14. Transistor Characteristics Lab

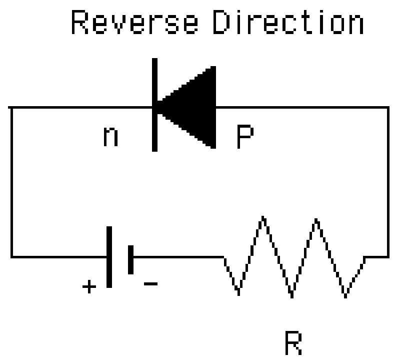
Introduction

Transistors are the active component in various devices like amplifiers and oscillators. They are called active devices since transistors are capable of amplifying (or making larger) signals. The properties of transistors will be studied in this module so basically the focus here is understanding how transistors work. The next module will focus on basic amplifier design. Transistors can also be used as switches but since this is not a course in digital electronics, we will not discuss the function of transistors.

Basic Bipolar Transistor Theory

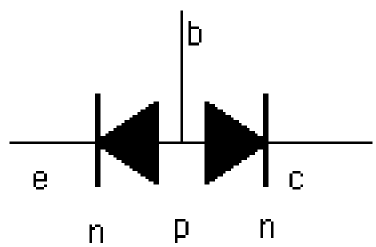
The basic Bipolar transistor or BJT is two diodes constructed back to back on a piece of silicon. (Another kind of transistor is the Junction Field Effect Transistor of JFET. The theory and labeling of the terminals is a little different for the JFET.) Recall that a diode consists of a n doped (or excess negative current carriers) and a p doped (or excess positive current carriers) semiconductor. The diode biased in the forward or conducting direction appears

while a diode in a circuit so that it is nonconducting or reverse direction is

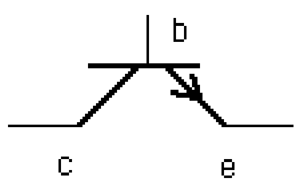


npn Transistor

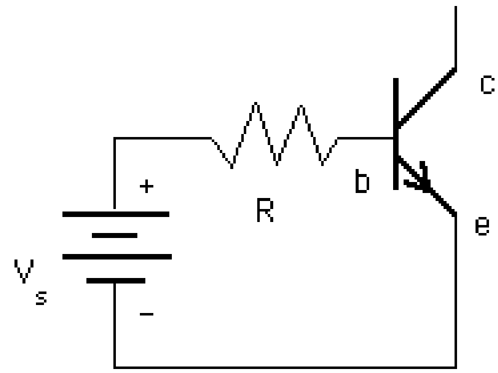
The basic transistor consists of two diodes back to back. If the two p doped regions are next to each other then



and what results is a npn transistor. Two laboratory diodes wired back-to-back will NOT make a transistor. In a real transistor, the region of the two p regions is very narrow or thin so that the carriers can diffuse across the region freely. The symbol for the npn transistor is



Bipolar transistors have three terminals: base, emitter, and collector.
DEVICE FOR REMEMBERING: The arrow on the npn transistor is **N**ot **P**ointed i**N**.   When the battery is attached to the base-emitter junction of the npn transistor as indicated below, current will flow as the base-emitter junction is in the forward direction.



You can calculate the base current I_b using

$$V_{battery} = I_b\, R + V_{be} \qquad (1)$$

where $V_{be} = 0.7$ Volts for silicon. In the above diagram, the battery voltage is labeled V_s. For example, suppose the battery voltage is $V_{battery}$=12 Volts and R=1.0 kΩ then the base current is from equation (1)

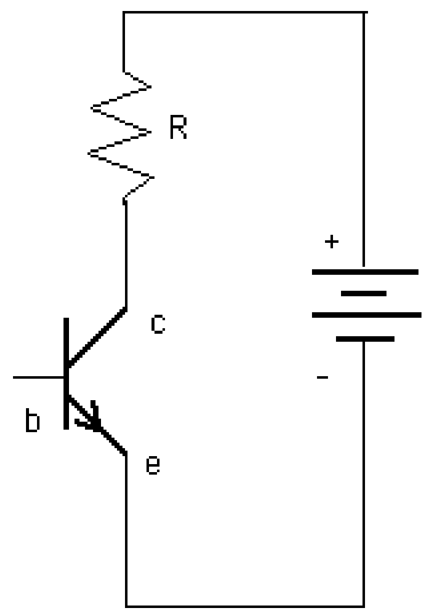
$$I_b = \frac{V_{battery} - V_{be}}{R} = \frac{12\ \text{Volts} - 0.7\ \text{Volts}}{1\ \text{k}\Omega} = 11\ \text{mAmps} \qquad (2)$$

since *Mathematica* yields

$$\frac{12 - 0.7}{1000}$$

0.0113

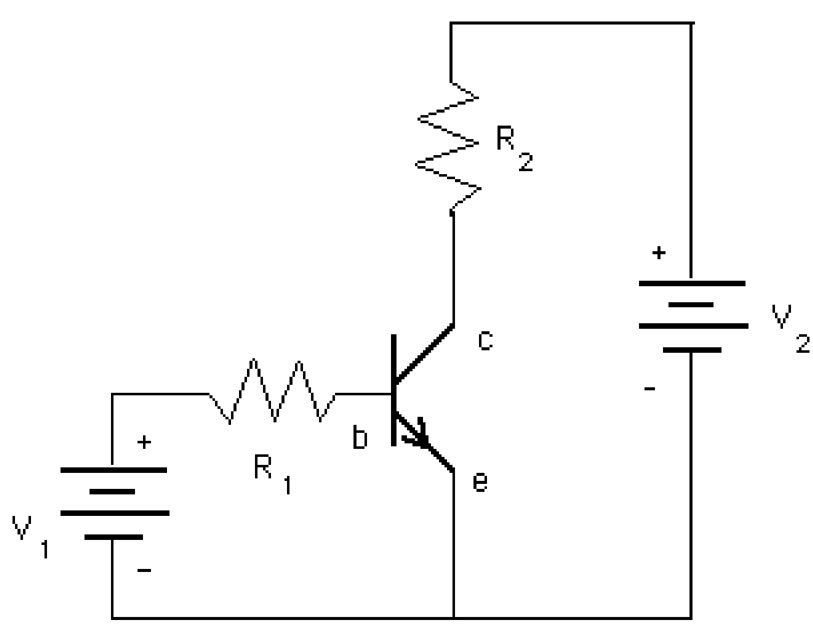
Suppose you have the following different transistor circuit



Current does NOT flow is the above circuit. The base-emitter junction is biased in the forward direction HOWEVER, the base-collector junction is in the REVERSE direction so no current flows.

Biasing the Base-Emitter Junction

Combine the previous two circuits so that base-emitter junction is in the forward direction so for a npn transistor we would place the battery thus



The surprising thing about transistors is that when a base current flows (because the base-emitter junction is biased in the forward direction as above) then a collector current will also flow even though the base-collector junction is biased in the reverse direction. Also, the collector current is much larger than the base current. This is called TRANSISTOR ACTION and is the single most outstanding property of transistors.

The above argument makes it intuitively clear that the emitter current is greater than the base current (also see equation #3 below). A property of transistors is that the ratio

$$\beta = \frac{I_c}{I_b}$$

is always a constant regardless of the size of I_c or I_b. This ratio is typically in the range 100<β<300 and is the basis of the current amplification property of transistors.The base current is said to CONTROL the collector current since the size of I_b determines the size of I_c. It also follows from the above equation that when $I_b = 0$ then $I_c = 0$.

Example: Suppose β=100 and I_b = 1.5 ma. How large is I_c ?

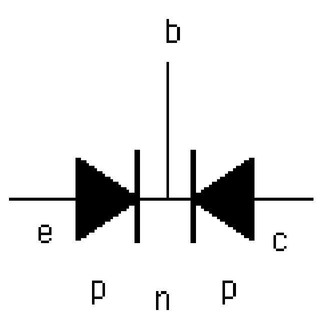
```
β = 100.;
Ib = 1.5;
Ic = β * Ib
```

```
150.
```

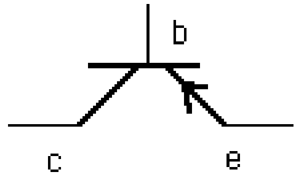
Obviously the collector current is much larger than the base current.

pnp Transistor

When the two n regions are next to each other (as below) then one has a pnp transistor.

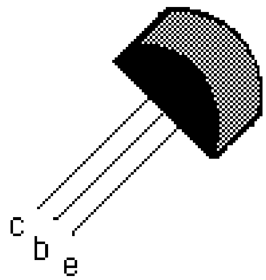


It should be clear that one of the diodes in a transistor is in the forward direction emitter-collector while one of the diodes is in the reverse direction. The symbol for the pnp transistor is

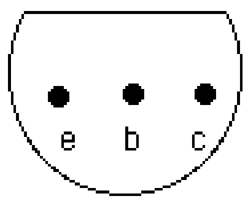


so the direction of the arrow is reverse from the npn transistor.

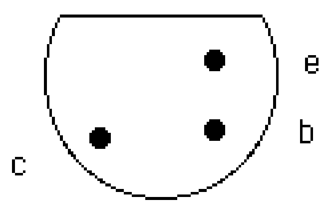
Transistors like the 2N2222 or PN2907 come in a variety of cases and either metal or plastic. One style is of plastic case or package is indicated below



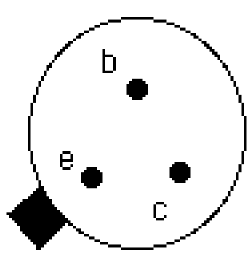
or just the bottom view is



Another style plastic case (**view from below**) appears



Finally the **view from the bottom** of a transistor in a metal package



A Simple Circuit for Measuring Transistor Characteristics

As we said, bipolar transistors have three terminals: base, emitter, and collector. Transistors characteristics are graphs of the various currents ($I_b$is current into the base, I_e is current out of the emitter, and $I_c$is current into collector) and voltages. Conservation of charge yields

$$I_b + I_c = I_e \qquad (3)$$

This means we need to measure only two currents as the other is determined from equation (1). Actually the base current is usually quite small compared with the other two currents and to a good approximation $I_c \cong I_e$ and this is worthwhile remembering.

Also, involved are the voltages measured between the terminals:

V_{ce} = collector – emitter voltage

V_{cb} = collector – base voltage

V_{be} = base – emitter voltage = 0.7 volts for silicon

These voltage should be measured with you digital VOM meter instead of using the oscilloscope since at least for this lab we are interested in the DC voltages. (Also, if you use an oscilloscope you have to be mindful of ground problems. More on this next lab.)

The base-emitter junction is biased in the forward direction so only the intrinsic voltage drop across a pn junction appears. This voltage drop is a constant 0.7 for a silicon based junction. (If less common germanium is used instead of silicon, the voltage drop is 0.3 volts)

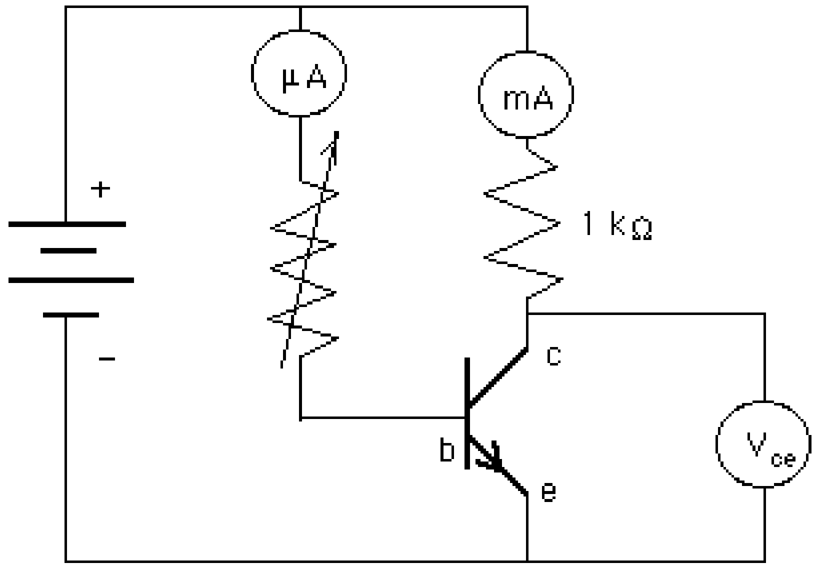
Conservation of potential yields

$$V_{cb} + V_{be} = V_{ce} \qquad (4)$$

This means we need to measure only two voltages as the others are given by equation (2). Actually we need measure only one voltage since V_{be}=0.7 volts for silicon. (Remember the base-emitter junction is in the forward direction.) Equation (2) can be written for a silicon transistor

$$V_{cb} + 0.7 = V_{ce} \qquad (5)$$

The transistor characteristics are useful in amplifier design as well as understanding how transistors operate. The data below were collected for the example of a npn 2N36443 transistor using the circuit below. (You will be using a 2N2222 transistor so your data will be different.)



The battery was 9 volts and is the power supply in the lab. The fixed resistor is 1 kΩ while the variable resistor is actually several fixed resistors with the values indicted as R_B in the table below. The fixed resistor is called the collector resistor and has the value R_C = 1 kΩ in the above circuit.

If you use a pnp transistor, reverse the polarity of the battery. The base-emitter voltage can be calculated using the battery voltage V_{battery} and subtracting the voltage drop across the base resistor (assuming you have recorded the current I_b By the way, for the 2N2222 transistor you will use, I_b is in the mA range.).

Characteristic Data:

R_B	I_b [μA]	I_c [mA]	V_{ce}
1 MΩ	9	0.9	8.1
680 kΩ	13	1.3	7.7
470 kΩ	19	1.9	7.1
330 kΩ	27.3	2.8	6.2
270 kΩ	33.3	3.3	5.7
220 kΩ	40	4.1	5.0
200 kΩ	45	4.5	4.5
180 kΩ	50	5	4.0
160 kΩ	56	5.6	3.4
150 kΩ	60	6	3
120 kΩ	75	7.5	1.5
110 kΩ	82	8.0	1.0
100 kΩ	90	9	0.3

First we graph the base current I_b versus collector current I_c using

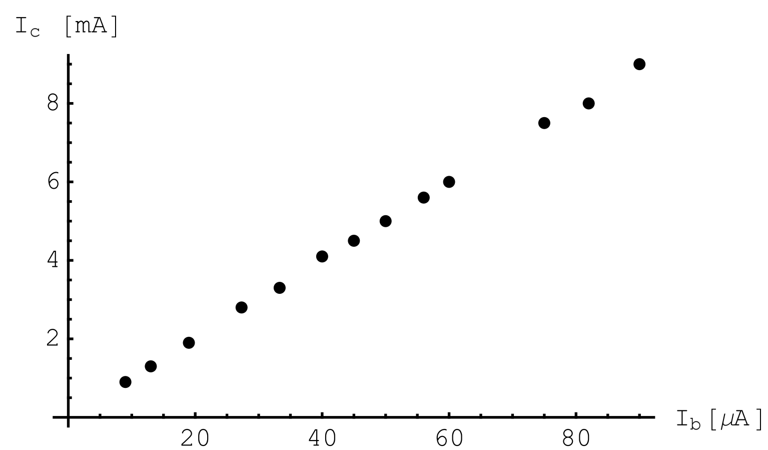
```
BCdata = 
```

9	0.9
13	1.3
19	1.9
27.3	2.8
33.3	3.3
40	4.1
45	4.5
50	5
56	5.6
60	6
75	7.5
82	8.0
90	9

;

Notice in the graph below that when the base current I_b is zero, the collector current I_c is also zero.

```
ListPlot[BCdata, PlotStyle → PointSize[0.02],
  AxesLabel → {"Ib[μA]", "Ic  [mA]"}]
```



- Graphics -

All the data fall on a straight line (regardless of the value of V_{CE}) and the slope of the line is β given by

$$\beta = \frac{\Delta I_c}{\Delta I_b} \quad \text{or} \quad \beta = \frac{I_c}{I_b} \tag{6}$$

since one data point can be taken as $I_b = I_C = 0$. Equation (6) is sometimes called "the Transistor Equation" since it is so important to understanding how transistors work. The numerical value of β for the above transistor is

$$\beta = \frac{(4.5 - 4.1) * 10^{-3}}{(45 - 40) * 10^{-6}}$$

80.

NOTE: β is called h_{fe} on the digital multimeter when you measure the transistor characteristic. The collector-emitter voltage V_{ce} and collector current I_c data is

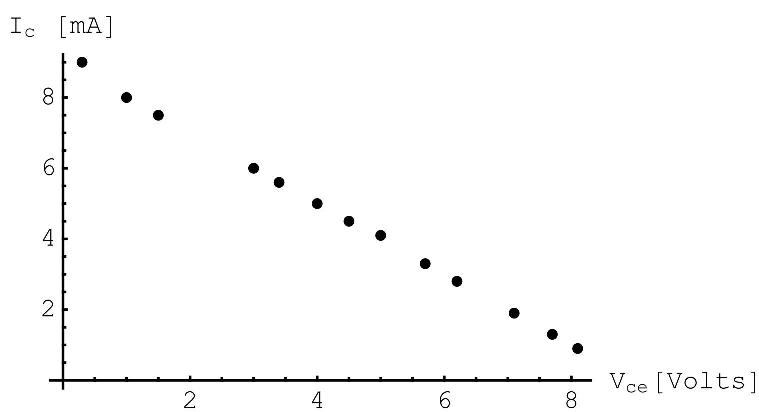
VcIcdata =

8.1	0.9
7.7	1.3
7.1	1.9
6.2	2.8
5.7	3.3
5.0	4.1
4.5	4.5
4.0	5
3.4	5.6
3	6
1.5	7.5
1.0	8.0
0.3	9

;

and the graph of the graph of the collector voltage V_{ce} versus the collector current I_c is a straight line

```
ListPlot[VcIcdata, PlotStyle → PointSize[0.02],
 AxesLabel → {"Vce [Volts]", "Ic  [mA]"}]
```



- Graphics -

From equation (6) if we know the value of I_C in the above graph, then $I_B = I_C/\beta$. Since β=100 for example, $I_B << I_C$. Suppose for example I_C=10 mA and β=100, then I_B = 0.1 mA.

By the way, if you do a series of measurements of I_C versus V_{CE} all with the same I_B and you plot the results on the above graph, then you will get a horizontal straight line. The reason is that I_B determines I_C regardless of the value of V_{CE}.

The above graph is sometimes called the "load line" since the slope is determined by the value of R_C (see below) which often is the load resistor for the transistor circuit.

Determining the Collector Voltage V_{ce}:

The collector voltage V_{ce} is determined in the above experiment directly with a meter. However, this voltage can also be easily calculated as we shall see. First calculate the base current I_b using

$$V_{battery} = I_b R_B + V_{be} \tag{7}$$

and thus

$$I_b = \frac{V_{battery} - V_{be}}{R_B} \tag{8}$$

$V_{be} = 0.7$ for silicon transistors and the battery voltage is usually fixed $\left(V_{battery} = 9\,V\right.$ in the above example) so I_b is determined by R_B. For example, R_B=220,000 Ω yields $I_b = 0.03$ mA

```
V_battery = 9.0;
V_be = 0.7;
R_B = 220 000;
I_b = (V_battery - V_be) / R_B
```

0.0000377273

Thus the base current is about I_b=38 μA which is not to far from the measured value. The β=40 is measured in the experiment or given in the transistor spec sheet and this allows us to calculate the collector current

```
β = 80.;
I_c = β * I_b
```

0.00301818

The calculated collector current is about I_c=3.0 mA and again this agrees well (OK within 25%) with the experimental data (4.1 mA). At last, the collector-emitter voltage V_{ce} is given via

$$V_{battery} = I_c R_C + V_{ce} \tag{9}$$

where R_C=1.0 kΩ , $V_{battery}$=9.0 Volts and we just calculated I_c=3.0 mA. Solving equation (9) for V_{ce} yields

$$V_{ce} = V_{battery} - I_c R_C \tag{10}$$

```
Vbattery = 9.0;
Ic = 0.0030;
RC = 1000;
Vce = Vbattery - Ic * RC
```

```
6.
```

This is not too far from V_{ce} =5.0 volts in the data table.

If you use equation (10) and solve for I_C as a function of V_{CE} you get

$$I_c = -\frac{1}{R_C} V_{ce} + \frac{V_{battery}}{R_C} \tag{11}$$

so the slope is negative and has the value $\frac{1}{R_C}$ and the intercept is $I_c=\frac{V_{battery}}{R_C}$ when V_{ce}=0.

Laboratory Exercise

1. Use the 2N2222 transistor and build a circuit like the above to measure the currents and voltages indicated above. Using the manufacturers spec sheet, what is the maximum value of the battery you can use?
2. Graph your results.
3. Use the multimeter to measure β and see if the value agrees with what you measured.
4. Look up the manufacturer's transistor characteristics on the web using a search engine like google. Type in the model (e.g. "2N2222" and "characteristic"). How does the manufacturer's β compared with your measured value?

APPENDIX: Some 2N2222A Characteristics from various websites:

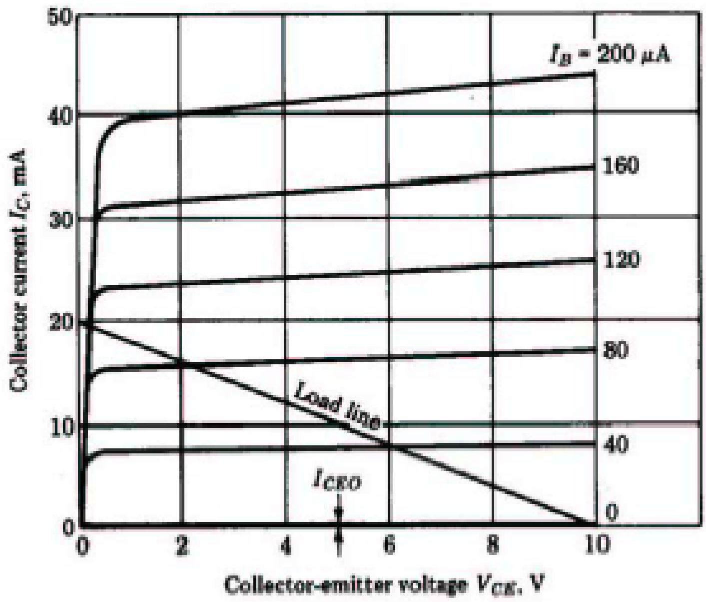
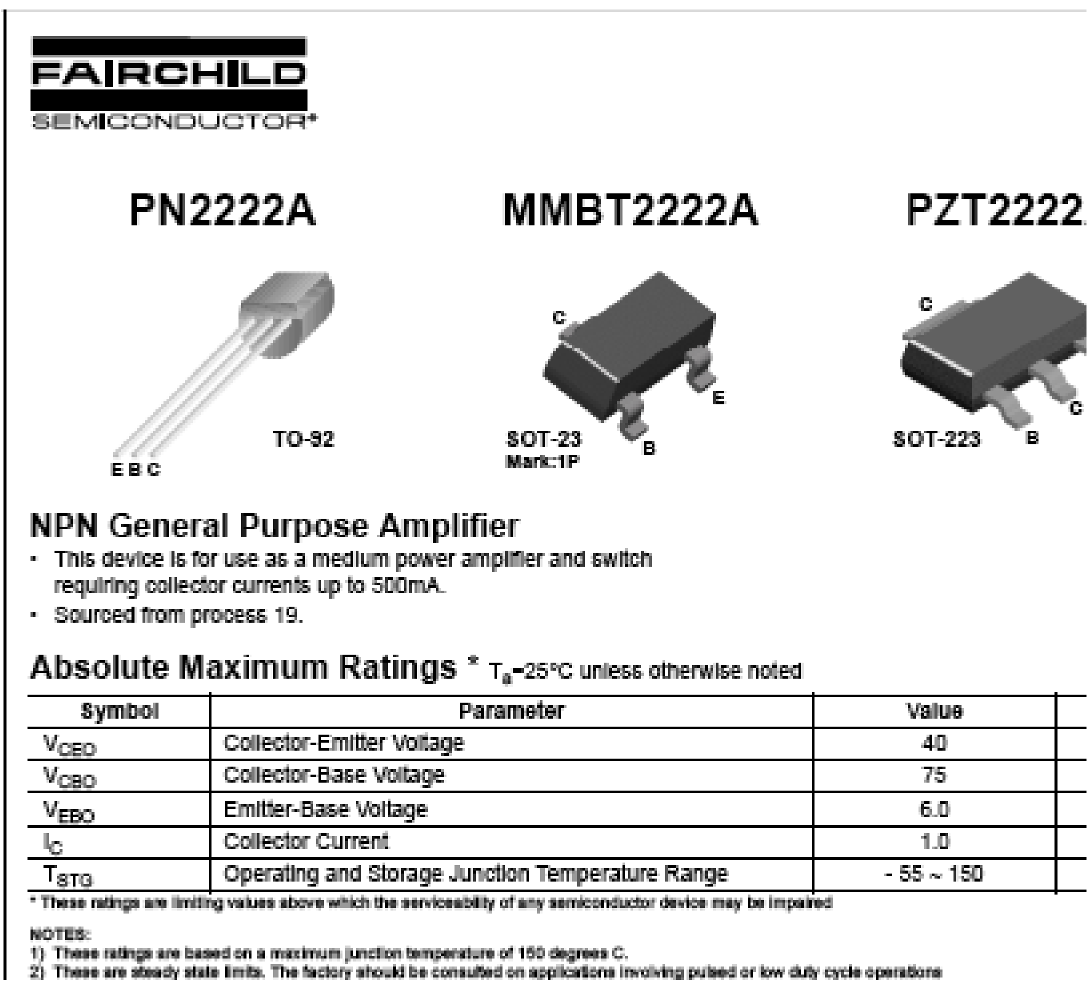


Figure 3-9 Common-emitter o
put characteristics of a 2N222
n-p-n silicon transistor. A lo
line corresponding to V_{CC} = 1(
and R_L = 500 is superimpose

Fairchild is one of many manufacturers of the 2N2222A and the characteristics are listed below.



FAIRCHILD SEMICONDUCTOR®

PN2222A **MMBT2222A** **PZT2222**

TO-92 E B C

SOT-23 Mark:1P C B E

SOT-223 C B C

NPN General Purpose Amplifier

- This device is for use as a medium power amplifier and switch requiring collector currents up to 500mA.
- Sourced from process 19.

Absolute Maximum Ratings * T_a=25°C unless otherwise noted

Symbol	Parameter	Value
V_{CEO}	Collector-Emitter Voltage	40
V_{CBO}	Collector-Base Voltage	75
V_{EBO}	Emitter-Base Voltage	6.0
I_C	Collector Current	1.0
T_{STG}	Operating and Storage Junction Temperature Range	- 55 ~ 150

* These ratings are limiting values above which the serviceability of any semiconductor device may be impaired

NOTES:
1) These ratings are based on a maximum junction temperature of 150 degrees C.
2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations

Electrical Characteristics T_a=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Ma
Off Characteristics				
$BV_{(BR)CEO}$	Collector-Emitter Breakdown Voltage *	I_C = 10mA, I_B = 0	40	
$BV_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10μA, I_E = 0	75	
$BV_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10μA, I_C = 0	6.0	
I_{CEX}	Collector Cutoff Current	V_{CE} = 60V, $V_{EB(off)}$ = 3.0V		1
I_{CBO}	Collector Cutoff Current	V_{CB} = 60V, I_E = 0 V_{CB} = 60V, I_E = 0, T_a = 125°C		0.0 1
I_{EBO}	Emitter Cutoff Current	V_{EB} = 3.0V, I_C = 0		1
I_{BL}	Base Cutoff Current	V_{CE} = 60V, $V_{EB(off)}$ = 3.0V		2
On Characteristics				
h_{FE}	DC Current Gain	I_C = 0.1mA, V_{CE} = 10V I_C = 1.0mA, V_{CE} = 10V I_C = 10mA, V_{CE} = 10V I_C = 10mA, V_{CE} = 10V, T_a = -55°C I_C = 150mA, V_{CE} = 10V * I_C = 150mA, V_{CE} = 10V * I_C = 500mA, V_{CE} = 10V *	35 50 75 35 100 50 40	 30
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage *	I_C = 150mA, V_{CE} = 10V I_C = 500mA, V_{CE} = 10V		0. 1.
$V_{BE(sat)}$	Base-Emitter Saturation Voltage *	I_C = 150mA, V_{CE} = 10V I_C = 500mA, V_{CE} = 10V	0.6	1. 2.