Investigating Temperature and Voltage Dependence in NPN Bipolar Junction Transistors

Garik Livingston and Lily Nguyen

PHY 353L Modern Laboratory
Department of Physics
The University of Texas at Austin
Austin, TX 78712, USA

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Abstract

In this experiment, we varied the voltage supplied to the base of a npn BJT transistor and measured the current running through the collector to form a data set which we fitted to the Ebbers-Moll equation. From this fit we calculated the thermal voltage (V_T) and saturation current (I_s). Both these paramaters have strong temperature dependence and from our fit we determined an experimental value for the boltzman constant of $k = 1.378 \times 10^{-23} \pm 8.4 \times 10^{-26} \frac{J}{K}$ for the silicon transistor and a value of k = $5.6 \times 10^{-23} \pm 4.000 \times 10^{-24} \frac{J}{K}$ for the germanium transistor. We also determined an experimental value for the band gap of the transistors with a $E_g = 1.48 \pm 0.012 eV$ for silicon and $E_g = 0.158 \pm 0.003 eV$ for germanium.

1 Introduction

1.1 Physics Motivation

Semiconductors are essential components of modern electronics due to their unique electronic properties: a valence band filled with electrons and a nearly empty conduction band, separated by an energy band gap V_g. The ability of electrons to transition from the valence band to the conduction band under specific conditions, such as thermal excitation or applied voltage, forms the basis for the functionality of semiconductor devices like transistors [4].

In this experiment, we investigate the behavior of an NPN bipolar junction transistor (BJT) by examining the relationship between the collector current I_C and the base-emitter voltage V_{BE}. The transistor's function depends on the exponential dependence of I_C on V_{BE}, described by the Ebers-Moll equation:

$$I_C = I_S \left(e^{eV_{BE}/kT} - 1\right)$$

where I_S is the saturation current, e is the elementary charge, k is Boltzmann's constant, and T is the absolute temperature [3]. This exponential behavior arises from the Boltzmann factor, which governs the probability of electron excitation across the band gap:

$$P(E) \propto e^{-E/kT}$$

By measuring I_C as a function of V_{BE} at different temperatures, we can extract both Boltzmann's constant k and the band gap V_g of the semiconductor material. These measurements not only reinforce the theoretical principles of semiconductor physics but also demonstrate the practical application of transistors in amplification and switching, which are fundamental to all modern electronic devices [4].

1.2 Historical context

The invention of the bipolar junction transistor (BJT) in 1947 by John Bardeen, Walter Brattain, and William Shockley marked a pivotal moment in semiconductor technology. Their initial device, the germanium point-contact transistor, exhibited power gain but was unstable and difficult to reproduce due to sensitivity to surface states and impurities. Shockley later developed the p-n junction transistor, which proved more reliable by utilizing bulk conduction of minority carriers. This advancement earned the trio the Nobel Prize in Physics in 1956 [2].

Early transistors were difficult to manufacture consistently. The development of grown junction transistors in 1952 improved stability, but the process remained complex and wasteful. The introduction of the alloyed junction transistor in the same year simplified production and reduced material waste. By 1954, diffused junction transistors allowed for more precise control over transistor properties, enabling higher-frequency operation. The shift from germanium to silicon further improved performance due to silicon's lower reverse currents and better thermal stability. The first commercial silicon transistors were produced by Gordon Teal in 1954, with planar transistors introduced by Jean Hoerni in 1960, enabling mass production and miniaturization [2].

A crucial distinction between germanium and silicon lies in their respective band gaps. Germanium, with a smaller band gap of approximately $0.67\,eV$, exhibits higher intrinsic carrier concentrations and is more sensitive to temperature changes. In contrast, silicon, with a larger band gap of $1.1\,eV$, offers better thermal stability and lower leakage currents, making it preferable for modern electronic applications [1]. These differences influence the behavior of transistors, particularly the saturation current and thermal voltage, both of which are key parameters in this experiment.

These advancements laid the foundation for modern experimental techniques. Early measurements were manual and prone to errors, while today's experiments leverage automated voltage sweeps with precise current measurements using instruments like the Keithley picoammeter. Controlled temperature environments, achieved through heating setups and thermocouples, allow for detailed analysis of the temperature dependence of the collector current I_C. These techniques facilitate the verification of theoretical models such as the Ebers-Moll equation and the determination of constants like Boltzmann's constant and the semiconductor band gap, as demonstrated in this experiment.

2 Theoretical background

Semiconductors are materials characterized by an electronic structure consisting of a valence band filled with electrons and a conduction band that is nearly empty at low temperatures. These bands are separated by an energy gap, known as the band gap V_g. At absolute zero, semiconductors behave as insulators, with no electrons in the conduction band. However, at finite temperatures, some electrons gain enough thermal energy to cross the band gap, enabling electrical conduction. The likelihood of electron excitation across the band gap is determined by the Boltzmann factor:

$$P(E) \propto e^{-E/kT}$$

where E is the energy required for excitation, k is Boltzmann's constant, and T is the absolute temperature[4].

An NPN bipolar junction transistor (BJT) consists of two n-doped regions (the emitter and collector) separated by a thin p-doped base. When a positive voltage is applied to the base relative to the emitter (V_{BE}), it reduces the potential barrier, allowing electrons from the emitter to be injected into the base. Due to the thinness of the base and the applied positive voltage at the collector, most of these electrons drift into the collector, resulting in a measurable collector current I_C [3].

The relationship between the collector current I_C and the base-emitter voltage V_{BE} is described by the Ebers-Moll equation:

$$I_C = I_S \left(e^{\frac{eV_{BE}}{kT}} - 1 \right)$$

where I_S is the saturation current, e is the elementary charge, k is Boltzmann's constant, and T is the absolute temperature. This equation illustrates the exponential dependence of I_C on V_{BE}, a fundamental property that allows transistors to function as amplifiers and switches in electronic circuits[3].

The saturation current I_S itself is temperature-dependent and follows the relation:

$$I_S \propto e^{-V_g/kT}$$

This indicates that I_S increases exponentially with temperature as more electrons acquire sufficient energy to cross the band gap V_g. By plotting $\ln(I_S)$ against $1/T$, the band gap of the semiconductor can be extracted from the slope of the linear fit:

$$\ln(I_S) = -\frac{V_g}{kT} + \text{constant}$$

Additionally, analyzing the exponential dependence of I_C on V_{BE} at various temperatures allows for the determination of Boltzmann's constant. The thermal voltage V_T, defined as:

$$V_T = \frac{kT}{e}$$

also plays a crucial role in the transistor's behavior, influencing the rate at which I_C increases with V_{BE}[1].

In this experiment, we measure I_C as a function of V_{BE} at different temperatures to extract both Boltzmann's constant and the semiconductor band gap. These measurements validate theoretical models and provide insight into the intrinsic properties of semiconductor materials like silicon and germanium.

3 Experimental setup

3.1 Apparatus

Ideas behind the particular technique should be briefly discussed. Enclose references. Sketches, pictures, and suitable schematics should be included and explained concisely. All major components of the system should be mentioned and their role clearly motivated. This section is not simply a list of components and it is not an instruction manual.

3.2 Data Collection

We setup our circuit to have a variable supply of voltage to the base (V_{be}) while measuring the collector current (I_c) readings from the pico ampmeter. We then supplied voltage to the thermocouple and watied for the temperature of the transistor to reasonbly level out before we recorded a I_c vs V_{be} data set.

3.3 Data Analysis

We took the dataset of I_c vs V_{be} and fitted it to Ebbers moll equation. By fitting our dataset to this equation we determined an experimental value for V_T using the curve fit function from scipy. We then performed a least square analysis on our V_T vs T dataset where we expect the slope to equal $\frac{k}{e}$. We performed this analysis on the dataset from both the silicon and germanium transistor.

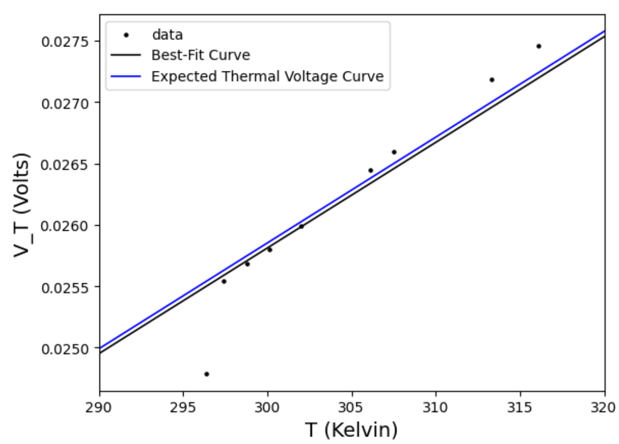

Figure 1: Silicon temperature vs thermal voltage graph. The data points collected are represented by the black dots, our best-fit slope is the solid black curve, and the expected slope of $\frac{k}{e}$ is the solid blue curve.

From our I_c vs V_{be} dataset, we also determined an experimental value for I_s using the

Temps (K)	V_T	Err(V_T)
296.4	0.0247	0.000137
297.4	0.02554	3.54e-05
298.8	0.02568	2.763e-05
300.1	0.02579	3.376e-05
302.0	0.02599	3.060e-05
306.1	0.02644	2.216e-05
307.5	0.02659	2.194e-05
313.3	0.02718	1.825e-05
316.1	0.02746	1.864e-05

Table 1: Predicted and observed numbers of events classified in the Far Detector as fully and partially reconstructed charged current interactions shown for all running periods.

curve fit funciton from scipy. As our range of temperatures [296K,316K] was small, we performed a linear regression on the $\ln(I_s)$ vs $\frac{1}{T}$ dataset. We calculated the

4 Results

Clearly present the result of your analysis. Make sure you include the uncertainties. No experimental result can be quoted without an error attached to it.

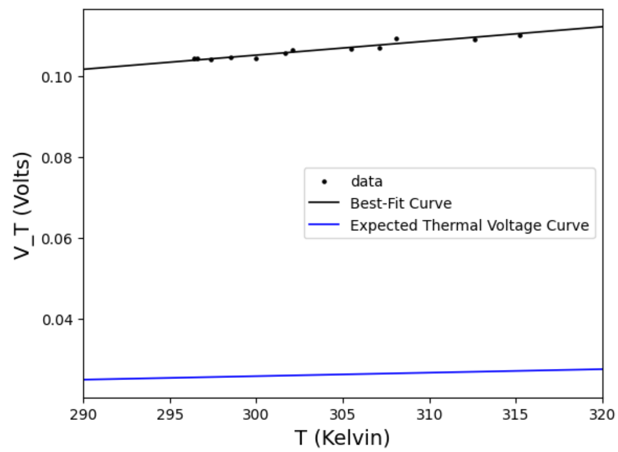

Figure 2: Germanium temperature vs thermal voltage graph. The data points collected are represented by the black dots, our best-fit slope is the solid black curve, and the expected slope of $\frac{k}{e}$ is the solid blue curve.

Your results should be compared with predictions and other measurements.

5 Summary and conlcusions

Summarize briefly the results of the experiment. Acknowledge (i.e., thank for) contributions or help of your partner(s) and or others (TA, machine shop, software used, ...).

References

[1] P. J. Collings, *Simple measurement of the band gap in silicon and germanium*, American Journal

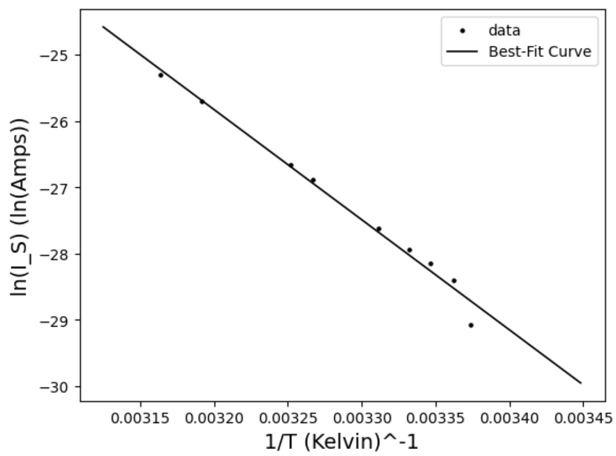

Figure 3: Silicon saturation current vs temperature. The data points collected are represented by the black dots, and our best-fit slope is the solid black curve.

of Physics, **48**(3), 197–199 (1980). https://doi.org/10.1119/1.12172https://doi

[2] L. Łukasiak and A. Jakubowski, "History of Semiconductors," *Journal of Telecommunications and Information Technology*, vol. 1, pp. 3–9, 2023. Available: https://doi.org/10.26636/jtit.2010.1.1015

[3] G. W. Neudeck, *The Bipolar Junction Transistor*, 2nd ed., Addison-Wesley, 1989.

[4] S. T. Thornton and A. F. Rex, *Modern Physics for Scientists and Engineers*, 3rd ed., Thomson, Brooks/Cole, 2006.

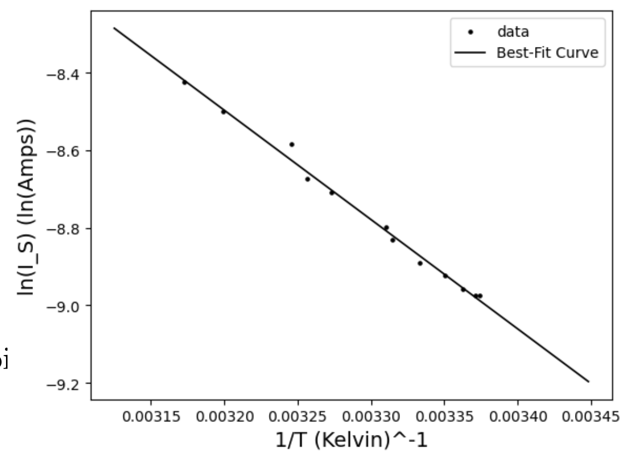

Figure 4: Germanium saturation current vs temperature. The data points collected are represented by the black dots, and our best-fit slope is the solid black curve.