UNIVERSITY OF CALIFORNIA AT BERKELEY
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## EE105 Lab Experiments

# Report 3: Bipolar Junction Transistor Characterization

Solutions

3.1 & 3.2 For each measurement of $V_{BE}$, $V_{BC}$, $I_B$, and $I_C$, fill in the corresponding entry in Table 1 and compute the resulting $\beta$ and $\alpha$.

| Parameters | Forward Active | Saturation | Cutoff | Reverse Active |
|---|---|---|---|---|
| $V_{BE}$ | 0.6 V | 0.596 V | −2.68 V | −4.55 V |
| $V_{BC}$ | −1.72 V | 0.473 V | −7.33 V | 0.492 V |
| $I_B$ | 2.2 nA | 3.2 nA | 0 A | 3.5 nA |
| $I_C$ | 0.5 mA | 0.363 mA | 0 A | −0.0126 mA |
| $\beta$ | 227.27 | N/A | N/A | −3.6 |
| $\alpha$ | 0.9956 | N/A | N/A | 0.7826 |

**Table 1:** Regions of operations and measurements

3.1.2 Measure $V_{BE}$ and $V_{BC}$. What is the region of operation?

Forward active

$$\boxed{V_{BE} = 0.6 \text{ V}}$$
$$\boxed{V_{BC} = -1.72 \text{ V}}$$

3.1.3 Measure $I_B$ and compute $\beta$.

$$\beta = \frac{I_C}{I_B} = \frac{0.5 \text{ mA}}{2.2 \text{ nA}} = 227.27$$

$$\boxed{I_B = 2.2 \text{ nA}}$$
$$\boxed{\beta = 227.27}$$

3.1.4 Calculate $I_E$ using $\alpha$ and measure $I_E$. Do the results agree?

$$\alpha = \frac{\beta}{1+\beta} = \frac{227.27}{1+227.27} = 0.9956$$

$$\text{(Calculated) } I_E = \frac{I_C}{\alpha} = 0.50221 \text{ mA}$$

$$\boxed{\alpha = 0.9956}$$

$$\text{(Calculated) } \boxed{I_E = 0.50221 \text{ mA}}$$

$$\text{(Measured) } \boxed{I_E = 0.5022 \text{ mA}}$$

3.1.5 Measure $I_B$ and $I_C$ with your fingers around the BJT. How do the values compare to the values without heating the BJT?

$I_C$ increases, but $I_B$ stays the same.

$$\boxed{I_B = 2.2 \text{ nA}}$$

$$\boxed{I_C = 0.5045 \text{ mA}}$$

3.1.6 Explain, using the equation you know for collector current, how you'd expect $I_C$ to vary with temperature. Does this agree with your experimental results? If not, explain why this might be the case. *Hint: $I_S$ depends on the intrinsic carrier concentration $n_i$ and the diffusion coefficients $D_n$ and $D_p$. Intuitively, how would $n_i$, $D_n$, and $D_p$ change with temperature? How would $I_S$ change with temperature as a result?*

If you consider $I_S$ a constant, as we have often done in this class, you may think it obvious that the collector current should decrease if $T$ increases, since $I_C = I_S\left(e^{qV_{BE}/kT} - 1\right)$. However, $I_S$ in fact depends on $n_i$, $D_n$, and $D_p$ in the following way (for a general PN junction):

$$I_S = qn_i^2 A\left(\frac{D_p}{N_d W_n} + \frac{D_n}{N_a W_p}\right)$$

Intuitively, you should know that $n_i$ increases with temperature (since more thermal energy allows more charge carriers to be intrinsically mobiler) and that $D_n$ and $D_p$ increase with temperature (diffusion is more rapid at higher temperatures). If you look up equations for these values, you'll find your intuition is correct, as $n_i \propto e^{-E_g/2kT}$, $D_n = \mu_n kT/q$, and $D_p = \mu_p kT/q$.

Thus, a reasonable explanation for why $I_C$ increases with temperature is that the increase in $I_S$ outweighs the decrease in $e^{qV/kT}$.

3.1.7 Does $\beta$ agree with the value listed in the datasheet? If not, explain why you might see discrepancies.

Discrepancies may come from fabrication variation, temperature dependence, and measurement error.

3.1.8 Set $V_{BB}$ to 4 V and $V_{CC}$ to 2 V. Measure $I_B$, $I_C$, $V_{BE}$, and $V_{BC}$. What is the region of operation?

Saturation

$$\boxed{I_B = 3.2 \text{ nA}}$$
$$\boxed{I_C = 0.363 \text{ mA}}$$
$$\boxed{V_{BE} = 0.596 \text{ V}}$$
$$\boxed{V_{BC} = 0.473 \text{ V}}$$

3.1.9 Set $V_{BB}$ to $-3$ V and $V_{CC}$ to 5 V. Measure $I_B$, $I_C$, $V_{BE}$, and $V_{BC}$. What is the region of operation?

Cutoff

$$\boxed{I_B = 0 \text{ A}}$$
$$\boxed{I_C = 0 \text{ A}}$$
$$\boxed{V_{BE} = -2.68 \text{ V}}$$
$$\boxed{V_{BC} = -7.33 \text{ V}}$$

3.1.10 Swap the emitter and collector. Set $V_{BB}$ to 4 V and keep $V_{CC}$ at 5 V. Measure $I_B$, $I_C$, $V_{BE}$, and $V_{BC}$. What is the region of operation?

Reverse Active

$$\boxed{I_B = 3.5 \text{ nA}}$$
$$\boxed{I_C = -0.0126 \text{ mA}}$$
$$\boxed{V_{BE} = -4.55 \text{ V}}$$
$$\boxed{V_{BC} = 0.492 \text{ V}}$$

Use all of the data you've collected up to this point to fill out Table 1.

3.2.2 Attach the plot of the I-V curve to this worksheet. Label the two regions of operation and draw the boundary between them.

See Figure 1 for the BJT I-V curve.

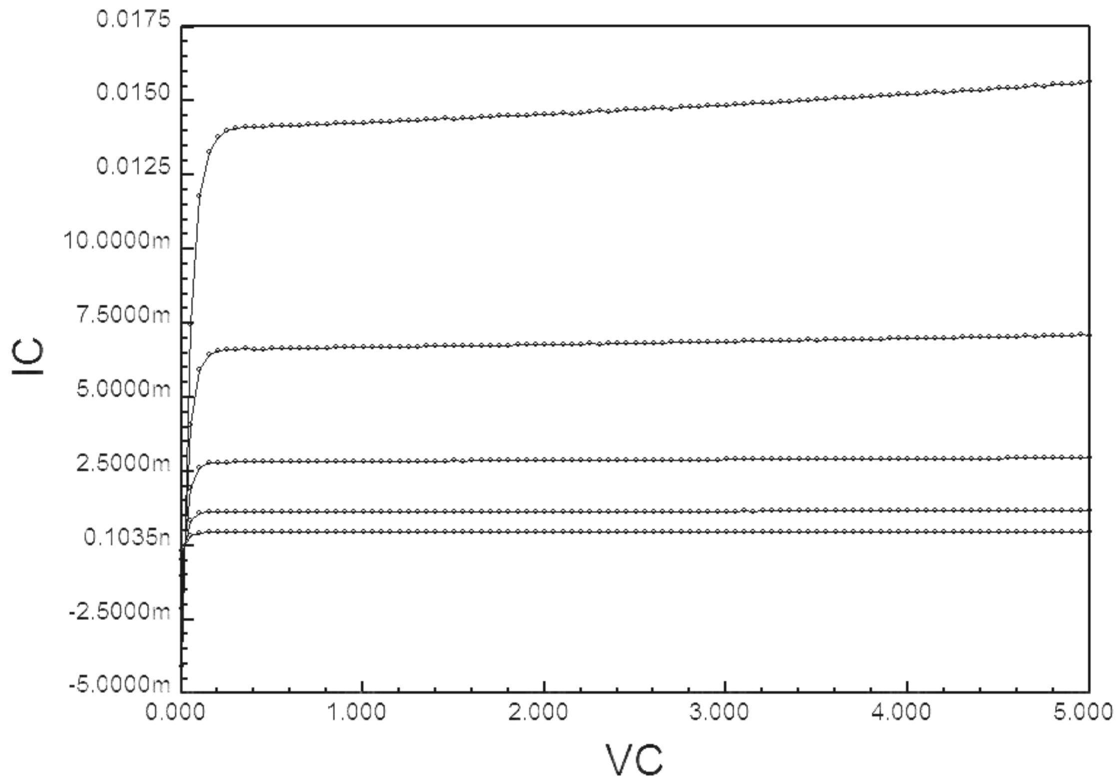


**Figure 1:** I-V curves for a BJT.

3.2.3 Use the I-V curve to determine $V_A$.

$$V_A = I_{C,SAT} \cdot r_o$$

$$r_o = \frac{1}{\text{Slope in Forward Active}}$$

$$\boxed{V_A = 173.077 \text{ V}}$$

3.2.4 Repeat your calculation of $V_A$ for base voltages of 0.625 V, 0.65 V, 0.675 V, and 0.7 V (you can step the base voltage in ICS to get this data). Does $V_A$ depend on $V_B$? Why?

$V_A$ depends on $V_B$. $V_A$ being constant with $V_B$ is just an approximation. In reality, changing $V_B$ (holding $V_E$ constant) will change the quasi-neutral base width due to the change in depletion width in the base-emitter junction. Therefore, $V_A$, which captures the effect of the change in depletion width in the base-collector junction relative to the quasi-neutral base width, changes with $V_B$ when $V_E$ is

| $V_B$ | $V_A$ |
|---|---|
| 0.600 V | 173.077 V |
| 0.625 V | 145.987 V |
| 0.650 V | 111.111 V |
| 0.675 V | 77.77 V |
| 0.700 V | 57.5 V |

**Table 2:** Early voltage calculations

held constant.

3.3.2 Attach the plot of the I-V curve to this worksheet. What semiconductor device does this I-V curve look like?

See Figure 2 for the I-V curve. This device looks like a diode.

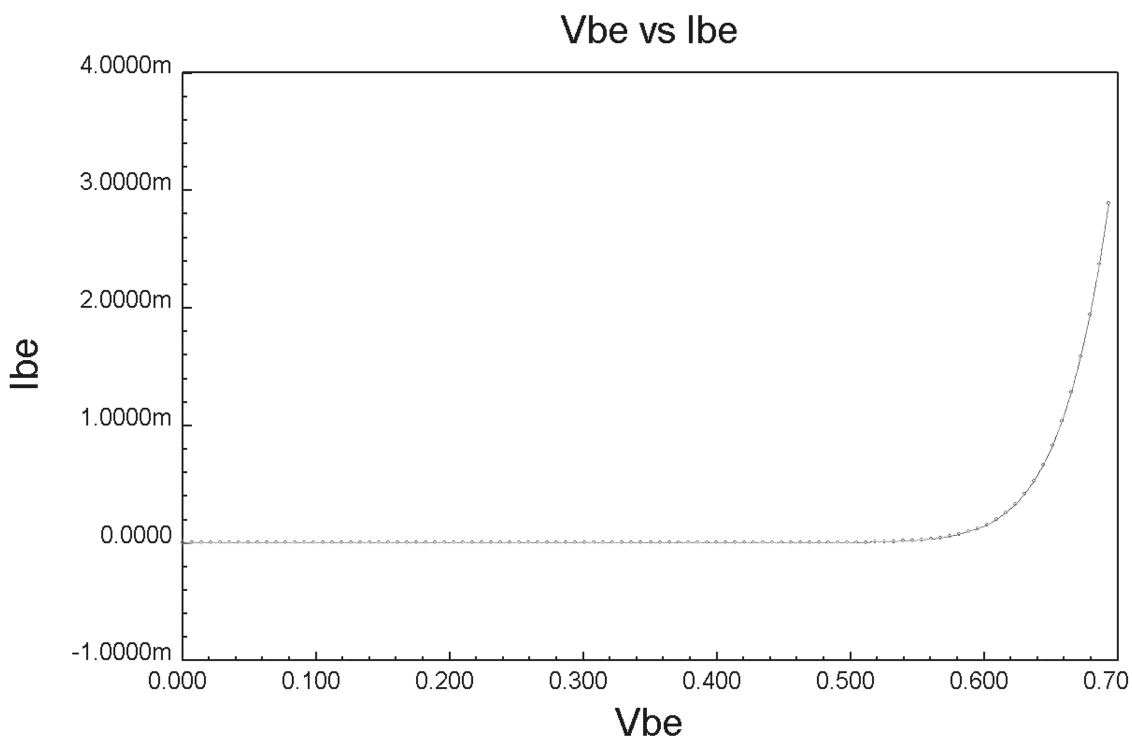


**Figure 2:** I-V characteristic of a diode-connected BJT.

3.4.2 Measure $I_{B1}$, $I_{C1}$, $I_{B2}$, and $I_{C2}$. Calculate $\beta_1$ and $\beta_2$.

$$\beta_1 = \frac{I_{C1}}{I_{B1}} = \frac{0.0286 \text{ mA}}{0.3 \text{ nA}} = 95.33$$
$$\beta_2 = \frac{I_{C2}}{I_{B2}} = \frac{6.9 \text{ mA}}{0.0289 \text{ mA}} = 238.75$$

$$\boxed{I_{B1} = 0.3 \text{ nA}}$$
$$\boxed{I_{C1} = 0.0286 \text{ mA}}$$
$$\boxed{I_{B2} = 0.0289 \text{ mA}}$$
$$\boxed{I_{C2} = 6.9 \text{ mA}}$$
$$\boxed{\beta_1 = 95.33}$$
$$\boxed{\beta_2 = 238.75}$$

3.4.3 What is the overall current gain, $\beta_{tot}$? Use the formula you derived in the prelab to calculate the total current gain from $\beta_1$ and $\beta_2$ and compare the calculation to your measurement.

$$\begin{aligned}\text{(Calculated) } \beta_{tot} &= \beta_2(1+\beta_1) \\ &= 238.75 \cdot (1 + 95.33) \\ &= 22998.79\end{aligned}$$

Measurement error:

$$\frac{23000 - 22998.79}{22998.79} = 5.26 \times 10^{-5}$$

$$\text{(Measured) } \boxed{\beta_{tot} = 23000}$$
$$\text{(Calculated) } \boxed{\beta_{tot} = 22998.79}$$