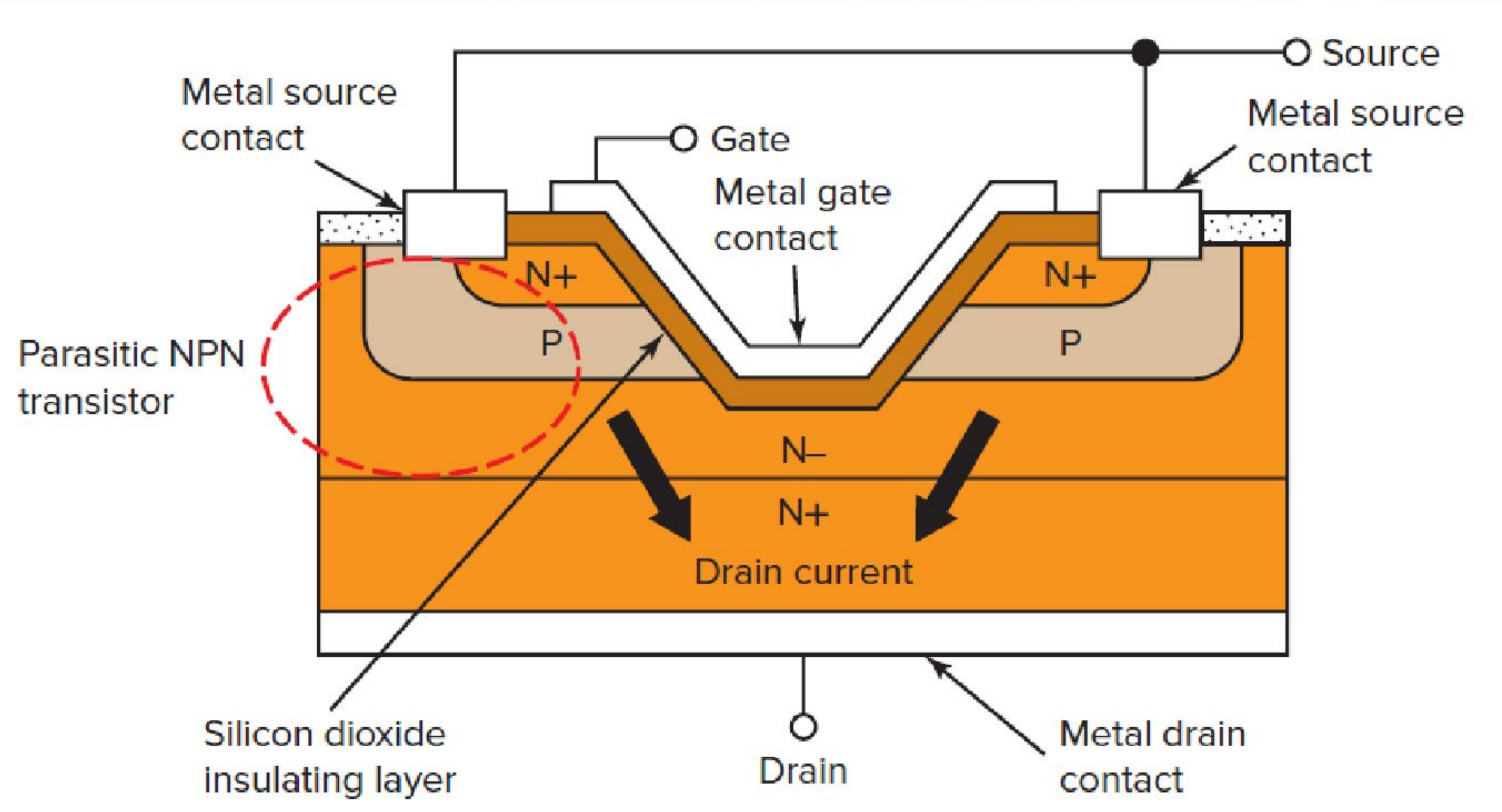
Fig. 5-37 2N6284 Darlington Power internal circuit and TO-3 case.



Power Transistors (11)

In addition to extra components being placed inside transistor cases, there can be ***parasitic components***. Figure 5-38 shows the internal structure of a power vertical metallic oxide semiconductor (VMOS) transistor. The name derives from the V-shaped channel. If the parasitic BJT turns on, it cannot be turned off because the gate has no control over it. This phenomenon is known as **latchup**, which can lead to device destruction. The parasitic BJT might be turned on by a voltage drop across the P-type body region. To avoid latchup, the body and source are typically short-circuited within the device package.

Fig. 5-38 Power VMOS structure.

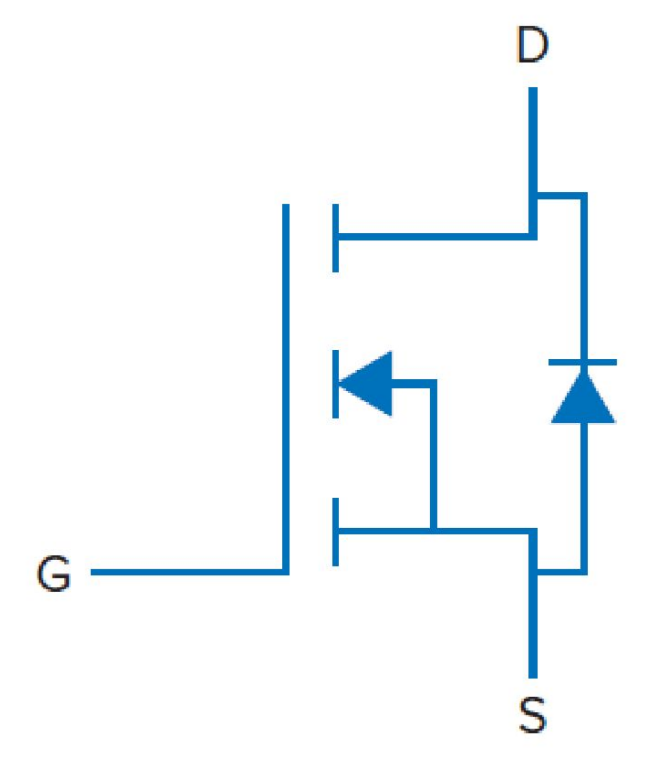


Power Transistors (12)

Figure 5-39 shows the schematic symbol for the transistor shown in Fig. 5-38. The gate is insulated from the N channel. Note that the schematic symbol shows no electrical connection between the G terminal and the D or S terminal. Also note the diode across the S and D terminals. This is the integral body diode that can be seen by looking closely at Fig. 5-38. There is a parasitic diode between the source (which forms the P portion of the diode) and the drain (which forms the N portion).

The body diode is convenient in circuits that require a path for any possible reverse drain current (often called the *freewheeling current*). Inductive loads store energy, and when a MOSFET turns off, the body diode can provide a safe path for the discharge current.

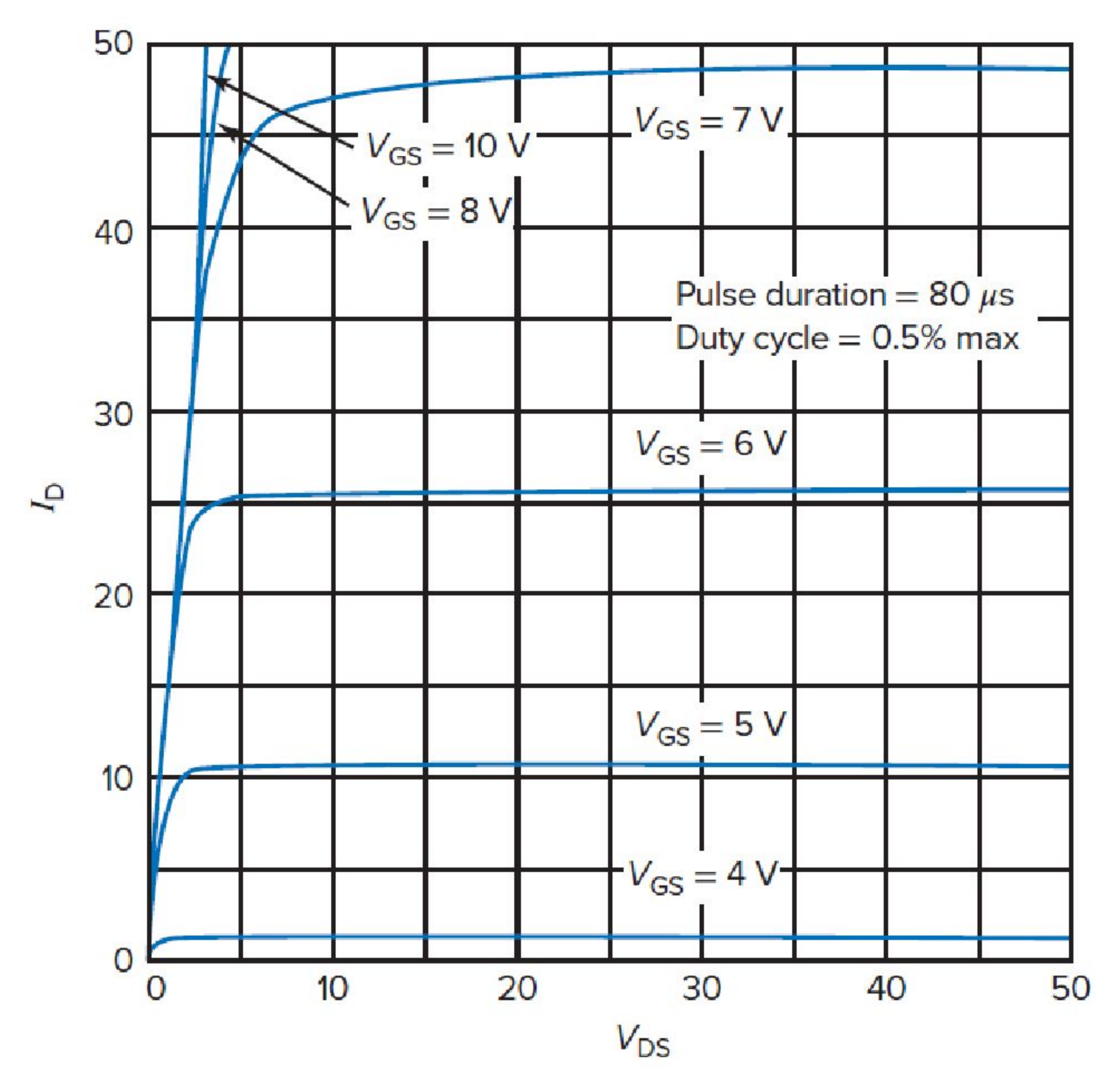
Fig. 5-39 Enhancement mode power N-channel MOSFET schematic symbol shows the integral body diode.



Power Transistors (13)

Figure 5-40 shows the V_{DS} versus I_D characteristic curves for an enhancement mode power MOSFET. The drain current is definitely enhanced by the gate voltage. As you can see, the current becomes high for gate voltages greater than 4 V. For much lower gate voltages, such as those near 0 V, the transistor will be off. As we learned before, enhancement mode transistors are normally off and must be turned on by applying gate voltage. Note that the specified pulse duration is short and specified at a very small duty cycle. Otherwise, the transistor would be destroyed by heat.

Fig. 5-40 Power enhancement-type MOSFET characteristic curves



Power Transistors (14)

With high-power transistors, the drive requirements become important. Both BJT and MOSFET transistors can handle high power. Although BJTs can fail due to second breakdown, they are still good choices for some applications. MOSFETs are voltage-driven or voltage-controlled. This is an advantage in power devices. The driver only has to supply a changing voltage. In BJTs, the driver has to supply current and voltage. Darlingtons are easier to drive but also can fail from second breakdown, so MOSFETs might be preferred. However, MOSFETs still require some drive power due to their input capacitance. In switching circuits with fast rise times or in high-frequency designs, the capacitance means there will have to be input current. Recall that rapid voltage change causes significant current in capacitive circuits.

Power Transistors (15)

Yet another advantage of MOSFETs is that they don’t have a problem with minority carrier storage that can limit how quickly a transistor can be turned off. In switching circuits, when the transistors are on, they are turned on hard (they are said to be ***saturated***). To turn off an NPN transistor, for example, all the minority electrons in the base have to be cleared out before the device shuts off. There are lots of those in a saturated BJT. PNPs have the same issue.

Power BJTs are not as popular as they once were. They are still a viable technology, but MOSFETs are often better even though they may cost a bit more.

Power Transistors (16)

The insulated gate bipolar transistor (IGBT) is yet another choice. Figure 5-41 shows the structure and symbol for an IGBT. These devices can operate into the kilowatt region and are similar in structure to VMOS transistors. The major difference is that a P-type substrate is added at the bottom of the structure. This P-layer serves to lower the on-resistance of the device via a process known as ***hole injection***. Holes from the added P layer move into the N region when the device is conducting. The added holes greatly improve the conductivity of the N channel (more current carriers mean better conductivity). Hole injection allows for very high current densities in IGBTs. Current density is rated in amperes per square millimeter (A/mm^2).

Power Transistors (17)

Semiconductor manufac-turers such as ON Semiconductor^{TM} sell unpack-aged dies such as the NGTD21T65F2, which is about 20 mm^2 and rated at 200 A. With a high current density, a given device size can support more current flow. High current densities are important for power transistors.

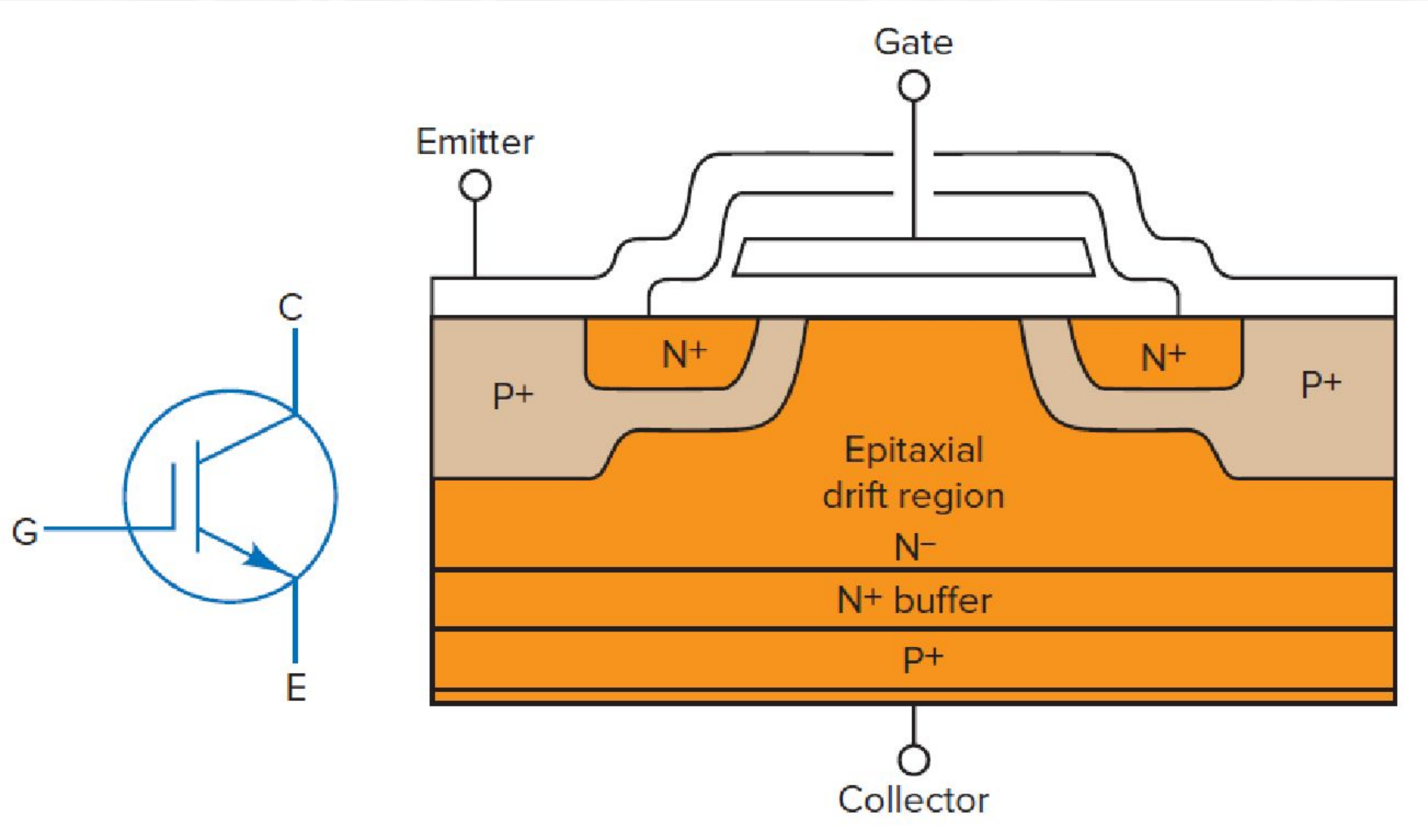


Fig. 5-41 IGBT transistor schematic symbol and structure.

Power Transistors (18)

Figure 5-42 shows the saturation curves and the case (package) for one IGBT. Saturation curves are used to predict how a device behaves when it is turned on very hard (saturated). The elected operating point in the red circle represents an R_{CE} value of only 8.33 mΩ:

$$R_{CE} = V_{CE}/I_C = 2\text{ V}/240\text{ A} = 8.33\text{ m}\Omega$$

In switching circuits, the main idea is to keep the power dissipated in a switch as low possible. Here is a quick review of how power is calculated:

1. $P = V \times I$ (the definition equation)
2. $P = I^2R$ (as R_{CE} or R_{DS} approaches 0, so does the power)
3. $P = V^2/R$ (as V_{SAT} approaches 0, so does the power)

Equation 2 above comes into play with IGBTs and MOSFETs, and equation 3 comes into play with BJTs. VSAT, the collector saturation voltage, should be as low as possible in switches. It is typically less than 0.4 V in power BJTs.

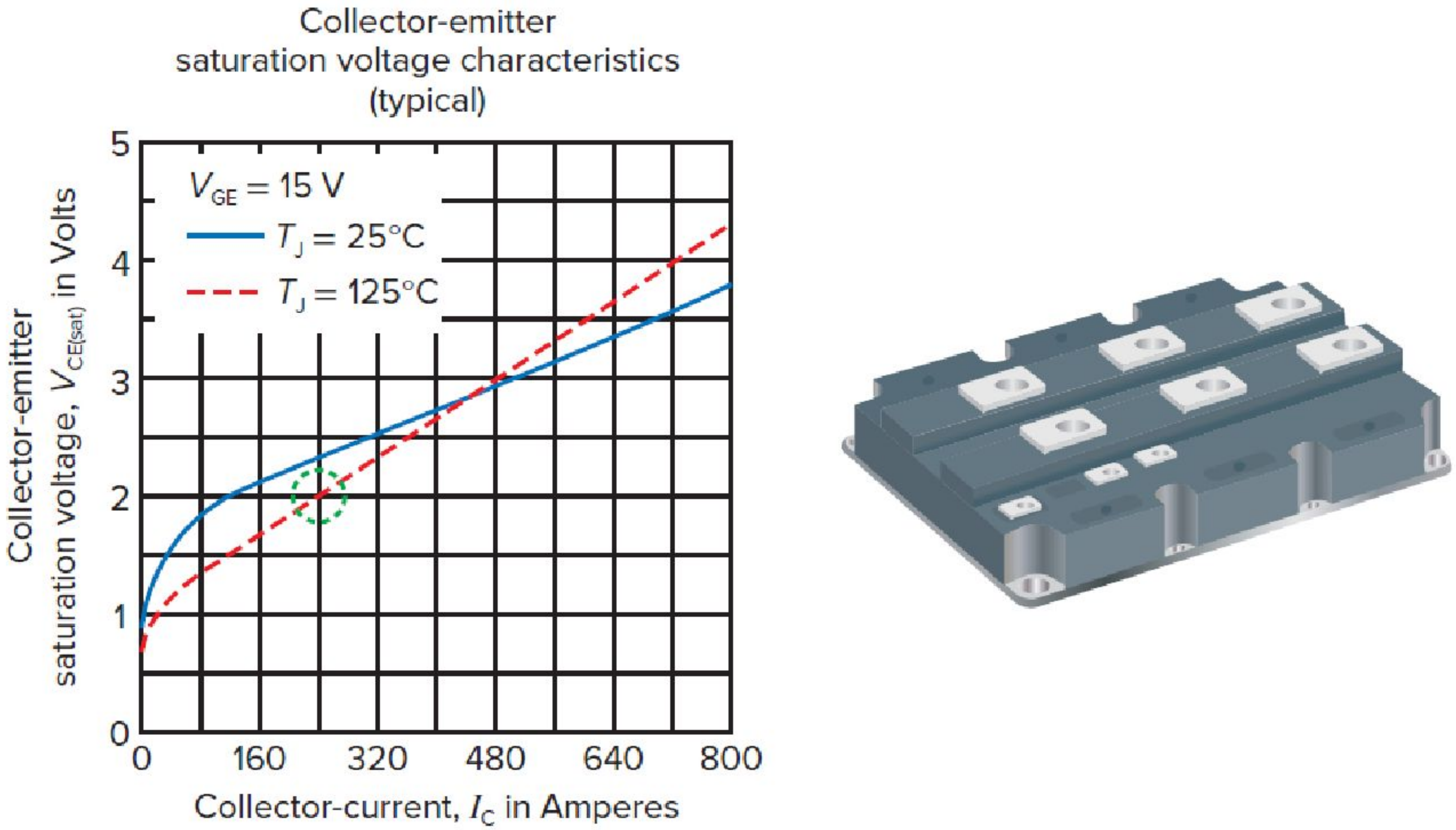


Fig. 5-42 IGBT collector current versus saturation voltage curves and case style.

Power Transistors (19)

IGBTs can be compared to MOSFETs, as shown in Table 5-2.

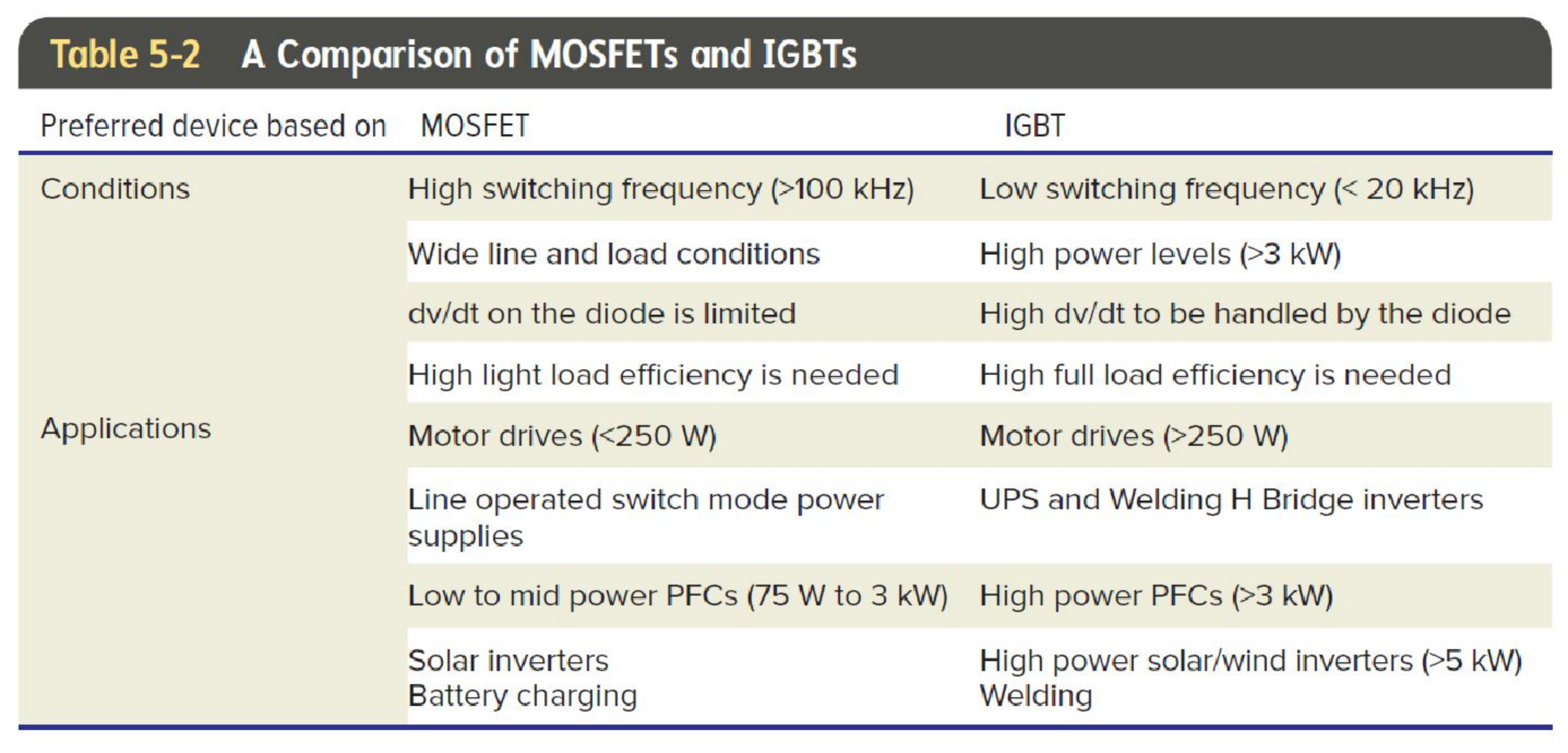


Table 5-2 A Comparison of MOSFETs and IGBTs

Preferred device based on	MOSFET	IGBT
Conditions	High switching frequency (>100 kHz)	Low switching frequency (< 20 kHz)
	Wide line and load conditions	High power levels (>3 kW)
	dv/dt on the diode is limited	High dv/dt to be handled by the diode
	High light load efficiency is needed	High full load efficiency is needed
Applications	Motor drives (<250 W)	Motor drives (>250 W)
	Line operated switch mode power supplies	UPS and Welding H Bridge inverters
	Low to mid power PFCs (75 W to 3 kW)	High power PFCs (>3 kW)
	Solar inverters Battery charging	High power solar/wind inverters (>5 kW) Welding

Power Transistors (20)

The thermal model of a transistor is shown in Fig. 5-43. Heat flow can be modeled as current flow. The model shows there are three thermal resistances: the thermal resistance of the junction to the case ($R\theta_{JC}$), the case to the heat sink ($R\theta_{CS}$), and the heat sink to the ambient ($R\theta_{SA}$). $R\theta_{JC}$ is due to the thermal resistance of the material used to mount the die to the case (solder). As the chip heats, the heat will move on to the case through the equivalent resistance ($R\theta_{JC}$). $R\theta_{CS}$ is the resistance for heat flow from the transistor case to the heat sink. Note that silicon grease and a mica washer are sometimes used to lower $R\theta_{CS}$. $R\theta_{SA}$ is the resistance for heat flow from the case to the ambient environment.

Power Transistors (21)

Designers may have to choose a large metal heat sink or use fan cooling to reduce that resistance. Knowing the ***total resistance*** will allow you to calculate the ***total temperature difference*** just as total voltage can be calculated for a series electrical circuit when the flow is known.

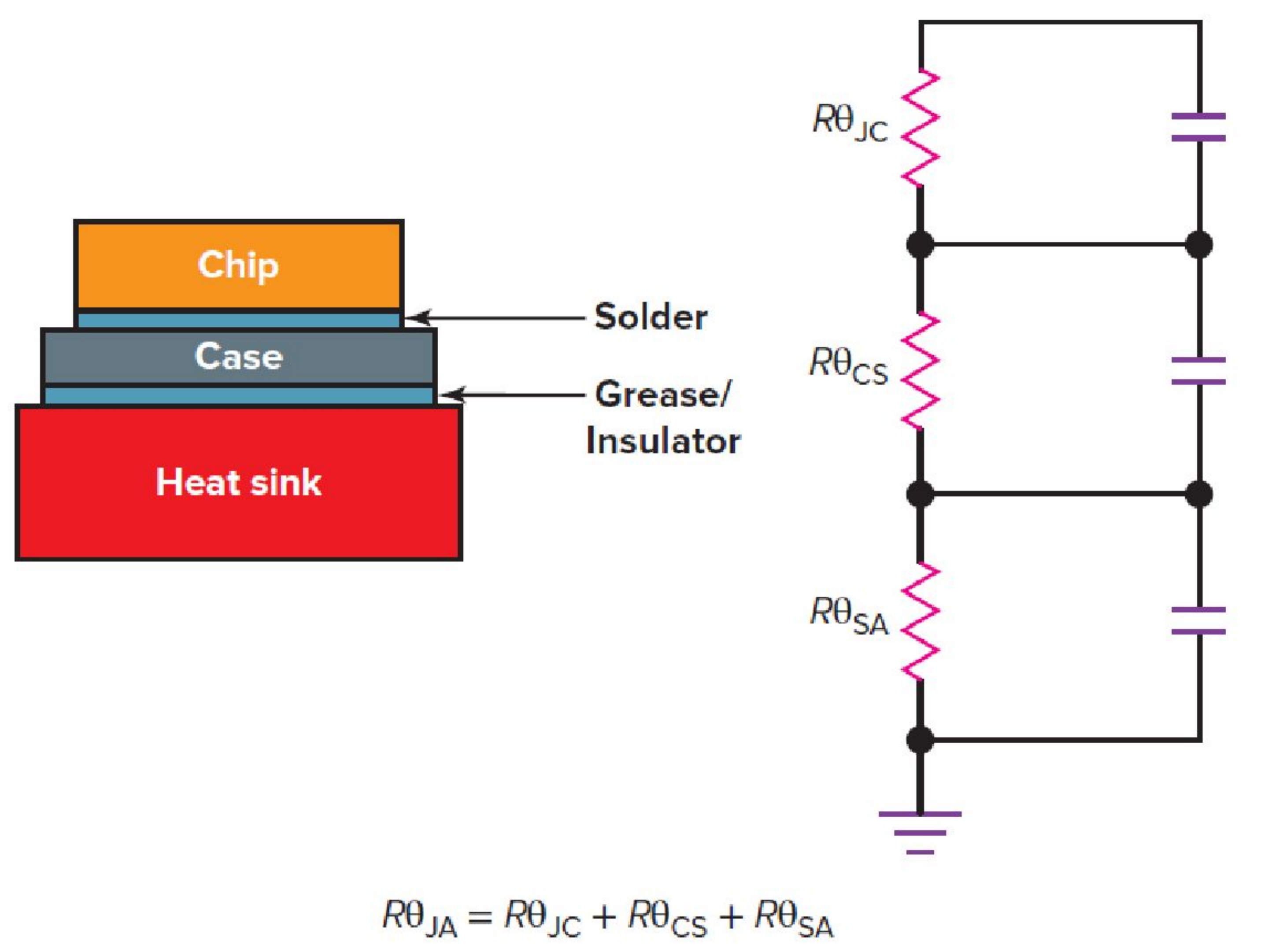


Fig. 5-43 Thermal equivalent circuit.

Power Transistors (22)

The thermal model shown in Fig. 5-43 also shows capacitors; these model ***thermal capacitance***. Thermal capacitance is equivalent to thermal mass. It takes time to charge a capacitor, and it takes time to raise or lower temperature based on thermal mass. People who cook know about ***thermal mass***. It takes a lot longer to bring a quart of water to a boil than to do the same with a cup. Thermal mass is important in pulse circuits (they have smaller duty cycles). In a pulse circuit, the total thermal mass will help limit how hot it gets.

Power Transistors (23)

The handling of power devices is also important. Figure 5-46 shows that lead bending must be done in a way that does not stress the device.

Power transistors fail more often than small-signal transistors. The former normally run hot, which shortens the life. Technicians typically replace more power transistors than they do small-signal transistors. Usually, an exact replacement is the best bet. If a substitution is required, the same type and polarity are mandated. The maximum ratings for voltage, current, and power should not be exceeded. Sometimes manufacturers recommend an upgraded device. It ***might*** be possible to adapt a different type but ***safety*** and ***reliability*** could be compromised; therefore, this practice is not advised. When a power device is replaced, the mounting hardware and possibly the application of a special thermal compound (such as silicon grease) are important considerations.

Power Transistors (24)

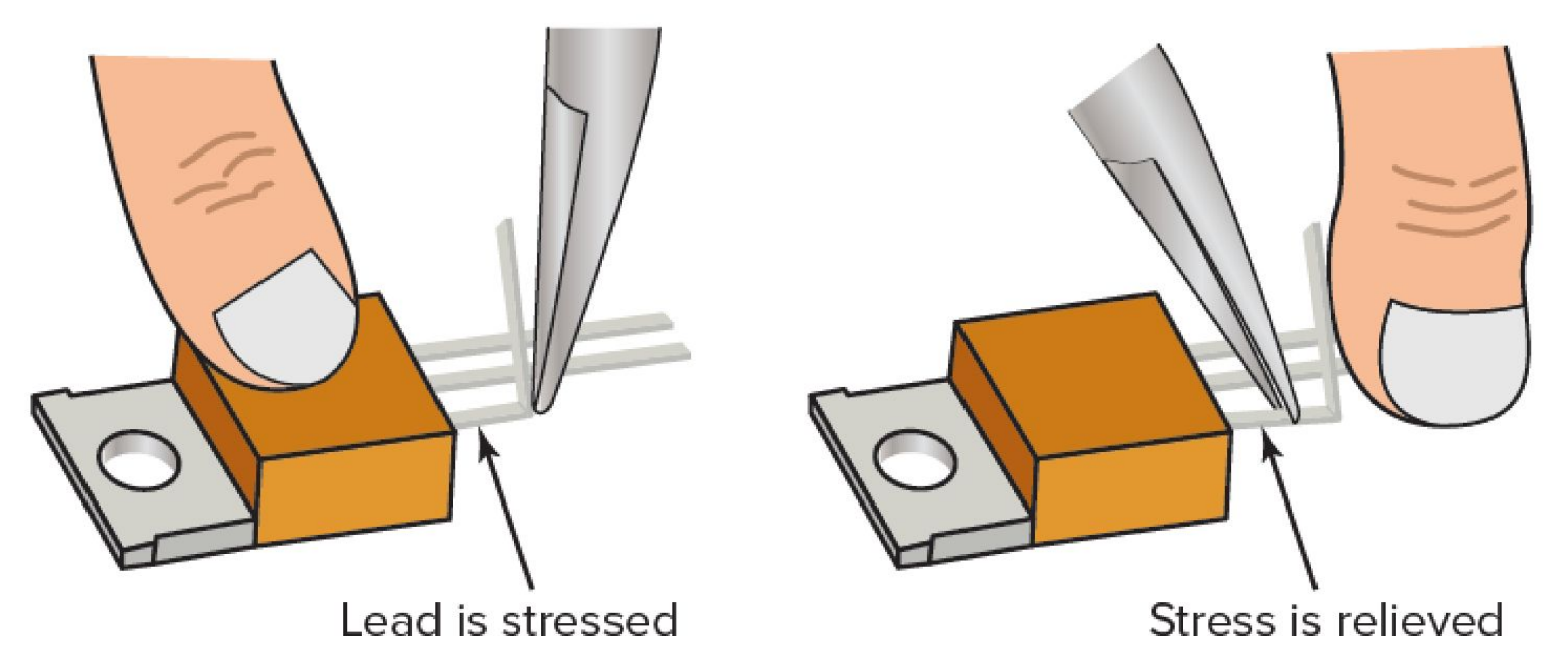


Fig. 5-46 Stressing transistor leads should be avoided.

Transistors as Switches

The term “solid-state switch” refers to a switch that has no moving parts. Transistors lend themselves for use as switches because they can be turned on with a base current or a gate voltage to produce a low resistance path (the switch is on), or they can be turned off by removing the base current or the gate voltage to produce a high resistance (the switch is off). They are very widely applied because they are small, quiet, inexpensive, reliable, capable of highspeed operation, easy to control, and relatively efficient.

Figure 5-47 shows a typical application. It is a computer-controlled battery conditioner. It is used to determine the condition of rechargeable batteries. It automatically cycles a battery from charge to discharge to charge while it monitors both battery voltage and temperature. Modern rechargeable batteries are often expensive. Many require specific charging methods for maximum life.

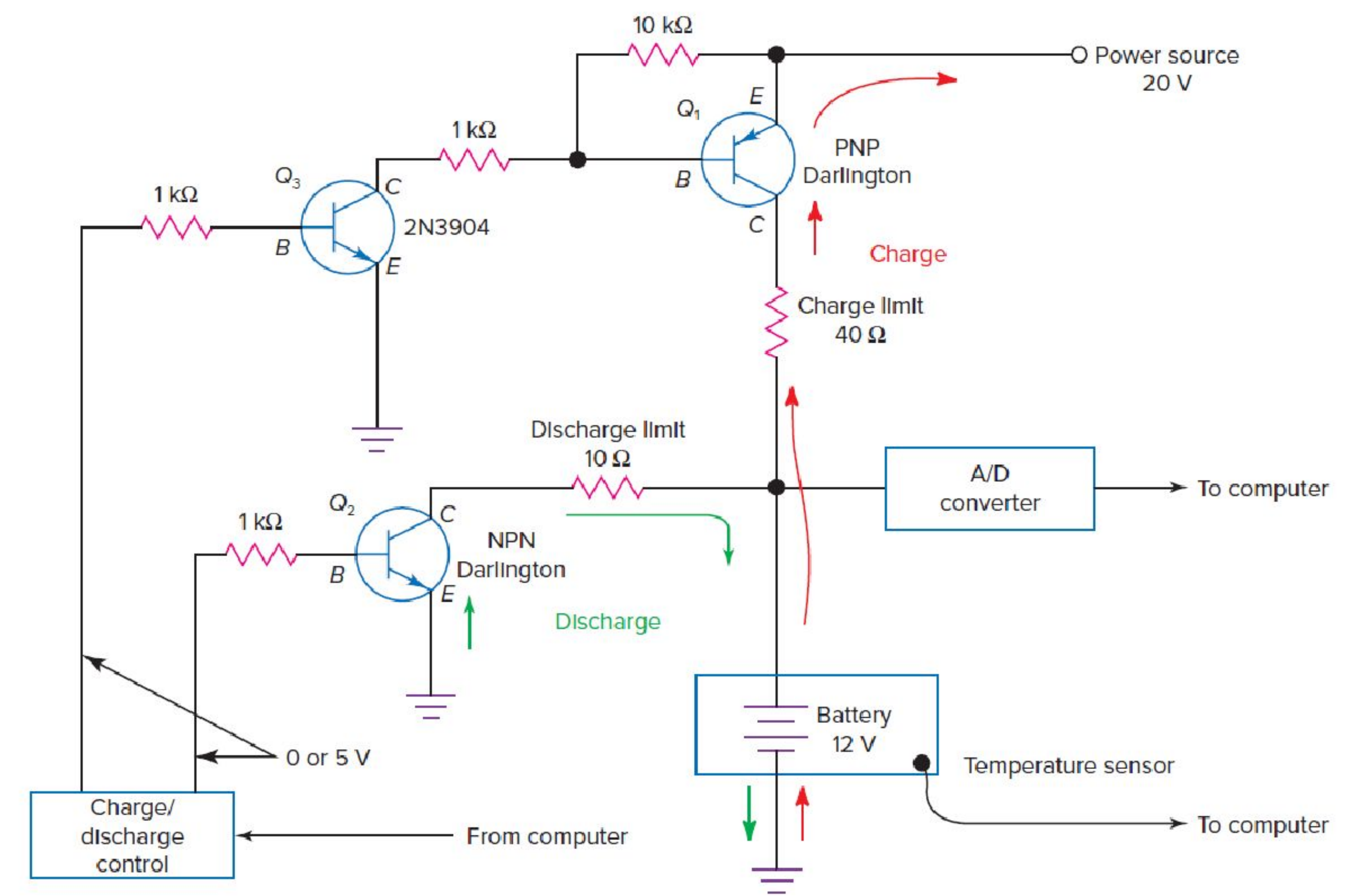
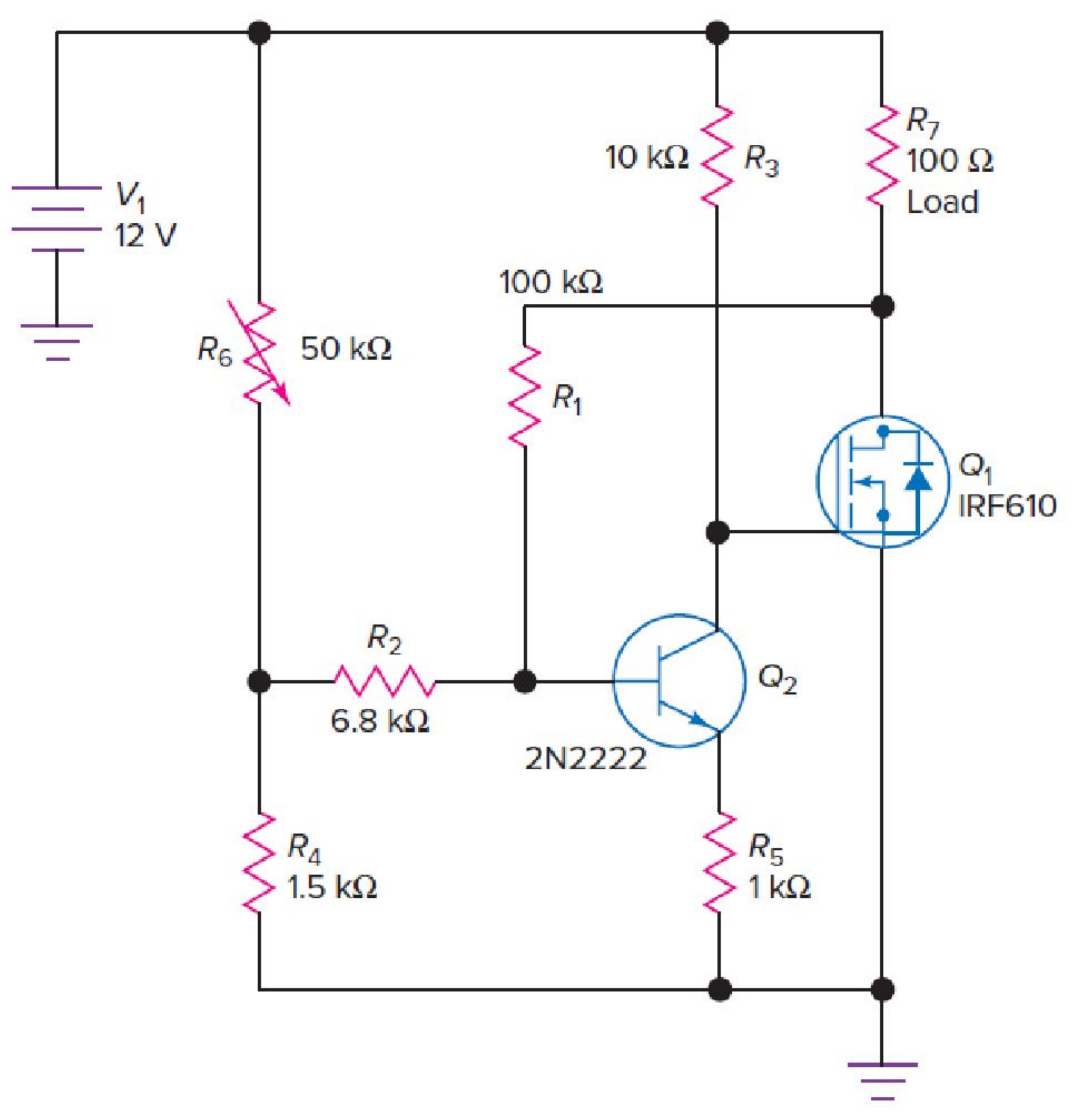


Fig. 5-47 Computer-controlled battery conditioner

Transistors as Switches (1)

Figure 5-48 is a dusk-to-dawn controller without a mechanical relay or a phototransistor. This circuit uses a light-dependent resistor (LDR) as a sensor along with two transistors that act as switches. The LDR is made of a material that conducts better when exposed to light. When the sun comes up, Q_2 turns on, and its collector voltage drops to some low value, as does the gate voltage of Q_1. The load is now off (lights off at dawn). When darkness comes, the resistance goes up and Q_2 turns off. With Q2 off, its collector voltage goes high, as does the gate of Q_1, turning it on; the load is now on (lights go on at dusk).

Fig. 5-48 Dusk-to-dawn control circuit.



Transistors as Switches (2)

Figure 5-49 is another on-off controller but this one is controlled by a push-button. Q_2 and Q_3 form a latch. When a latch is off it will stay off until some event triggers it on. The event here is initiated by pushing button S_1. This results in the discharge of C_1 into the base of Q_2. Q_2 will turn on and current will flow in R_1 and R_2. The current in R_1 causes a voltage across the base-emitter junction of Q_3 and it turns on. With Q_3 on, Q_2 stays on when S_1 is released. Q_2 and Q_3 are now latched on. The load is off because the gate voltage of Q_4 is at a low voltage. Q_1 is also on and C_1 discharges through R_7. With the capacitor discharged, the circuit is ready for the next press of the button (S_1) which will turn the load on.

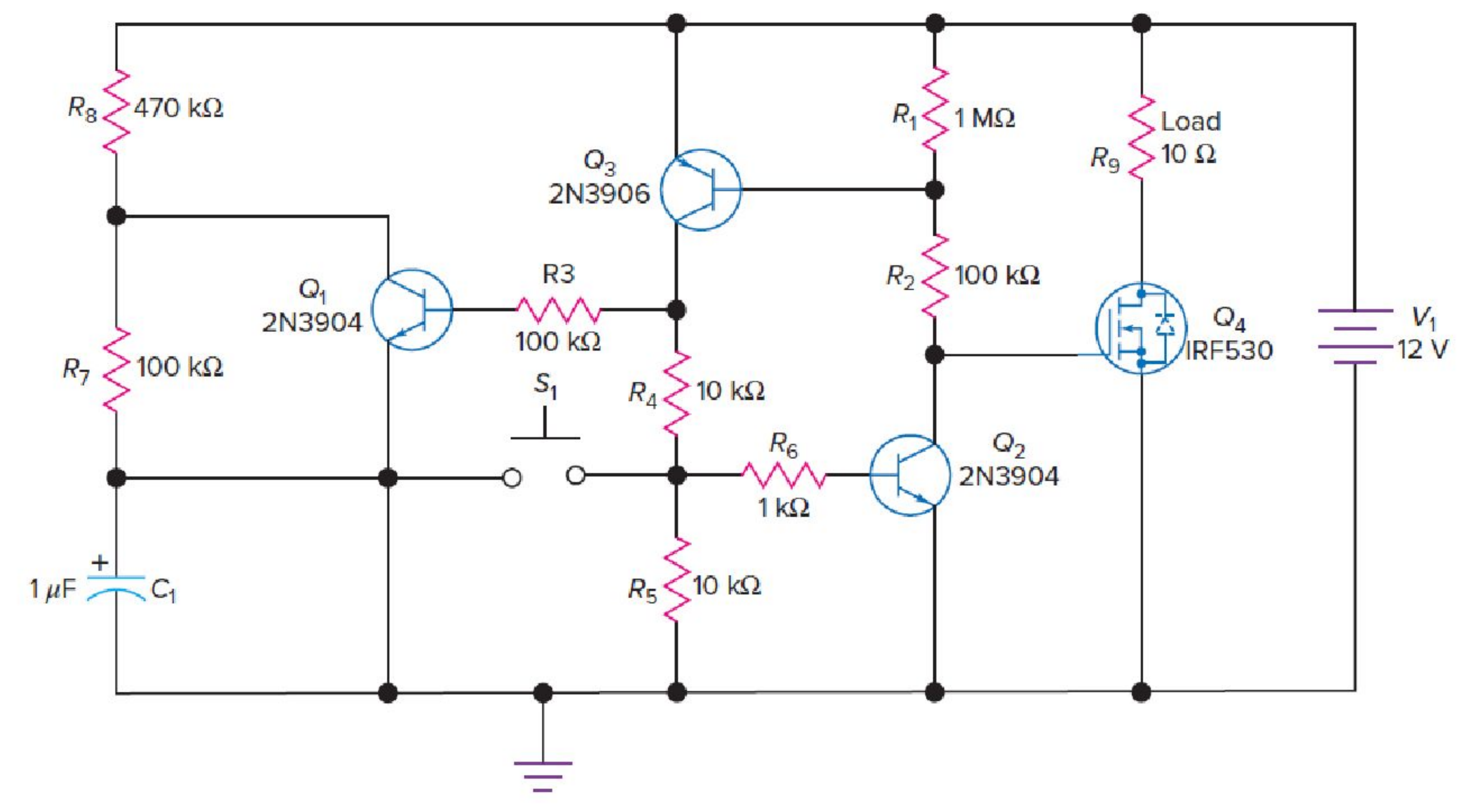


Fig. 5-49 Push button control.

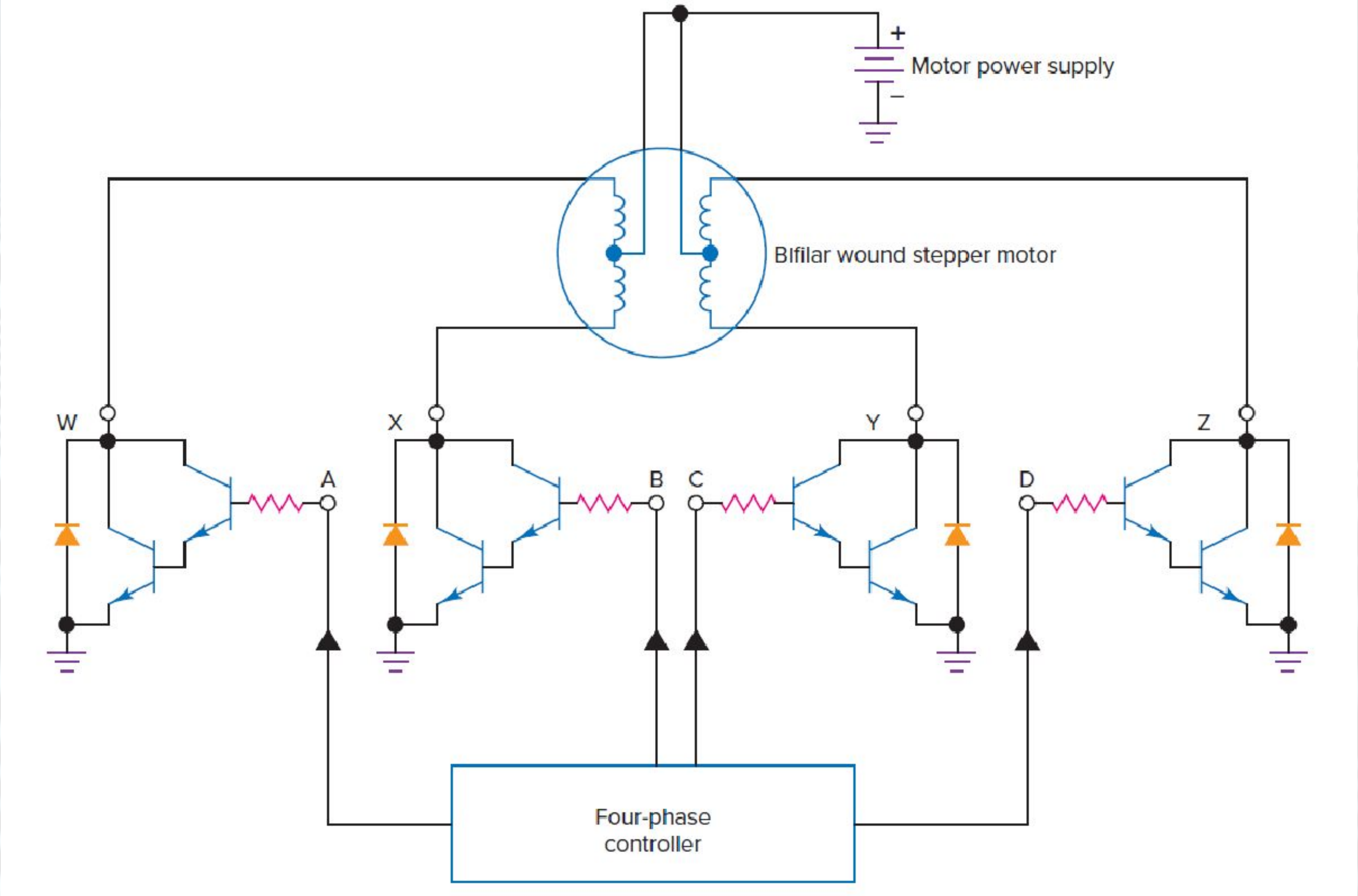
Transistors as Switches (3)

Figure 5-50 shows another application for transistor switches. Stepper motors can be used in applications where tight control of speed and position is required. Such applications include computer disk drives, numerically controlled (automated) lathes and milling machines, and automated surface mount assembly lines. The shaft of a stepper motor moves in defined increments such as 1, 2, or 5 degrees per step. If a motor is a 1-degree type, then 180 pulses will move the shaft exactly one-half turn. As Fig. 5-50(b) shows, four groups of pulses are required with this particular motor.

Transistors as Switches (4)

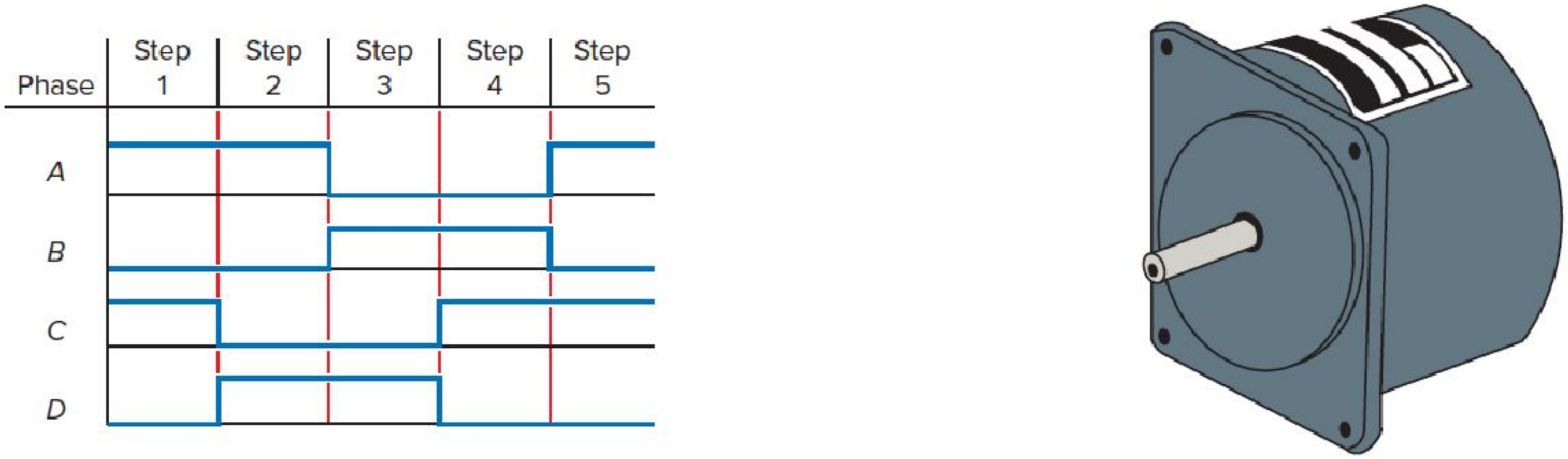
A computer or a microprocessor sends precisely timed waveforms to the switching transistors to control the four motor leads: W, X, Y, and Z in Fig. 5-50(a). The control waveforms are shown as phases A, B, C, and D in Fig. 5-50(b); note that they are rectangular. This is typical when transistors are used as switches. They are either on or off (high or low). Figure 5-50(d) shows that power MOSFETs can also be used to control stepper motors.

Fig. 5-50(a) Control of stepper motors.



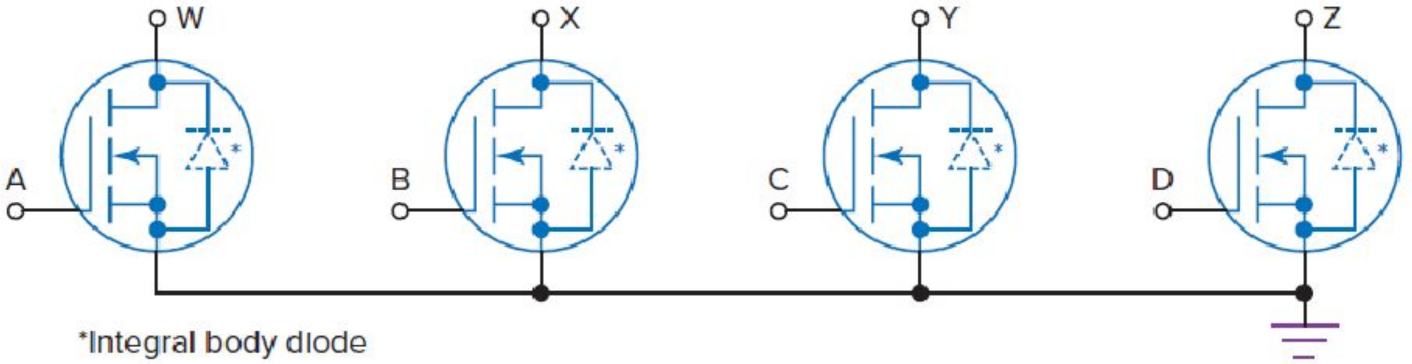
(*a*) Darlington switching transistors

Fig. 5-50(b-d) Control of stepper motors.



(*b*) Controller waveforms

(*c*) Stepper-motor appearance



*Integral body diode

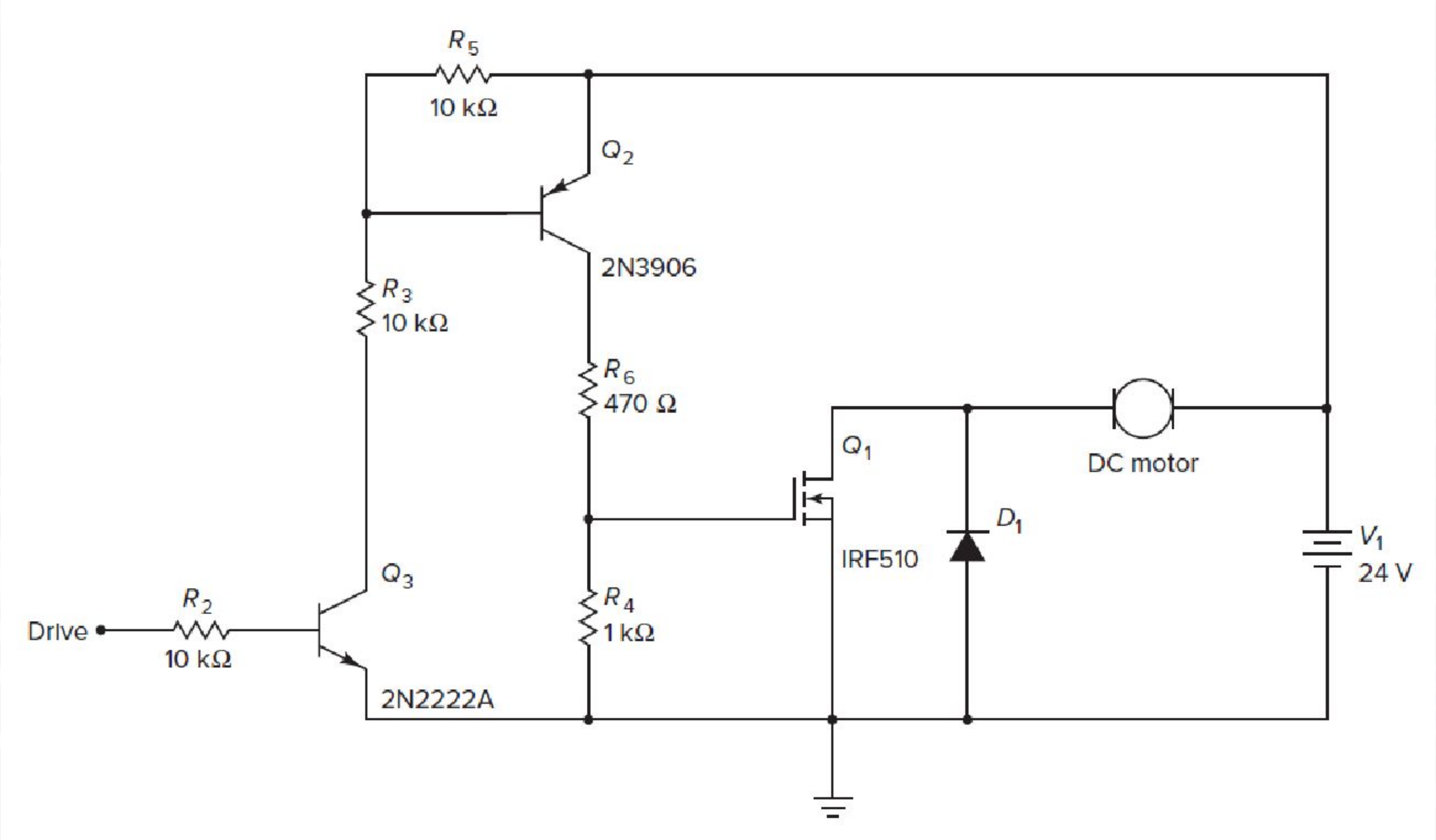
(*d*) Power MOSFET switching transistors

Transistors as Switches (5)

Figure 5-51 shows control of a dc motor. The circuit achieves on-off control by applying a +5-V drive signal to Q_3 to turn the motor on and a 0-V drive signal to turn the motor off. Also, pulse-width modulation (PWM) can be used to control the speed of the motor over a wide range.

Circuits such as the one in Fig. 5-51 are widely used, since power FETs are inexpensive, can have very low on-resistance, and operate efficiently at high frequencies (which makes them attractive in PWM applications).

Fig. 5-51 Control of a dc motor.



Transistors as Switches (6)

So far, the transistor switches discussed have been used for turning loads on and off. There is another category called an analog switch, which is used to control the flow of analog signals. For example, analog switches can be used to select among different signal sources in a sound system (tuner, MP3 player, CD, DVD, and so on). Generally, they are offered as integrated circuits, but it is possible to use enhancement-mode transistors to achieve this function. Figure 5-52 shows an example circuit, and Fig. 5-53 shows example waveforms.

In Fig. 5-52, the switching transistor is a 2N7002, which is an N-channel, enhancement-mode MOSFET. This device shows a low resistance from source to drain when a positive voltage is applied to the gate terminal.

Transistors as Switches (7)

The signal source is connected to the source terminal, and the drain terminal provides the output signal. The control turns the transistor on by applying a voltage to the gate. Figure 5-53 shows the input signal in red and the output signal in blue. Note that the output signal is being switched on and off. The control signal in this case is a square wave. When it goes positive, the switch is on and the sine wave appears at the output. The input signal and the output signal in Figs. 5-52 and 5-53 are of the same amplitude. In other words, this is a switch and ***not a amplifier***.

Fig. 5-52 MOSFET analog switch.

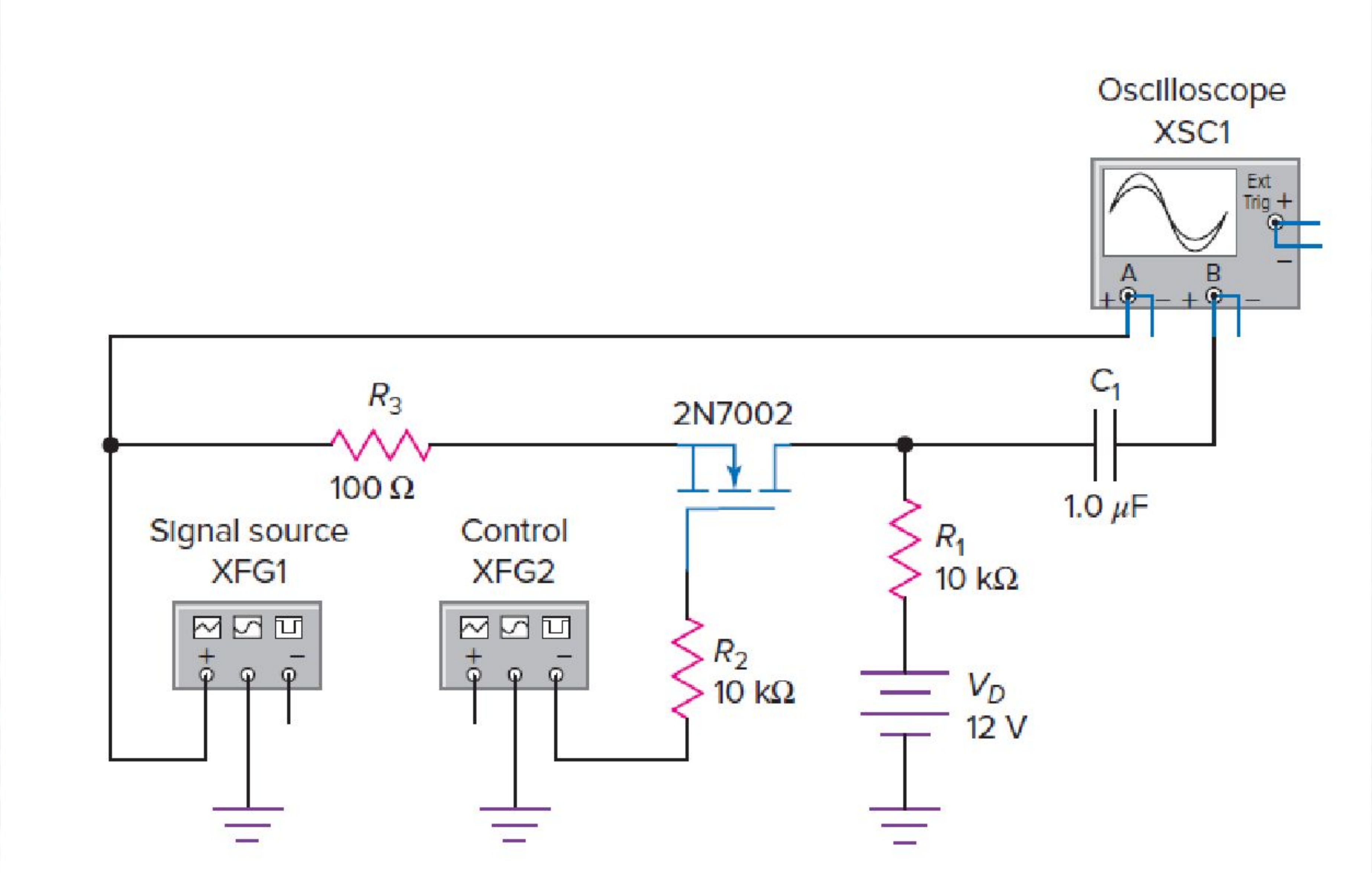
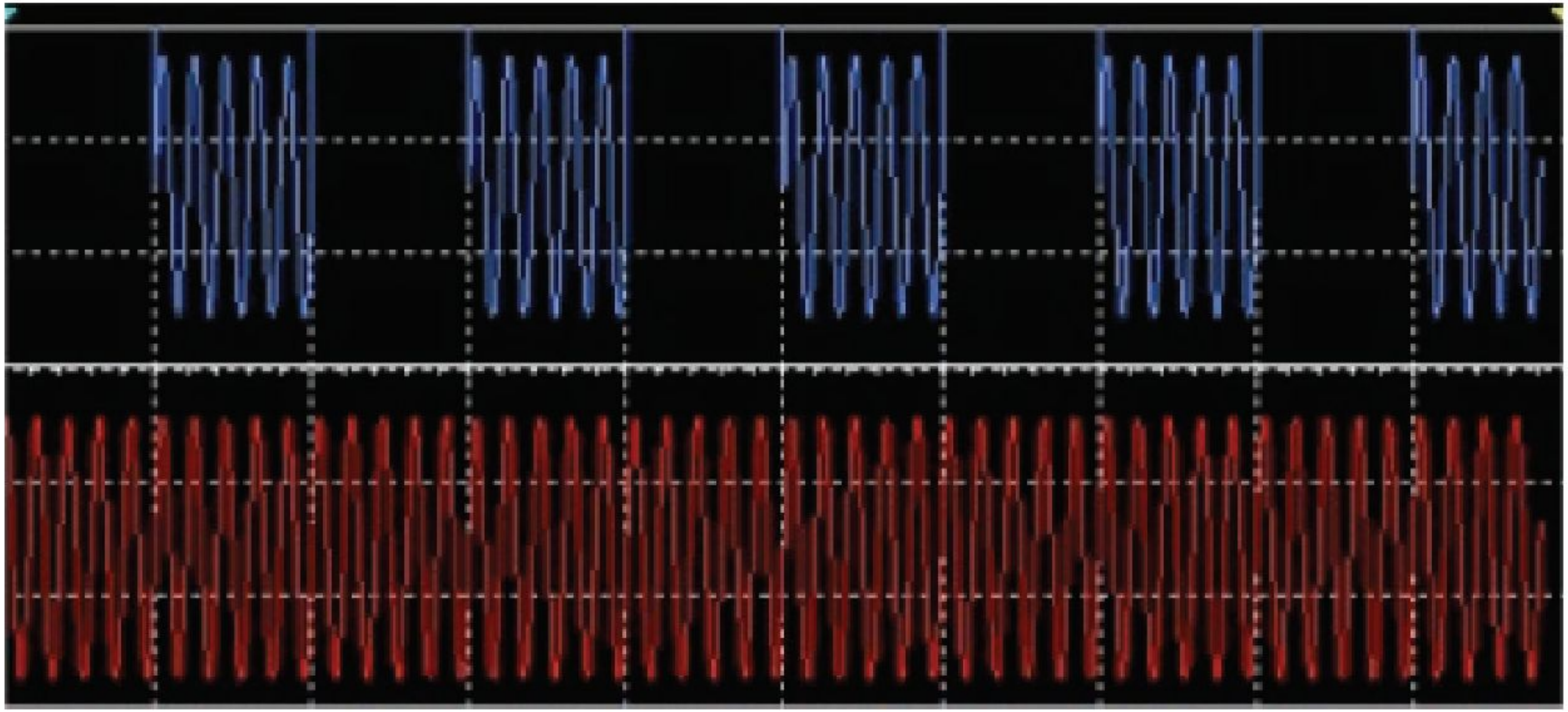


Fig. 5-53 Simulated analog switch waveforms.



Summary

1. Gain is the basic function of any amplifier.
2. Gain can be calculated using voltage, current, or power. In all cases, the units cancel and gain is simply a number.
3. Power gain is the product of voltage gain and current gain.
4. The term voltage amplifier is often used to describe a small-signal amplifier.
5. The term power amplifier is often used to describe a large-signal amplifier.
6. Bipolar junction transistors are manufactured in two polarities: NPN and PNP. The NPN types are more widely applied.
7. In a BJT, the emitter emits the carriers, the base is the control region, and the collector collects the carriers.

Summary (1)

8. The schematic symbol of an NPN transistor shows the emitter lead arrow Not Pointing iN.

9. Normal operation of a BJT requires that the collector-base junction be reverse-biased and the base-emitter junction be forward-biased.

10. Most of the current carriers coming from the emitter cannot find carriers in the base region with which to combine. This tends to make the base current much less than the other currents.

11. The base is very narrow, and the collector bias attracts the carriers coming from the emitter. This tends to make the collector current almost as high as the emitter current.

12. Beta (β), or h_{FE}, is the current gain from the base terminal to the collector terminal. The value of β varies considerably, even among devices with the same part number.

Summary (2)

13. Base current controls collector current and emitter current.
14. Emitters of PNP transistors produce holes. Emitters of NPN transistors produce electrons.
15. A collector characteristic curve is produced by plotting a graph of I_C versus V_{CE} with I_B at some fixed value.
16. Collector voltage has only a small effect on collector current over most of the operating range.
17. A power curve can be plotted on the graph of the collector family to show the safe area of operation.
18. Collector dissipation is the product of collector-emitter voltage and collector current.
19. Germanium transistors require a base-emitter bias of about 0.2 V to turn on. Silicon units need about 0.6 V.

Summary (3)

20. Silicon transistors are much more widely used than germanium transistors.
21. Substitution guides provide the technician with needed information about solid-state devices.
22. The physical characteristics of a part can be just as important as the electrical characteristics.
23. Transistors can be tested with curve tracers, dynamic testers, ohmmeters, and with various in-circuit checks.
24. Most transistors fail suddenly and completely. One or both PN junctions may short or open.
25. An analog ohmmeter can check both junctions, identify polarity, identify leads, check gain, indicate leakage, and may even identify the transistor material.

Summary (4)

26. Leakage current I_{CEO} is β times larger than I_{CBO}.
27. Phototransistors are biased on with light.
28. Phototransistors can be packaged with LEDs to form devices called optoisolators or optocouplers.
29. Bipolar transistors (NPN and PNP) use both holes and electrons for conduction.
30. Unipolar transistors (N-channel and P-channel types) use either electrons or holes for conduction.
31. A BJT is a normally off device. It is turned on with base current.
32. A JFET is a normally on device. It is turned off with gate voltage. This is called the depletion mode.
33. A MOSFET uses an insulated gate structure. Manufacturers make both depletion-type and enhancement-type MOSFETs.

Summary (5)

34. An enhancement-mode MOSFET is a normally off device. It is turned on by gate voltage.

35. Field-effect transistors have a very high input resistance.

36. The abbreviations VFET and VMOS are used to refer to power field-effect transistors that have a vertical flow of current from source to drain.

37. Power FETs do not have some of the limitations of power bipolar transistors. The FETs are voltage-controlled, they are faster (no minority-carrier storage), they do not exhibit thermal runaway, and they are not prone to secondary breakdown.

38. Power FETs operate in the enhancement mode.

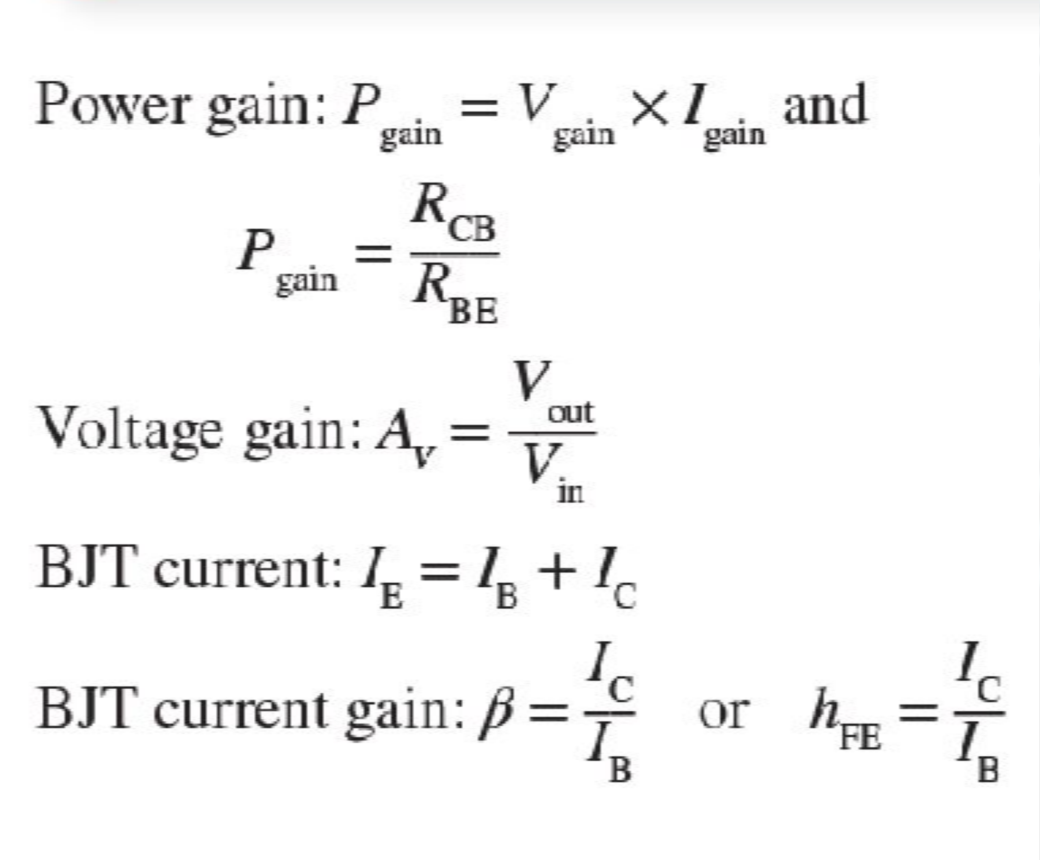
Summary (6)

39. Transistors that are controlled by light are useful for applications such as dusk-to-dawn circuits.
40. Combining LEDs and transistors in the same package provides functions such as optoisolators and photo relays.
41. When a bipolar junction transistor is operated as a switch, there is going to be either no base current or a lot of base current.
42. A switching transistor is either turned on hard (saturated) or is off.

Summary (7)

43. Ideally, switching is very efficient since an open switch shows no current for zero power dissipation, and a closed switch shows no voltage drop, which is another case of zero power dissipation.
44. In switching circuits, the control waveforms are often rectangular.
45. When inductive loads are being switched, some sort of protection device or circuit is needed because of the CEMF generated by the inductance.
46. The thermal resistance unit called θ has a dimension of °C/W.
47. Circuits with hysteresis have two trip points.

Related Formulas



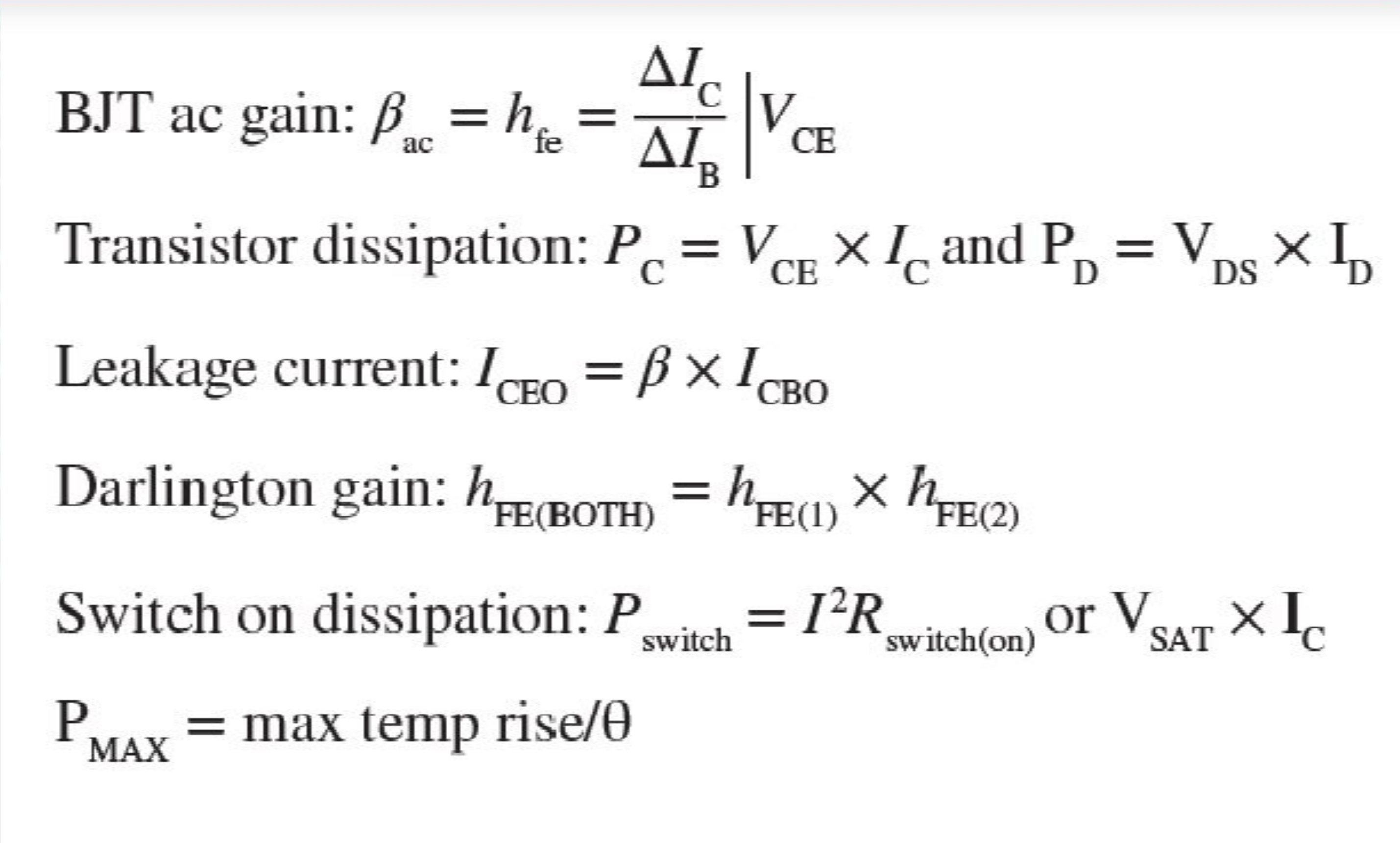
Power gain: $P_{\text{gain}} = V_{\text{gain}} \times I_{\text{gain}}$ and

$$P_{\text{gain}} = \frac{R_{\text{CB}}}{R_{\text{BE}}}$$

Voltage gain: $A_v = \dfrac{V_{\text{out}}}{V_{\text{in}}}$

BJT current: $I_{\text{E}} = I_{\text{B}} + I_{\text{C}}$

BJT current gain: $\beta = \dfrac{I_{\text{C}}}{I_{\text{B}}}$ or $h_{\text{FE}} = \dfrac{I_{\text{C}}}{I_{\text{B}}}$



BJT ac gain: $\beta_{\text{ac}} = h_{\text{fe}} = \dfrac{\Delta I_{\text{C}}}{\Delta I_{\text{B}}}\Big|V_{\text{CE}}$

Transistor dissipation: $P_{\text{C}} = V_{\text{CE}} \times I_{\text{C}}$ and $\text{P}_{\text{D}} = \text{V}_{\text{DS}} \times \text{I}_{\text{D}}$

Leakage current: $I_{\text{CEO}} = \beta \times I_{\text{CBO}}$

Darlington gain: $h_{\text{FE(BOTH)}} = h_{\text{FE(1)}} \times h_{\text{FE(2)}}$

Switch on dissipation: $P_{\text{switch}} = I^2 R_{\text{switch(on)}}$ or $\text{V}_{\text{SAT}} \times \text{I}_{\text{C}}$

P_{MAX} = max temp rise/θ