DREXEL UNIVERSITY
Electrical and Computer Engineering
College of Engineering

Drexel University

Electrical and Computer Engineering Dept.

Electronic Devices Laboratory, ECE-370

TITLE: **Short-Base Diode and Bipolar Junction Transistor (BJT)**

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SECTION: **060**

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Introduction

In this lab, we will analyze the different effects caused by the length of a diode on the current-voltage (DCIV) characteristics of the Bipolar Junction Transistor or BJT. As a result of this lab, we will gain a better understanding of the DCIV characteristics of Base Emitter and Base Collector junctions of the BJT.

Theory

This lab explores the behavior of short-base diodes and Bipolar Junction Transistors (BJTs), focusing on how structural parameters such as base length and doping concentrations influence their current-voltage (DCIV) characteristics.
In a short-base diode, the n-region is much shorter than the minority carrier diffusion length ($W n \ll L p$ W n ≪L p), as shown in Figure 1. This results in a linear minority carrier concentration profile within the n-region, where recombination is negligible. The minority carrier concentration in steady-state is expressed as:

$$\boxed{\delta p_n(x) = p_{n0}\left(e^{\frac{V_a}{V_t}} - 1\right)\left(\frac{x_n + W_n - x}{W_n}\right)}$$

where p_{n0} is the equilibrium hole concentration, Va is the applied voltage, Vt is the thermal voltage, and Wn is the width of the n-region. This linear profile simplifies the expression for current density:

$$J_p = -qD_p \frac{d\big(\delta p_n(x)\big)}{dx} = \frac{qD_p p_{n0}}{W_n}\left(e^{\frac{V_a}{V_t}} - 1\right)$$

This shows that short-base diodes achieve greater current density compared to long-base diodes due to the absence of significant recombination within the n-region.

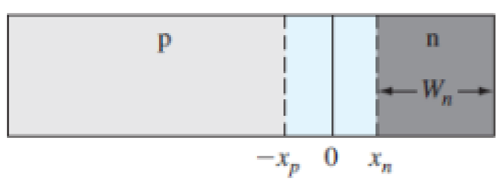


Figure 1: Geometry of a short-base diode, where $Wn \ll Lp$

BJTs are devices composed of two PN junctions sharing a thin base region, as shown in Figure 2. In an NPN BJT operating in the active region, the base-emitter (BE) junction is forward-biased, and the base-collector (BC) junction is reverse-biased. Electrons injected from the emitter into the base diffuse across the base and are collected at the BC junction. This process generates the collector current (I_C), which is primarily determined by the base-emitter voltage (V_{BE}). Simultaneously, a base current (I_B) flows due to holes injected into the emitter.

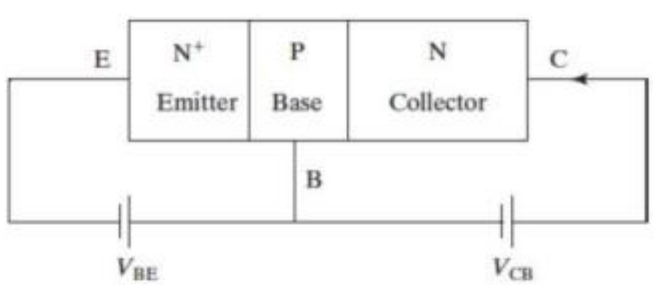


Figure 2: Geometry of the BJT and biasing for operation in Active region

The ratio of collector current to base current is defined as the common-emitter current gain:

$$\beta_F = \frac{I_C}{I_B}$$

Additionally, the common-base current gain (α_F) is defined by the relationship:

$$I_C = \alpha_F * I_E$$

The two gains are related as:

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F}$$

where α_F approaches unity for efficient BJTs. These relationships are critical for understanding the amplification behavior of BJTs.

BJTs operate in three distinct regions, as illustrated in Figure 3:

- Cutoff Region: Both junctions are reverse-biased, resulting in minimal current flow.
- Active Region: The BE junction is forward-biased, and the BC junction is reverse-biased, allowing the transistor to amplify input signals.
- Saturation Region: Both junctions are forward-biased, resulting in maximum current flow.

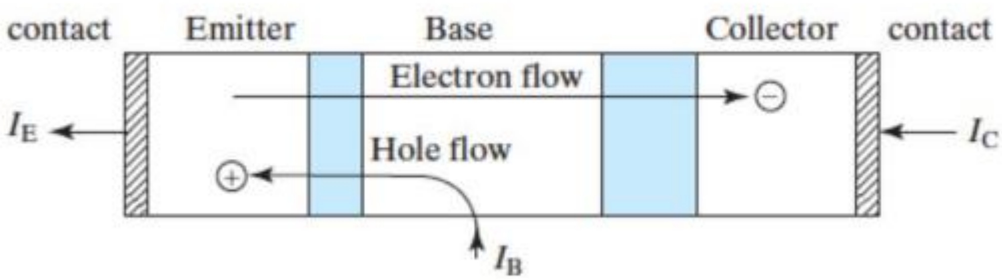


Figure 3: Current flow through the BJT

This lab investigates the current-voltage characteristics of both short-base diodes and BJTs to better understand their operation under varying structural and biasing conditions.

Experimental Procedure

1. Go to NanoHub, and from the PN Junction Lab, consider the following cases:
    a. Default Base Length
    b. Long Base (L=LP*5)
    c. Short Base (L=LP*0.1)

    Where Lp is the diffusion length. For each case, collect the IV curve

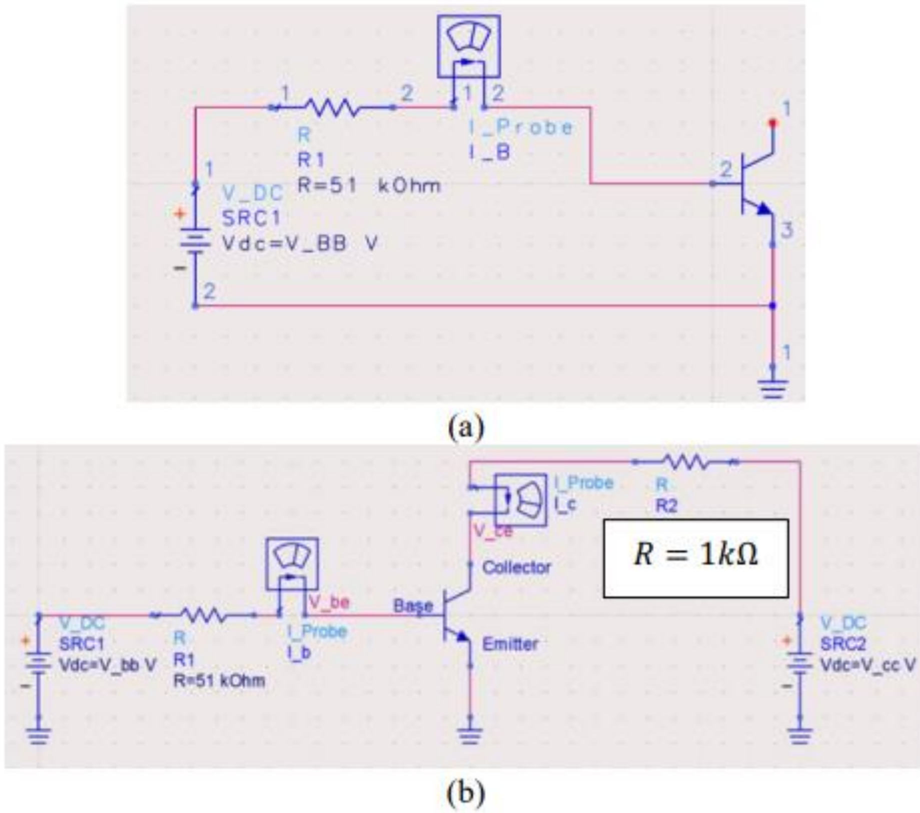


Figure 4: (a) Experimental Setup for finding necessary VBB to obtain values of IB and (b) for measuring DCIV parameters for the BJT

2. Build the circuit shown in Figure 4.a. Adjust VBB to obtain current readings of IB = 0 A, 10 µA, 20 µA, and 30 µA and record the values of VBB.
3. Build the circuit shown in Figure 4.b. For each IB, vary VCC to achieve the VCE values in the below table. Record VBE, VCC, and IC for each VCE, where VBE and VCE are oscilloscope probes. (NOTE: this data will $R = 1k\Omega$ be represented by plots in the report so if you are providing the table, the table should be featured in an appendix at the end of the report)
4. Build the circuit shown in Figure 5. Vary the base-emitter voltage from 0V to 1V in steps of 0.002V and record the collector-emitter voltage and collector current while applying the maximum Vcc that was required as part of the DCIV collection.

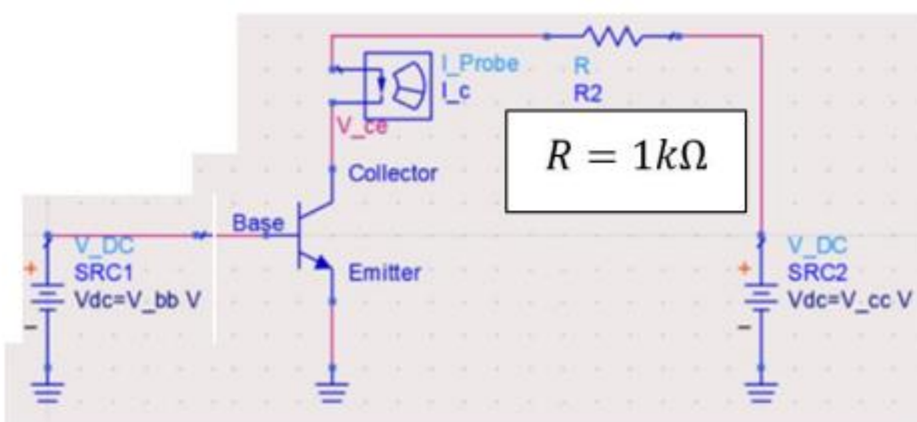


Figure 5: Schematic for Voltage Transfer Characteristic of BJT

5. Using the NanoHub BJT Lab tool:
    a. the NanoHub BJT Lab tool: a. Using the default values for the length of each region (base, emitter, and collector), set the doping as follows: Emitter =1e+18, Base=1e+16, Collector: 1e+15
        i. Extract the plot of β vs Ic
        ii. Find the value of β at 20 µA current
    b. Increase the emitter doping to 1e+19, and repeat the above parts
    c. Return the doping concentrations to the default value. The default base length is 2µm. Run the simulation and extract plot of current density against position
    d. Change the base length to 4 µm and extract plot of current density against position
    e. Change the base length to 10 µm and extract plot of current density against position

Results

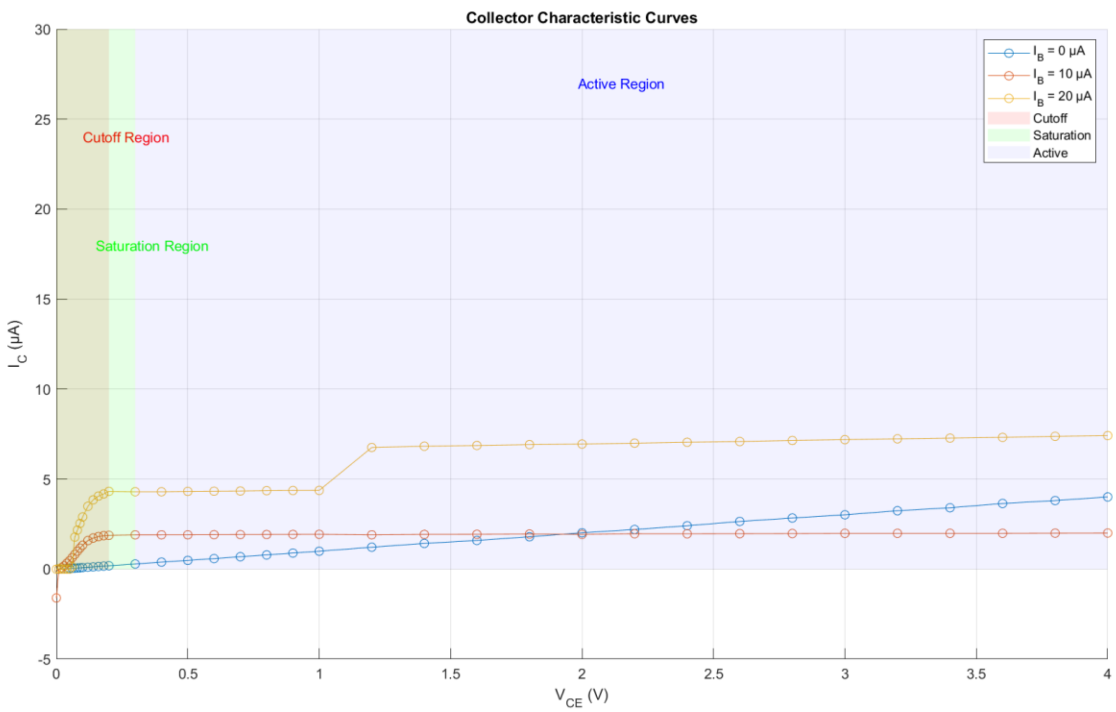


Figure 6. Collector Characteristic Curve

β values for each I_B in the active region:	
$I_B (\mu A)$	β
10	.1952
20	.3110
30	.1738

Table 1. Active Region values of Beta for each I_B

α and γ values for each I_B:		
$I_B (\mu A)$	α	γ
10	.97	.995

20	.965	.993
30	.96	.998

Table 2. Values of α and γ for I_B

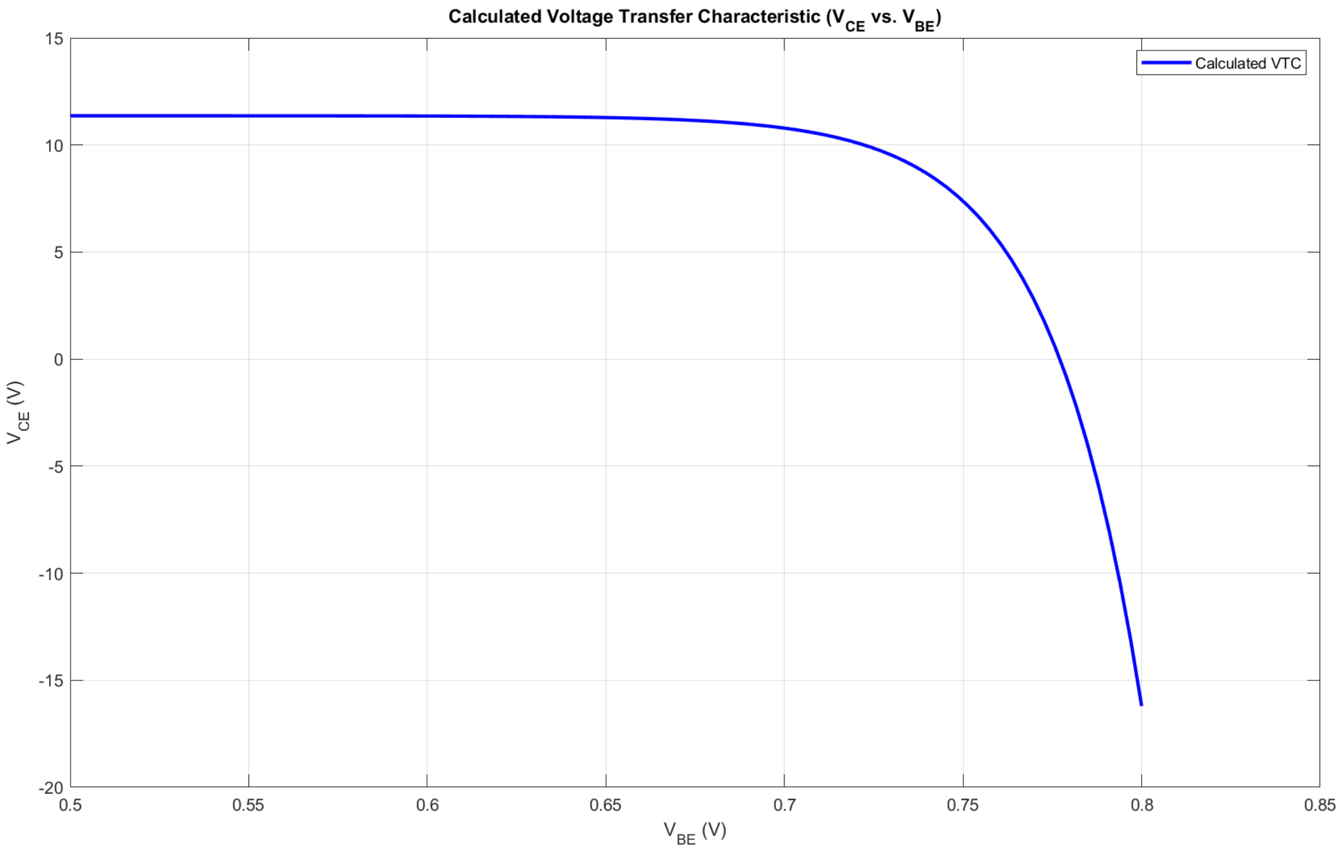


Figure 7. Calculated Voltage Transfer Characteristic

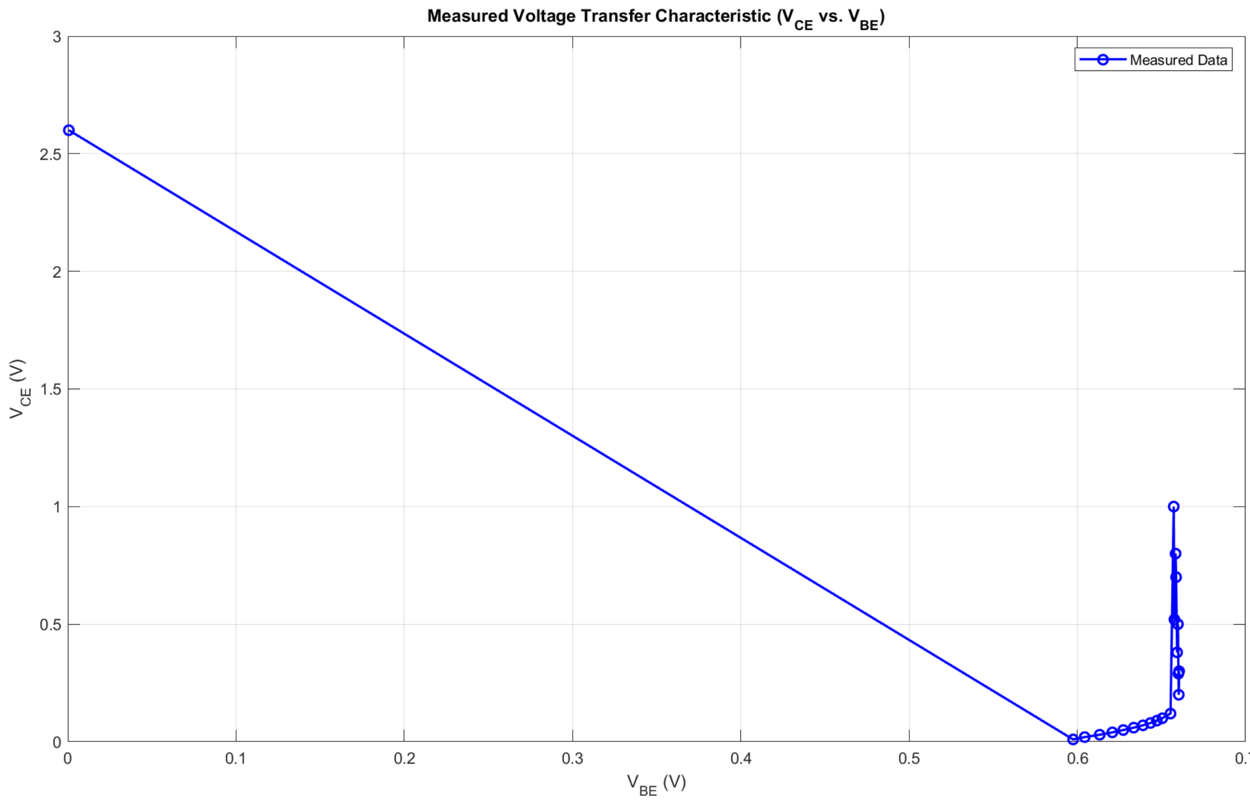


Figure 8. Measured Voltage Transfer Characteristic

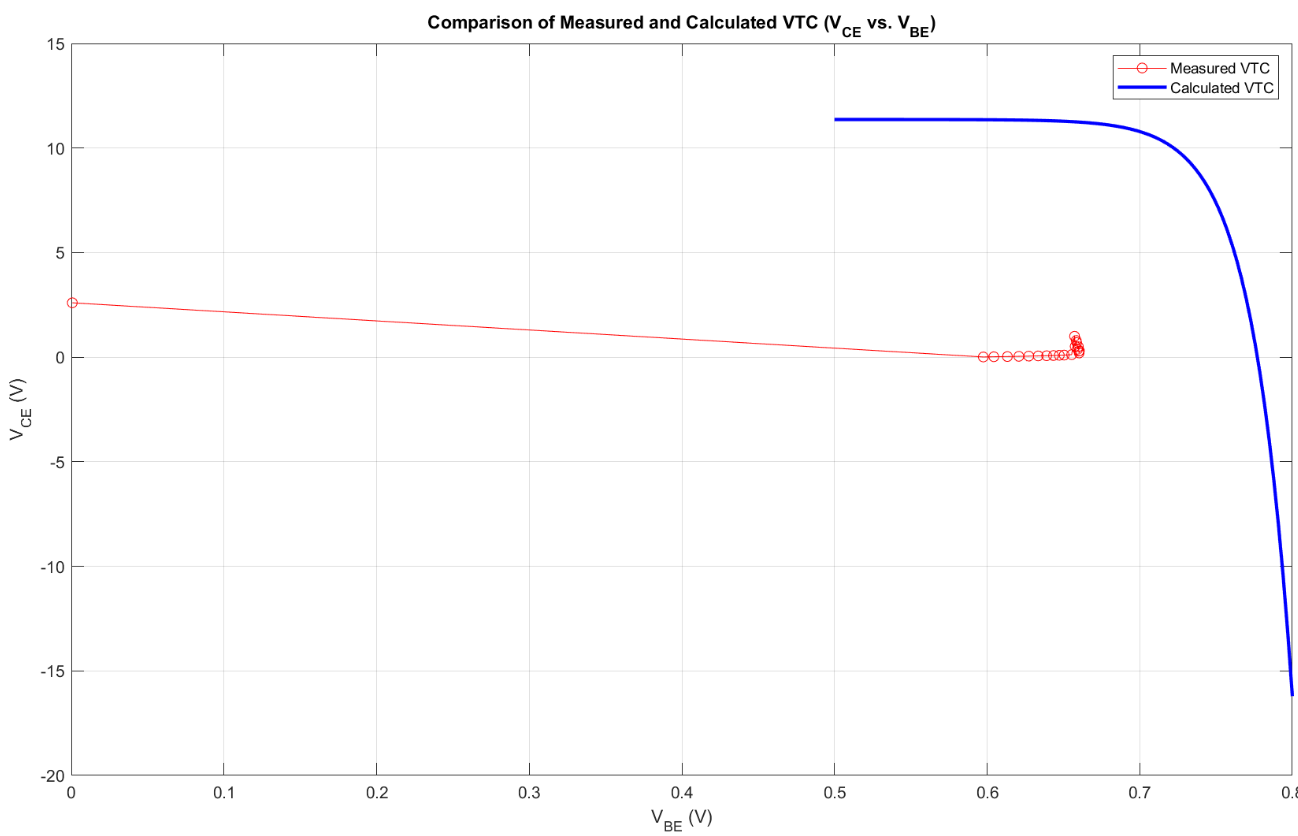


Figure 9. Measured and Calculated VTC

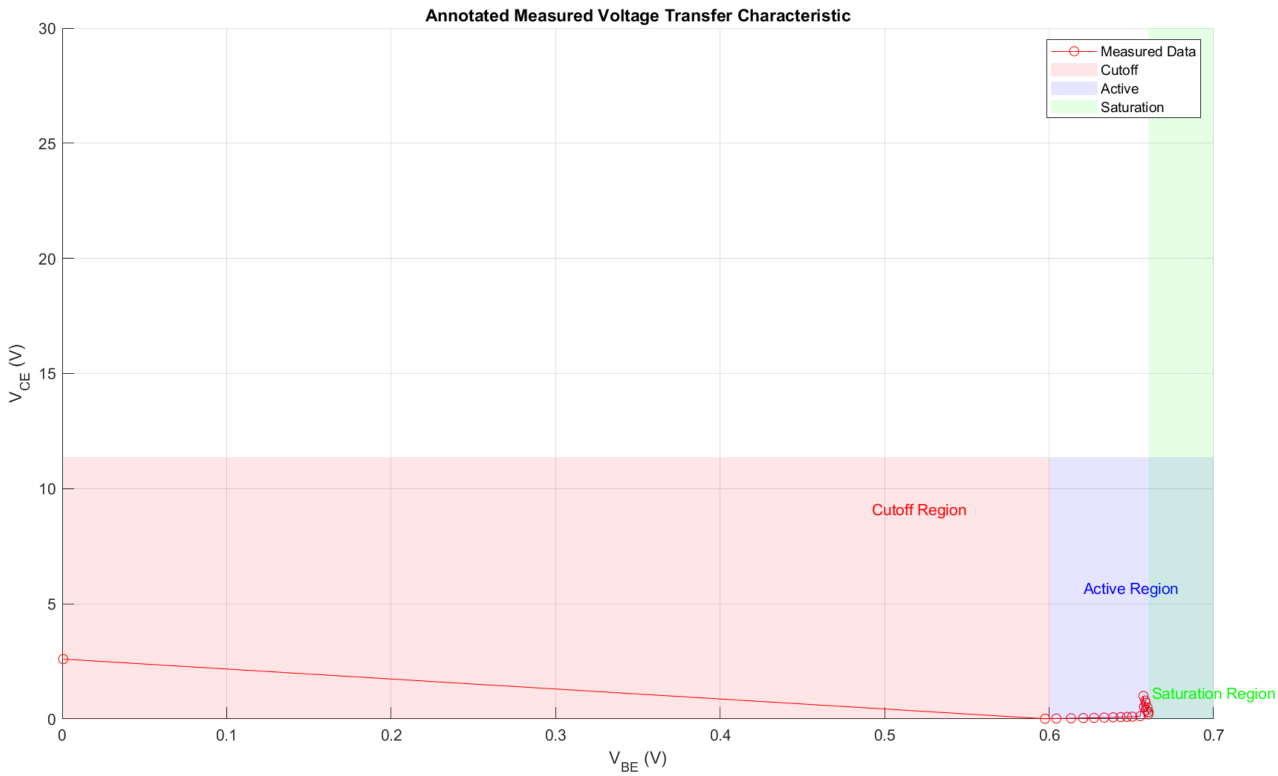


Figure 10. Measured Voltage Characteristic

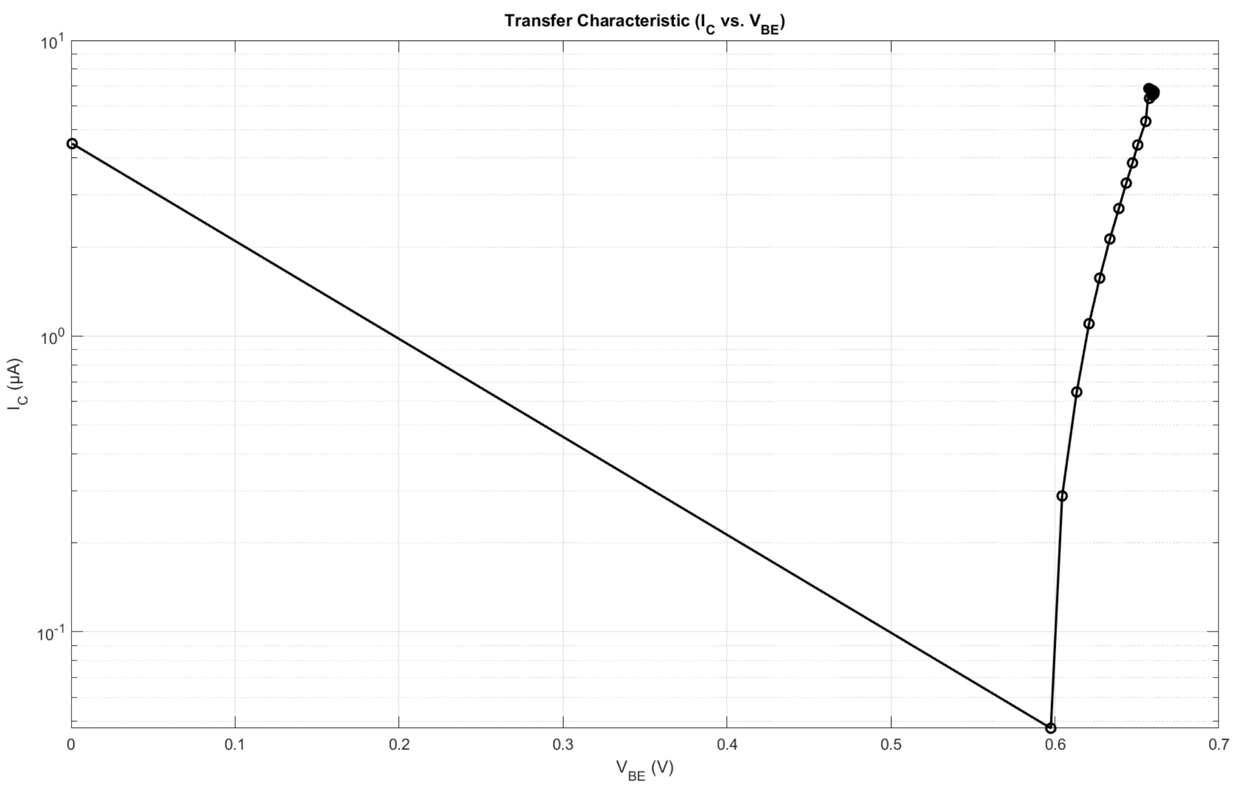


Figure 11. Transfer Characteristic

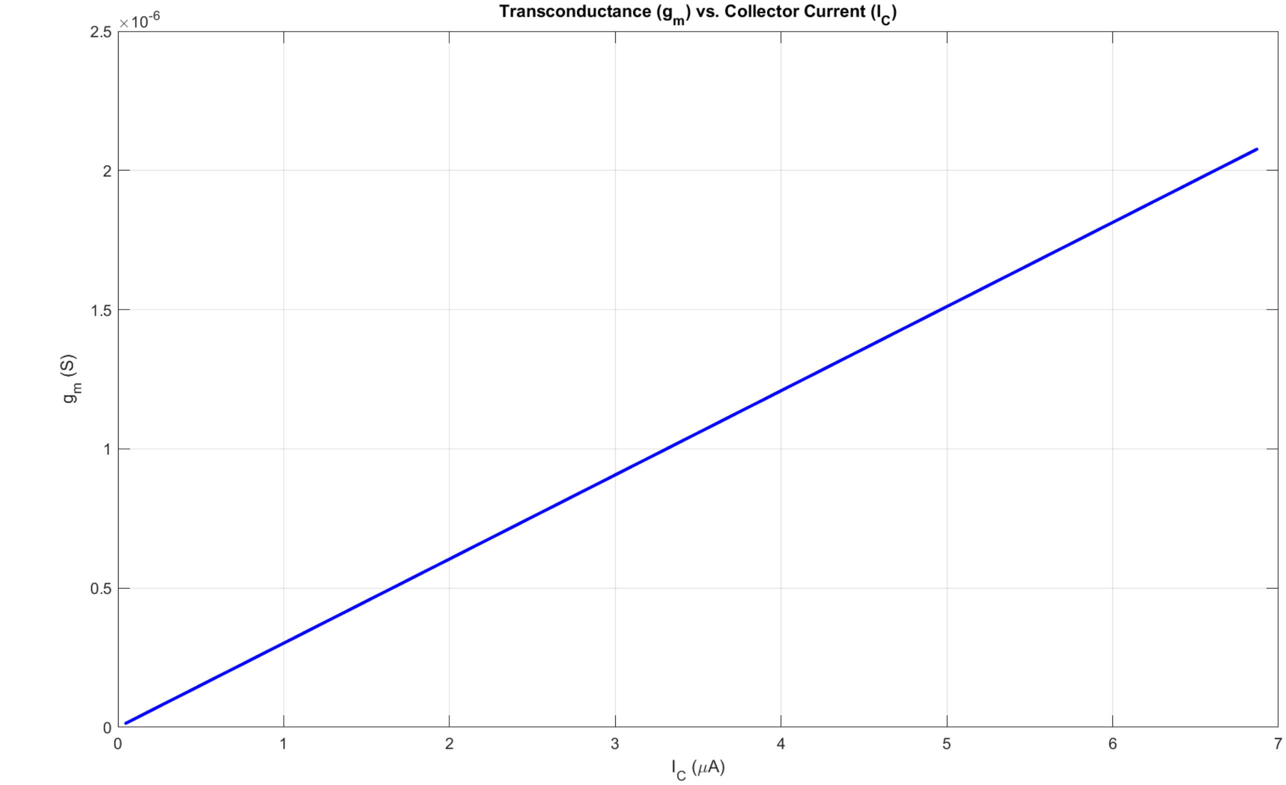
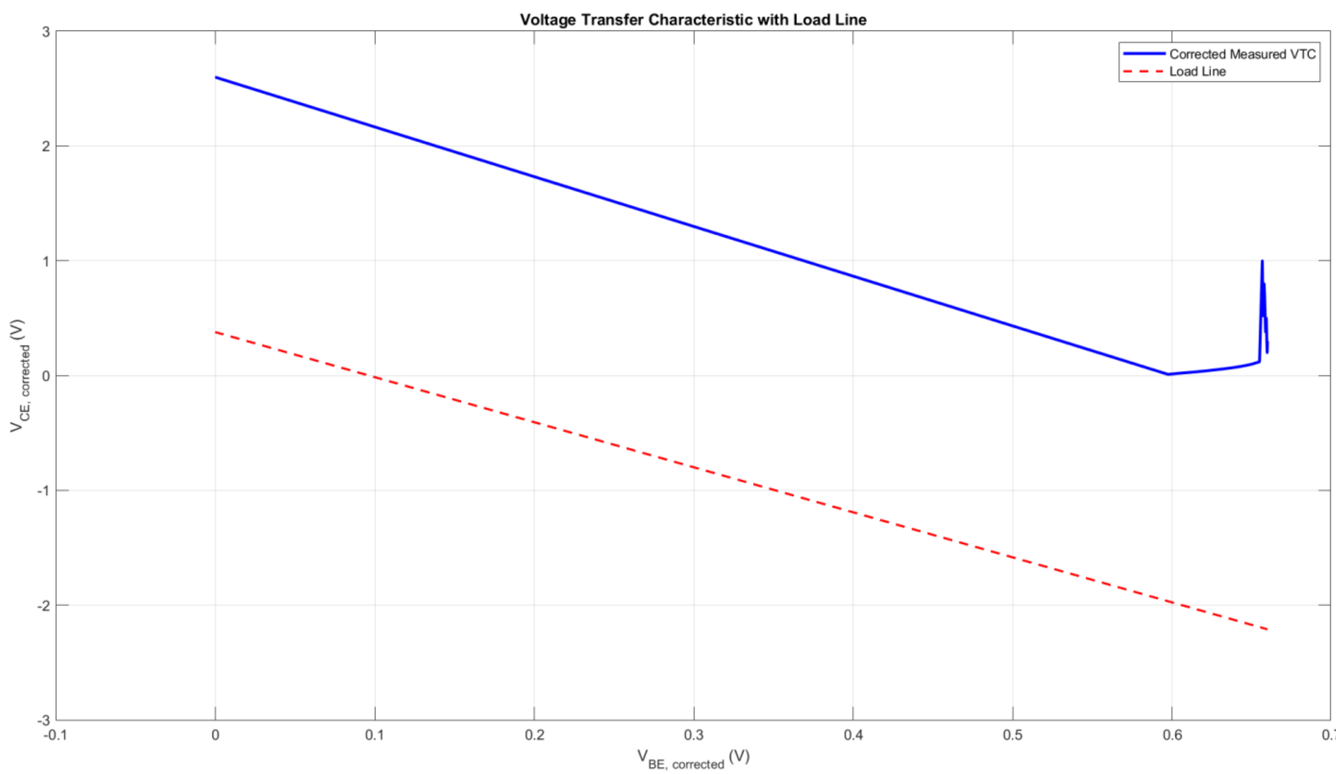


Figure 12. Transconductance vs Collector Current



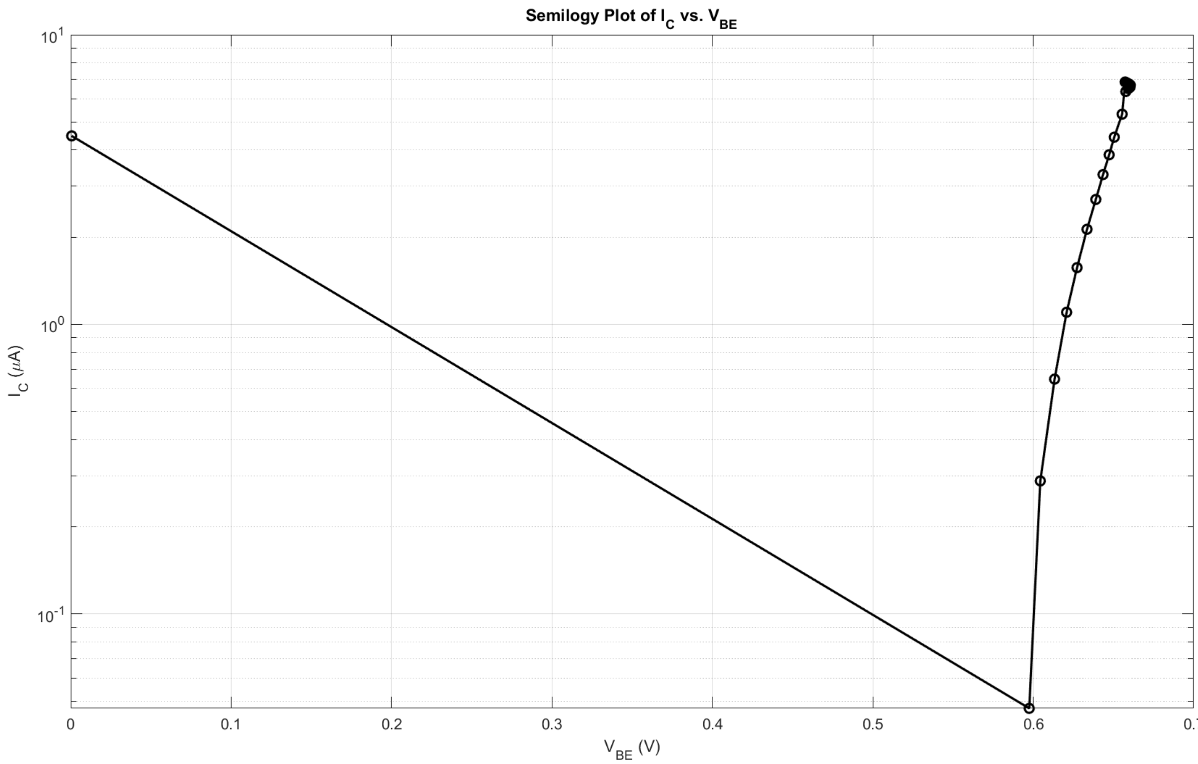


Figure 13. I_C vs V_{BE}

Series Resistance	223.852Ω
Turn on Voltage	.63mV
Reverse Saturation Current	$2.3489e^{-14}A$
Ideality Factor	1.2749
Transconductance	.55 ms

Table 3.

PN Junction Simulation

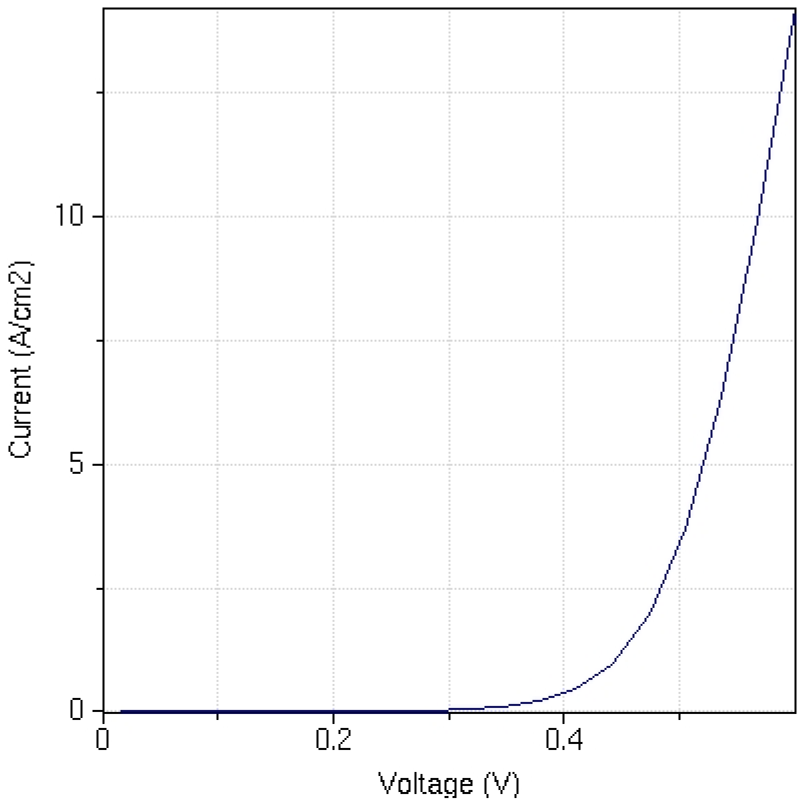


Figure 14. I-V Curve for PN-Junction with Default Base Lengths

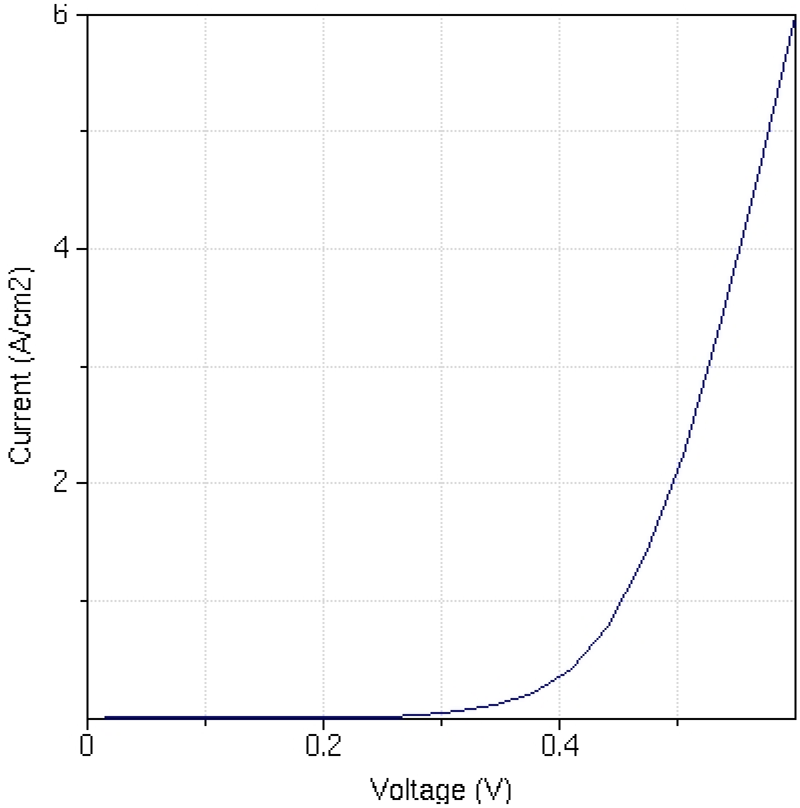


Figure 15. I-V Curve for PN-Junction with Long Base Length factored by 5

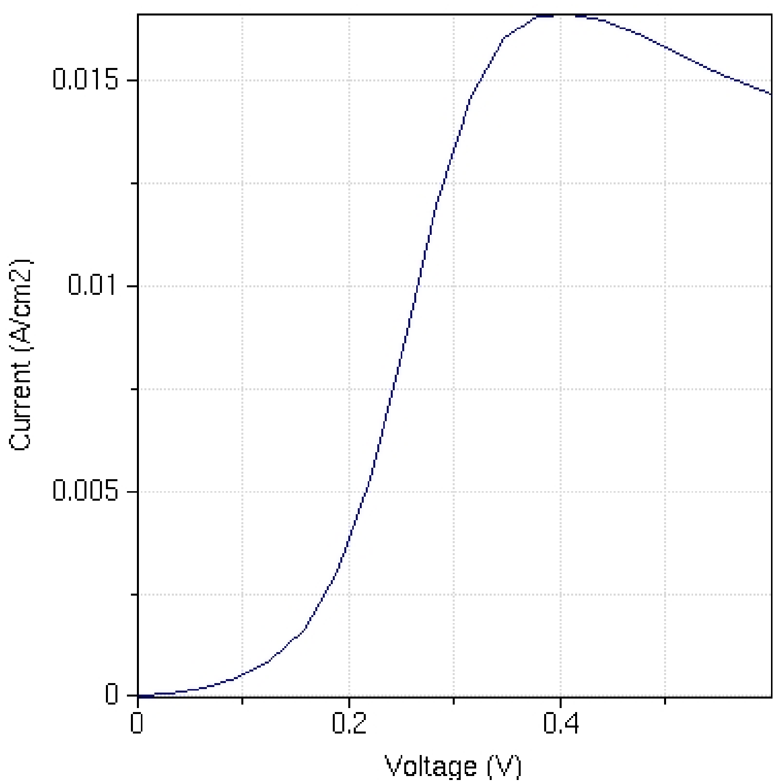


Figure 16. I-V Curve for PN-Junction with Short Base Length factored by 0.1

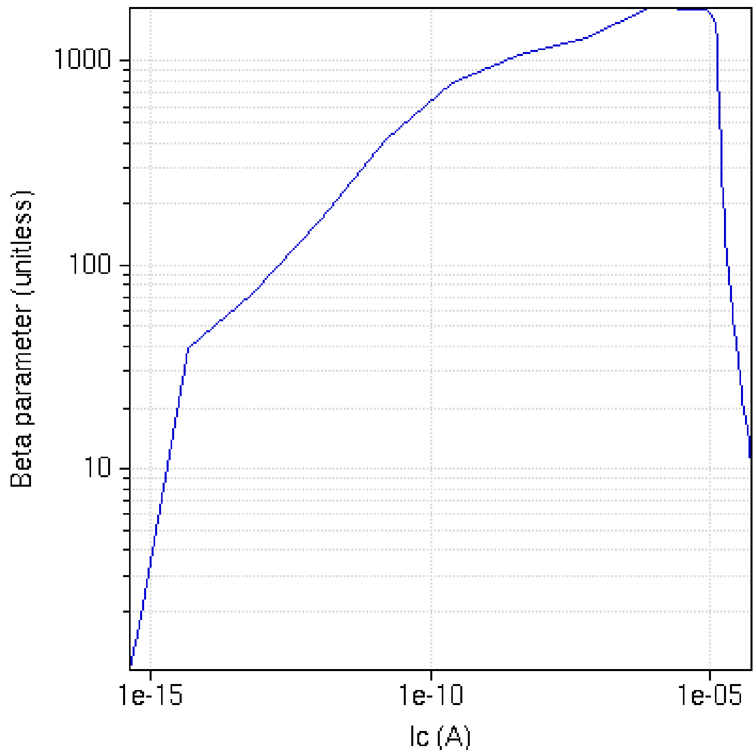


Figure 17. $\beta\ vs\ I_c$ with Default Region Lengths and Doping Settings

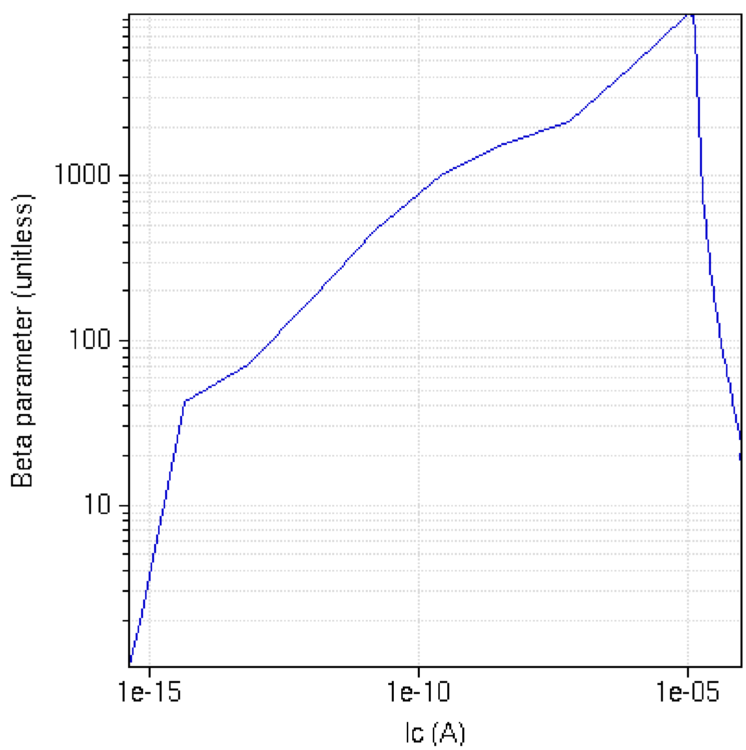


Figure 18. β vs I_c with Default Region Lengths and Emitter Doping at $1 \cdot 10^{19}$

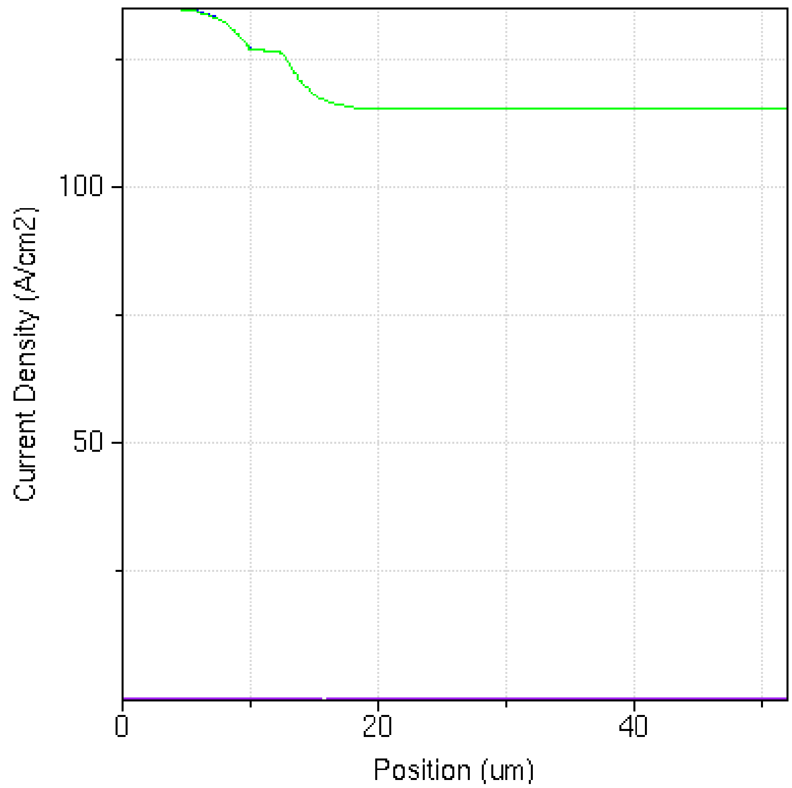


Figure 19. Current Density vs Position with Base Region Length $2\mu m$

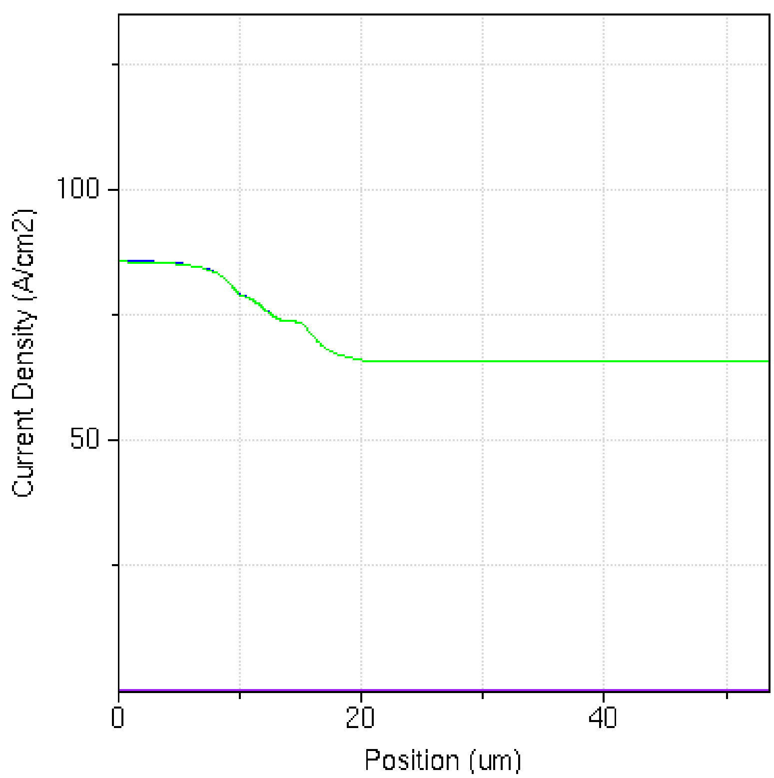


Figure 20. Current Density vs Position with Base Region Length $4\mu m$

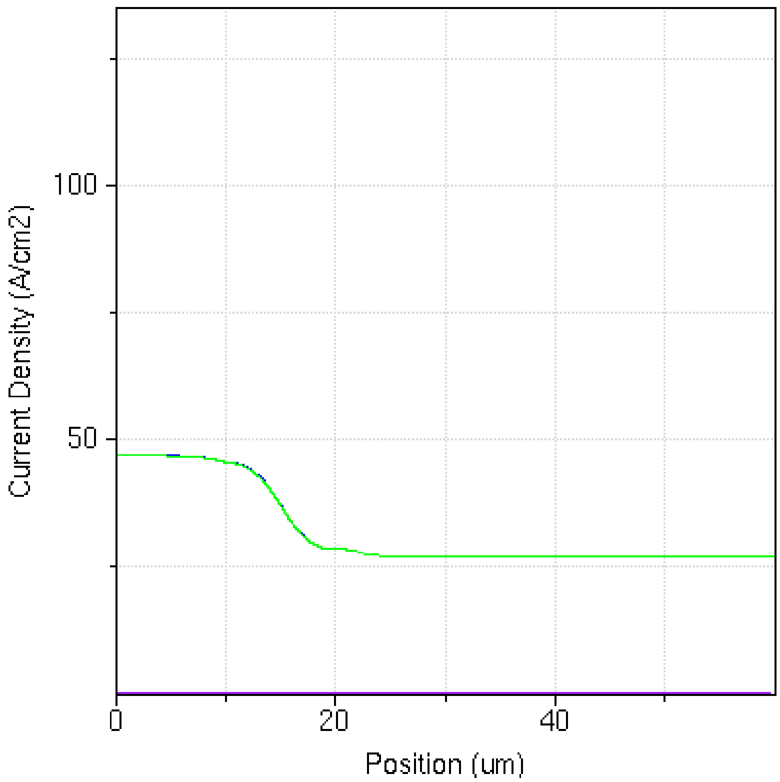


Figure 21. Current Density vs Position with Base Region Length $10\mu m$

Discussions

PN Junction Simulations

a. Compare the slope of the two DCIV curves.

The slope of the DC current-voltage (DCIV) curve represents the rate that current exponentially increases with applied voltage. For the short base diode graph, the slope is significantly steeper compared to the long base diode. This means that for a small increase in voltage, the current rises much faster in the short base diode. On the other hand, the long base diode exhibits a shallower slope. This shows a slower increase in current for the same voltage increment.

b. How much better is the short base diode in terms of current for the same applied voltage?

In terms of current performance for the same applied voltage, the short base diode performs significantly better. For example, at approximately 0.4 V in forward bias, the current in the short base diode is about 0.015 A, while the current in the long base diode is considerably lower, closer to 6 A. This improved performance in the short base diode is due to the reduced recombination losses which allow more electrons to reach the junction and contribute to current flow.

c. Is the long base or short base diode faster in terms of turn-off time? Why?

The short base diode is also faster in terms of turn-off time compared to the long base diode. This is because the carriers in the short base diode have a shorter distance to travel, reducing the transit time. Also, the long base diode experiences more recombination within the base region which lead to higher stored charge that must dissipate during turn-off, slowing its response. The short base diode, by minimizing recombination losses and supporting higher injection efficiency, has less stored charge, which contributes to its faster turn-off performance.

BJT Simulations

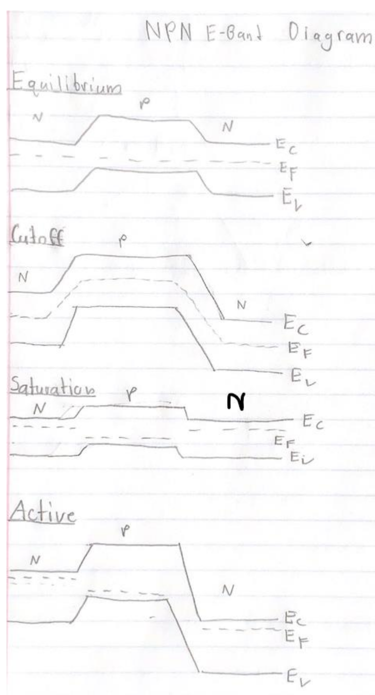
a. Explain how emitter doping effects current. How is β affected by doping concentration?

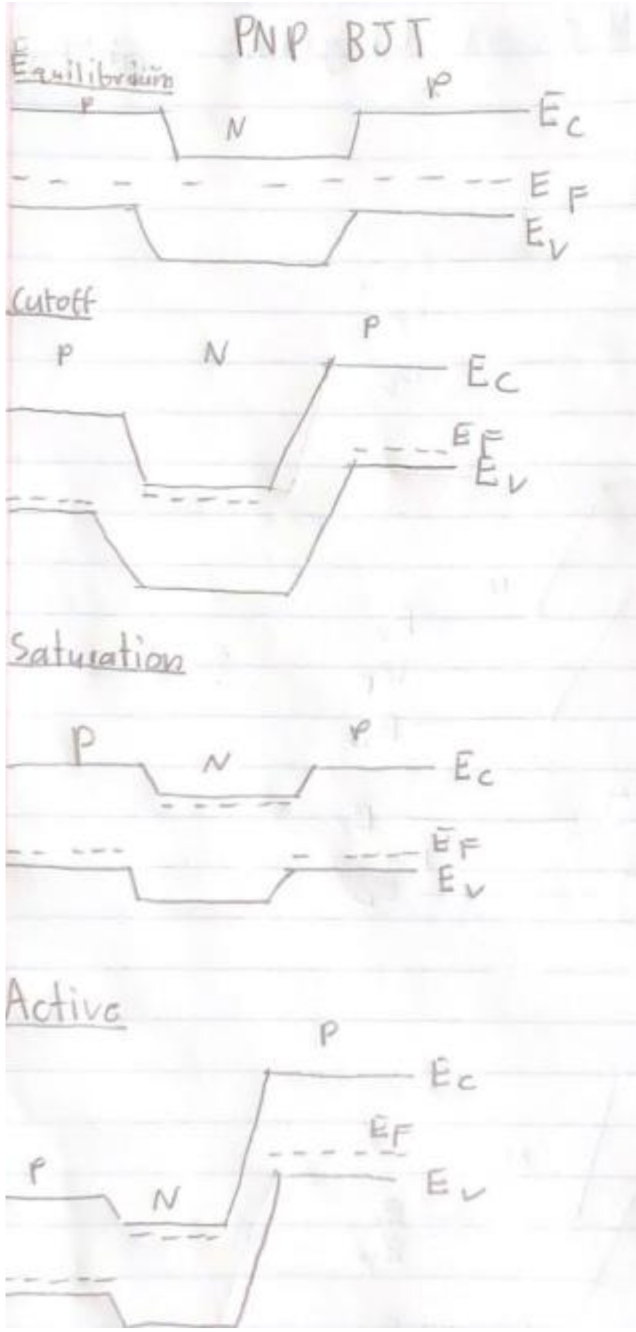
Increasing the emitter doping concentration in a BJT has a significant effect on the current and current gain β. Heavier doping of the emitter enhances injection efficiency, ensuring that most carriers injected into the base (for an NPN transistor) are electrons, rather than holes being injected back into the emitter. This results in a higher collector current. Additionally, β, which represents the ratio of collector current to base current, improves with increased emitter doping because the injection efficiency is higher, and recombination losses in the base are reduced. However, excessive doping can lead to bandgap narrowing, which may counteract these benefits and reduce β.

b. Explain how base length affects currents in the BJT.

The length of the base also affects currents in the BJT. A short base minimizes carrier recombination within the base region, allowing a greater proportion of carriers injected from the emitter to reach the collector. This results in higher collector current and improved β. This behavior is evident in the current density plots, where shorter base lengths show higher and more uniform current densities across the base region. Conversely, a long base increases the likelihood of recombination in the base, reducing the number of carriers reaching the collector. As a result, the collector current and β decrease. The current density plots for longer base lengths clearly show a significant drop in current density as carriers traverse the base.

c. Draw the energy band diagrams for both NPN and PNP BJT in equilibrium, cutoff, saturation, and active biasing.





i. Repeat part h for parts iii and iv using a similar methodology to find these values as was done in the solar cell lab by taking the natural log of the IV characteristic. Compare these values to what was more directly measured when you applied VBE = 0 and measured Ic

Series Resistance	223.852Ω
Turn on Voltage	.7mV
Reverse Saturation Current	$3.3104e^{-6}A$
Ideality Factor	-175.0961

j. Compare the measured transconductance from h.vi. to the datasheet

$$g_m = .072\ s$$

k. From the measured voltage transfer characteristic, what is the largest amplitude of signal that can be input without changing the region of operation? What is the resulting voltage gain.

Largest input amplitude = 0.01V
A = -.227

Conclusion

In conclusion, the lab was successful in analyzing the effects that the lengths of a diode had on the DCIV characteristics of a BJT. This lab greatly improved our understanding of the DCIV characteristics of both the Base Emitter and Base Collector junctions of the BJT.

Appendix

Appendix A: Short Based Diode and BJT Lab Manual
Figure 1-5: Theory and lab procedure
Source: Drexel University

Appendix B: NanoHub Graphs
Figure
Source: https://nanohub.org/resources/bjt

Source: https://nanohub.org/resources/pntoy