A High Temperature 4H-SiC Voltage Reference for Depletion Mode GaN-Based Circuits

ZiHao Zhang, Jebreel M. Salem, and Dong Sam Ha
Multifunctional Integrated Circuits and System (MICS) Group
Bradley Department of Electrical and Computer Engineering
Virginia Tech, Blacksburg, Virginia, 24061, USA
E-mail: {zihaozh, jebmms10, ha}@vt.edu

***Abstract*— High temperature electronics are highly demanded for many applications such as automotive, space, and oil and gas exploration. Electronic circuits for those applications are required to operate reliably without using bulky cooling systems. Circuits based on silicon (Si) suffer from high leakage currents at high temperatures. Silicon Carbide (SiC) circuits, on the other hand, are suitable for high temperature applications due to the wide bandgap and offer high breakdown voltage and low leakage current.**

This paper presents a negative voltage reference for high temperature applications using commercial-off-the-shelf (COTS) 4H-SiC transistors. The proposed voltage reference adopts Widlar bandgap reference topology, and it aims to provide a negative reference voltage for Gallium Nitride (GaN) circuits operating at high temperatures. Measurement results indicate that the proposed circuit provides a negative reference voltage with a low temperature coefficient of 42 ppm/ºC for temperatures ranging from 25 °C to 250 °C. The proposed circuit also operates reliably for a wide supply voltage range of -7.5 V to -15 V for the temperature range.

***Index Terms*— High temperature voltage reference, negative voltage reference generator, high temperature electronics, 4H-SiC circuits.**

I. Introduction

Extreme environment electronic devices are highly demanded in recent years for many applications such as automotive, space, mining and deep-well drilling. For instance, the depletion of the easy accessible oil and gas wells has motivated the oil and gas industry to drill deeper. However, as the depth of oil wells increases, the temperature and pressure also rise. Resultantly, it necessitates electronic systems to operate reliably in harsh environments.

Typical silicon device technologies are rated with maximum junction temperatures of less than 125 °C [1]-[2]. Wide bandgap power transistors such as SiC and GaN, on the other hand, offer high junction temperatures and low thermal resistances. Typical GaN transistors operate in depletion mode to require negative bias voltages. GaN high-electron-mobility-transistor (HEMT) RF devices are used for high temperature RF circuits [3]-[6], and those circuits require temperature-compensated negative gate bias voltages to maintain reliable performance at high temperatures.

Fig. 1 shows a block diagram of a bias circuit to supply a negative bias voltage to a GaN circuit. The DC/DC converter generates a negative supply voltage for the voltage reference, which in turn provides a stable negative reference voltage to the biasing circuit. A unique requirement of the voltage reference is to be able to operate at high temperatures in addition to being insensitive to process, supply voltage, and temperature variations.

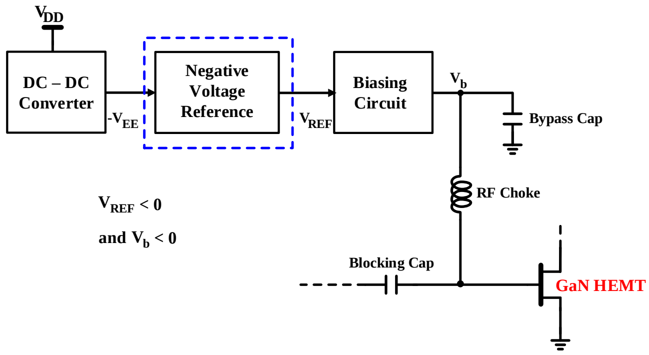

Fig. 1. Negative voltage reference for a GaN circuit.

Few commercial negative voltage references can operate up to 125 ºC [7]. There are several high temperature voltage reference generators reported recently [8]-[10], but few negative voltage references applicable to depletion mode GaN HEMT circuits [12]. Banu et al. report a temperature compensated postive voltage reference designed with 4H-SiC MESFETs [8]. The reference generator consists of a voltage regulator, a voltage reference, and a temperature sensor, and the circuit is tested up to 250 ºC. The measurement results show large chip-to-chip variations in the reference voltage, which is expected for such a complex circuit. Three convetional bandgap voltage references (BGVR) in 4H-SiC bipolar technology are reported in [9]. The three BGVRs exhibit 46 ppm/ºC, 120 ppm/ºC, and 131 ppm/ºC voltage varations for temperatures ranging from 25 ºC up to 500 ºC. However, the circuits are not immune to supply voltage variations. Rahman et al. reported high-temperature voltage and current references in SiC CMOS [10]. The voltage reference is based on a convetional bandgap circuit and uses a startup circuit and a proportional-to-absolute temperature (PTAT) current reference to compensate temperature variations. Their work reports 98.8 ppm/°C voltage variations over a temperature range of 25 ºC to 300 ºC. However, the circuit sufferes from a low power supply rejection ratio, which is typical for voltage references with the convetional bandgap circuit topology. Refer to [11] for the convetional bandgap circuit topology. All abovementioned designs are for positive voltage references. A negative voltage reference based on GaN HEMT devices is presented in [12]. The voltage reference has 0.5 mV/ºC (≈ 238 ppm/°C) temperature variations over temperatures ranging from 25 ºC – 250 ºC.

This paper presents a high temperature negative voltage reference based on COTS SiC BJT, in which a major design objective is low circuit complexity. The proposed circuit operates reliably for temperatures ranging from 25 ºC to 250

°C without employing a cooling and/or heat extraction technique. The proposed circuit also operates reliably for a wide supply voltage range of -7.5 V to -15 V for the temperature range. This paper is organized as follows. Section II describes the proposed voltage reference. Section III presents measurement results under a wide temperature range. Section IV concludes the paper.

II. PROPOSED VOLTAGE REFERENCE GENERATOR

This section presents the proposed voltage reference, which aims to provide a negative reference voltage for biasing circuits over a wide temperature range from 25 °C to 250 °C. Like other voltage references, it should be insensitive to process, voltage and temperature vairations. The design procedure involves device and material selection, circuit design, bias point selcetion, and prototyping.

A. Device and Material Selection

All active and passive components should be able to operate at high temperatures. The active device used for the proposed circuit is a commercial GeneSiC GA05JT01-46, normally-off silicon carbide npn bipolar junction transistor [13]. The power transistor has a high breakdown voltage of 100 V. It has the maximum junction temperature T_J of 210 °C, which is the highest among available COTS. The junction-to-case thermal resistance is 9.86 °C/W. Passive components for the proposed circuit are limited to resistors. Vishay thin film resistors are chosen due to its low tolerance of 0.1% and a low temperature coefficient of 15 to 55 ppm/°C over temperatures ranging from -55 °C to 250 °C.

PCB board materials also should be able to withstand high temperatures. Rogers 4003C is selected due to its dimensional stability. Estimate shows negligible expansion of the board, and the glass transition temperature of the material is greater than 280 °C, which is sufficiently high to avoid a structural failure for our prototype. The final consideration is the bonding material. A typical commercial off-the-shelf solder melts below 200 °C. Indium Corporation's "Indalloy 151" is chosen for our prototype due to its reliable connections at high temperatures and high melting temperature of 296 °C.

B. Design and Analysis of the Voltage Reference Generator

The proposed negative voltage reference shown in Fig. 2 adopts Widlar bandgap topology composed of npn transistors. The circuit consists of two blocks: the top block is for temperature compensation and the bottom one for a current source. The supply voltage is negative for the circuit to generate a negative reference voltage. The compensation circuit exploits the negative temperature coefficient of the base-emitter voltage V_{BE3} of Q_3 and the positive temperature coefficient of the difference of the two base-emitter voltages of Q_1 and Q_2 or $\Delta V_{BE}=V_{BE1}- V_{BE2}$. The reference voltage is expressed as follows:

$$V_{REF} = -V_{BE3} - \frac{R_2}{R_3}\Delta V_{BE} \qquad (1)$$

A nominally zero temperature coefficient can be obtained for V_{REF} by setting the parameters of (1) appropriately.

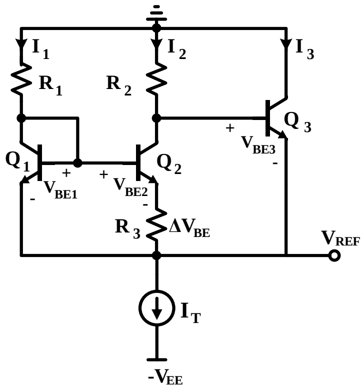

Fig. 2. Design concept for the voltage reference generator.

The other key part to the voltage reference is the current source I_T. A V_{BE}-based current source is adopted for the proposed circuit. Fig. 3 shows the schematic diagram of the current source. The current I_T is obtained as follows. The collector current I_{C5} of Q_5 is:

$$I_{c5} = I_{s5} e^{\frac{V_{BE5}}{V_T}} \qquad (2)$$

where I_{S5} is the saturation current of Q_5, and V_T is the thermal voltage of the transistor, and V_{BE5} can be expressed as:

$$V_{BE5} = V_T \ln\left(\frac{I_{C5}}{I_{S5}}\right) \qquad (3)$$

Noting $I_{C5} = I_5 = \frac{V_{EE}-V_{BE4}-V_{BE5}}{R_5}$, (3) can be rewritten as:

$$V_{BE5} = V_T \ln\left(\frac{V_{EE}-V_{BE4}-V_{BE5}}{I_{S5}R_5}\right) \qquad (4)$$

Hence,

$$I_T \cong \frac{V_{BE5}}{R_4} = \frac{V_T}{R_4} ln\left(\frac{V_{EE}-V_{BE4}-V_{BE5}}{I_{S5}R_5}\right) \qquad (5)$$

It can be seen from (5) that current I_T is weakly dependent on the supply voltage $V_{EE,}$ which is a major advantage of the topology. Noting that $V_T = kT/q$, where k is the Boltzmann's constant, T is the temperature in Kevin, and q is the charge of an electron. The current is sensitive to temperature variations. The temperature dependence can be mitigated through appropriate selection of the base currents and resistors with an appropriate low temperature coefficient.

C. Characterization of 4H SiC Transistors

A SiC transistor GeneSiC GA05JT01-46 is chosen for our prototype, and its temperature effects are investigated. Fig. 4 shows simulation results on collector current versus temperature under various base currents. As the temperature

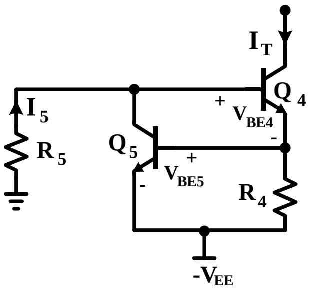

Fig. 3. A V_{BE}-based current source.

increases, the collector current decreases for a given base current. The temperature dependency of the collector current increases as the base current increases. Therefore, a small base current is more desirable to make a SiC transistor circuit less sensitive to temperature variations, and it is especially important for the current source without any temperature compensation. The bias base current for the current source is set to less than 2 mA for our prototype.

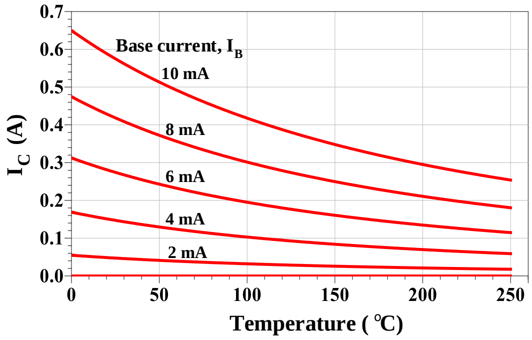

Fig. 4. Collector current versus temperature at different base currents.

D. Prototyping

The final circuit diagram of the proposed negative voltage reference is shown in Fig. 5. The top part highlighted in green is the temperature compensated reference generator and consists of three BJTs and three low TC resistors, R_1= 10 Ω, R_2=49.9 Ω, and R_3=3.01 Ω. The bottom part highlighted in blue is the current source, and it consists of two BJTs and two low TC resistors, R_4 = 7.7 Ω and R_5 = 49.9 Ω.

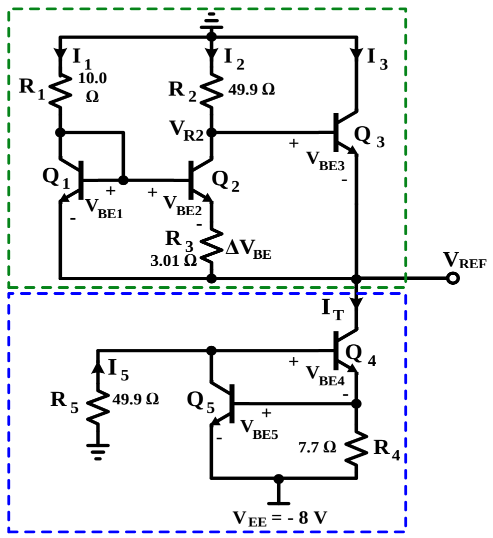

Fig. 5. Proposed negative voltage reference.

The proposed negative voltage reference shown in Fig. 6 is prototyped with 4H-SiC GeneSiC GA05JT01-46 transistors and Vishay thin film resistors, and assembled on a RO4003C PCB. Two connectors are used for the supply voltage and the reference voltage, and the other four connectors are added to

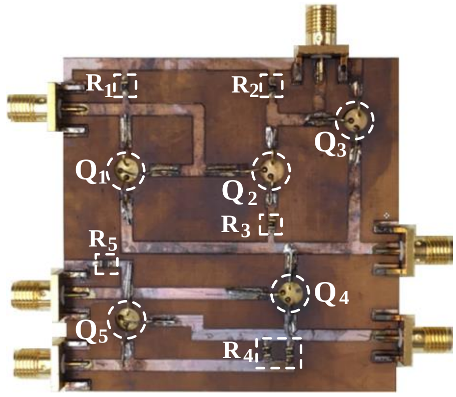

Fig. 6. Prototype of the proposed negative voltage reference.

monitor internal voltages during testing inside a temperature oven.

III. MEASUREMENT RESULTS

The prototype was tested over temperatures ranging from 25 °C to 250 °C. This section presents the measurement setup, measurement results, and performance comparison with other voltage references.

A. Experiment Setup

An experiment setup to measure the performance of the prototype is shown in Fig. 7. The prototype is placed inside a Yamato oven, and high temperature cables threaded into the top vents of the oven connect the prototype and measurement instruments. Five multimeters monitor voltages of five different nodes.

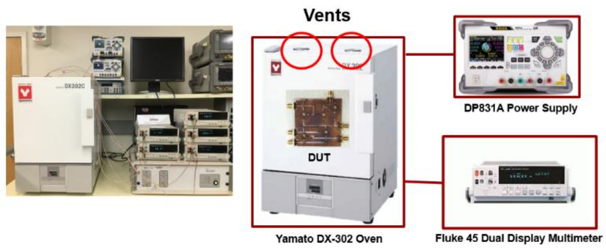

Fig. 7. Measurement setup.

B. Measurement Results

The reference voltage V_{REF} over the temperature range of 25 °C to 250 °C is shown in Fig. 8. It also shows two relevant voltages, -V_{BE3} and -(R_2/R_3)ΔV_{BE} denoted as -αΔV_{BE}, whose sum is equal to V_{REF}. The measurement result indicates that V_{REF} is fixed to around -3.23 V and nearly independent of temperature variations. The temperature coefficient is only about 42 ppm/°C, which is obtained as (max V_{REF} – min V_{REF})/(normal V_{REF} ×(T_{max} – T_{min}))×10^6. As expected, the two voltages, -V_{BE3} and -αΔV_{BE}, show opposite temperature coefficients to result in minimal temperature dependence for V_{REF}.

The dependence of the reference voltage due to supply voltage variations is measured over the temperature range from 25 °C to 250 °C, and measurement results for five

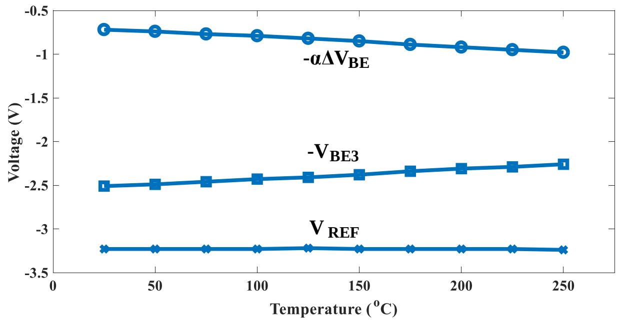

Fig. 8. Reference voltage versus temperature.

different temperatures are shown in Fig. 9. The result indicates that the reference voltage is nearly independent of the supply voltage as long as it remains from -7.5 V to -15 V C. As the temperature decreases, the magnitude of the low supply voltage decreases such as -6.0 V at room temperature. The power supply sensitivity is -52.3 dB, which is estimated using 20 Log_{10} $(\Delta V_{VREF}/\Delta V_{VDD})$.

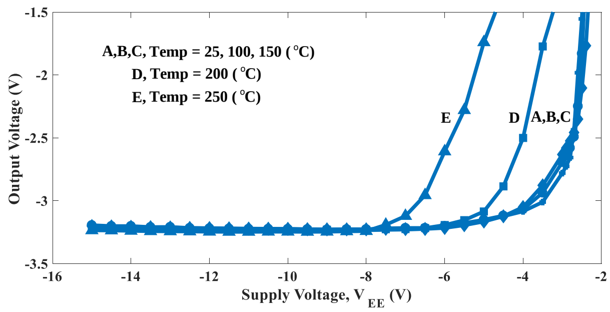

Fig. 9. Reference voltage versus supply voltage.

Table 1 compares the performance of this work with other high temperature voltage references. The works in [8] and [9] are based on ICs, and the voltage reference in [12] is realized using a GaN-on-Si HEMT platform. In spite of low complexity of the proposed reference circuit, its performance is comparable to other reference generators. Note that the power supply sensitivity of the proposed reference is the lowest among the four reference generators. The current consumption of the proposed circuit is large (=362 mA) under the supply voltage of -8 V. However, it is not a major concern for the target application, downhole communications for oil and gas exploration. We observed that the current consumption can be reduced by more than ten times simply increasing the resistances of the circuit without any major performance degradation.

IV. Conclusion

A high temperature negative voltage reference based on 4H-SiC transistors is presented. The major design objective is low circuit complexity, which adopts only five npn transistors and avoids any op amps. The measurement results indicate that the voltage reference provides nearly constant -3.23 V with a low temperature coefficient of 42 ppm/°C over temperatures ranging from 25 °C to 250 °C and supply voltages ranging from -7.5 V to -15 V. The power consumption of the reference generator is rather large, which can be reduced readily by increasing the resistances of the circuit.

TABLE I. Comparison of this work with other high temperature references

Parameter	This work	[8]	[9]	[12]
Technology	4H-SiC bipolar	4H-SiC MESFET	4H-SiC bipolar	GaN
Vref @ 25°C (V)	-3.234	4.9	3.16	-2.1
Temperature (°C)	25-250	25-250	25-500	25-250
TC (ppm/°C)	42	15	46	≈ 238
Power supply sensitivity (dB)	-52.3	-42.4	-17.3	-35
Supply voltage (V)	-8	30	7.5	-9

Reference

[1] J. D. Cressle, and H. A. Mantooth, eds. *Extreme Environment Electronics*, CRC Press, 2012.

[2] B. Parmentier, O. Vermesan, and L. Beneteau, “Design of high temperature electronics for well logging applications,” *in Proc. Int. Conf. HITEN*, Oxford, U.K., July 8–11, 2003.

[3] J. M. Salem, and D. S. Ha. "A resistive GaN-HEMT mixer for a cable modem operable up to 250° C for downhole communications, " *Journal of Microelectronics and Electronic Packaging*, vol 14, no. 1, pp. 17-25, Jan. 2017.

[4] M. Cunningham and D. S. Ha, “A high Temperature wideband low noise amplifier for downhole applications,” *International Symposium on Circuits and Systems (ISCAS)*, pp. 938-941, May 22–25, 2016.

[5] J. M. Salem and D. S. Ha, “A high temperature active GaN-HEMT downconversion mixer for downhole communications,” *International Symposium on Circuits and Systems (ISCAS)*, pp. 946-949, May 22–25, 2016.

[6] S. R. Hiemstra, B. M. Kerrigan, and D. S. Ha, “A high temperature linear wideband power amplifier for a downhole communication system,” *in Proc. of the 2017 High Temperature Electronics Network (HiTEN)*, Cambridge, U.K., July 10–12, 2017.

[7] Ampleon, “ Bias module for 50 V GaN demonstration boards,” AN11130 Datasheet, Sep 2015.

[8] V. Banu, P. Godignon, M. Alexandru, M. Vellvehi, X. Jordà, and J. Millàn, “Demonstration of temperature compensated voltage reference integrated circuit designed with 4H-SiC MESFETs,” *IEEE Int. Semiconductor Conf. (CAS)*, pp. 233–236, Oct. 2014.

[9] R. Hedayati, L. Lanni, A. Rusu, and C. Zetterling, "Wide temperature range integrated bandgap voltage references in 4H-SiC," *IEEE Electron Device Letters*, vol. 37, no. 2, pp. 146-149, Feb. 2016.

[10] A. Rahman, A. M. Francis, S. Ahmed, S. K. Akula, J. Holmes, and A. Mantooth, “High-temperature voltage and current references in silicon carbide CMOS,” *IEEE Trans. Electron Devices*, vol. 63, no. 6, pp. 2455–2461, June 2016.

[11] B. Razavi, *Design of Analog CMOS Integrated Circuits*, 2nd ed. New York: McGraw-Hill Education, 2016.

[12] K.-Y. Wong, W. Chen, and K. J. Chen, “Integrated voltage reference generator for GaN smart power chip technology,” *IEEE Trans. Electron Devices*, vol. 57, no. 4, pp. 952–955, Apr. 2010.

[13] GeneSiC Semicondcutor, “Normally – OFF Silicon Carbide Junction Transistor,” GA05JT01-46 Datasheet, Dec. 2014.