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500 °C Bipolar SiC Linear Voltage Regulator

Saleh Kargarrazi, *Member, IEEE*, Luigia Lanni, Stefano Saggini, *Member, IEEE*, Ana Rusu, *Member, IEEE*, and Carl-Mikael Zetterling, *Senior Member, IEEE*

***Abstract*— In this paper, we demonstrate a fully integrated linear voltage regulator in silicon carbide NPN bipolar transistor technology, operational from 25 °C up to 500 °C. For 15-mA load current, this regulator provides a stable output voltage with <2% variation in the temperature range 25 °C–500 °C. For both line and load regulations, degradation of 50% from 25 °C to 300 °C and improvement of 50% from 300 °C to 500 °C are observed. The transient response measurements of the regulator show robust behavior in the temperature range 25 °C–500 °C.**

***Index Terms*— Bipolar junction transistor (BJT), high-temperature IC, regulators, silicon carbide (SiC).**

I. Introduction

SILICON carbide (SiC) is suggested as an advantageous candidate for high-temperature electronics, because of its wide bandgap. High-temperature electronics are promoted by industries, such as downhole drilling, automotive, aviation, and aerospace. Therefore, much research has been conducted in SiC electronics for elevated temperatures. High-temperature integrated digital logic circuits [1], operational amplifiers [2], [3], and Schmitt triggers [4] are a few examples.

In this paper, we demonstrate a SiC bipolar linear voltage regulator capable of solid performance from room temperature up to 500 °C. Although this circuit topology is not expected to have a high efficiency [5], it was selected, since requiring only transistors and resistors, it could be fabricated in the available process technology [6]. Other high-temperature linear voltage regulators have been demonstrated up to date. A silicon-on-insulator (SOI) linear voltage regulator has reported a maximum operating temperature of 200 °C [7], and an nMOS SiC regulator has been successfully operated up to 300 °C [8].

II. SiC Design

The linear voltage regulator circuit is shown in Fig. 1. It consists of an error amplifier stage, a pass device, feedback resistive network, and output resistive loads, all integrated on chip. The reference voltage is, however, provided externally at this stage. This facilitates the measurement, because the reference voltage can be tuned in order to achieve different output levels. Nevertheless, since the feedback resistors are integrated, the voltage regulator is categorized as a fixed voltage regulator. The feedback resistors (as a voltage–voltage network) sense the output, and a division of the sensed voltage is compared with the reference voltage. The error (difference between reference and sensed voltage) is amplified by the error amplifier, which in turn sets the dc bias at the base of the pass device. Consequently, any variation in the output will change the dc bias of the pass device and hence the output will be regulated.

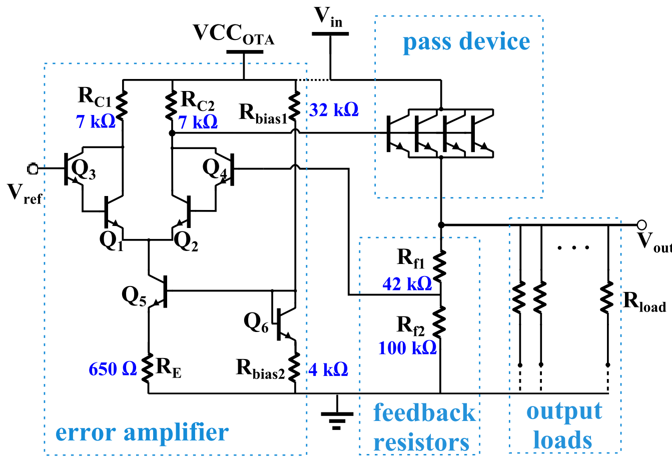

Fig. 1. Linear voltage regulator schematic (the resistor values are at room temperature).

The error amplifier employs a single-stage operational transconductance amplifier (OTA). Unlike MOSFET amplifiers, bipolar junction transistor (BJT) counterparts suffer from high base current and lower input impedance. To alleviate this drawback, the differential pair of the OTA is designed with a Darlington configuration. The pass device is the output stage of the regulator, which has an emitter-follower configuration. It is a current amplifier that does not provide voltage gain and so has little role in the loop gain of the regulator.

A. Loop Gain Analysis

Regulator gain is defined by (1), where A is the open-loop gain of the OTA and f is the feedback gain given by

$$A_f = \frac{A}{1 + A \cdot f} \tag{1}$$

$$f = \frac{R_{f2}}{R_{f1} + R_{f2}}. \tag{2}$$

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S. Kargarrazi, L. Lanni, A. Rusu, and C.-M. Zetterling are with the School of Information and Communication Technology, KTH Royal Institute of Technology, Stockholm 164 40, Sweden (e-mail: salehk@kth.se; luigia@kth.se; arusu@kth.se; bellman@kth.se).

S. Saggini is with the Dipartimento di Ingegneria Elettrica, Gestionale e Meccanica, University of Udine, Udine 33100, Italy (e-mail: stefano.saggini@uniud.it).

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Assuming equal V_{be} and forward current gain (β) for all the BJTs, the dc loop gain in no-load condition is

$$G_{\text{loop}} = A \cdot f \approx \frac{1}{8V_T} \frac{\beta}{\beta + 1} \frac{V_{\text{in}} - V_{\text{be}}}{\left(1 + \frac{R_{\text{bias1}}}{R_{\text{bias2}}}\right) + \frac{R_{\text{bias1}}}{(\beta+1)R_E}} \frac{R_{C1}}{R_E} \cdot f. \tag{3}$$

The performance of the linear voltage regulator depends on the dc loop gain. Equation (3) indicates that the dc loop gain is temperature dependent, in which $V_T(=kT/q)$, β, and V_{be} (-2 mV/°C) vary by temperature and influence the equation.

B. Temperature Compensated Biasing

The resistors values fall as temperature rises up to ~200 °C. Assuming a constant biasing current for the OTA, decrease of the resistors R_{C1} and R_{C2} can significantly reduce the gain of the OTA. The biasing network can be designed in order to provide higher collector current for the gain stages as temperature increases.

The current tail value for the OTA is derived from the equation of biasing network. It can be approximated as

$$I_{\text{tail}} \approx \frac{V_{\text{in}} - V_{\text{be}}}{\left(1 + \frac{R_{\text{bias1}}}{R_{\text{bias2}}}\right) \cdot R_E}. \tag{4}$$

Considering the effect of V_{be} (-2 mV/°C) and R_E in (4), it is concluded that more tail current is available for the OTA at higher temperatures, which results in higher gain of the OTA. This effect opposes the OTA gain reduction due to the temperature dependence of R_{C1} and R_{C2}. Therefore, the biasing network helps to compensate the gain reduction caused by temperature increase.

C. Stability Issue

The system has two poles; one of them is associated with the base of the pass device and the other one with the output of the regulator. Owing to the low output impedance of the pass device in emitter-follower configuration, the pole associated with the output of the regulator is pushed to high frequencies. The OTA has only one gain stage; there is no any other low-frequency node in the loop, and the stability of the voltage regulator can be inferred.

D. Chip Layout

The 4H–SiC process technology used for fabricating this circuit has already been reported in [6] and [9]. Starting from a six-layer epitaxial structure, vertical NPN transistors and integrated resistors in the highly doped collector layer were realized. The linear voltage regulator circuit consists of ten BJT devices with the size of 125.5 μm × 85 μm. Fig. 2 shows the fabricated regulator, and an extra pass device that can be characterized separately.

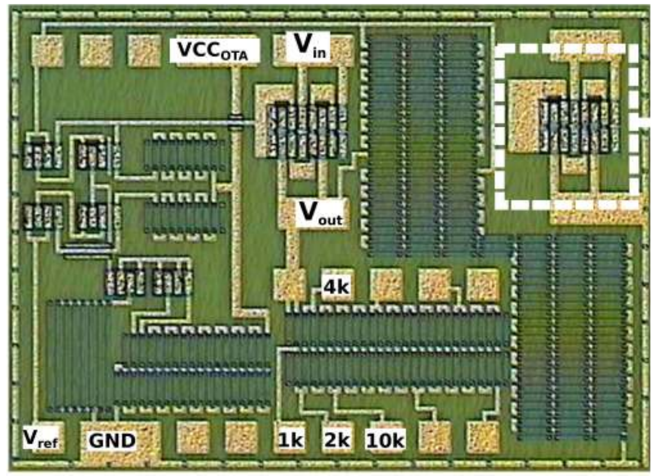

Fig. 2. Optical image of the fabricated chip (1.9 mm × 1.4 mm). Dashed box: extra pass device.

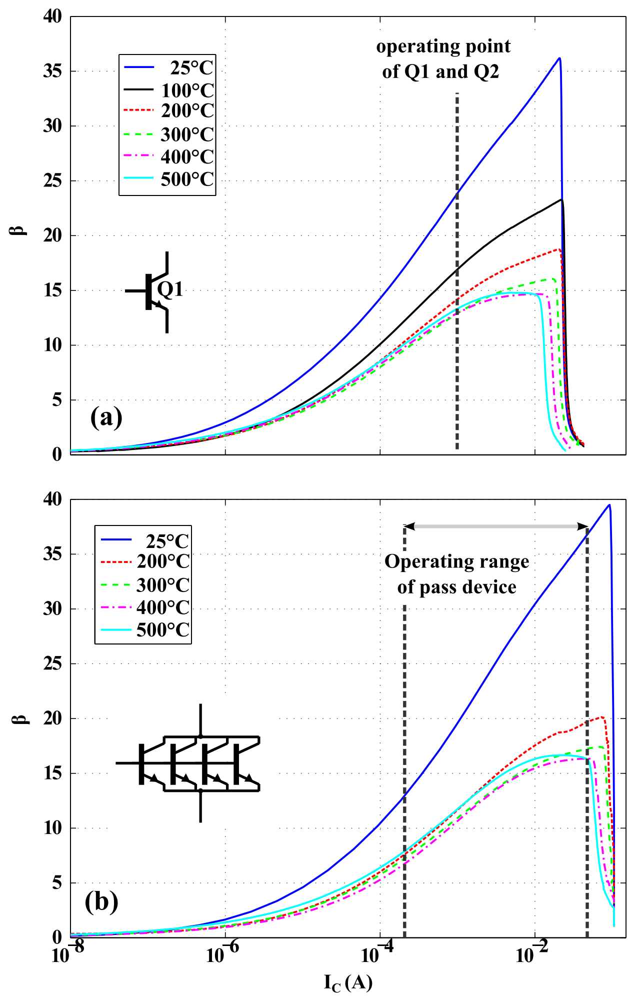

Fig. 3. Measured current gain plot with $V_{\text{BC}} = 0$ of (a) single BJT (with an indication to the operation point of Q_1 and Q_2 in OTA stage) and (b) pass device (with an indication of operating range based on different load currents).

III. Experimental Results and Discussions

On-wafer characterization was performed on a temperature-controlled hot-stage. The measurements were conducted using either parameter analyzer or oscilloscope at each temperature.

A. Device Characterization

A single BJT and the pass device were characterized individually. Fig. 3 presents the current gain plot of a single BJT and the pass device with $V_{\text{BC}} = 0$ V. Fig. 3(b) also

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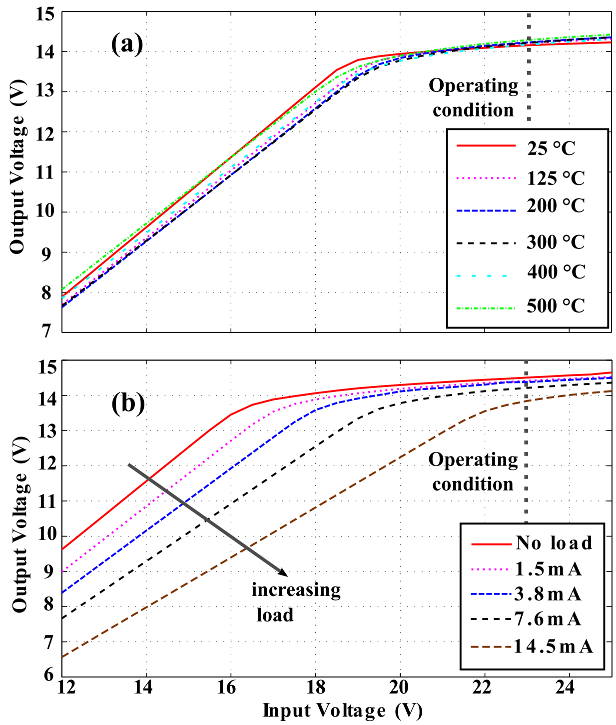

Fig. 4. (a) Measured output variation at different temperatures (25 °C–500 °C) in medium load condition (7 mA/2 kΩ). (b) Output variation at 300 °C in different load conditions.

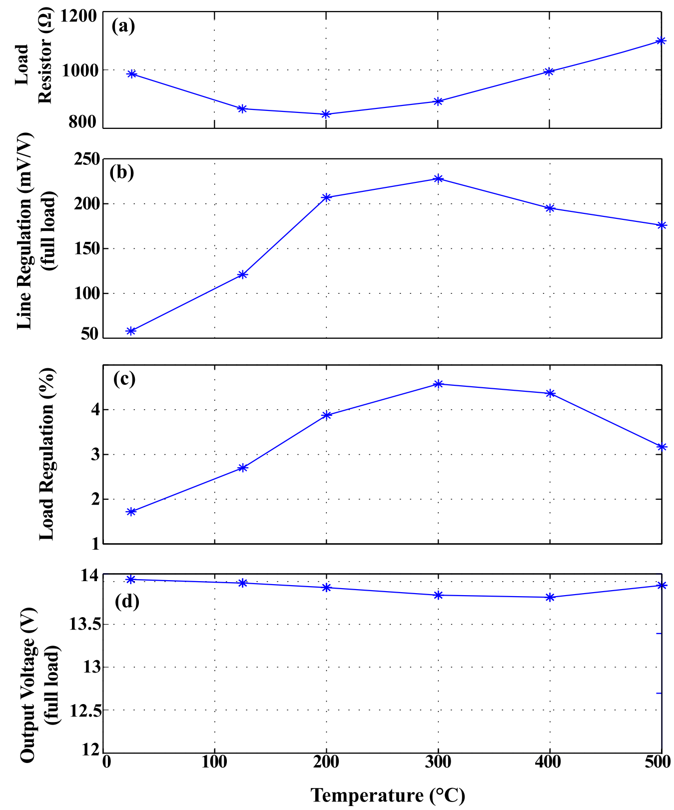

Fig. 5. Measured temperature behavior. (a) Load resistor (corresponds to the 1-kΩ designed resistor). (b) Line regulation in full-load condition. (c) Load regulation. (d) Output voltage in full-load condition.

highlights the operating range of the pass device in different loading conditions. The pass device consists of four devices in parallel and compared with the single BJT provides higher collector current ratings, as can be observed in Fig. 3(b).

B. Circuit Characterization

The feedback resistors ratio defines the relation between the output and the reference voltage: $V_{\text{out}} = V_{\text{ref}} \cdot (1 + R_{f1}/R_{f2})$. Using a 10 V reference voltage and an input of 23 V, result in 14.3 V output voltage in no-load condition. All of the measurements of this paper were performed with VCC_{OTA} and V_{in} connected to the same power supply. The input voltage is swept and the output voltage is measured.

The measured output versus input of the regulator for a medium load condition (7 mA/2 kΩ) is shown in Fig. 4(a). The regulated voltage is fairly robust in the range 25 °C–500 °C. Furthermore, in order to investigate the load regulation, the regulator was loaded with different on-chip resistors. Fig. 4(b) presents the output variation in different load conditions. Each current value in Fig. 4(b) corresponds to an integrated resistor of Fig. 2. The load currents are measured at each temperature considering the temperature variation of the integrated resistors. Fig. 5(a) shows the variation of the 1-kΩ resistor in the temperature range 25 °C–500 °C.

C. Performance Evaluation

Line and load regulations $[(\Delta V_{\text{out}}/\Delta V_{\text{in}}), (\Delta V_{\text{out}}/\Delta I_{\text{load}})]$ are two performance metrics of voltage regulators. To further explore the performance of the SiC NPN linear voltage regulator, the line regulation in full-load condition (15 mA) and the load regulation are derived and presented in Fig. 5(b) and (c), respectively. The line regulation is calculated based on ±5% variation from the nominal input voltage. It varies in the range 30–65 (mV/V) in no-load condition and in the range 50–230 (mV/V) in full-load condition. The load regulation follows a similar trend and remains in the range 2%–5% for the whole temperature range up to 500 °C. Both the line and the load regulations have the maximum at 300 °C. After this temperature, both parameters slightly improve. Moreover, the regulator output voltage temperature variation is <2% in the range 25 °C–500 °C [Fig. 5(d)], suggesting stable operation of the circuit in this wide range of temperature.

To measure the transient response of the regulator to instantaneous current loads, the output voltage was initially measured at a nominal input voltage (23 V). The reference voltage was adjusted in order to get 15 V at the output in no-load condition. A 1-kΩ on-chip resistor was used as the load, whose one end is connected to the output of the regulator and the other end is floated. The floated end was controlled with a voltage pulse source providing a 10-kHz square wave pulse with rise and fall times of 350 ns, switching between GND and 15 V [Fig. 6(a)]. The measured output voltage and current are shown in Fig. 6(b) and (c), respectively. Because of the on-chip loads, this measurement method accounts for the loads at high temperatures. However, the current passing through the on-chip resistor cannot accurately

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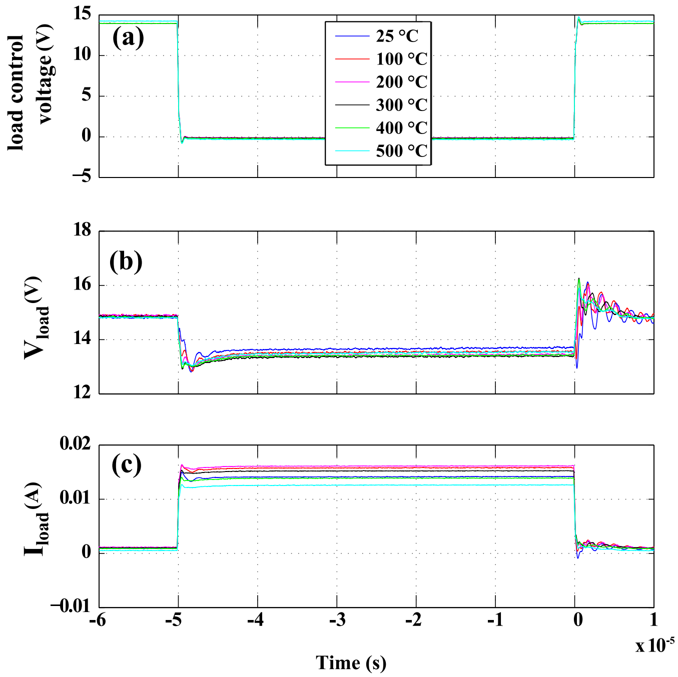

Fig. 6. Transient response to 15-mA current. (a) Control voltage. (b) Load voltage. (c) Load current.

be controlled due to the temperature dependence of the resistor. Therefore, the output currents are calculated based on the measurement of the on-chip resistor at each temperature.

In turn ON and turn OFF, the load voltage settles after 5 and 10 μs, respectively. Lower output resistance of regulator in turn ON leads to lower RC constant and faster transition in comparison with turn OFF. It has to be noted that the transient measurements are also limited by the slow response of the pulse source (350 ns) used as control voltage. In turn OFF, an overshoot ~16 V is observed before the load voltage settles at 15 V. The undershoot value in turn ON is negligible. The regulator shows a robust transient response versus temperature with almost no transient performance degradation from room temperature up to 500 °C.

The linear voltage regulator in no-load condition consumes 61–81 mW at 23 V power supply in the whole range of temperature. In full-load condition, the loss in the pass device is added (120 mW) that leads to an efficiency of ~50% over the entire temperature range. This is expected for a bipolar linear voltage regulator with a pass device operating in active region [5].

Although no other voltage regulator for temperatures >300 °C has been reported so far, Table I compares this design with a recent nMOS linear voltage regulator aimed for high-temperature, high-power applications [8]. The nMOS linear voltage regulator has been designed and tested for load currents as high as 2 A, and therefore targets a wide range of power applications, whereas the reported bipolar regulator is designed for loads ~15 mA, using a simpler OTA and a smaller pass device together with on-chip feedback and load resistors.

TABLE I

COMPARISON OF THIS WORK WITH A RECENT HIGH-TEMPERATURE LINEAR VOLTAGE REGULATOR

	NMOS 4H-SiC [8]	Bipolar 4H-SiC (this work)
Load current	2A (high-power)	15mA (low-power)
Temperature	300 °C	500 °C
Integration level	External feedback resistors	Fully-integrated
OTA Complexity/Gain	3 gain stages (36 dB)	1 gain stage (30 - 34 dB)
Chip size	$3.1mm^2$	$2.6mm^2$

To improve the performance of the voltage regulator (i.e., line and load regulations), higher loop gain is desired, and therefore an OTA with more gain stages should be employed. In addition, to achieve higher output power, a pass device with higher current capability (e.g., by paralleling more BJTs) should be used. Higher load current also translates into higher base current for the pass device. Considering the low current gain of the BJT devices (~50), using a pass device with Darlington topology is suggested. However, high dropout voltage of the Darlington pair ($2 \cdot V_{\text{be}}$) should also be considered. Furthermore, the external reference voltage, as the only off-chip component, can also be integrated on-chip in the future attempts.

IV. CONCLUSION

A fully integrated linear voltage regulator in 4H–SiC bipolar technology is demonstrated, and its operation in the temperature range from 25 °C up to 500 °C is discussed. For 15 V output voltage and up to 15-mA load current, a stable output voltage with <2% variation with temperature is observed in the whole temperature range. The line and load regulations vary in the range 50–230 (mV/V) (full-load condition) and 2%–5%, respectively. The voltage regulator circuit consumes 61–81 mW from a 23 V power supply in no-load condition. In addition, the transient response of the regulator to a 15-mA load current shows no significant performance degradation with temperature increase.

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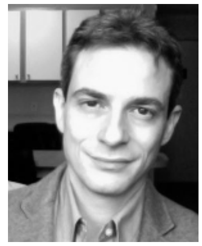
Saleh Kargarrazi (M'10) received the B.Sc. degree in electrical engineering from the Ferdowsi University of Mashhad, Mashhad, Iran, in 2008, and the M.Sc. degree in system-on-chip design from the KTH Royal Institute of Technology, Stockholm, Sweden, in 2010, where he is currently pursuing the Ph.D. degree.

His current research interests include analog and digital IC design in bipolar SiC for high-temperature power applications.

Luigia Lanni received the M.Sc. degree in electronic engineering from the University of Naples Federico II, Naples, Italy, in 2009, and the Ph.D. degree in information and communication technology with a specialization on micro and nanoelectronics from the KTH Royal Institute of Technology, Stockholm, Sweden, in 2014.

She is currently with Intel Corporation, Hillsboro OR, USA.



Stefano Saggini received the (*cum laude*) Degree in electronic engineering and the Ph.D. degree in electronic engineering from the Polytechnic University of Milan, Milan, Italy, in 2000.

He has been an Assistant Professor with the University of Udine, Udine, Italy, since 2006. His current research interests include the integration of digital and mixed-signal controller for switched-mode power supply and energy harvesting systems.

Ana Rusu (M'92) received the M.Sc. degree in electronics and telecommunications from the Technical University of Iaşi, Iaşi, Romania, in 1983, and the Ph.D. degree in electronics from the Technical University of Cluj-Napoca, Cluj-Napoca, Romania, in 1998.

She has been with the KTH Royal Institute of Technology, Stockholm, Sweden, since 2001, where she is currently a Professor of Electronic Circuits for Integrated Systems.

Carl-Mikael Zetterling (S'91–M'97–SM'01) received the M.Sc. degree in electrical engineering and the Ph.D. degree from the KTH Royal Institute of Technology, Stockholm, Sweden in 1991 and 1997, respectively.

He is currently a Professor of Solid State Electronics. His field of research is process technology and device design of high power devices and high temperature integrated circuits in SiC.