A High Temperature Reference Voltage Generator with SiC Transistors

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Abstract

Natural resources are always collected from harsh environments, such as mines and deep wells. Currently, depleted oil wells force the gas and oil industry to drill deeper. As the industry drills deeper, temperatures of these wells can exceed 210 °C. Contemporary downhole systems have reached their depth and temperature limitations in deep basins and are no longer meet the high requirements in harsh environment industries. Therefore, robust electronic systems that can operate reliably in harsh environments are in high demand. This thesis presents a high temperature reference voltage generator that can operate reliably up to 250 °C for a downhole communication system. The proposed reference voltage generator is designed and prototyped using 4H-SiC bipolar transistors. Silicon carbide (SiC) is a semiconductor material that exhibits wide bandgap, high dielectric breakdown field strength, and high thermal conductivity. Due to these properties, it is suitable for high-frequency, high-power, and high-temperature applications. For bypassing the lack of high temperature p-type SiC transistors (pnp BJT, PMOS) and OpAmp inconvenience, an all npn voltage reference architecture has been developed based on Widlar bandgap reference concept. The proposed reference voltage generator demonstrates for the first time a functional high temperature discrete reference voltage generator that uses only five 4H-SiC transistors to achieve both temperature and supply independent. Measurement results show that the proposed voltage reference generator provides an almost constant negative reference voltage around -3.23 V from 25 °C to 250 °C regardless of any change in power supply with a low temperature coefficient (TC) of 42 ppm/°C.

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ZiHao Zhang

Table of Contents

List of Figures

List of Tables

Chapter 1

1 Introduction

Contents

1.1 Motivation

With the development of modern technology, human beings have explored more and more territories of the earth and even outer space. All these achievements cannot be done without tools (electronic devices) that can operate in harsh environments.

Extreme environment electronic devices are highly demanded in a lot of fields like Automotive, Space, Mining and Deep-well drilling etc. in recent years. For instance, the oil drilling industry. With the development of the oil and gas industry, oil wells are currently depleted. In order to explore unexploited wells, the industry is forced to drill deeper. However, as the depth of oil wells increases, the temperature and pressure also rise. Therefore, robust electronic systems that can operate reliably in those harsh environments are in high demand.

Temperature is one major challenge for downhole electronic systems. In deep basins, the temperature can go beyond 210 °C. Nevertheless, current oil drilling operations can only work at temperatures that are below 210 °C [1]-[2]. It is because existing electronics used in downhole systems can merely operate up to 150 °C before being recovered from wells. Due to weight, power consumption, and system complexity, conventional cooling and extraction techniques are impractical to use in downhole systems. In addition, existing systems have a low data rate of 4 Mbps at temperatures below 210 °C [1]. Hence, as more sophisticated sensors and tools become necessary to explore more areas with higher accuracy, existing systems are unable to keep pace with growing demand. As a part of a downhole communication system, a voltage reference can be used to bias other circuits such as low noise amplifier (LNA), power amplifier (PA), Mixer, etc.

The goal of this work is to design a SiC reference voltage generator that can provide a negative reference voltage over a wide temperature range. The reference voltage generator not only needs to operate reliably up to 250 °C without need for cooling and heat extraction techniques, but also should feature both temperature independence and supply independence.

1.2 Summary of This Work

The reference voltage generator is designed as a part of a downhole communication system. The purpose of this voltage reference is to generate a constant reference voltage that can be used to bias other circuits in the system.

The proposed reference voltage generator is designed and implemented with 4H-SiC bipolar transistors due to their high thermal performance. The circuit provides an almost constant negative reference voltage around -3.23 V from 25 °C to 250 °C regardless of any change in power supply with a low temperature coefficient (TC) of 42 ppm/°C.

For bypassing the lack of high temperature p-type SiC transistors (pnp BJT, PMOS) and operational amplifiers inconvenience, an all npn voltage reference architecture has been developed based on Widlar bandgap reference concept. The proposed voltage reference continues Widlar’s work by implementing the ideal current source with an electronic current source. This is the first discrete reference voltage generator that uses only five 4H-SiC bipolar transistors to achieve both temperature independence and supply independence at the temperature range from 25 °C to 250 °C.

1.3 Thesis Organization

This thesis consists of five chapters. Chapter 2 provides all the necessary background information for this proposed reference voltage generator. Some relevant high temperature voltage reference works in recent years are discussed at the end of the chapter. Chapter 3 covers detailed design procedure. Chapter 4 covers the measurement setup, procedure and experiment results for the propose reference voltage generator. At the end of the chapter, overall performance comparing with other high temperature voltage references is presented. Last but not least, Chapter 5 concludes the work by summarizing the achievements and discussing future work/improvements.

Chapter 2

2 Background

Contents

Chapter 2 covers definitions, terms as well as background information that is necessary to understand this work. At the end of this chapter, some relevant voltage reference works in recent years are discussed.

2.1 Definitions and Terms

2.1.1 Reference Circuits

A reference circuit establishes a voltage or current that is a known fixed value. It is a critical part in a system block since the quality of the dc voltage and current sources directly influence the overall performance of a circuit. Although a power supply voltage could be used to derive a reference voltage or current, in some cases, the power supply is not always controlled with sufficient accuracy. Figure 2.1 shows an example of how a reference circuit works in a mixed analog-digital circuit [3].

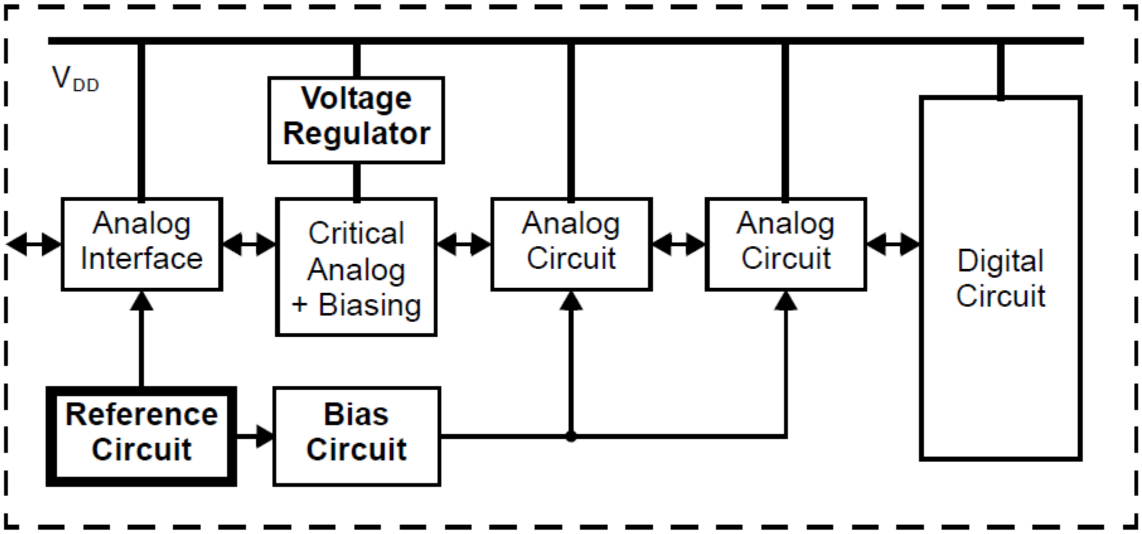

Figure 2.1: System block of a mixed analogy-digital integrated circuit [3]. [fair use]

2.1.1.1 Voltage Reference

As mentioned above, a voltage reference, as its name implies, is a circuit that generates an exact output voltage. In theory, the output of a voltage reference does not depend on process, the operating voltage, temperature, load current, or the passage of time [4].

A voltage reference can be categorized into three different levels according to its performance [5]. They are zero-order references, first-order references, and second-order references or higher-order references. The zero order references are the most basic ones. This level of references usually has poor performance in temperature compensation. In other words, the outputs of these types of reference can experience a temperature drift from 1.5 to 5 mV/°C. First-order reference, on the other hand, are temperature compensated. The reason these references are called first-order references is because "the first-order term of the polynomial relationship with respect to temperature is effectively canceled [5]". First-order references have a better performance in temperature compensation comparing with zero-order reference. Typically, a temperature drift of 50 to 100 ppm/°C is performed for the first-order voltage references. However, there are some applications, such as low-voltage power supply systems and high-performance data converters, that first-order voltage references cannot supply due to higher accuracy requirements. For this reason, second-order as well as higher-order voltage references are used to achieve this end. The temperature drift is usually less than 50 ppm/°C for second-order or higher-order references.

The bandgap of silicon has been proven to be the quantity that is most widely used for generating a reference with high accuracy. It is also a constant value that does not change with variations in device dimensions, temperature, and dopant concentrations [3]. The bandgap voltage reference, as its name implies, outputs a dc voltage, whose value is equal to the bandgap energy of the semiconductor used [4]. It is one of the most commonly used voltage reference circuit in various fields of applications, such as automotive and DA converters, for many years [6].

2.1.1.1.1 Parts per million (ppm)

PPM in the section 2.1.1.1 stands for parts per million. In reference circuit design, this quantity is used to evaluate the accuracy of the output. For a 1.25V voltage reference, one ppm presents one-millionth of 1.25V, which is 1.25 μV.

2.1.1.2 Current Reference

A current reference circuit is a device that generates a dc current. Unlike a voltage reference circuit, the current reference does not have to be temperature-independent. Nevertheless, the output variation with temperature must be well characterized and controlled since most voltage references are dependent on and are derived from current references. The most commonly used reference current is a proportional-to-absolute temperature (PTAT) current, whose output current is proportional to temperature linearly. Due to its the linear relation with temperature, the PTAT current is predictable and practical in many applications. The squared PTAT ($PTAT^2$) current is another commonly used reference. Its output current is proportional to the square of the temperature. This type of reference current is mostly used in second-order or higher-order voltage references. Meanwhile, temperature-independent current references are also useful. These currents are usually obtained by combining temperature-dependent current or derived from voltage references [5].

2.1.2 Temperature Independence

As mentioned in section 2.1.1.1, voltage reference generates a dc voltage with low PVT (process, voltage, temperature) sensitivity. If a reference is temperature-independent, it is usually process-independent because most process parameters vary with temperature.

Therefore, temperature independence is one of the critical parts in most voltage reference design.

2.1.2.1 Temperature Coefficient

Temperature coefficient (TC), which is also known as temperature drift or temperature sensitivity, is a quantity to evaluate the temperature performance of a reference circuit over a given operating temperature range. When V_{IN} is fixed, TC is defined as follow:

$$TC = \frac{V_{REF(max)} - V_{REF(min)}}{V_{REF(nom)} \times (T_{max} - T_{min})} \times 10^6 \ (ppm/°\mathrm{C}), \tag{2.1}$$

where $V_{REF(max)}$ and $V_{REF(min)}$ are the maximum and minimum output reference voltages, $V_{REF(nom)}$ represents the nominal output reference voltage, and T_{max} as well as T_{min} are the maximum and minimum operating temperature for the reference circuit. The TC can range from a few parts per million per degree Celsius (ppm/°C) to hundreds of ppm/°C depending on the requirement of different applications [4].

2.1.2.2 Temperature Compensation

The way to achieve temperature independence is to use temperature compensation techniques. Compensating between the PTAT and complementary-to-absolute temperature (CTAT) voltages or currents is the main idea of remedy the temperature dependency of a voltage reference circuit [4]. In the circuit of a temperature-independent reference, three sub-circuits are involved to compensate the temperature. The first and second sub-circuits generate the PTAT and CTAT voltages or currents while the third sub-circuit sums the two temperature dependent voltages or currents with proper weighting to get a zero TC output. Equation 2.2, 2.3 and Figure 2.2 shows the basic idea of temperature compensation.

$$V_{REF} = m_1 V_{CTAT} + m_2 V_{PTAT}, \tag{2.2}$$

$$\frac{\partial V_{REF}}{\partial T} = m_1 \frac{\partial V_{CTAT}}{\partial T} + m_2 \frac{\partial V_{PTAT}}{\partial T} = 0. \tag{2.3}$$

Since $\frac{\partial V_{CTAT}}{\partial T}$ is less than zero, which is the slope of V_{CATA}, and $\frac{\partial V_{PTAT}}{\partial T}$ is great than zero, which is the slope of V_{PTAT}, a zero TC V_{REF} can be obtained with proper choice, usually are positive integers, of m_1 and m_2.

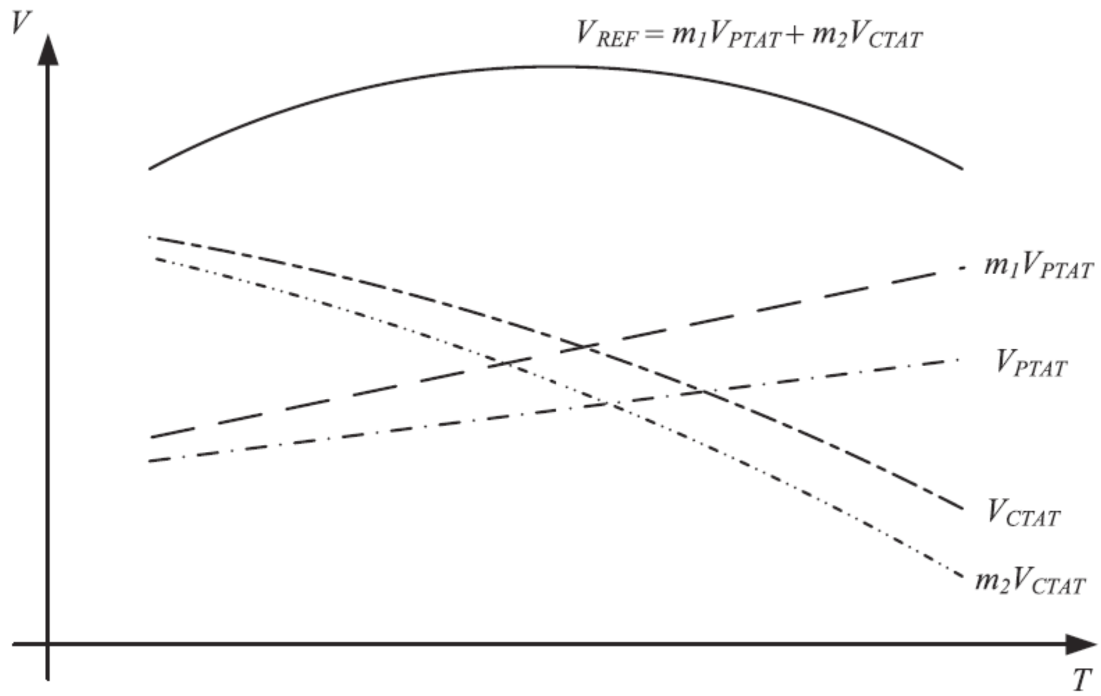

Figure 2.2: Illustration of temperature compensation of a voltage reference [4]. [Fair use]

In Figure 2.2, the reference voltage V_{REF} is not a zero TC voltage because in practical V_{REF} can only achieve a near-zero TC.

Obviously, V_{CTAT} and V_{PTAT} play important roles in temperature compensation of a voltage reference. Therefore, generating PTAT and CTAT voltages has become critical in the design of temperature-independent voltage reference. It has been proven that bipolar transistors can provide both PTAT and CTAT voltages [7].

2.1.2.2.1 Negative-TC Voltage (CTAT Voltage)

The negative-TC voltage, also known as CTAT voltage, as its name implies, varies complementary to absolute temperature, which means the voltage decreases as temperature rises. As an important component in the voltage reference circuit, the bipolar junction transistor (BJT) is commonly used for the generation of temperature dependent voltage [4]. The base-emitter voltage (V_{BE}) of bipolar transistors is commonly used as CTAT voltage.

Neglecting the Early effect, the collector current for a bipolar device, which is biased in the forward active region, is given by

$$J_C(T)A_E = J_S(T)A_E \exp\left(\frac{V_{BE}}{V_T}\right), \tag{2.4}$$

$$I_C(T) = I_S(T) \exp\left(\frac{V_{BE}}{V_T}\right), \tag{2.5}$$

where $J_C(T)$ is the collector current density, T is the absolute temperature in K, A_E is the base-emitter junction area, $J_S(T)$ is the saturation current density. $I_C(T)$ and $I_S(T)$ are the temperature dependent collector current and saturation current, which are the results of current density times the base-emitter junction area. Meanwhile, V_T is the thermal voltage, which is given by

$$V_T = \frac{kT}{q}, \tag{2.6}$$

where k is the Boltzmann constant, which is equal to 1.38×10^{-23} J/°C, and q is the charge of an electron, which is equal to 1.6×10^{-19} C. V_T is equal to 25.9 mV at room temperature, where T = 300 K. Then

$$V_{BE}(T) = V_T \ln\left(\frac{I_C(T)}{I_S(T)}\right). \tag{2.7}$$

According to Johns and Martin [3], the base-emitter voltage of the BJT can be expressed as follow:

$$V_{BE}(T) = V_{G0}\left(1 - \frac{T}{T_r}\right) + V_{BE}(T_r)\left(\frac{T}{T_r}\right) - \frac{\rho kT}{q}\ln\left(\frac{T}{T_r}\right) + \frac{kT}{q}\ln\left(\frac{J_C(T)}{J_C(T_r)}\right), \tag{2.8}$$

where V_{G0} is the bandgap voltage of silicon at 0 K, which is equal to 1.206 V, T_r is a reference temperature, ρ is a process dependent temperature constant. Furthermore, the temperature dependent collector current can be described by

$$\frac{I_C(T)}{I_C(T_r)} = (\frac{T}{T_r})^{\theta}, \tag{2.9}$$

$$\frac{J_C(T)}{J_C(T_r)} = (\frac{T}{T_r})^{\theta}, \tag{2.10}$$

where θ is the order of the temperature behavior of the current. In other words, if θ = 0, the collector current is a constant value that is independent on temperature. If θ = 1, the collector current has a linear relation with temperature. Therefore, the base-emitter voltage then can be simplified as follow:

$$V_{BE}(T) = V_{G0}\left(1 - \frac{T}{T_r}\right) + V_{BE}(T_r)\left(\frac{T}{T_r}\right) - (\rho - \theta)\frac{kT}{q}\ln\left(\frac{T}{T_r}\right), \tag{2.11}$$

It is noticeable that $V_{BE}(T)$ is a complex function of temperature. Equation 2.11 suggests that the $V_{BE}(T)$ not only varies with temperature, but also varies with biasing condition and transistor size. However, according to Kok and Tam [4], $V_{BE}(T)$ decreases almost linearly with temperature with a rate of - 1.73 mV/K at 300K. Figure 2.3 shows the temperature behavior of the base-emitter voltage of BJT with different biasing condition.

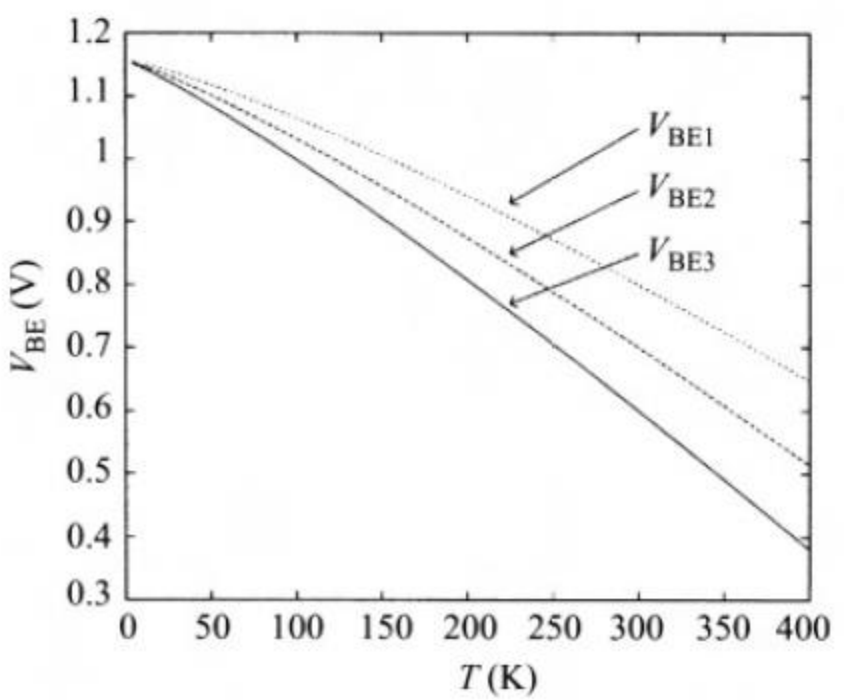

Figure 2.3: Temperature behavior of V_{BE} with different biasing condition [6]. [fair use]

2.1.2.2.2 Positive-TC Voltage (PTAT Voltage)

The positive-TC voltage, also known as PTAT voltage, as its name implies, varies proportional to absolute temperature, which means the voltage increases as temperature rises. The difference of the V_{BE} between two bipolar transistors with different current densities exhibits a positive TC.

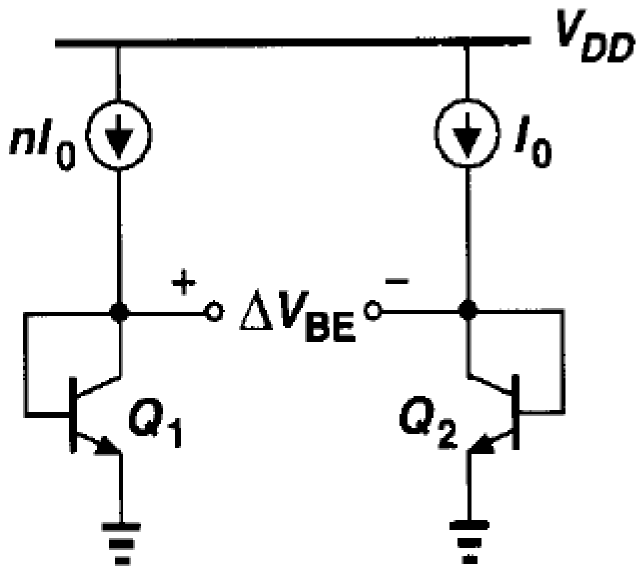

Figure 2.4: Generation of positive-TC voltage (same transistor size) [7]. [fair use]

Figure 2.4 illustrates the generation of a positive-TC voltage using two identical transistors with unequal current densities. The difference voltage is given by

$$\Delta V_{BE} = V_{BE1} - V_{BE2}, \tag{2.12}$$

where V_{BE1} and V_{BE2} are the base-emitter voltage of transistors Q_1 and Q_2. Neglecting the base currents and applying Equation 2.7 into Equation 2.12, then

$$\Delta V_{BE} = V_T \ln\left(\frac{nI_0}{I_{S1}}\right) - V_T \ln\left(\frac{I_0}{I_{S2}}\right). \tag{2.13}$$

Since the two transistors are identical, I_{S1} is equal to I_{S2}. Then

$$\Delta V_{BE} = V_T \ln(n)\,, \tag{2.14}$$

where V_T is the thermal voltage and equal to $\frac{kT}{q}$. Taking the derivative of the ΔV_{BE} will get:

$$\frac{\partial \Delta V_{BE}}{\partial T} = \frac{\mathrm{k}}{\mathrm{q}} \ln(n). \tag{2.15}$$

From Equation 2.15, it is obvious that the ΔV_{BE} is a linear function of temperature. Figure 2.5 shows the temperature behavior of the ΔV_{BE} when n is equal to 8.

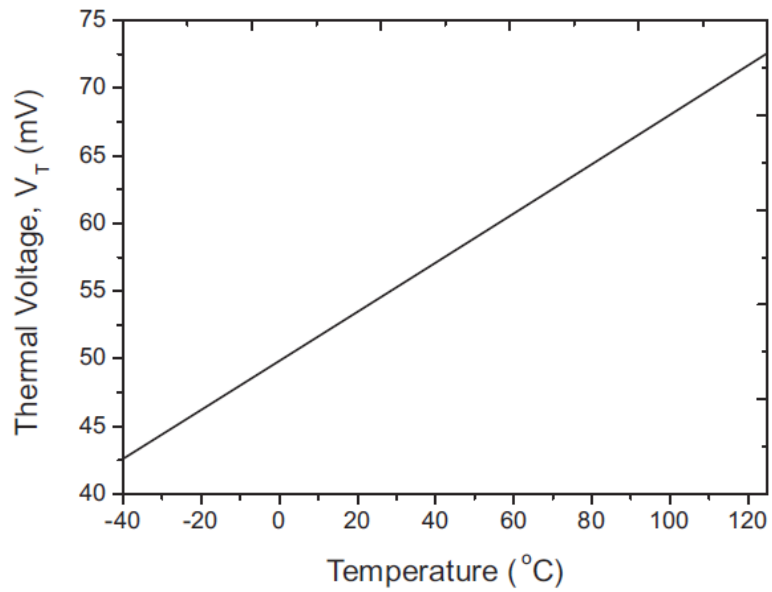

Figure 2.5: Temperature behavior of ΔV_{BE} when n = 8 [4]. [fair use]

In some bandgap reference design, the ΔV_{BE} is generated by two transistors with different size with same unequal current densities as shown in Figure 2.6.

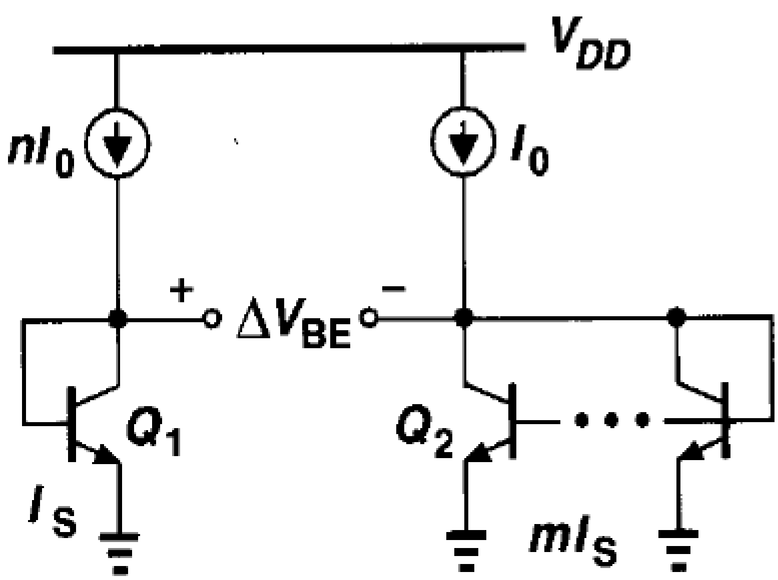

Figure 2.6: Generation of positive-TC voltage (different transistor size) [7]. [fair use]

Then the difference voltage can be expressed as follow:

$$\Delta V_{BE} = V_{BE1} - V_{BE2},$$

$$\Delta V_{BE} = V_T \ln\left(\frac{nI_0}{I_S}\right) - V_T \ln\left(\frac{I_0}{mI_S}\right), \tag{2.16}$$

$$\Delta V_{BE} = V_T \ln(nm)\,, \tag{2.17}$$

$$\frac{\partial \Delta V_{BE}}{\partial T} = \frac{\mathrm{k}}{\mathrm{q}} \ln(nm), \tag{2.18}$$

where m is the area-ratio between Q2 and Q1. Although the size of the transistor changes, the ΔV_{BE} is still a PTAT voltage.

2.1.3 Power Supply Independence

Other than temperature variation, power supply variation is also critical to the performance of voltage references. A high performance reference circuit should show no or little dependency on power supply. In other words, the output of a supply-independent voltage reference should not vary much if supply voltage changes. Power supply sensitivity is a quantity that evaluates the output performance when power-supply changes. The power supply sensitivity can be calculated using the equation below:

$$Power\ supply\ sensitivity = 20 \log\left(\frac{\Delta V_{Power-supply}}{\Delta V_{output}}\right). \tag{2.19}$$

In order to get a good power supply sensitivity, the bandgap reference core must be supplied from a regulated voltage or a current source. Some supply-independent reference topologies will be discussed in Section 2.2.

2.2 Reference Topologies

This section consists of two parts. In the first part, some conventional voltage reference topologies are described. Moreover, some current reference topologies are covered in the second part.

2.2.1 Voltage Reference Topologies

2.2.1.1 Diode References

2.2.1.1.1 Forward-Biased Diode Reference

One of the simplest voltage reference is called forward-biased diode reference. It is simply constructed by a resistor and a diode or a diode-connected transistor as shown in Figure 2.7 [5]. The reference voltage is generated by forcing current to flow through a p-n junction diode or a diode-connected transistor. The resistor in the circuit can be replaced with a current source or a junction filed-effect transistor (JFET) to optimize current overhead and area. This topology is easy to design since there are only two components in the circuit. However, this circuit exhibits a negative TC of approximately -2.2 mV/°C. In addition, the output accuracy is degraded if the input voltage varies. It is because of the changing in biasing current of the diode when input voltage changes. If the output is used to drive load currents, the accuracy of the circuit can also be affected [5].

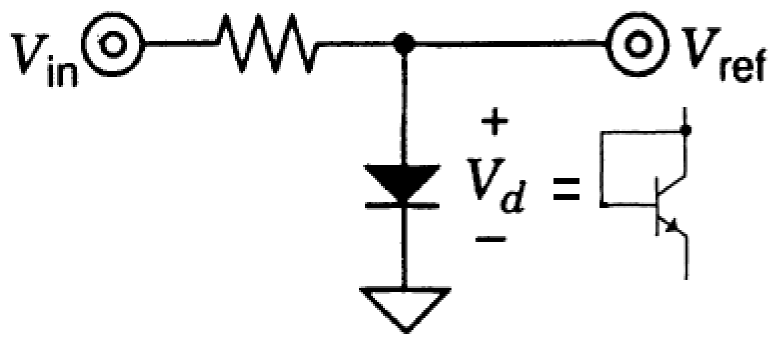

Figure 2.7: Forward-biased diode voltage reference [5]. [fair use]

2.2.1.1.2 Zener Diode Reference

Zener diode reference is another commonly used diode reference. The structure of the circuit is the same as the forward-biased diode reference as shown in Figure 2.8. The only difference is the replacement of a diode with a Zener diode. The reference voltage is generated by forcing current to flow into the cathode of the diode. The diode then goes into reverse-breakdown region. Most Zener diodes have a breakdown voltage between 5.5 to 8.5 V, which makes the Zener diode reference suitable for high-voltage applications with supply voltage greater than 6 to 9 V [5]. In addition, unlike the forward-biased diode, large changes in load-current does not fluctuate diode voltage much in reverse-breakdown region. Therefore, this topology has a low output resistance, which is typically around 10 to 300 Ω. Nevertheless, this circuit is not temperature-independent as the forward-biased diode reference circuit. The circuit exhibits a positive TC of approximately +1.5 to 5 mV/°C [5].

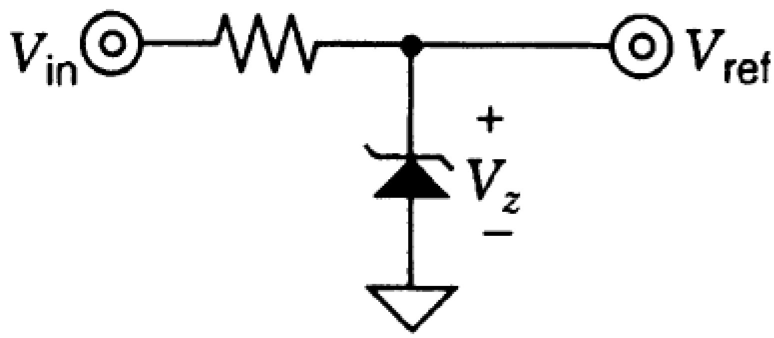

Figure 2.8: Zener diode voltage reference [5]. [fair use]

2.2.1.2 Widlar Bandgap Reference

Widlar bandgap reference circuit is one of the early bandgap voltage references that was invented by Robert J. Widlar in 1971 [8]. It was implemented with junction isolated bipolar technology as shown in Figure 2.9.

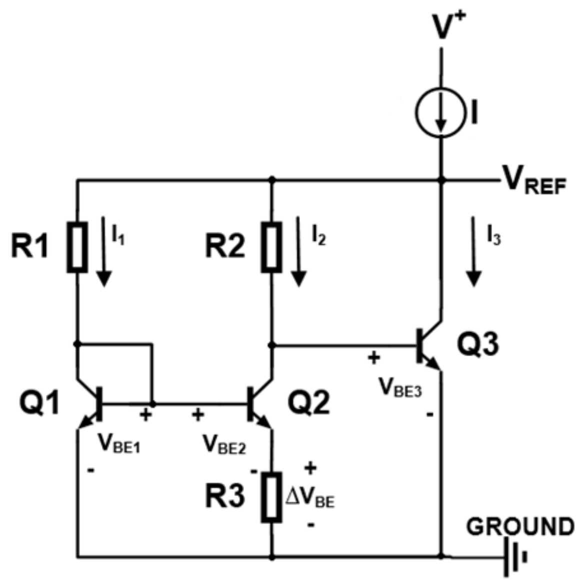

Figure 2.9: Widlar bandgap voltage reference.

The Widlar bandgap voltage reference used temperature compensation technique that discussed in Section 2.1.2.2, where transistors Q1 and Q2 generate a PTAT voltage, ΔV_{BE}, across the resistor R3 and transistor Q3 establishes a CTAT voltage, V_{BE3}. The circuit then can be analyzed by the following equations:

$$V_{BE1} = V_{BE2} + I_2 \times R3, \tag{2.20}$$

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = I_2 \times R3. \tag{2.21}$$

In addition,

$$\Delta V_{BE} = V_T \ln\left(\frac{I_1}{I_{S1}}\right) - V_T \ln\left(\frac{I_2}{I_{S2}}\right) = V_T \ln\left(\frac{I_1 I_{S2}}{I_2 I_{S1}}\right). \tag{2.22}$$

Then,

$$I_2 = \frac{\Delta V_{BE}}{R3} = \frac{V_T}{R3} \ln\left(\frac{I_1 I_{S2}}{I_2 I_{S1}}\right). \tag{2.23}$$

Assuming that $V_{BE1} = V_{BE3}$, then

$$I_1 \times R1 = I_2 \times R2. \tag{2.24}$$

Therefore,

$$I_2 = \frac{V_T}{R3} \ln\left(\frac{R2 I_{S2}}{R1 I_{S1}}\right). \tag{2.25}$$

The output reference voltage is given by

$$V_{REF} = I_2 \times R2 + V_{BE3}, \tag{2.26}$$

$$V_{REF} = \frac{R2}{R3} \Delta V_{BE} + V_{BE3}, \tag{2.27}$$

$$V_{REF} = \frac{R2 V_T}{R3} \ln\left(\frac{R2 I_{S2}}{R1 I_{S1}}\right) + V_{BE3}. \tag{2.28}$$

According to Gilbert [9], in order to achieve temperature-independent, the circuit should satisfy the equation

$$K = \frac{V_{R2}}{V_T \ln(nm)}, \tag{2.29}$$

where n is the ΔV_{BE} current-density ratio, m is the area ratio between transistors Q2 and Q1 discussed in Section 2.1.2.2.1, and K is equal to R2 over R3, which is typically in the range of 3 to 15. Note that R2 should greater than R3 while designing the circuit since V_{BE3} has a large negative TC. ΔV_{BE} needs to be amplified by a weighted factor in order to get a larger positive TC voltage. In this way, the Widlar bandgap voltage reference could generate a stable low TC reference around 1.23 V.

The advantages of this topology are obvious. The concept of this circuit is straight forward. Only three active devices are needed to achieve low TC output voltage. However, a separate biasing current source is used for this topology to reduce the influence caused by supply variation. Although the current source can be replaced by a resistor, the output voltage would highly depend on power supply. As mentioned before, the proposed voltage reference is based on this work and continues his work by implementing the ideal current source with an electronic current source which will be detailed in Chapter 3. Load and current drive sensitivity is another issue for this topology, which can be solved by using a buffer amplifier. In addition, the buffer amplifier can scale the output to some useful levels, such as 2.5 V, 5 V, and 7 V.

2.2.1.3 Brokaw Bandgap Reference

Brokaw bandgap reference, which was invented by Paul Brokaw in 1974, is one of the most popular and widely used voltage reference circuit for decades. Many voltage references used today are still inspired by this topology. Figure 2.10 below shows the Brokaw bandgap voltage reference [10].

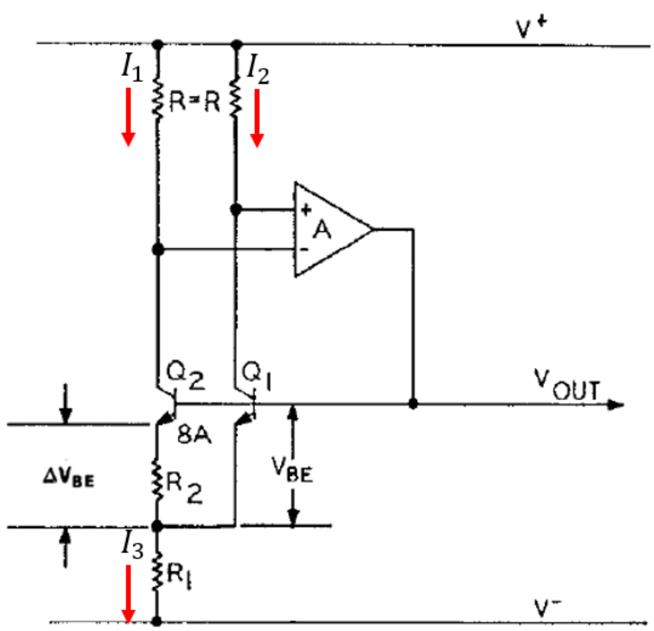

Figure 2.10: Brokaw bandgap voltage reference [10]. [fair use]

Comparing to the Widlar bandgap reference, the Brokaw bandgap reference uses only two bipolar transistors instead of three transistors to generate both V_{BE} and ΔV_{BE}. In addition, unlike Widlar bandgap reference requiring a separate biasing source, the operating currents of the Brokaw bandgap reference are determined by the cell itself.

The two resistors on the top of the circuit are set to be equal. With the ideal infinite-gain amplifier, the currents I_1 and I_2 are force to be equal. The emitter area ratio in this design is set to be 8, which means transistor Q2 has eight times the current density of transistor Q1. Then the circuit can be analyzed as follow

$$V_{BE(Q1)} = V_{BE(Q2)} + I_1 \times R2, \tag{2.30}$$

$$\Delta V_{BE} = V_{BE(Q1)} - V_{BE(Q2)} = I_1 \times R2. \tag{2.31}$$

From Equation 2.22, we know that

$$\Delta V_{BE} = V_T \ln\left(\frac{I_1}{I_{S1}}\right) - V_T \ln\left(\frac{I_2}{I_{S2}}\right) = V_T \ln\left(\frac{I_1 I_{S2}}{I_2 I_{S1}}\right).$$

Since $I_1 = I_2$,

$$I_3 = I_1 + I_2 = 2I_1. \tag{2.32}$$

Moreover,

$$I_1 = \frac{\Delta V_{BE}}{R2} = \frac{V_T}{R2} \ln\left(\frac{I_1 I_{S2}}{I_2 I_{S1}}\right). \tag{2.33}$$

The output is given by

$$V_{REF} = I_3 \times R1 + V_{BE(Q1)}, \tag{2.34}$$

$$V_{REF} = \frac{2\Delta V_{BE}}{R2} \times R1 + V_{BE(Q1)}. \tag{2.35}$$

One advantage of this topology is that this circuit provides on-chip output buffering. This improves the drive capacity and can scale the output to other useful levels. However, the performance of the Brokaw is highly depending on the operational amplifier (Op Amp). If the amplifier does not have a sufficiently large loop gain, the output performance would be affected.

2.2.2 Current Reference Topologies

2.2.2.1 V_{BE}-Based Current Reference

Figure 2.11 shows a V_{BE}-based current reference. As its name implies, the output current of this reference is determined by the base-emitter voltage of transistor Q1.

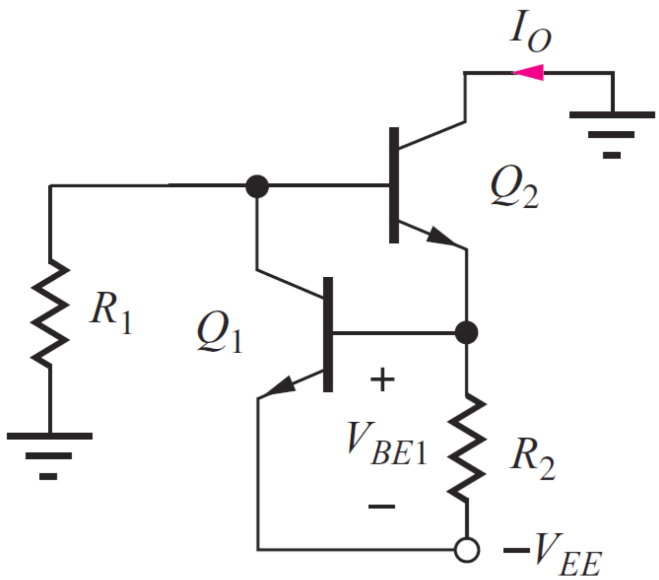

Figure 2.11: V_{BE}-based current reference [11]. [fair use]

Assuming both transistors Q1 and Q2 have high current gain, I_{C1} is obtained as follow [11]:

$$I_{C1} = \frac{V_{EE} - V_{BE1} - V_{BE2}}{R_1}. \tag{2.36}$$

Neglecting the base currents, the output current is equal to the current flowing through R2:

$$I_o = \frac{V_{BE1}}{R2} \tag{2.37}$$

According to Equation 2.7, the base-emitter voltage of Q1 is given by

$$V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_{S1}}\right). \tag{2.38}$$

Therefore, the output current can be expressed as:

$$I_o = \frac{V_T}{R2} \ln\left(\frac{V_{EE} - V_{BE1} - V_{BE2}}{I_{S1} R1}\right). \tag{2.39}$$

From Equation 2.39, the output current is logarithmically dependent on supply voltage. Although this current reference is almost supply-independent, the output current suffers a temperature drift.

2.2.2.2 Supply-Independent MOS Reference

Figure 2.12 shows a supply-independent MOS reference. This topology was constructed by two current mirrors and a resistor.

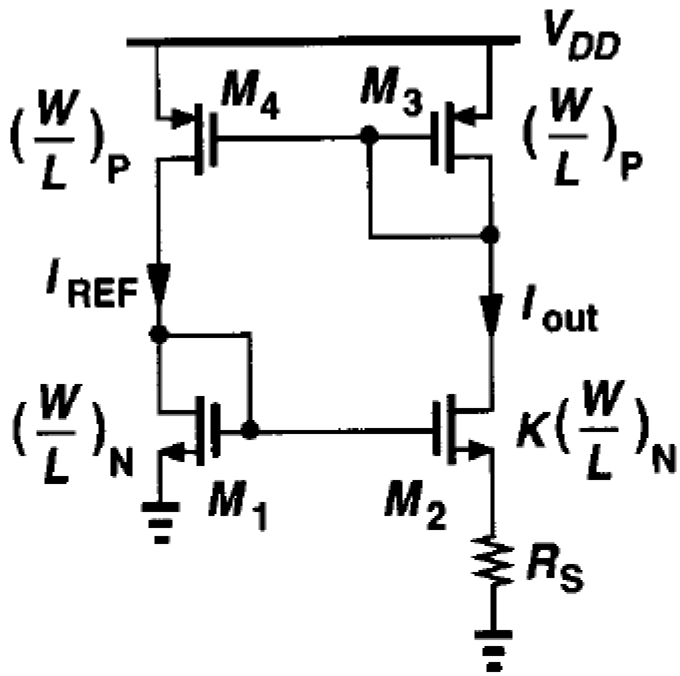

Figure 2.12: Supply-independent MOS reference [7]. [fair use]

Since the size of M3 is the same as that of M4, the output current is equal to the reference current on the left. The drain currents of M1 and M2 are given by

$$I_{D(M1)} = I_{REF} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_N (V_{GS1} - V_{TH1})^2, \tag{2.40}$$

$$I_{D(M2)} = I_{out} = \frac{1}{2}\mu_n C_{ox} K\left(\frac{W}{L}\right)_N (V_{GS2} - V_{TH2})^2. \tag{2.41}$$

In addition,

$$V_{GS1} = V_{GS2} + R_s I_{out}, \tag{2.42}$$

$$\sqrt{\frac{2I_{out}}{\mu_n C_{ox}\left(\frac{W}{L}\right)_N}} + V_{TH1} = \sqrt{\frac{2I_{out}}{\mu_n C_{ox} K\left(\frac{W}{L}\right)_N}} + V_{TH2} + R_S I_{out}. \tag{2.43}$$

Assuming $V_{TH1} = V_{TH2}$, the output current then can be derived as

$$I_{out} = \frac{2}{\mu_n C_{ox}\left(\frac{W}{L}\right)_N} \times \frac{1}{R_S^2} \times (1 - \frac{1}{\sqrt{K}})^2. \tag{2.44}$$

It is obvious that the output current does not vary when supply changes. However, this current reference is also not temperature-independent. In addition, a start-up circuit is needed for the circuit due to zero-current state could occur for this topology.

2.3 High Temperature Semiconductors Research

High temperature applications have become one of the most popular topics in recent years. The maximum operating temperature of electronic devices has also become higher and higher every year. This section covers some commonly used high temperature materials in analog circuit.

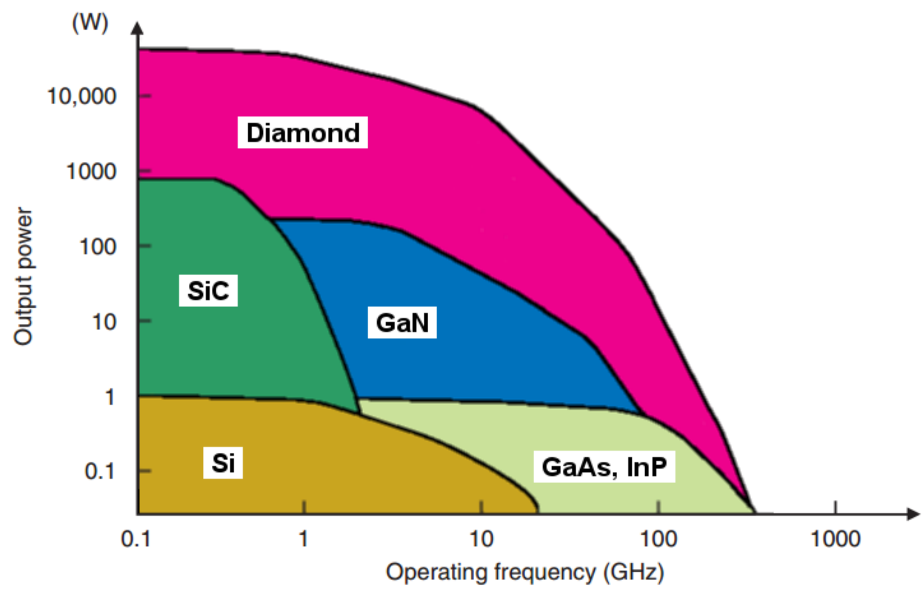

Figure 2.13: Operating frequency and output power chart of semiconductors [12]. [fair use]

Figure 2.13 shows the frequency and power limits of six semiconductor materials, which are silicon (Si), gallium arsenide (GaAs), indium phosphide (InP), silicon carbide (SiC), gallium nitride (GaN), and diamond.

2.3.1 Si

Although Si dominates the marketplace for decades, the material has reached its theoretical limits for present technology. In harsh environment, electronics usually need to operate continuously under high temperature. For most Si electronics, the maximum junction temperature is only around 150 °C. In other words, if the Si devices operate in the environment with temperature higher than150 °C, the electronics will have to be cooled so that they can work properly. In addition, the electrical characteristics of Si vary with temperature and time, which would result reliability issue [13]. Therefore, Si material can no longer meet all the requirements for harsh environment applications.

2.3.2 GaAs and InP

GaAs and InP are similar in terms of physical properties. As a result, they have the same performance in operating frequency and output power as shown is Figure 2.13. GaAs is the second widespread substrate material other than Si. On the other hand, InP has a better performance in gain, noise figure, and power than GaAs. Since both materials have a wide operating frequency, GaAs and InP are good choices for radio frequency (RF) applications. However, for high-power and high-temperature applications, the two materials, due to their low thermal conductivity, are not as good as SiC and GaN [14].

2.3.3 SiC

SiC is a IV–IV compound material comprised of Si and carbon (C). SiC exhibits three times the bandgap, ten times the dielectric breakdown field strength, and three times the thermal conductivity compared to Si. Because of these properties, SiC is a semiconductor material that is suitable for high-frequency, high-power, and high-temperature applications. High-temperature circuit which can operate from 200°C to 500°C is desired for harsh environment applications. Currently, 4H-SiC and 6H-SiC are the two popular SiC polytypes [13]. The proposed reference voltage generator is designed and prototyped using 4H-SiC bipolar transistors.

2.3.4 GaN

GaN is another wide-bandgap semiconductor that has a wide bandgap, high breakdown electric field strength, high saturated drift velocity of electrons, and a high thermal conductivity. Although the thermal conductivity of GaN is not as good as that of SiC, GaN exhibits a higher operating frequency, which makes it more suitable for high temperature RF applications compare to SiC, GaAs and InP.

2.3.5 Diamond

According to Figure 2.13, diamond has the best theoretical performance among these semiconductor materials, which makes it a perfect candidate for replacing Si in harsh environment applications. However, processing is still an issue that have not been solved.

2.4 Temperature Effects on Device Physics

Table 2.1 shows the physical properties of the semiconductors, which are discussed in previous section. SiC, GaN, and diamond are good choices for high-frequency, high-power, and high-temperature applications. This section explains why some of the physical properties need to be concerned when choosing a device for high temperature applications and their relationship with temperature.

Table 2.1: Physical properties of semiconductors [12]-[14]. [fair use]

Property	Si	GaAs	InP	6H-SiC	4H-SiC	GaN	Diamond
Bandgap (eV)	1.12	1.42	1.34	3.03	3.26	3.45	5.45
Breakdown field (kV/cm)	300	400	500	2500	2200	2000	10000
Saturation Velocity ($\times 10^7$ cm/s)	1.0	1.0	1.9	2	1.6	2.3	2.7
Mobility (cm^2/V•s)	1450	8500	4000	500	1000	800	2200
Dielectric constant	11.7	12.9	14	9.66	10.1	8.9	5.5
Thermal conductivity (W/cm•K)	1.5	0.46	0.68	4.9	4.9	1.3	22
Operating temperature (°C)	250	350	300	>500	>500	>500	-

2.4.1 Bandgap

Bandgap is a critical property of semiconductor for high-temperature operation. A semiconductor has a bandgap that is three or more times than that of Si is considered as a wide-bandgap semiconductor. Wide-bandgap semiconductors are often the candidate for replacing Si in high temperature operation. The relationship between bandgap and temperature is given by [15]

$$E_g(T) = E_g(0) - \frac{\alpha_E T^2}{T + \beta_E}, \quad (2.45)$$

where Eg(T) is the bandgap energy at temperature T in Kelvin, Eg(0) is the bandgap energy at 0 K, and α_E and β_E are material specific constants. From equation above, it is obvious that the bandgap energy decreases as temperature rise.

2.4.2 Thermal conductivity

Thermal conductivity is another important physical property that is need to be concerned when choosing a device for high temperature applications. According to Ozpineci and Tolbert [13], the junction to case thermal resistance is given by

$$R_{th-jc} = \frac{d}{\lambda A}, \quad (2.46)$$

where d is thickness, λ is thermal conductivity, and A is cross sectional area. Based on the equation, higher thermal conductivity causes lower junction to case thermal resistance. A device with a low thermal resistance can conduct heat easily to surrounding. Therefore, for high temperature operation, low thermal resistance is desired. Based on the data in Table 2.1, diamond has the highest thermal conductivity of 22 follow by 4H-SiC and 6H-SiC. It is notable that GaN has the worst thermal conductivity among these semiconductor materials.

2.5 Literature Survey

Since extreme environment applications are new area in recent years. Only countable number of works on high temperature voltage reference exist in the literature at the writing of this paper. In this section, three most relevant works are discussed.

In 2010, an integrated reference voltage generator using GaN HEMT and Schottky diodes is demonstrated [16]. It is stated in the paper that the circuit can operate from room temperature up to 250 °C with an average temperature drift of less than 0.5 mV/°C, which is around 238 ppm/°C. In addition, it is also mentioned that this voltage reference has a low power supply sensitivity of -35 dB.

In 2014, a functional high temperature integrated voltage reference was developed with 4H-SiC MESFET devices [17]. The voltages reference has a wide temperature range, which is from 25 °C to 250 °C. It also features low output voltage variations when temperature and supply change. It is suggested in the paper that the TCs of this work is 15-33 ppm/°C. Although this voltage reference has a good performance with change in both temperature and supply, due to Vth sensitivity of MESFETs, large chip-to-chip variation occur in experimental results.

Early 2016, three conventional integrated bandgap voltage references were fabricated in bipolar 4H-SiC technology and characterized over a very wide temperature range from 25 °C to 500 °C [18]. Temperature coefficients for these voltage references are 46 ppm/°C, 131 ppm/°C, and 120 ppm/°C. However, all three voltage references are not supply-independent.

A comparison of the propose voltage reference with above three works will be shown in table 4.1 in Chapter 4.

Chapter 3

3 Proposed High Temperature Voltage Reference Design

Contents

The objective of the proposed voltage reference is to provide a constant reference voltage that can be used for biasing purpose by other circuits in a downhole communication system such as LNA, PA, mixer, etc. over a wide temperature range, which is from 25 °C to 250 °C. In Chapter 3, the design procedure of this proposed voltage reference is discussed in detail. First of all, the specifications for the design are presented. Once the specifications are discussed, system overview of this project is presented. Then final schematic and selection of topology are covered. After these, device and interface selection, bias point selection, positive/negative TC voltage design, V_{BE}-based reference design, prototype as well as tuning are described in remaining sections.

3.1 Specifications

Table 3.1 below shows the given specifications for the proposed voltage reference.

Table 3.1 : Design specifications.

Design Parameter	Design Requirement
Material	SiC
Temperature Range	25 °C - 250 °C
Vref @ 25 °C	-3.23 V
Temperature Coefficient	< 50 ppm/°C or < 0.162 mV/°C

SiC has proven its capability for high temperature operation among those semiconductor materials in the Section 2.3 and 2.4 due to its wide bandgap and high thermal conductivity.

As mentioned before, one key objective of the proposed voltage reference is to be able to operate at a wide temperature range up to 250 °C. The output reference voltage needs to be negative is due to the negative bias voltage of the GaN devices used in LNA, PA, mixers, etc.

Typical TC for a commercial voltage reference currently is 5 ppm/°C to 170 ppm/°C from -40 °C to 85 °C. It might get a lot worse when temperature goes higher. Therefore, 50 is a reasonable value for high temperature voltage references.

Although it is not listed in the specification, the reference voltage generator should have a low power supply sensitivity.

3.2 System Overview

Figure 3.1 shows an overview of the downhole communication system for this project. The system contains ten channels, 2 MHz each, with guard bands of 0.5 MHz in each receive (Rx) and transmit (Tx) band. The Rx and Tx bands are separated with 10 MHz. The entire RF system, which consists of a PA, LNA, mixer, voltage reference, etc. is shown in Figure 3.2. The reference voltage generator, as mentioned before, was designed for biasing purpose for this downhole communication system.

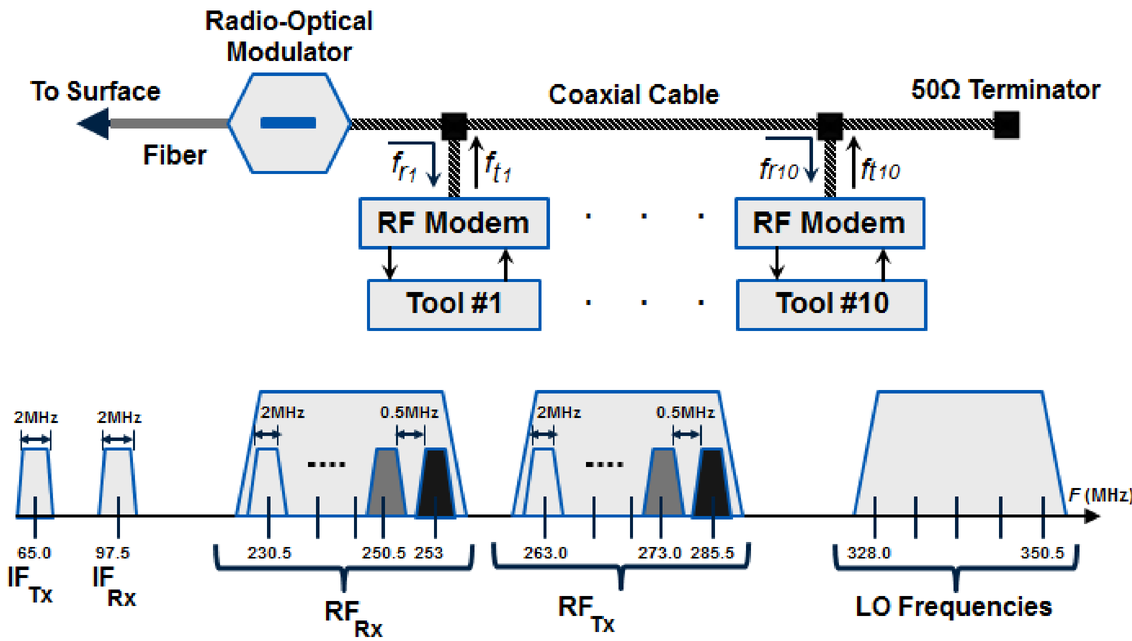

Figure 3.1: System overview.

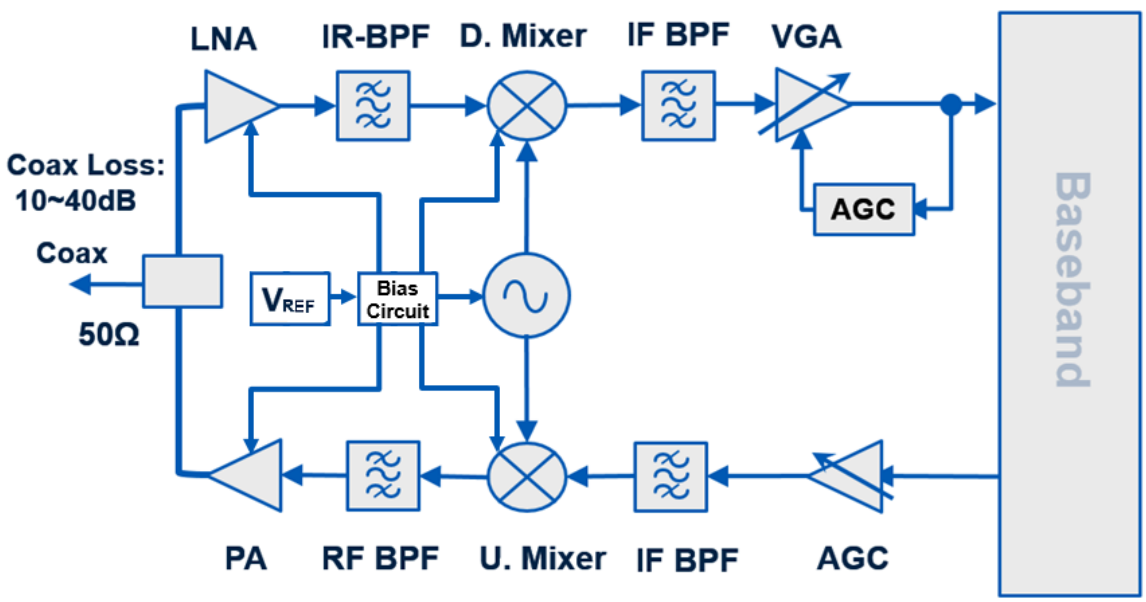

Figure 3.2: System block diagram for RF modem.

3.3 Final Schematic

For bypassing the lack of high temperature p-type SiC transistors (pnp BJT, PMOS) and OpAmp inconvenience, an all npn voltage reference architecture has been developed based on Widlar bandgap reference concept.

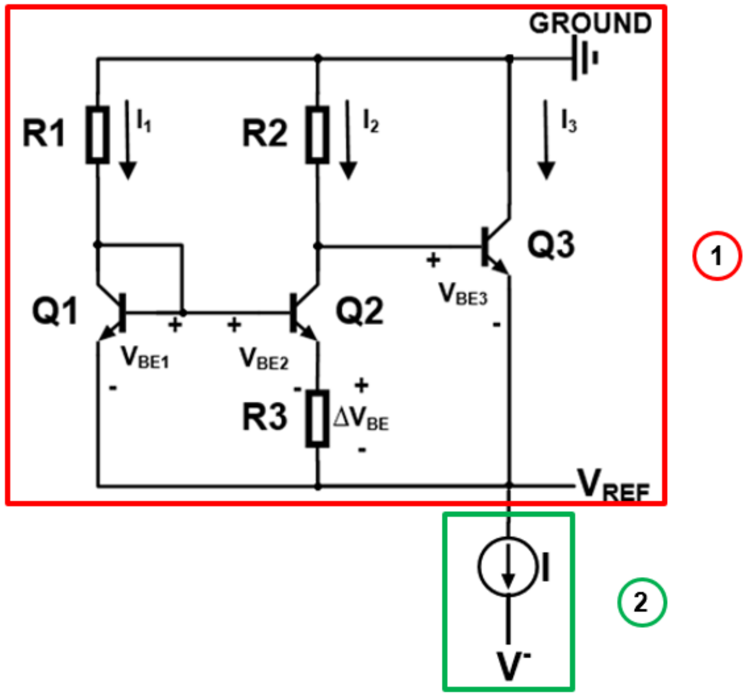

Figure 3.3: Design concept.

Figure 3.3 presents the design concept of the proposed voltage reference. Similar as Widlar bandgap voltage reference in Figure 2.9, this design consists of two portions: the temperature compensation circuit on the top and the ideal current source on the bottom. From Figure 3.3, it is found that the ground is placed on the top of the temperature compensation circuit, where was the output of the Widlar bandgap. A separate biasing current source has been moved to the bottom of the circuit. In this way, a negative reference voltage, whose value is close the bandgap of SiC, can be obtained from the emitter of transistor Q3, where was the ground for the Widlar bandgap.

The role for the upper portion is to provide the thermally compensated voltage with low temperature coefficient. The transistors Q1 and Q2 generate a ΔV_{BE} across R3, which is a positive TC voltage. The ratio between R2 and R3 compensates the positive TC voltage. A negative TC voltage V_{BE3} is generated by the transistor Q3. Then the output, which is the sum of the positive TC voltage and the negative TC voltage, is taken from the emitter of the transistor Q3.

Figure 3.4 presents the complete final schematic of the proposed reference voltage generator design. The biasing current source in Figure 3.3 is implemented by the V_{BE} based reference. The reason this particular current source is chosen is because the output current is only logarithmically dependent on changes in supply voltage. In other words, this circuit is almost supply independent. In addition, the output current is determined by the base-emitter voltage of Q5, which simplifies the design.

Table 3.2 lists the components value that are used in this proposed reference voltage generator.

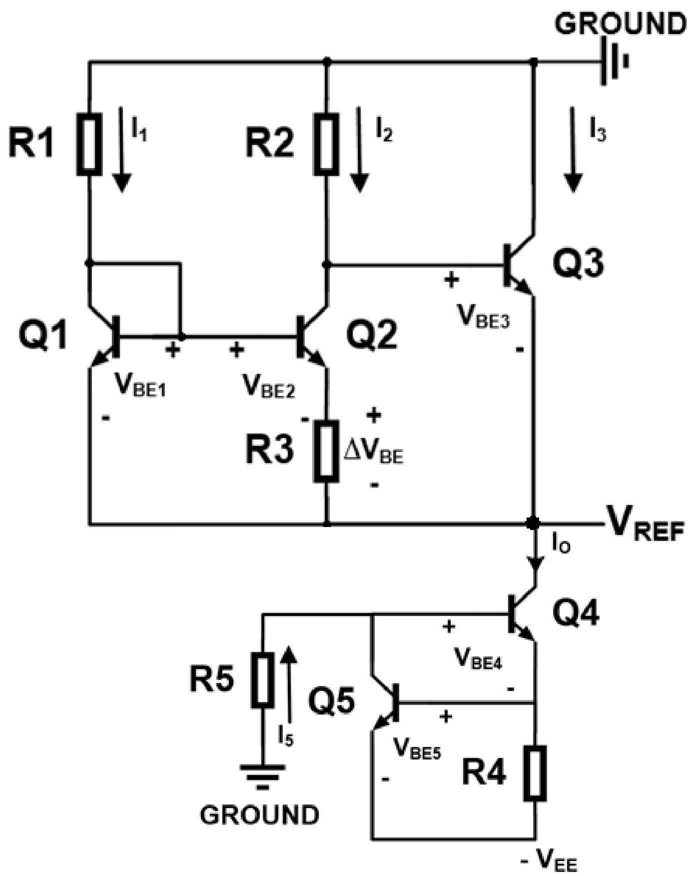

Figure 3.4: Final Schematic.

Table 3.2 : Components values.

Components	Value	Manufacturer
Q1 – Q5	-	GeneSiC
R1	10 Ω	Vishay
R2	49.9Ω	Vishay
R3	3.01 Ω	Vishay
R4	7.7 Ω	Vishay
R5	49.9Ω	Vishay

3.4 Active Device Selection

For high temperature applications, not only transistors need to operate at harsh environment, but every part of the circuit should be able to operate at high temperature reliably. According to the specification, SiC transistor is required for this design. GeneSiC GA05JT01-46 is chosen to be the active device in this design at the time. Because it has the highest rated maximum junction temperature, T_J, of any commercial off-the-shelf SiC transistors available and is a npn bipolar power transistor, which can provide both negative-TC and positive-TC voltages. It is a commercial normally-off silicon carbide junction transistor. The selected transistor features high operating temperature, low thermal resistance, low output capacitance, excellent gain linearity, high circuit efficiency, high amplifier bandwidth, etc. Due to these advantages, this device can be used in applications such as down hole oil drilling, geothermal instrumentation, general purpose high-temperature switching, and so on. In addition, a model for this transistor was provided along with the data sheet so that simulation tools can be used while designing. Table 3.3 shows some key parameter of this transistor.

Table 3.3 : Key parameters of GA05JT01-46 [19].

Parameter	Value
Maximum Operating Temperature	225 °C
Power Dissipation	20 W
DC Current Gain @ V_{DS}=5V, I_D=5A, T_J=225°C	69
Thermal Resistance, junction-case	9.86 °C/W

3.5 Passive Device and Interface Selection

The only passive device used in this design is resistor. Vishay thin film resistors are chosen due its low tolerance of 0.1% and TC of 25 ppm/°C from -55 °C to 250 °C [20].

Furthermore, the interface materials should also be able to withstand high temperature operation. Rogers 4003C was selected as PCB material because of its excellent dimensional stability [21].

Johnson/Cinch Connectivity Solution RF connectors are selected as end-mount connectors due to its high melting points materials.

The final consideration is the bonding material. Standard commercial off-the-shelf solder melts below 200 °C. In this design, a melting point between 280 °C to 300 °C is desired. Indium Corporation's "Indalloy 151" was chosen because of its reliable connections at high temperature and high melting temperature of 296 °C [22].

3.6 Bias Point Selection

Since the GeneSiC GA05JT01-46 is a power device, the datasheet only provides large base current IV curves. However, analog circuit like voltage reference usually draw very little power. Therefore, it is important and necessary to characterize the transistor to see the capability of the transistor while operates at small base currents.

The IV curves were taken by using Accent Optical Technologies DiVA D265 Dynamic I(V) Analyzer. Figure 3.5 shows the measured IV curve for the transistor at 25 °C. The reason these curves have negative slopes is because the device was getting hot while measuring.

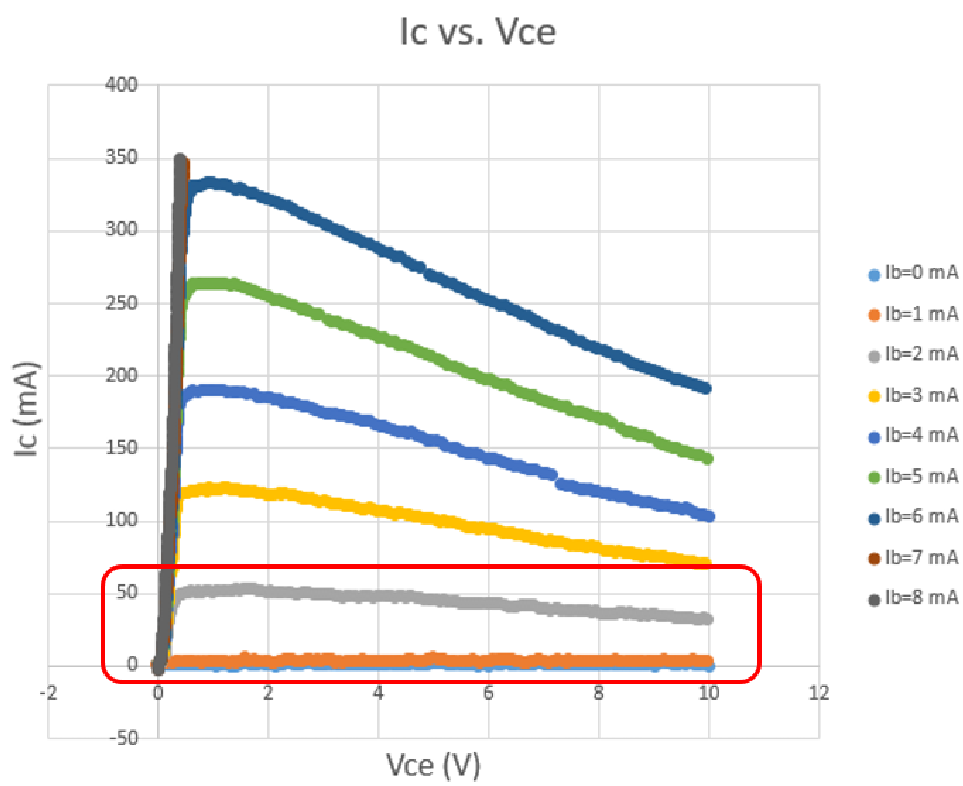

Figure 3.5: IV curve @ 25 °C.

Although power consumption is not a concern for this design, bias points are selected within the red rectangular region to make the power consumption as low as possible. In other words, the base current of the transistor should be chosen under 2.5 mA. The bias points in this design depend on the design of temperature compensation circuit, which is covered in Section 3.7.

Furthermore, the maximum operating temperature of the transistor is 225 °C, which is lower than the specification requires. Although the company has affirmed that the transistor can work at 250 °C over long durations with no significant change in parameters, it is still necessary to characterize the transistor under small base currents at 250 °C. Figure 3.6 shows the measured IV curve for the transistor at 250 °C. And it confirms that the transistor is able to operate at high temperature around 250 °C.

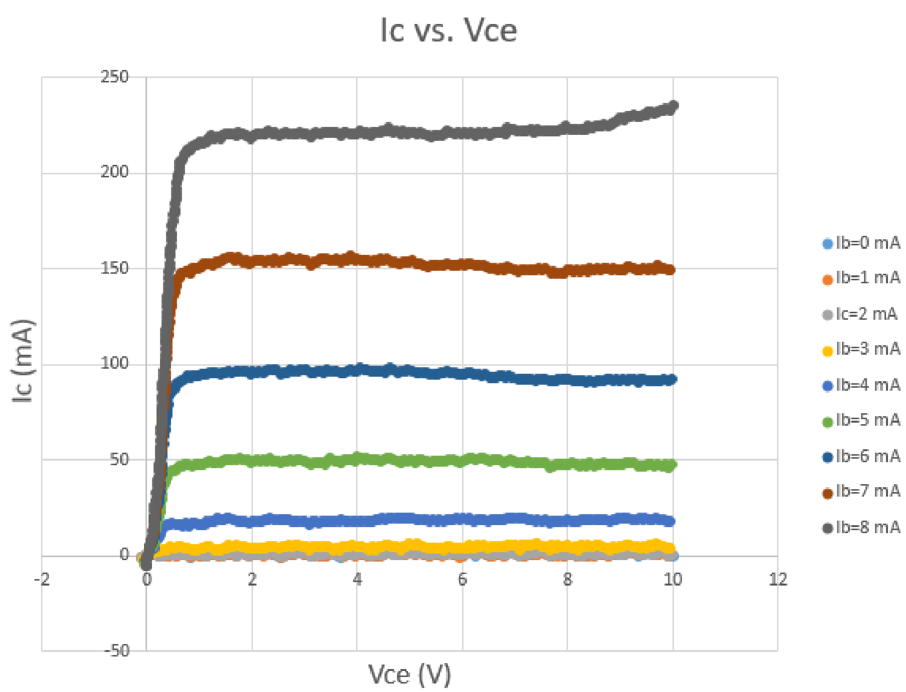

Figure 3.6: IV curve @ 250 °C.

3.7 Circuit Analysis and Design

Considering the circuit in Figure 3.4, the temperature compensation circuit can be analyzed by the following equations

$$V_{REF} = -(I_2 \times R_2 + V_{BE3}), \quad (3.1)$$

$$I_2 = \frac{V_{BE1} - V_{BE2}}{R_3} = \frac{\Delta V_{BE}}{R_3}. \quad (3.2)$$

Then,

$$V_{REF} = -\left(\frac{R_2}{R_3}\Delta V_{BE} + V_{BE3}\right). \quad (3.3)$$

According to Equation 2.13,

$$\Delta V_{BE} = V_T\, ln\left(\frac{I_1}{I_{S1}}\right) - V_T\, ln\left(\frac{I_2}{I_{S2}}\right) = V_T\, ln\left(\frac{I_1 I_{s2}}{I_2 I_{s1}}\right). \quad (3.4)$$

In this voltage reference design, the transistor ratio between Q1 and Q2 was set to 1. Therefore, Equation 3.4 can be further simplified by canceling I_{S1} and I_{S2},

$$\Delta V_{BE} = V_T\, ln\left(\frac{I_1}{I_2}\right). \quad (3.5)$$

Assuming that $V_{BE1} = V_{BE3}$, then

$$\frac{I_1}{I_2} = \frac{R_2}{R_1}. \quad (3.6)$$

Finally, the output of the temperature compensation circuit is given by

$$V_{REF} = -\left(\frac{R_2}{R_3}V_T\, ln\left(\frac{R_2}{R_1}\right) + V_{BE3}\right), \quad (3.7)$$

where

$$V_T = \frac{kT}{q}.$$

From Equation 3.7, it is noticed that the designed reference voltage generator is a first-order reference. The PTAT voltage, V_T, is amplified by $\frac{R_2}{R_3} ln\left(\frac{R_2}{R_1}\right)$ to compensate the CTAT voltage, V_{BE3}. Since the temperature compensation circuit of this design is based on a bandgap voltage reference, the output of the proposed voltage reference then equals to the bandgap voltage of the transistor used. The GeneSiC GA05JT01-46 is a 4H-SiC junction transistor with a bandgap of 3.23 eV [19]. Therefore, the output reference voltage of the proposed reference voltage generator is approximately -3.23 V.

Furthermore, the total current in the temperature compensation circuit is supplied by the output of the V_{BE} based reference. Based on Equation 2.37 and 2.39, the output current is given by

$$I_O = I_1 + I_2 + I_3 \approx \frac{V_{BE5}}{R_4} = \frac{V_T}{R_4} ln\left(\frac{V_{EE} - V_{BE5} - V_{BE4}}{I_{s5} R_5}\right). \tag{3.8}$$

According to Equation 3.6, the relationship between I_1 and I_2 is as follow

$$I_1 = \frac{R_2}{R_1} I_2. \tag{3.9}$$

Then, the relationship between I_O and I_2 can be expressed as follow

$$I_O = \left(\frac{R_2}{R_1} + 1\right) I_2 + I_3, \tag{3.10}$$

$$I_2 = \frac{I_O - I_3}{\frac{R_2}{R_1} + 1}. \tag{3.11}$$

Based on Equation 3.2 and 3.11, I_2 is given by

$$I_2 = \frac{I_O - I_3}{\frac{R_2}{R_1} + 1} = \frac{V_T \, ln\left(\frac{R_2}{R_1}\right)}{R_3}. \tag{3.12}$$

Then the output of the proposed reference voltage generator is given by

$$V_{REF} = -\left(\frac{R_2}{R_3} V_T \, ln\left(\frac{R_2}{R_1}\right) + V_{BE3}\right) = -\left(\frac{I_O - I_3}{\frac{R_2}{R_1} + 1} \times R_2 + V_{BE3}\right), \tag{3.13}$$

where

$$V_T = \frac{kT}{q}.$$

Theoretically, any values of R_1, R_2, R_3, R_4, and R_5 that satisfy Equation 3.13 can be used for this design. However, since the transistors used in this design are power transistors, the values of resistor should be small to ensure the transistors operate in their working region. For the temperature compensation circuit, R_1, R_2, and R_3 were set to be 10 Ω, 49.9 Ω and 3.01 Ω respectively. After R_1, R_2, and R_3 are defined, the total current of the temperature compensation circuit is known by adding I_1, I_2, and I_3. Since I_O is the collector current of the transistor Q4 in Figure 3.4, once I_O is defined, I_{b4} andV_{BE4} then can be obtained. In this design, R_4 was set to be 7.7 Ω, which is the result of two 15.4 Ω resistors in parallel. The reason R_4 needs to be small is because large R_4 could lead large V_{BE5} and I_{C5}, which will consume more power. Once R_4 is set, V_{BE5} is equal to R_4*I_O. After that, I_{C5} then can be defined. Finally, using Equation 2.36, R_5 can be calculated, which is around 50 Ω.

3.8 Circuit Simulation

A SPICE model is provided by GeneSiC along with the data sheet [19]. This model can be used in LTspice software for simulation of the GA05JT01-46. Since the GA05JT01-46 is a power device, the model is not that accurate when transistor have small bias current. In other words, the measured results do not match the simulation results as shown in Figure 3.8. At the same base current, for example 2 mA, there is a 60 mA difference between simulation and measured collector current. Figure 3.7 shows the transistor IV curve schematic in LTspice. One single transistor is used for each simulation and measurement setup.

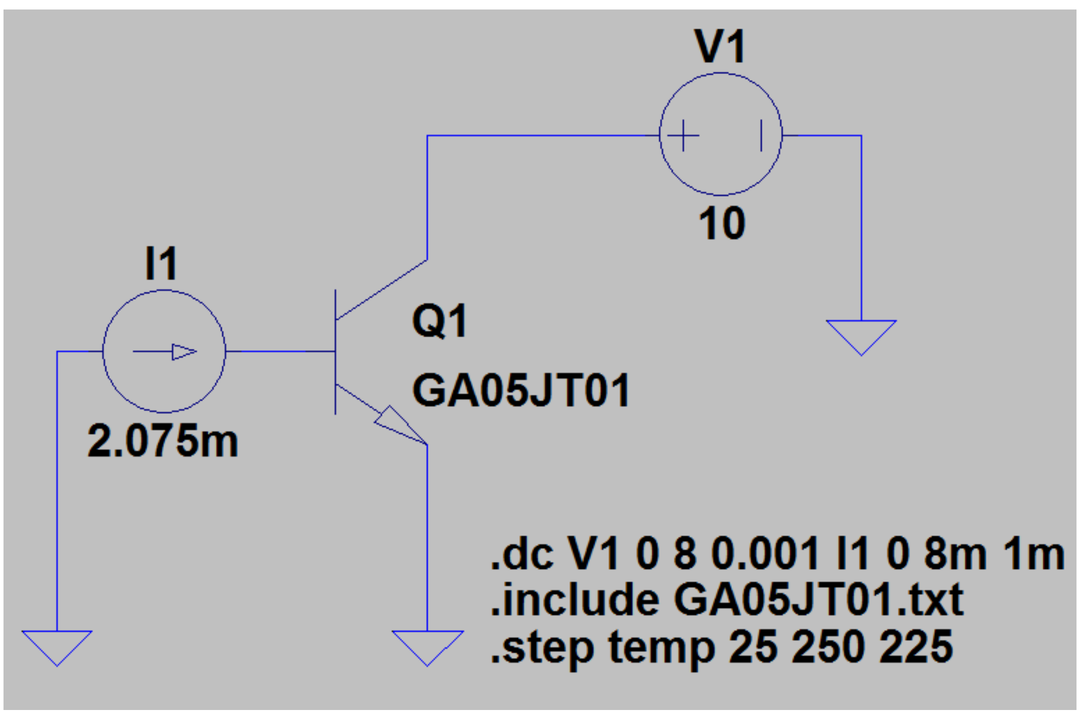

Figure 3.7: Transistor IV curve schematic (single transistor) in LTspice.

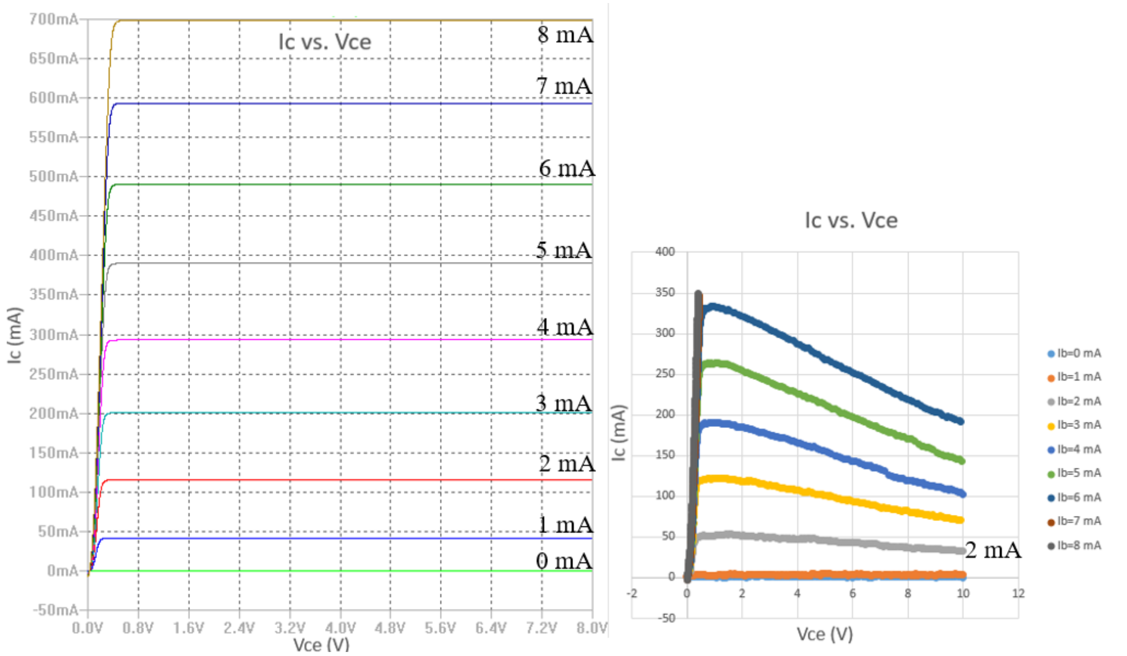

Figure 3.8: IV curves @ 25 °C: simulation (left) and measured (right).

In order to improve the accuracy of the simulation results, a five-transistor-in-series model is developed in the simulation software to be the equivalent of one single transistor in the measurement as shown in Figure 3.9.

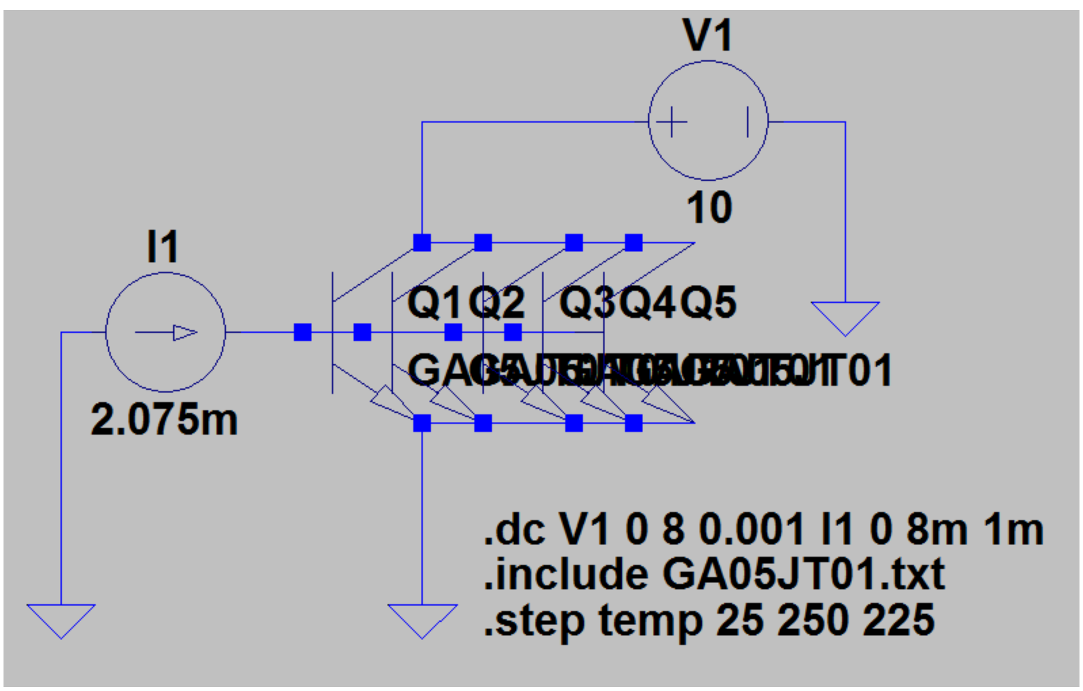

Figure 3.9: Transistor IV curve schematic (five transistors) in LTspice.

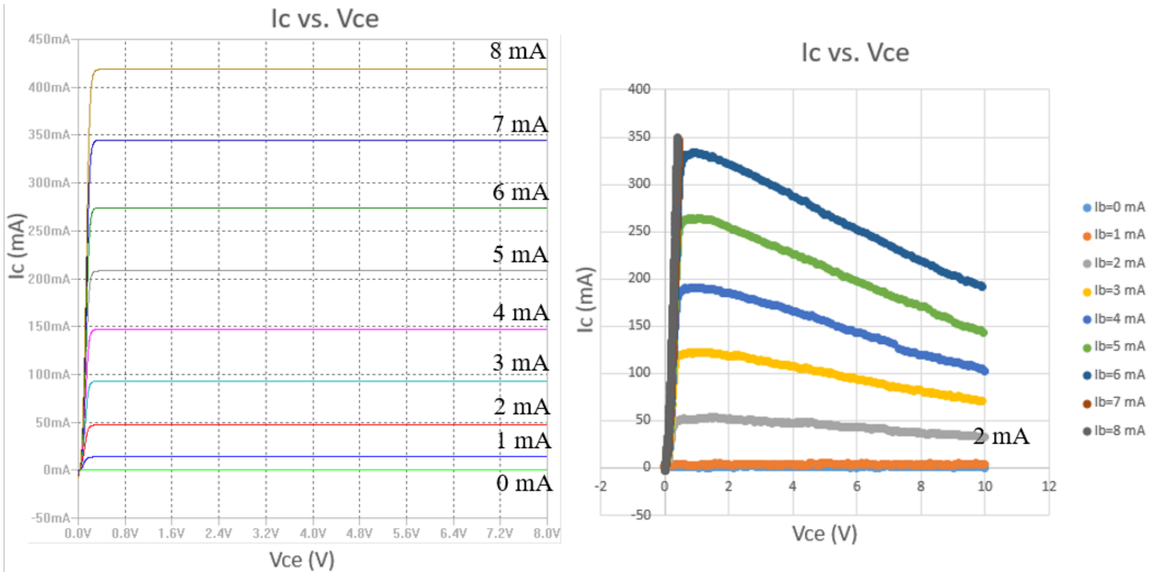

Figure 3.10: IV curves @ 25 °C: simulation (left) and measured (right).

For small base currents, which are less than 3 mA, the simulation results are close to the measurement results as shown in Figure 3.10.

Figure 3.11 shows the final schematic of the proposed voltage reference in LTspice. The five-transistor-in-series models are used in this schematic instead of single transistor so that relatively accurate results can be obtained from simulation.

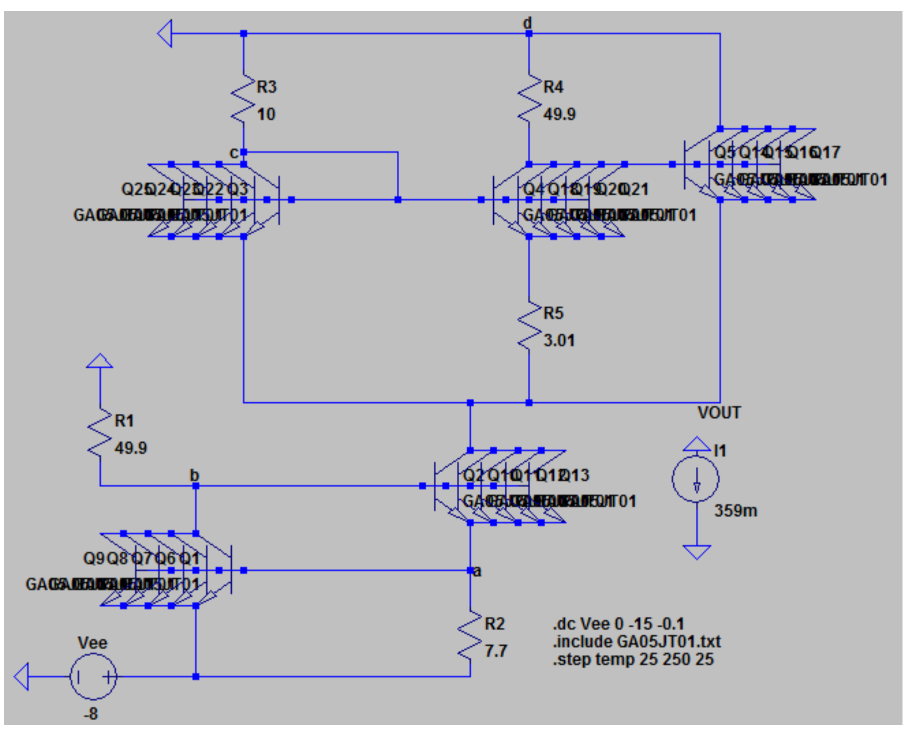

Figure 3.11: Final Schematic in LTspice.

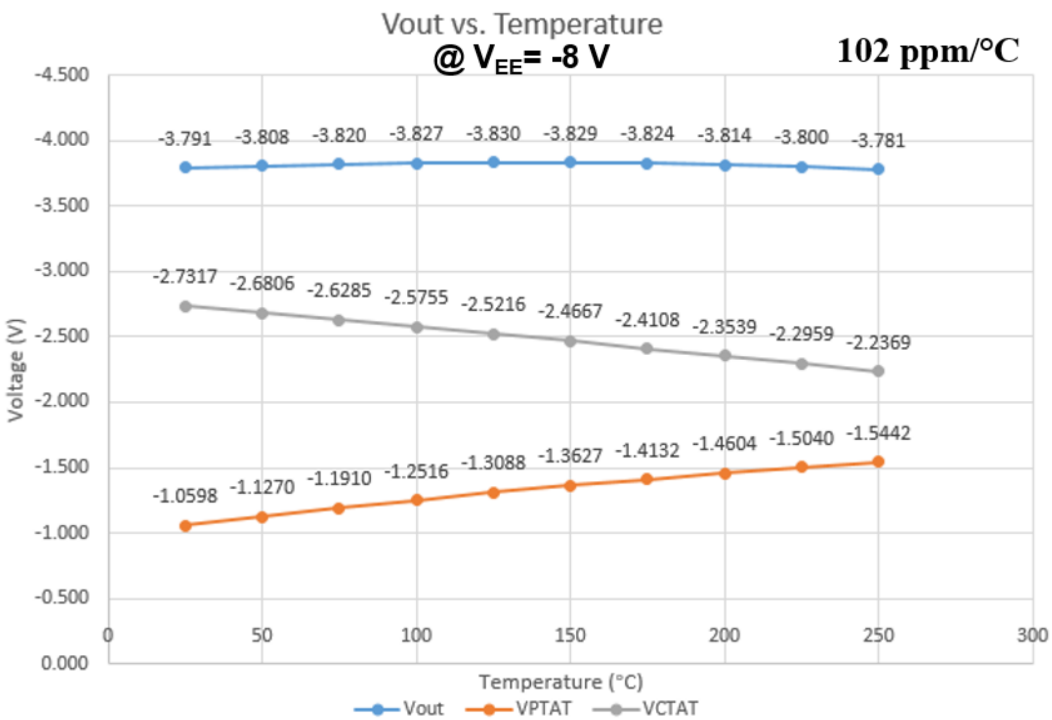

Figure 3.12: Simulation results: Output vs. Temperature @ V_{EE} = -8 V.

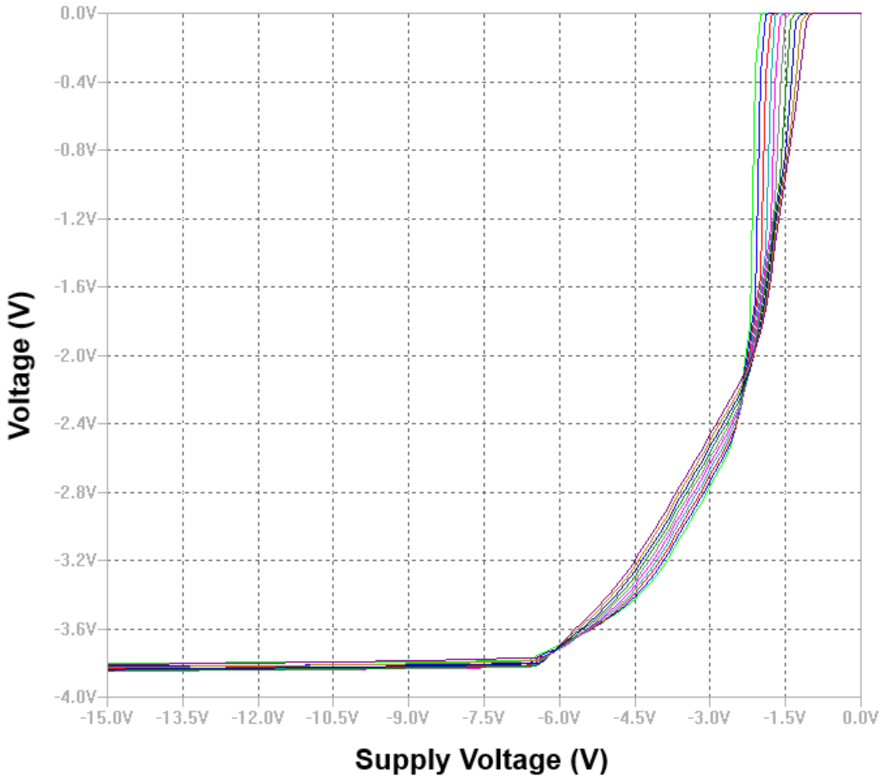

Figure 3.13: Simulation results: Output vs. Supply.

Figure 3.12 shows the simulated temperature performance of the proposed design. The output reference voltage is compensated by the PTAT and CTAT voltages. The average TC is 102 ppm/°C. Due to the accuracy issue of the model, the output voltage is intentionally designed to be greater than the bandgap voltage of 3.23. In this way, the output of the actual prototype is close to 3.23. Figure 3.13 shows the simulation results when supply varies. The output is almost supply-independent after supply reaches -6.5 V.

3.9 Prototype

Figure 3.14 shows the layout of the proposed reference voltage generator. The layout was generated using Eagle PCB design software. After that, the board was printed with a milling machine (LPKF ProtoMat S43) in the Center for Power Electronics System (CPES) lab at Virginia Tech as shown in Figure 3.15.

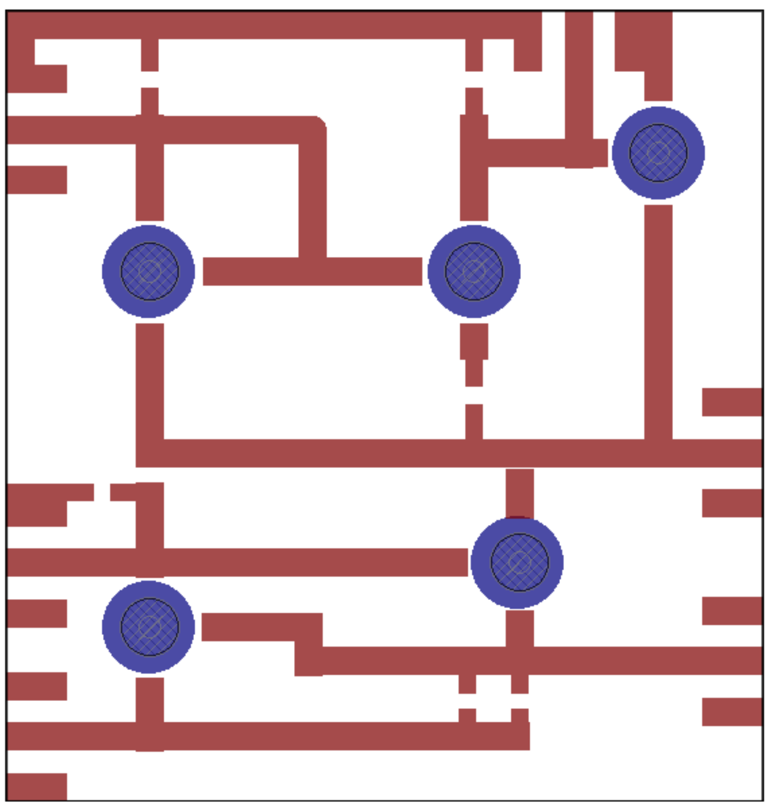

Figure 3.14: Layout of the proposed voltage reference.

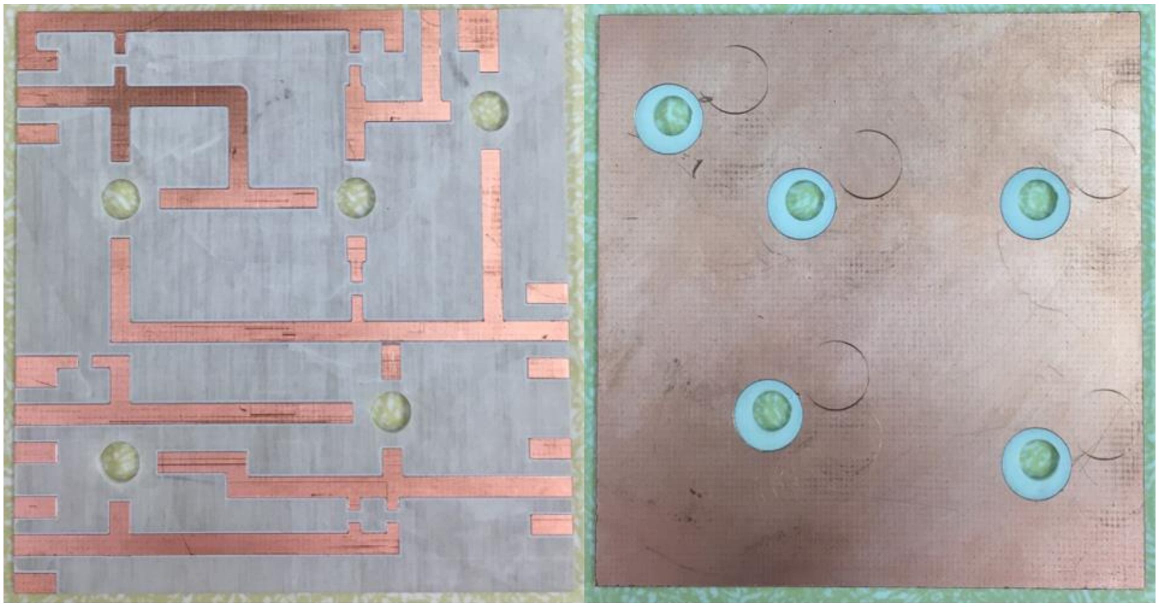

Figure 3.15: Final prototype PCB layout (front (Left) and back (Right)).

Once the board was printed, the selected active and passive components were soldered onto the board with high temperature solder paste. Figure 3.16 shows the final prototype of the proposed reference voltage generator. Five transistors were inserted from the back to the front. Six connectors were mounted on the prototype. Except the output and supply port, the other four connectors are used to monitor different voltages in the proposed voltage reference circuit to ensure the voltage reference was working properly.

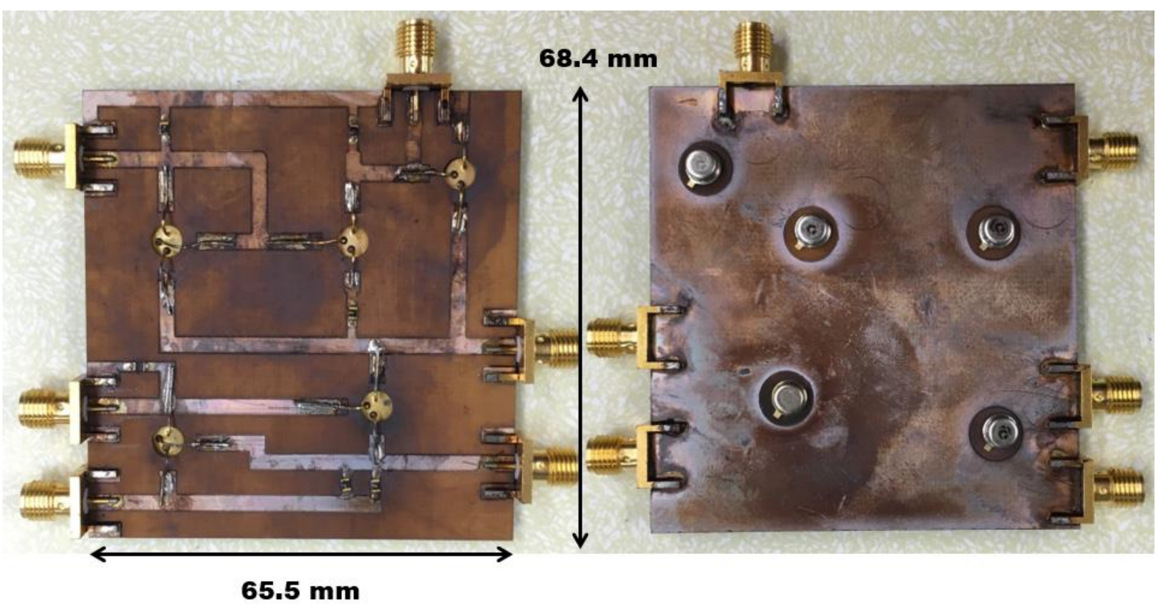

Figure 3.16: Final Prototype (front (Left) and back (Right)).

3.10 Tuning

The measurement results are not always close to the simulation results. During the design process, assumption was made that transistor Q1 and Q2 had the same saturation current Is since they are identical. However, the saturation current varies with bias current and temperature. As a result, smaller output voltage and large TC occurred for the prototype. One way to tune the output, as mentioned in Section 3.8, is to make the output greater than the bandgap voltage of 3.23. Tuning the ratio between R2 and R1 or R2 and R3 is another way to improve the output voltage value and TC of the circuit.

Chapter 4

4 Experimental Results

Contents

In this chapter, the measurement for the propose reference voltage generator are discussed in detail. First of all, the testing instruments that are used while measuring and the test setup are covered. Following by the testing instruments and setup introduction, a detailed test procedure is provided. Finally, the measurement results for the entire temperature range and overall performance comparing with other high temperature voltage references are presented.

4.1 Testing Instruments and Measurement Setup

4.1.1 Testing Instruments

4.1.1.1 Laboratory Drying Oven

Laboratory oven is one of the most necessary instruments for high temperature circuit measurements. A Yamato DX302C natural convection oven, as shown in Figure 4.1, was used for increasing the ambient temperature of the proposed voltage reference. According to its data sheet [23], the operating temperature range is from 5 °C to 300 °C with a ±10 °C variation inside the oven. It takes about forty-five minutes to reach the maximum temperature of 300 °C.

Figure 4.1: Yamato DC 302C convection oven [24]. [fair use]

4.1.1.2 Power Supply

A Rigol DP832A programmable linear dc power supply was used to provide a dc supply voltage for the proposed reference voltage generator. This is a triple output power supply [25]. Channel 1 and channel 2 can go as high as 30 V and 3A, while channel 3 is capable of 5 V an 3A. Negative supply voltage can be obtained by simply reversing the polarity of the channel. In addition, voltage and current limits are provided while setting the supply voltage to prevent the testing circuit from overload. The LCD display shows the set supply voltage, total current, and total power of the circuit in real time while measuring.

Figure 4.2: Rigol DP832A triple output power supply [26]. [fair use]

4.1.1.3 Multimeter

Five fluke 45 dual display multimeters were used to monitor five different voltages in the proposed voltage reference circuit to ensure the voltage reference was working properly and to help detecting which part of the circuit went wrong when the value of output voltage is not expected. This multimeter has two multifunction display and 16 different measurement capabilities [27].

Figure 4.3: Fluke 45 Dual Display Multimeter [28]. [fair use]

4.1.2 Measurement Setup

Figure 4.4 shows the entire measurement setup for the proposed reference voltage generator. The device under test (DUT) was placed inside the Yamato oven as shown in Figure 4.5. High temperature SMA cables, which were self-assembled with high temperature connectors and solder, were threaded into the oven from top vents and connected to the SMA female connectors on the DUT.

Figure 4.4: Test setup.

In the meantime, the combination of a BNC female to banana plug adapter connector and a BNC male to SMA female adapter is required for each power supply and multimeter to connect the high temperature cable.

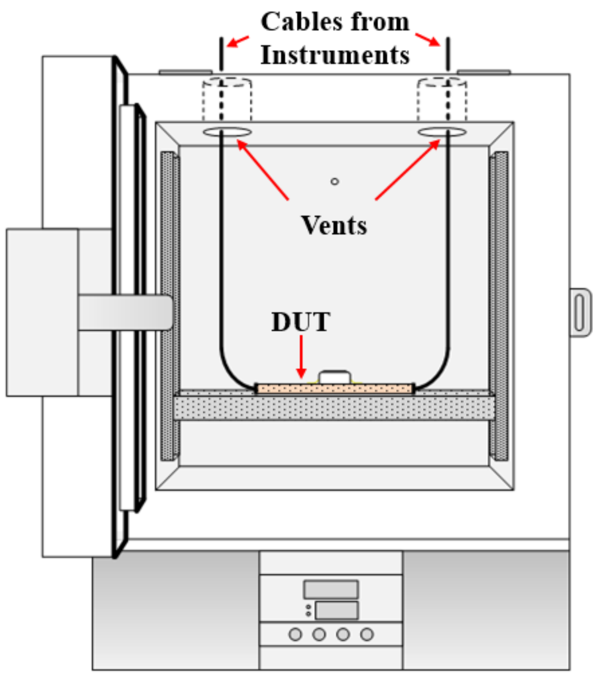

Figure 4.5: Measurement setup inside oven [29]. [fair use]

4.2 Test Procedure

The test procedure is simple but time consuming. With the same setup in Section 4.1.2, five multimeters are used to monitor five different voltages, which include output voltage, in real time. The DUT operates and is placed in the oven all the time during measurement. For temperature performance, increasing the oven temperature every 25 °C from room temperature to 250 °C and recording data of voltages at each temperature. In the meantime, at each desired temperature, the data were recorded every 10 minutes for 4 times to evaluate the time performance of the circuit. For supply variation, manually increasing power supply every 0.5 V from -2 V up to -15 V and recording all the data every 25 °C from room temperature up to 250 °C.

4.3 Measurements Results

4.3.1 Output vs. Temperature

The output performance with temperature variation of the proposed reference voltage generator is presented in Figure 4.6. As mentioned before, five different voltages, which include output voltage, were monitored by five multimeters. Data of each voltage were taken every 25 °C from room temperature up to 250 °C. It is obvious that the output voltage is almost independent of temperature and is the sum of V_{PTAT}, which is $\frac{R_2}{R_3}\Delta V_{BE}$, and V_{CTAT}, which is V_{BE3}. The average temperature coefficient is 42 ppm/°C, which meets the design specification.

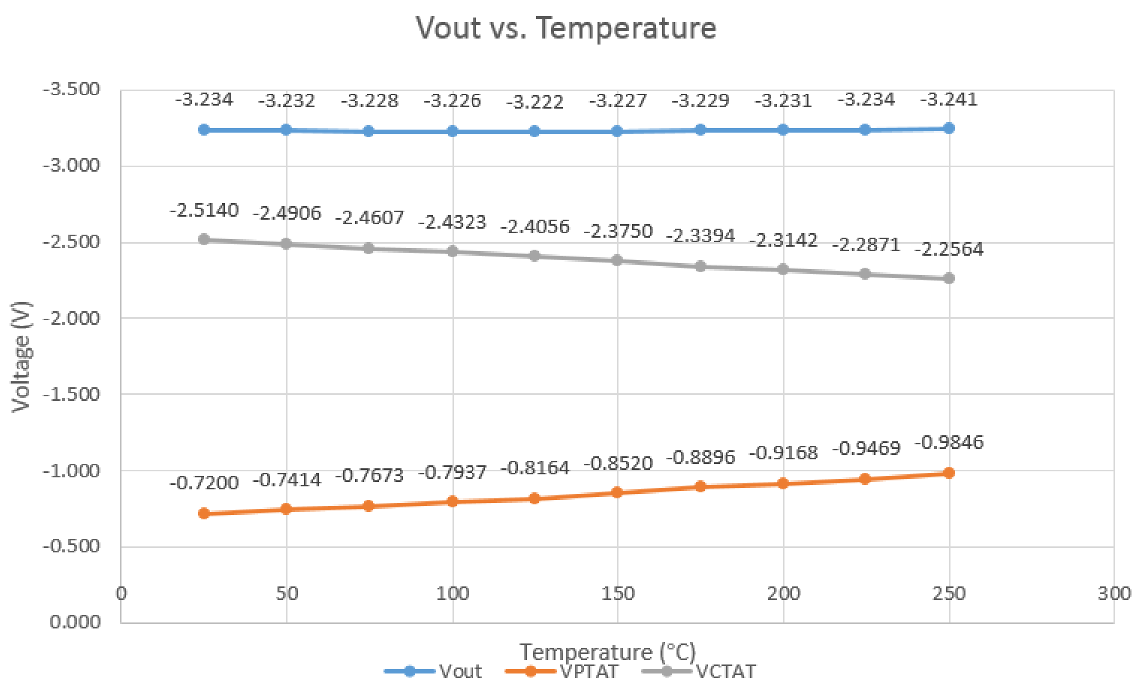

Figure 4.6: Output Voltage vs. Temperature.

4.3.2 Output vs. Supply

The output voltage variations with the power supply of the proposed voltage reference had also been tested over a wide temperature range and the results are shown in Figure 4.7.

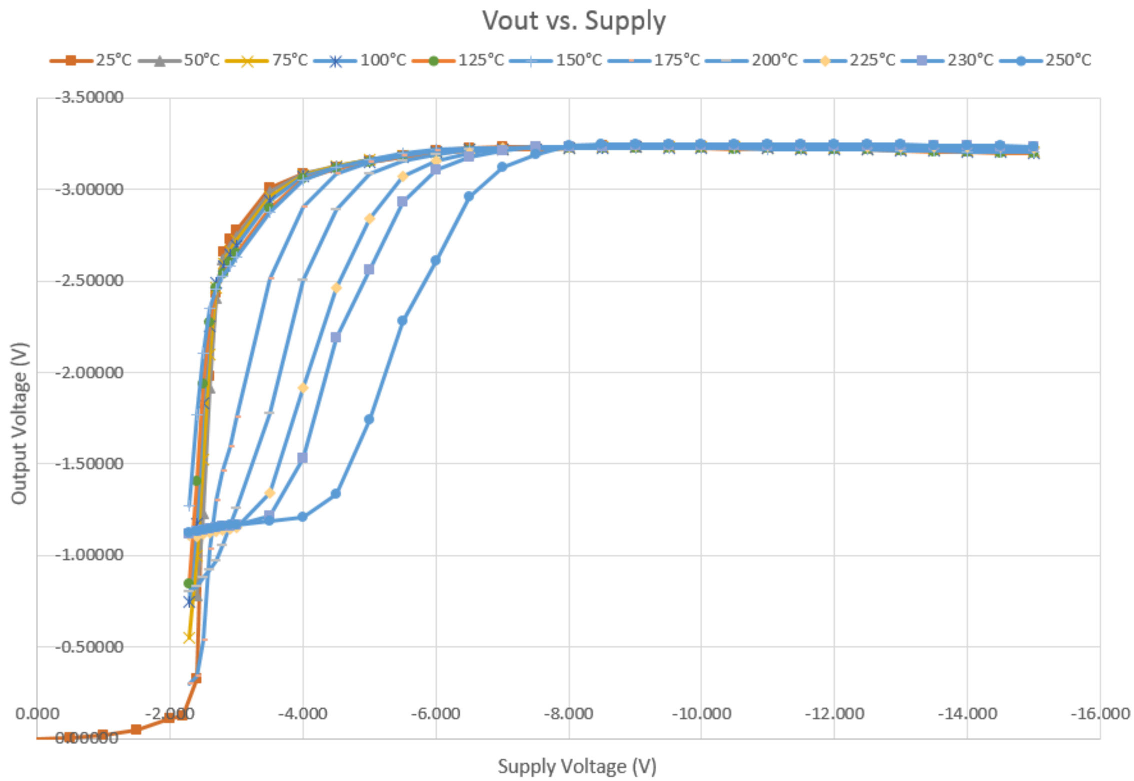

Figure 4.7: Output Voltage vs. Supply Voltage.

From 25 °C to 250 °C, the output data were taken every 0.5 V from -2 V up to -15 V every 25 °C. This result suggests that the output voltage is almost supply independent for power supply from -8 V to -15 V. It is calculated that the power supply sensitivity is -52.3 dB. Therefore, the proposed voltage reference provides an almost constant negative reference voltage around -3.23 V from 25 °C to 250 °C regardless of any change in power supply.

4.3.3 Reliability

Although the proposed voltage reference cannot be tested in the oven for hundreds of hours, it did operate at high temperature for dozens of hours while measuring. The output performance did not have any significant changes. Figure 4.8 shows the temperature performance of three measurements, where each measurement data was taken after the voltage reference operates at high temperature for several hours.

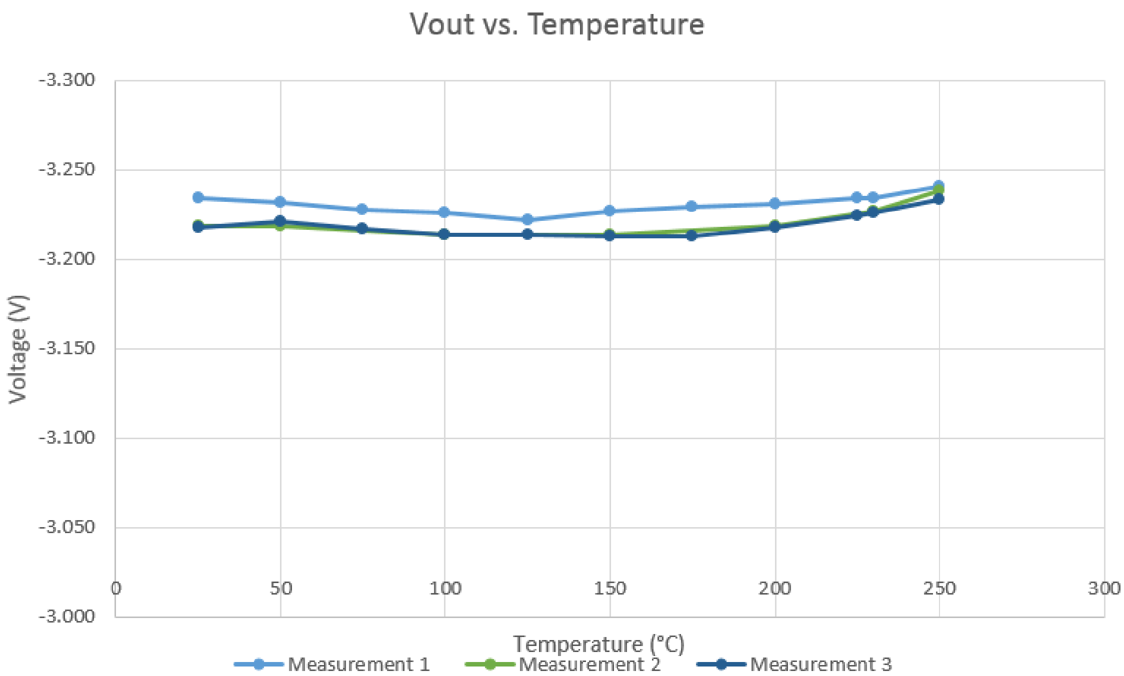

Figure 4.8: Continuous performance.

4.3.4 Overall Performance

Table 4.1 shows the comparison of this work with other high temperature voltage references. The proposed voltage reference meets all the design requirements. The TC of this voltage reference is better than average. In addition, this work has the best power supply sensitivity compare to the others. Since this work is a discrete component circuit and the transistor using is a power device, the power consumption is rather large. However, as mentioned before, power consumption is not a major concern of this work.

Table 4.1 : Comparison of this work with other voltage references.

Voltage reference	[16]	[17]	[18A]	This work
Technology	GaN	4H-SiC MESFET	4H-SiC bipolar	4H-SiC bipolar
Vref @ 25°C (V)	-2.1	4.9	3.16	-3.234
Temperature range (°C)	25-250	25-250	25-500	25-250
Temperature coefficient (ppm/°C)	<238	15	46	42
Power supply sensitivity (dB)	-35	-42.4	-17.3	-52.3
Supply voltage (V)	-9	30	7.5	-8
Power consumption (W)	7.2×10^{-3}	54×10^{-3}	29.25×10^{-3}	2.9
Area consumption (mm^2)	0.16	-	0.81	-

Chapter 5

5 Conclusion

Contents

5.1 Summary & Conclusion

A functional high temperature SiC discrete voltage reference has been demonstrated for the first time with 4H-SiC transistors. To avoid the necessity of using an OpAmp or p-type transistors, the schematic and the principle of the circuit is based on a new concept design that uses only npn transistors to achieve both temperature and supply independent with minimal transistors use. The measurement results show that over the temperature range from 25 °C to 250 °C, the voltage reference provides an almost constant negative reference voltage around -3.23 V from 25 °C to 250 °C regardless of any change in power supply with a low TC of 42 ppm/°C. The application of the proposed reference voltage generator is not limited to just oil industry. It can be used in industries like space, automotive, engines and so on.

5.2 Future Work/Improvements

There are several ways to improve this design in the future. First of all, a lower TC can be achieved by building a second-order or higher-order reference base on this design, which is a first-order reference. In addition, power consumption can be improved by modifying the circuit to have a small supply voltage. Performance may be improved by optimizing the bias point selection and resistor values. In the future, this voltage reference could also be implemented into an integrated circuit, which is much smaller compare to the current design.

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