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Wide Temperature Range Integrated Bandgap Voltage References in 4H-SiC

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***Abstract*—Three fully integrated bandgap voltage references (BGVRs) have been demonstrated in a 4H-SiC bipolar technology. The circuits have been characterized over a wide temperature range from $25^{\circ}C$ to $500^{\circ}C$. The three BGVRs are functional and exhibit $46\ {}^{ppm}/_{^{\circ}C}$, $131\ {}^{ppm}/_{^{\circ}C}$, and $120\ {}^{ppm}/_{^{\circ}C}$ output voltage variations from $25^{\circ}C$ up to $500^{\circ}C$. This paper shows that SiC bipolar BGVRs are capable of providing stable voltage references over a wide temperature range.**

***Index Terms*—Silicon Carbide, bandgap reference, BJT, high temperature integrated circuit, voltage reference.**

I. INTRODUCTION

SILICON Carbide (SiC) is a wide bandgap material emerging as an excellent candidate for high temperature applications. The superior performance of SiC for operation at elevated temperatures is mainly due to its wide energy bandgap (3.2 eV for 4H-SiC) that is three times larger than the Silicon counterpart. This leads to a high intrinsic temperature (the temperature where thermally generated intrinsic concentration approaches background doping) of about $1000^{\circ}C$ [1]. Bandgap voltage references (BGVRs) working over a wide temperature range are essential in many systems, for instance in high-resolution data converters operating in harsh environment.

SOI based bandgap references with a reference voltage with $3\,\%$ inaccuracy up to $250^{\circ}C$ have been demonstrated [2]. Wide-bandgap devices are attractive candidates for providing high precision voltage references for high temperature applications. Early work demonstrates a hybrid BGVR that operates up to $300^{\circ}C$ and employs SiC Schottky diodes and cool Si opamps [3]. In [4] an integrated voltage reference using GaN HEMT operating up to $250^{\circ}C$ is demonstrated. Recently, a MESFET 4H-SiC bandgap reference which operates up to $250^{\circ}C$ has been reported in [5]. In [6], CMOS SiC voltage references have been tested up to $300^{\circ}C$. In this letter, fully integrated bandgap references fabricated in bipolar 4H-SiC that are operational in a very wide temperature range from $25^{\circ}C$ to $500^{\circ}C$ are demonstrated. The circuits have been designed and fabricated using npn transistors, epitaxial resistors in the highly doped collector layer and one interconnect metal layer on 100-mm 4H-SiC wafers with six epitaxial layers. The SiC bipolar IC process is entirely ion implantation free which results in higher current gain with elimination of defects introduced by ion-implantation. For more details about the fabrication see [7]. Fig. 1 shows the characteristic of the SiC npn transistor that is used in the circuit design. The measured output characteristics of the npn transistor over a wide temperature range for $I_B = 100\mu A$ is illustrated in Fig. 1a. In addition, Fig. 1b shows the measured forward current gain (β) versus collector current at $V_{BC} = 0V$. The maximum β is reduced from 35.5 at $25^{\circ}C$ to 15.7 at $500^{\circ}C$. The temperature dependence of the collector sheet resistance (R_{sh}) extracted from TLM measurements performed on three dies is shown in Fig.. 2. As the temperature increases up to $200^{\circ}C$, the sheet resistance decreases due to the increased ionization of donors, whereas above $200^{\circ}C$, reduction of the mobility results in higher sheet resistance.

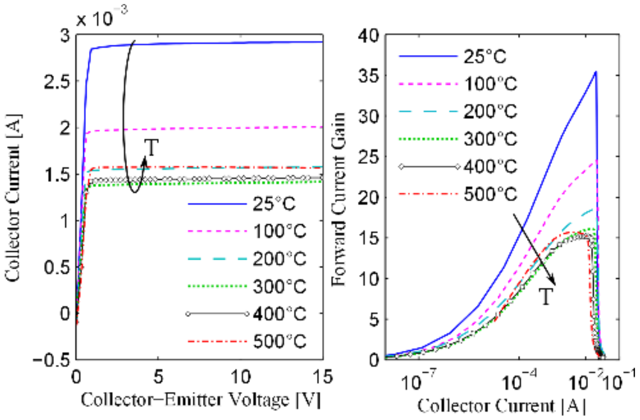

Fig. 1. (a) Measured output characteristic of SiC npn transistor, $I_B = 0.1\ mA$, from $25^{\circ}C$ to $500^{\circ}C$, (b) Measured forward current gain of SiC npn transistor at $V_{BC} = 0\,V$.

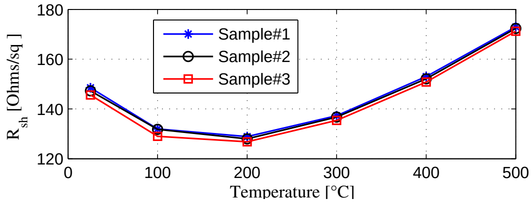

Fig. 2. Measured temperature dependence of the collector sheet resistance of three samples from $25^{\circ}C$ to $500^{\circ}C$.

II. CIRCUIT DESIGN

Three conventional bandgap references with and without opamp have been designed [8], [9]. Basically, the conventional bandgap references generate an output voltage insensitive to temperature, about the bandgap voltage of the semiconductor (about 3.2 V for SiC), by adding a proportional to absolute temperature (PTAT) voltage and a complementary to absolute

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temperature (CTAT) voltage. The latter is provided by V_{BE} that is inherently a CTAT voltage with a negative temperature coefficient of $-2\,{}^{mV}/{}_{^\circ C}$. The PTAT current can be obtained by subtraction of V_{BE} of two transistors with different emitter areas. Thereby, the reference output voltage of the bandgap [10] can be estimated as:

$$\begin{aligned} V_{ref} &= V_{BE} + K \cdot \Delta V_{BE} = V_G(T) + \frac{T}{T_r} V_{BE}(T_r) \\ &- \frac{T}{T_r} V_G(T_r) - \frac{kT}{q}(\eta - 1) ln(\frac{T}{T_r}) + K \cdot \frac{kT}{q} ln(\frac{J_2}{J_1}), \end{aligned} \tag{1}$$

where K is a constant, $\frac{J_2}{J_1}$ is the current density ratio of Q_2 and Q_1, $\frac{kT}{q}$ is the thermal voltage $V_T(26mV@25^\circ C)$, and $V_G(T_r)$ and $V_{BE}(T_r)$ are the bandgap voltage and base-emitter voltage at the reference temperature, respectively.

The conventional all npn Widlar BGVRs Type A, B, and C are shown in Fig. 3. BGVRs Type A and B eliminate the opamp and use feedbacks instead. In these circuits, the ΔV_{BE} drop across R_{PTAT} generates a PTAT current which then flows through R_1. The generated PTAT voltage is added to the V_{BE} at the output, which results in a temperature compensated voltage reference. The transistors' ratio and resistors' values have been chosen so that optimum curvature correction is achieved. The bandgap circuit Type B is highly symmetric providing that there are two feedback loops which keep the current of Q_1 and Q_2 equal. The ratio of 8 is chosen for Q_1/Q_2 to provide enough $\Delta V_{BE} = V_T ln(\frac{J_2}{J_1}) = V_T ln8$ for curvature correction. Compared to BGVRs Type A and B, the opamp in BGVR Type C provides more loop gain. However, the bandgap characteristics depend on the opamp performance such as offset and power-supply-rejection-ratio (PSRR). To prevent the circuit entering zero state, a start-up circuit is needed to inject a small current to node A. When the bandgap starts operating, the start-up circuit should turn off to eliminate errors introduced by injecting the current. In this configuration, a virtual ground at node A and B causes equal voltage drops across R_1 and R_2. Q_2 is 8 parallel transistors thus 8 times larger than Q_1, accordingly, V_{ref} can be estimated as:

$$\begin{aligned} V_{ref} &= V_{BE_2} + I_{C_2} \cdot (R_2 + R_{PTAT}) \\ &= V_{BE_2} + (1 + \frac{R_2}{R_{PTAT}}) \cdot V_T \cdot ln(8) \end{aligned} \tag{2}$$

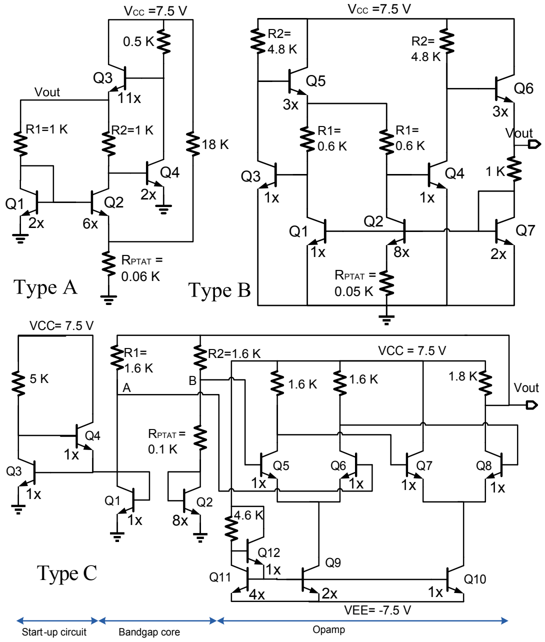
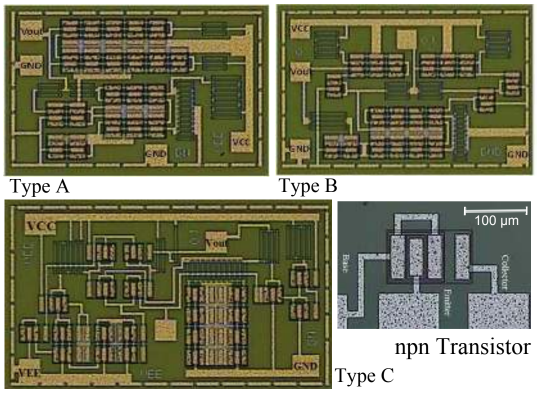


Fig. 3. The SiC bandgap reference circuit Type A, Type B, and Type C.



Type A

Type B

npn Transistor

Type C

Fig. 4. Microphotograph of the fabricated bandgap circuits Type A, B, C and closed view of the unit npn transistor (Emitter area = 30 × 70 μm^2) in 4H-SiC. For size reference, bond pads are 100 × 100 μm^2.

The bandgap circuits have been designed and simulated in Cadence using compiled Spice-Gummel-Poon (SGP) models from a previous batch at $25^\circ C$ and $200^\circ C$, while the simulation results presented in this letter are based on models extracted from devices fabricated together with the circuits. These new SGP models have been developed using ICCAP software in conjunction with Spectre. Since the temperature behavior of SiC transistors differs from Si counterparts and also considering the existence of unknown effects at extreme temperatures, a unique model that scales with temperature could not be developed. Therefore, binned temperature models (for $25^\circ C$, $100^\circ C$, $200^\circ C$, $300^\circ C$, $400^\circ C$, and $500^\circ C$) were developed and used to accurately simulate circuits over temperatures. Fig. 4 shows the microphotograph of the fabricated bandgap references Type A, B, C, and npn transistor. To mitigate the process variations and mismatches, the circuits are laid out symmetrically. Moreover, to enhance the accuracy of the PTAT resistors (R_{PTAT}), larger parallel resistors have been used to implement those resistors. BGVRs Type A and Type B have been designed and characterized with $V_{CC} = 7.5\,V$, whereas Type C is using $V_{CC} = 7.5\,V$ and $V_{EE} = -7.5\,V$ to power the integrated Opamp.

III. EXPERIMENTAL RESULTS

The bandgap circuits were tested over a wide temperature range from $25^\circ C$ up to $500^\circ C$ using on wafer measurement in a high temperature probe station and a Keithley 4200-SCS Parameter Analyzer. The measured results have been compared with simulated results based on the developed binned models using extracted parameters of a transistor right next to the circuits on a die halfway along the radius at $25^\circ C$, $100^\circ C$, $200^\circ C$, $300^\circ C$, $400^\circ C$, and $500^\circ C$. In addition, to attain

TABLE I
COMPARISON OF THREE FABRICATED BANDGAP REFERENCES IN 4H-SIC BJTS WITH BANDGAP REFERENCES IN OTHER TECHNOLOGIES

Bandgap reference	Type A	Type B	Type C	[2]	[3]	[4]	[5]	[6]
V_{ref} @$25°C$ (V)	3.16	4.35	4.19	1.18	1.447	-2.1	4.9	2.7@100$°C$
Temperature range	[25 500]$°C$	[25 500]$°C$	[25 500]$°C$	[25 250]$°C$	[25 300]$°C$	[25 250]$°C$	[25 250]$°C$	[100 300]$°C$
Temperature coefficient ($ppm/°C$)	46	131	120	112	26	< 238	15	194
Power supply sensitivity (dB)	-17.3	-15.2	-14.4	-	-	-35	-42.4	-
Supply voltage (V)	7.5	7.5	±7.5	4	±15	-9	30	18.5
Power consumption(mW)	29.25	22.45	68.75	1.28	-	7.2	54	-
Area consumption(mm^2)	0.81	0.95	1.2	-	-	0.16	-	0.27

better estimation of the circuit behavior, the variation of the resistors with temperature (calculated from Fig.2) has also been considered in the simulation phase.

Fig. 5 shows the measured V_{ref} of the fabricated BGVRs for three samples on different dies at the edge, halfway along the radius, and center of the wafer over a temperature range from $25°C$ to $500°C$. The achieved averaged voltage drift of the BGVR Type A is 0.23 $mV/°C$ from $25°C$ to $500°C$.

An averaged voltage drift of 0.64 $mV/°C$ was achieved for the BGVR Type B in the range from $25°C$ to $500°C$. However, a better averaged temperature coefficient (TC) of 10 $ppm/°C(0.046\ mV/°C)$ was observed for this BGVR in the temperature range $25°C$ to $200°C$. Finally, the BGVR Type C exhibits an averaged TC of 0.68 $mV/°C$ in the range $25°C$ to $500°C$. The high voltage variation of this bandgap compared to the other references is due to the offset at the opamp input causing non-equal voltage levels at node A and B, which leads to large voltage drift at the output. To overcome this problem an opamp with higher loop-gain [11] should be used along with a more accurate start-up circuit with lower current level.

The simulated V_{ref} of three BGVRs at six temperature bins from $25°C$ to $500°C$ are compared with the measured results in Fig.5. Simulated curves follow the measurement in all three BGVRs, which validates both the accuracy of the developed models and the circuits operation.

The output voltage variations with the supply voltage of the fabricated BGVRs have been tested and the results are shown in Fig. 6. Additionally, the power-supply-sensitivities (PSS) for ±20% supply variation are reported in Table I. The BGVRs are rather sensitive to supply voltages. To mitigate this problem on-chip regulators can be used to power the BGVRs.

Table I shows the comparison of this work with bandgap references in other technologies. BGVR Type A provides more stable V_{ref} compared to the other bipolar SiC BGVRs and can be used over the entire temperature range from $25°C$ to $500°C$. Whereas BGVR Type B has the best performance ($TC = 10\ ppm/°C$) up to $200°C$. SiC MESFETs show promising results over a small temperature range but large chip-to-chip variation due to V_{th} sensitivity [5]. On the other hand, the SiC BJTs BGVRs presented in this work, show reliable operation over a wide temperature range and low chip-to-chip variations.

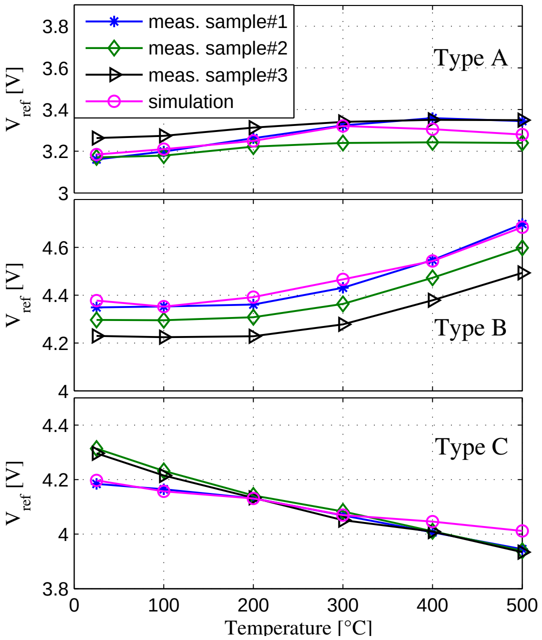


Fig. 5. Measured output voltage of three samples of fabricated BGVRs from $25°C$ to $500°C$.

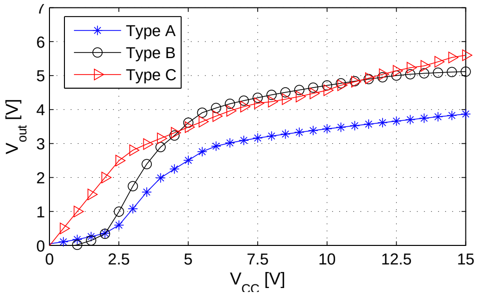


Fig. 6. Measured output voltage of the fabricated SiC BGVRs as a function of supply voltage at room temperature.

IV. CONCLUSION

Three different conventional BGVRs have been fabricated for the first time in bipolar 4H-SiC technology and characterized in the temperature range from $25°C$ to $500°C$. The measurement results show that the BGVR Type B has the best performance up to $350°C$. However, the BGVR Type A is more practical and can be used over the entire range from $25°C$ to $500°C$. The performance of the BGVR Type C is dependent on the performance of the opamp.

REFERENCES

[1] C.-M. Zetterling, *Process technology for silicon carbide devices*. London, UK: IEEE, 2002, DOI: 10.1049/PBEP002E.

[2] K. Grella, S. Dreiner, A. Schmidt, W. Heiermann, H. Kappert, H. Vogt, and U. Paschen, "High temperature characterization up to $450°C$ of MOSFETs and basic circuits realized in a silicon-on-insulator (SOI) CMOS technology," *Journal of microelectronics and electronic packaging*, vol. 10, no. 2, pp. 67–72, 2013, DOI: 10.4071/imaps.374.

[3] V. Banu, P. Brosselard, X. Jordá, P. Godignon, and J. Millán, "Demonstration of high temperature bandgap voltage reference feasibility on SiC material," in *Materials Science Forum*, vol. 645. Trans Tech Publ, 2010, pp. 1131–1134, DOI: 10.4028/www.scientific.net/MSF.645-648.1131.

[4] K.-Y. Wong, W. Chen, and K. J. Chen, "Integrated voltage reference generator for GaN smart power chip technology," *IEEE Transactions on Electron Devices*, vol. 57, no. 4, pp. 952–955, April 2010, DOI: 10.1109/TED.2010.2041510.

[5] V. Banu, P. Godignon, M. Alexandru, M. Vellvehi, X. Jorda, and J. Millan, "Demonstration of temperature compensated voltage reference integrated circuit designed with 4H-SiC MESFETs," in *Semiconductor Conference (CAS), 2014 International*. IEEE, 2014, pp. 233–236, DOI: 10.1109/SMICND.2014.6966445.

[6] A. Rahman, P. D. Shepherd, S. A. Bhuyan, S. Ahmed, S. K. Akula, L. Caley, H. Alan Mantooth, J. Di, A. Matthew Francis, and J. A. Holmes, "A family of CMOS analog and mixed signal circuits in SiC for high temperature electronics," in *Aerospace Conference, 2015 IEEE*. IEEE, 2015, pp. 1–10, DOI: 10.1109/AERO.2015.7119302.

[7] L. Lanni, B. G. Malm, M. Ostling, and C.-M. Zetterling, "500°C bipolar integrated OR/NOR gate in 4H-SiC," *Electron Device Letters, IEEE*, vol. 34, no. 9, pp. 1091–1093, Sept. 2013, DOI: 10.1109/LED.2013.2272649.

[8] R. J. Widlar, "New developments in IC voltage regulators," *IEEE Journal of Solid-State Circuits*, vol. 6, no. 1, pp. 2–7, Feb. 1971, DOI: 10.1109/JSSC.1971.1050151.

[9] A. P. Brokaw, "A simple three-terminal IC bandgap reference," *IEEE Journal of Solid-State Circuits*, vol. 9, no. 6, pp. 388–393, Dec. 1974, DOI: 10.1109/JSSC.1974.1050532.

[10] Y. P. Tsividis, "Accurate analysis of temperature effects in $I_C - V_{BE}$ characteristics with application to bandgap reference sources," *IEEE Journal of Solid-State Circuits*, vol. 15, no. 6, pp. 1076–1084, Dec. 1980, DOI: 10.1109/JSSC.1980.1051519.

[11] R. Hedayati, L. Lanni, S. Rodriguez, B. G. Malm, A. Rusu, and C.-M. Zetterling, "A monolithic, 500°C operational amplifier in 4H-SiC bipolar technology," *Electron Device Letters, IEEE*, vol. 35, no. 7, pp. 693–695, July 2014, DOI: 10.1109/LED.2014.2322335.