FEECE 2413
Electronics Laboratory

Lab #3: Bipolar Junction Transistor Basics

Goals

In this lab you will experiment with the *bipolar junction transistor* or the BJT. Initially you will bias a BJT in the three most common regions: active, saturation, and cut-off. In the active region you will determine the DC current gain of the transistor (β) and discover that β varies from BJT-to-BJT and with temperature.

You will learn about current gain by building a "touch switch" that lights an LED as you touch two low-current electrodes. A low-level current (a few microamperes) passing through your body is *amplified* by the BJT to a value that is sufficient to drive an LED (a milliampere or so).

As always, take your time during these experiments. Think about *what* you are being asked to do and *why* the experiments are important.

Once you are comfortable with the way BJTs work, you will design and test your own *automatic night light* using a light-sensitive resistor (CdS photocell), a BJT, an LED and assorted resistors.

Prelab

Prelabs will be submitted for grading prior to the lab. Keep a copy for your own use during the lab!

1. The voltage measured between the collector and ground in Figure 1 is 3.72 volts. What is the DC current gain (β) of the BJT in this circuit? (Assume $V_{BE} = 0.7$ V)

2. What is the smallest value of the R_B which will allow the BJT in Figure 1 to remain in the forward active region ($V_C > V_B$)? As R_B becomes smaller than this value, what region is the BJT operating in? (Hint: first find I_C and I_B)

3. You can force the BJT in Figure 1 into cutoff by adding another resistor from the base to ground. Assuming that the BJT is cutoff if $V_{BE} \leq 0.3$ volts, find the *maximum* value of this new resistor that will cause the BJT to operate in the cutoff region.

4. Read Part 2 (a) and sketch the circuit you think will work. Also draw the modified circuit as described in part 2 (b). You may change your design as you work through the lab, however. *(You do not need to draw the Optional Design Circuits 1 and 2*). Remember to indicate the values of the resistances and capacitors used in your design.

5. Read the lab experiment and see the instructor with any questions you may have.

Part 1: Basic BJT behavior

You have two 2N3904 BJTs in your parts kit. So that you can distinguish between them, cut the leads on one of the BJTs a *little* bit shorter. Name each BJT (Q_1 and Q_2) and note in your lab book which BJT has the shorter leads. Construct the circuit shown in Figure 1. Measure and record the values of both resistors, as usual. *Note:* Sometimes the emitter, base, and collector leads are labeled on the package or case of the BJT. If they are not labeled, refer to Figure 2.

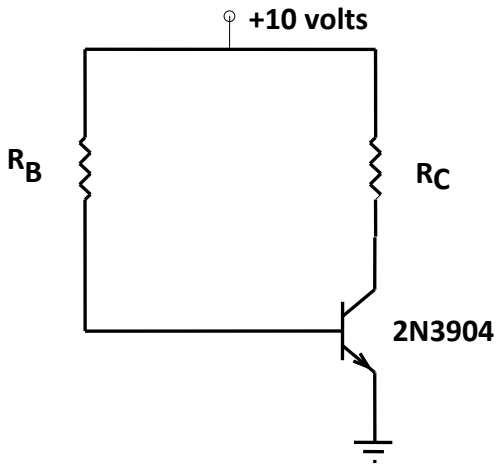


Figure 1. Basic BJT Biasing Circuit
R_B = 309 kΩ, R_C = 1 kΩ

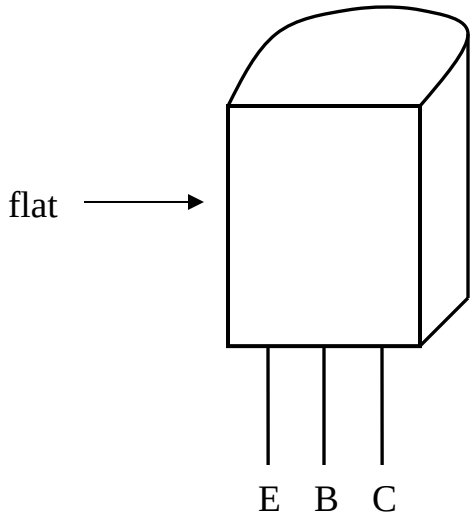


Figure 2. View of 2N3904 npn BJT

Concept: Forward active region of the BJT and the variation of β

The forward active region of the BJT is most commonly used for amplifier circuits. This is because the BJT behaves nearly linearly ($i_C = \beta \cdot i_B$) in the forward active region. In Lab 3 you will experiment with BJT amplifiers. For now, let's just look at the BJT biased in the forward active region.

a. Measure and record V_{CE} and V_{BE} for both transistors. **Explain why the BJTs are biased in the forward active region in terms of V_{BE} and V_{CE}.**

b. Calculate I_B, I_C, and β for each transistor from the data of part 1a.

c. A 2N3904 is set up on the curve tracer in the lab. From the i-v characteristics displayed on the curve tracer, find β for this device under the same bias conditions as part 1a. Ask the TA or Professor for help using the curve tracer!

d. Ask two other lab groups for their two values of β. Calculate the average and the standard deviation of the seven β's. **Discuss the problem you would have designing a circuit that *required* β=150 ±1%. Is this practical? In the data sheets at the end of the lab, h_{FE} is used as the symbol for β. Are all 7 of these transistors within specs?**

Note: If $<\beta>$ is the average value of β_1, β_2, and β_3, then the standard deviation is found from $\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\beta_i - <\beta>)^2}$ where n=3. You will use n=7.

e. Get the can of refrigerant from the instructor and cool the BJT in Fig.1 using a 1 second blast. Have your lab partner measure the maximum value of V_{CE}. Repeat the experiment and determine max[V_{BE}]. Calculate β for this BJT when it is cold. **Is this transistor within specification (see attached data sheets)? Would you want this circuit in your car stereo on a cold winter morning? Discuss this in your lab report.**

In this experiment so far you have determined that β varies from BJT to BJT. β also varies with temperature. Remember this! It is so important that the **first graph** in the spec sheets show the typical temperature variation. Later in electronics you will learn to design circuits which function more or less independently of β and therefore independent of temperature.

Concept: BJT saturation - a switch in the "on" position

In *saturation*, the BJT is acting like a switch in the "on" position. That is, the collector and emitter are nearly shorted together so the V_{CE} is approximately 0.1-0.3 volts.

f. Replace the 309 kΩ resistor in Figure 1 with another resistor which forces the BJT into the saturation region. Refer to the Prelab, question 2. Write the value of R_B you have chosen in your lab book and **describe your choice in the lab report**.

g. Measure $V_{CE(SAT)}$ and V_{BE} for both 2N3904's. **How much variation do you observe? How important is BJT-to-BJT variation if the saturation region is used?**

h. Calculate the current gain (I_C/I_B) for each of the BJTs when saturated. **Compare this number with β in the forward active region. If a high β is important, which region should you use?**

Concept: BJT cutoff - a switch in the "off" position

In cutoff the BJT is acting like a switch in the "off" position. That is, the path from collector to emitter is very nearly an open circuit.

i. There are a few ways to achieve cutoff. Try *each* of these and **record V_{CE}.**
   1) remove the base resistor so that $I_B = 0$
   2) short the base to ground so that $V_{BE} = 0$
   3) put a small resistor between base and ground such that $V_{BE} << 0.7$ v.

In part (3) above, use the result from your prelab. Note that this technique is important to understand since you may want to use it in the design section (Part 2).

Concept: A practical application of BJT current gain (a touch sensitive switch)

Using the BJT with the highest β, build the circuit in Figure 3. At the two terminals marked "touch points", insert two bared wires into your protoboard in a place where they can be easily touched with your finger.
The circuit lights the LED as you touch the two low-current electrodes. The low-level

current (a few microamperes) passing through your finger is *amplified* by the BJT to a value that is sufficient to drive an LED (a milliampere or so).

Note: The resistance of your finger depends on a number of factors. Among them is the level of stress you are under. This is one of the things a "lie detector" might measure! If you are having trouble getting the LED to light, try moistening your finger.

j. By measuring the appropriate node voltages, determine I_C, I_B, and the resistance of your finger (without directly measuring your finger with an ohmmeter!).

k. **If you completed a circuit --consisting only of an LED and a 10 V source-- with your finger, how much current would flow through the LED (see Fig. 4)? Would the LED emit visible light? Comment on the importance of the BJT in the circuit shown in Fig. 3.**

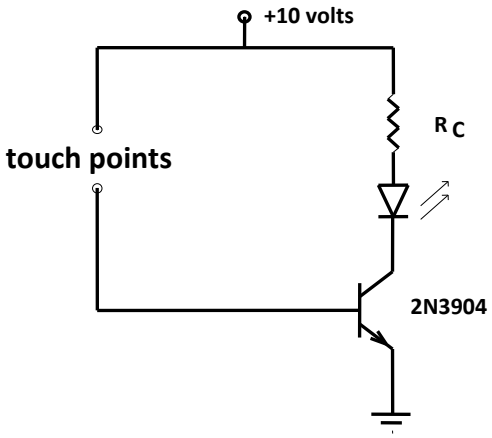


Figure 3. A touch sensitive switch: R_C = 1 kΩ

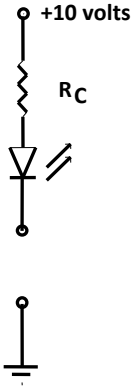


Figure 4. Non-amplified touch switch: Will it work?

Part 2: Designing an automatic night light

(a) You will need a light-sensitive resistor for this design. A cadmium sulfide (CdS) photocell has a low resistance when exposed to light (typically 1-4 kΩ) and a high resistance in darkness (typ. 50-100 kΩ). Using the CdS cell provided, measure and record the light and dark resistances in your lab notebook.

Now design a BJT circuit which turns a red LED *on* when the room lights are *off*. Conversely, the LED should extinguish when the room is lit again. (Cup your hands around the circuit to simulate darkness.)

(b) Once your circuit is working, you will notice that it is susceptible to flicker when the light is momentarily interrupted (for example, if auto headlights were to occasionally illuminate the sensor of an automated street light). This is definitely undesirable. **Modify** your circuit so that the illumination must remain either light or dark for about 1 second before a change in the LED status occurs. *Hint:* You will need to use a capacitor.

Shop Note: Electrolytic capacitors are polarized...that is, they have + and - terminals. If you connect the capacitor with reversed polarity, it will "leak" a small but devastating DC current through its terminals. Always discharge the capacitor *before* inserting it into the circuit. This prevents stored charge in the capacitor from destroying your work.

When your design is working, draw a schematic of the circuit, demonstrate it to the instructor, and get the instructor's *design approval* on your schematic.

In your lab notebook, describe the operation of your design, the rationale of picking the devices, and include a schematic with the instructor's design approval. All designs will be graded when you hand-in your notebook at the end of the semester.

Optional Design1: Modify your circuit so that the CdS photocell must be illuminated for 1 second before the light emitting diode goes off AND the photocell must be in the dark for 1 second before the LED turns on.

Optional Design2: Add a BJT inverter to your circuit so that an additional green LED is lit when the room lights are "on" but extinguished when the room is darkened. Make certain the red LED still functions as specified in the original design.

Equipment List -- Lab #3

Note: "*" indicates this component was used in Lab 2.

Keysight EDU36311A Tripple Output Programmable DC Power Supply *
Keysight EDU34450A Digital Multimeter *
Proto-Board model PB-103 *

4 banana plug-terminated test leads *
#20 hook up wire *
wire strippers *
Aerosol component coolant (non-CFC) *

Diodes:

Red LED	(1) *

Transistors:

2N3904	npn	(2)

CdS photocell ~1 kΩ - 100 kΩ range

Resistors: 1/4 W unless otherwise specified

1.0 kΩ	±5%	(1) *
4.7 kΩ	±5%	(1) *
10 kΩ	±5%	(1) *
47 kΩ	±5%	(1)
100 kΩ	±5%	(1) *
309 kΩ	±5%	(1)
1.0 MΩ	±5%	(1)

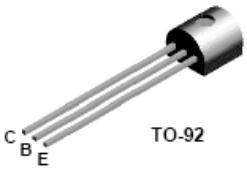
Electrolytic capacitors: 10 μF to 1000 μF, 10 WVDC or greater

From the instructor:

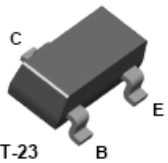
A Curve Tracer, set up with a 2N3904 BJT.

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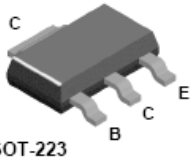
2N3904 MMBT3904 PZT3904



TO-92



SOT-23
Mark: 1A



SOT-223

NPN General Purpose Amplifier

This device is designed as a general purpose amplifier and switch. The useful dynamic range extends to 100 mA as a switch and to 100 MHz as an amplifier.

Absolute Maximum Ratings*

T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

*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.

Thermal Characteristics

T_A = 25°C unless otherwise noted

Symbol	Characteristic	Max			Units
		2N3904	*MMBT3904	**PZT3904	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

*Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06."

**Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm^2.

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NPN General Purpose Amplifier
(continued)

Electrical Characteristics
T_A = 25°C unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	I_C = 1.0 mA, I_B = 0	40		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10 µA, I_E = 0	60		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10 µA, I_C = 0	6.0		V
I_{BL}	Base Cutoff Current	V_{CE} = 30 V, V_{EB} = 3V		50	nA
I_{CEX}	Collector Cutoff Current	V_{CE} = 30 V, V_{EB} = 3V		50	nA
ON CHARACTERISTICS*					
h_{FE}	DC Current Gain	I_C = 0.1 mA, V_{CE} = 1.0 V I_C = 1.0 mA, V_{CE} = 1.0 V I_C = 10 mA, V_{CE} = 1.0 V I_C = 50 mA, V_{CE} = 1.0 V I_C = 100 mA, V_{CE} = 1.0 V	40 70 100 60 30	 300 	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA I_C = 50 mA, I_B = 5.0 mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA I_C = 50 mA, I_B = 5.0 mA	0.65	0.85 0.95	V V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 10 mA, V_{CE} = 20 V, f = 100 MHz	300		MHz
C_{obo}	Output Capacitance	V_{CB} = 5.0 V, I_E = 0, f = 1.0 MHz		4.0	pF
C_{ibo}	Input Capacitance	V_{EB} = 0.5 V, I_C = 0, f = 1.0 MHz		8.0	pF
NF	Noise Figure	I_C = 100 µA, V_{CE} = 5.0 V, R_S =1.0kΩ,f=10 Hz to 15.7kHz		5.0	dB
SWITCHING CHARACTERISTICS					
t_d	Delay Time	V_{CC} = 3.0 V, V_{BE} = 0.5 V,		35	ns
t_r	Rise Time	I_C = 10 mA, I_{B1} = 1.0 mA		35	ns
t_s	Storage Time	V_{CC} = 3.0 V, I_C = 10mA		200	ns
t_f	Fall Time	I_{B1} = I_{B2} = 1.0 mA		50	ns

*Pulse Test: Pulse Width ≤ 300 µs, Duty Cycle ≤ 2.0%

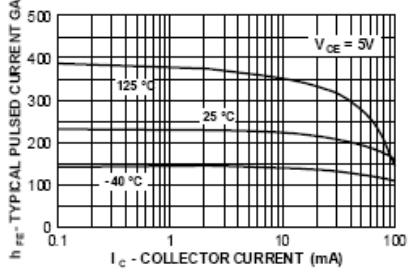
Spice Model

NPN (Is=6.734f Xti=3 Eg=1.11 Vaf=74.03 Bf=416.4 Ne=1.259 Ise=6.734 Ikf=66.78m Xtb=1.5 Br=.7371 Nc=2 Isc=0 Ikr=0 Rc=1 Cjc=3.638p Mjc=.3085 Vjc=.75 Fc=.5 Cje=4.493p Mje=.2593 Vje=.75 Tr=239.5n Tf=301.2p Itf=.4 Vtf=4 Xtf=2 Rb=10)

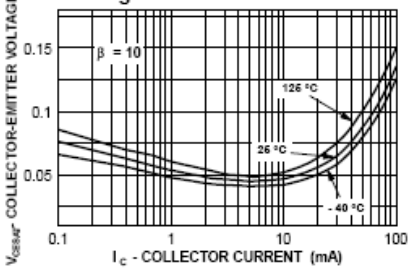
NPN General Purpose Amplifier
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Typical Characteristics

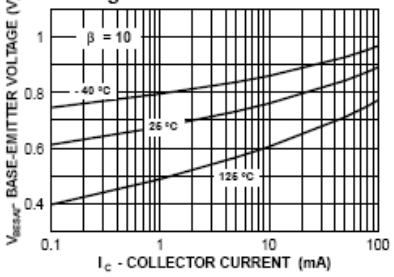
Typical Pulsed Current Gain vs Collector Current



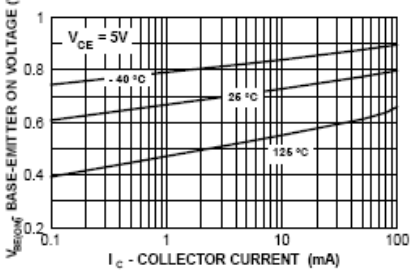
Collector-Emitter Saturation Voltage vs Collector Current



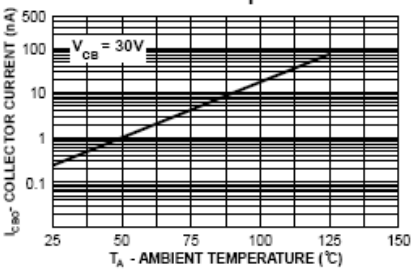
Base-Emitter Saturation Voltage vs Collector Current



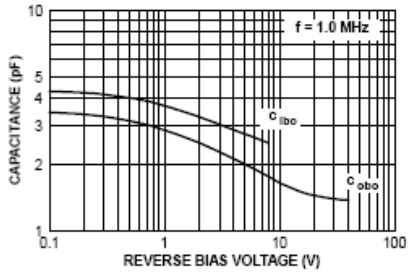
Base-Emitter ON Voltage vs Collector Current



Collector-Cutoff Current vs Ambient Temperature



Capacitance vs Reverse Bias Voltage



PSPICE Instructions:

Part 1

- Use Fig. 1 from the lab manual and complete a DC simulation with similar resistance values and supply voltage. Check if the BJT operates in the active saturation region or not. Display voltages across all the components (transistor and resistors) in your PSPICE schematic. Mark the currents (i.e. I_c and I_b) and check to compare the simulated value of β with the measurement.
- Change the resistor R_B value in your circuit as during your measurement, and run a DC simulation. Check if the BJT operates in saturation region or not. Display the PSPICE voltages across all the components (transistor and resistors). Mark the current I_c and I_b, and compare your β value with the measurement result.
- Similarly, repeat the DC simulation for the cutoff region.
- Construct the touch sensitive switch using the resistance value you measured with your finger tip during measurement, and annotate the voltages across all the components as well as the currents. Mention the region of operation.

Part 2:

- Set up the automatic night light circuit to simulate it. Use two different resistors for dark and light scenarios, and show the voltage drops across all components (LED, resistors and BJT). Verify your β value for the particular region of operation. Afterwards, add the capacitor in parallel with the variable resistor. Run a DC simulation and annotate the voltages and currents.