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A SiC BJT-Based Negative Resistance Oscillator for High-Temperature Applications

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ABSTRACT This brief presents a 59.5 MHz negative resistance oscillator for high-temperature operation. The oscillator employs an in-house 4H-silicon carbide BJT, integrated with the required circuit passives on a low-temperature co-fired ceramic substrate. Measurements show that the oscillator operates from room temperature up to 400 °C. The oscillator delivers an output power of 11.2 dBm into a 50 Ω load at 25 °C, which decreases to 8.4 dBm at 400 °C. The oscillation frequency varies by 3.3% in the entire temperature range. The oscillator is biased with a collector current of 35 mA from a 12-V supply and has a maximum dc power consumption of 431 mW.

INDEX TERMS 4H-SiC BJT, high-temperature, LTCC, negative resistance, oscillator.

I. INTRODUCTION

Silicon carbide (SiC) and gallium nitrite (GaN) technologies are excellent candidates for developing high-temperature (HT) sensor systems capable of operating beyond the commercial and military specifications of silicon-based-electronics [1]. Such HT sensor systems are desired for industries like spacecraft, oil and gas drilling, aviation and automotive [2]. However, the data from these sensors is of limited utility unless it is transmitted out of the hot environment using HT communication systems.

Oscillators are a critical component of communication systems and are used, along with other circuits, for frequency translation, modulation and demodulation of the signals in the transceiver chain. Several HT oscillators based on SiC and GaN devices have been previously reported in the literature. In [3], 230 °C operation of a Colpitts oscillator, based on Qorvo's GaN HEMT and prototyped on a Rogers-4003C substrate, has been demonstrated. A 58 MHz lamb-wave oscillator, based on GaN HEMT on Si substrate, has been shown to operate up to 250 °C in [4]. Both these oscillators were provided with fixed gate/drain voltages during their HT characterization. SiC MESFETs from Cree were used by NASA to prototype a number of HT oscillators on alumina substrates [5]–[9]. In contrast to [3] and [4], the gate voltage of these oscillators was varied with temperature to maintain a constant biasing current. In [5], 125 °C operation of a 515 MHz differential oscillator into a 50 Ω load has been presented. 1 GHz Clapp oscillators have been shown to operate up to 200 °C [6] and 270 °C [7]. In [8], 200 °C and 250 °C operation of 720 MHz and 940 MHz oscillators, respectively, have been demonstrated. In [9], 30 MHz and 90 MHz SiC MESFET Clapp oscillators have been shown to operate up to 470 °C. However the oscillators in [9] were unloaded whereas to facilitate integration with antennas or other blocks of a communication system, the oscillator is typically required to drive a 50 Ω load. Furthermore, the biasing network, which is an important part of the oscillator, was also not exposed to HT in [9]. In this brief, we present an oscillator working up to 400 °C while addressing the aforementioned issues. The oscillator employs an in-house SiC BJT and is prototyped on a low-temperature co-fired ceramic

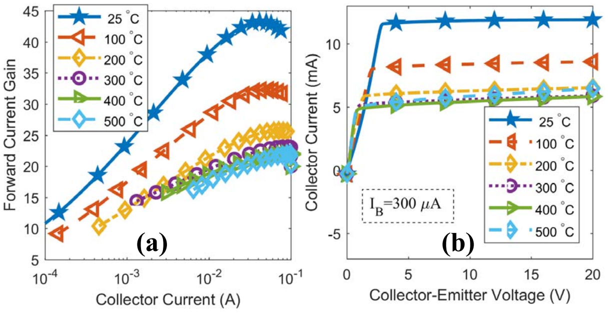

FIGURE 1. **(a) Forward current gain and (b) output characteristics of the SiC BJT at various temperatures.**

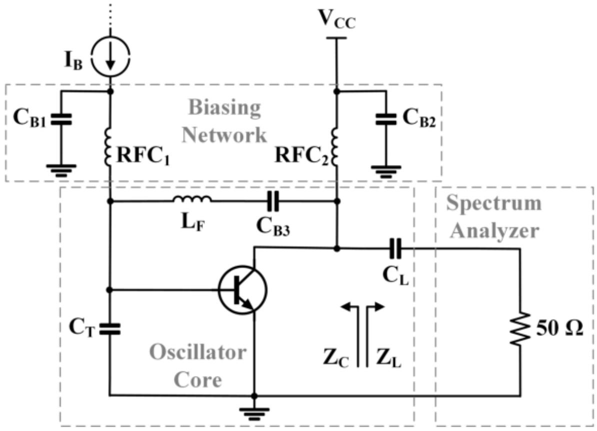

FIGURE 2. **Schematic of the negative resistance oscillator.**

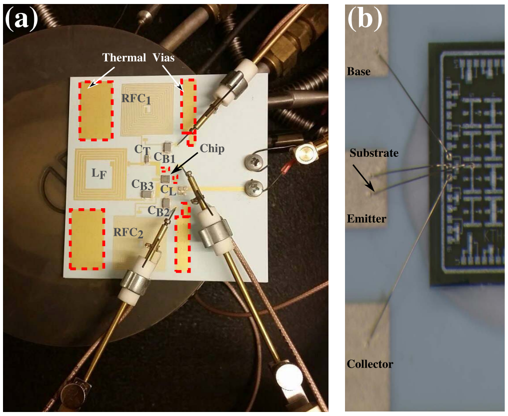

FIGURE 3. **(a) Oscillator prototype . (b) SiC chip showing the BJT in this work bond-wired to the LTCC (chip also includes BJT variants with different dimensions/finger count and characterization structures).**

(LTCC) board. The circuit is designed to have an oscillation frequency of 59.5 MHz, which is dictated by the specifications that we envision for our HT communication system [10], [11].

II. DESIGN AND PROTOTYPING

The SiC BJT used in this work was fabricated on a 4-in, 4H-SiC wafer with six epi-layers [10]. The BJT consisted of four emitter fingers, with a finger length and width of 40 μm × 10 μm, respectively. Fig. 1(a) and Fig. 1(b) shows the measured current gain and output characteristics of the BJT, respectively. More information on the fabrication and the high-frequency performance of SiC BJTs can be found in [10].

The proposed oscillator is shown in Fig. 2. It is based on a negative resistance oscillator (NRO) topology and is designed and simulated in Keysight ADS using the measured S-parameters of the SiC BJT at four temperatures (25 °C, 100 °C, 200 °C, and 300 °C). In order to oscillate, the NRO must satisfy the following start-up conditions while driving a 50 Ω load [12]:

$$|\mathrm{Re}\{Z_C(f_\circ)\}| > 50\ \Omega \tag{1}$$

$$\mathrm{Im}\{Z_C(f_\circ)\} = -\mathrm{Im}\{Z_L(f_\circ)\} \tag{2}$$

where $f_\circ$ (= 59.5 MHz) is the oscillation frequency while Z_C and Z_L are the impedances looking into and out of the collector of the BJT, respectively. Based on the simulations, a feedback inductor $L_F = 355$ nH and a terminating capacitor $C_T = 27$ pF were selected to fulfill the magnitude condition in (1). The resonance condition in (2) was achieved with a load capacitor $C_L = 15$ pF. The DC base current (I_B) and the collector voltage (V_{CC}) were supplied to the BJT through RF chokes RFC_1 and RFC_2, respectively. The RF chokes were designed to have a parallel self-resonance frequency around $f_\circ$ to provide high-impedance to AC signals at resonance. The bypass capacitors $CB_1 = CB_2 = 10$ nF were used to shunt the AC signal leaking through the RF chokes to ground. The DC block capacitor $CB_3 = 10$ nF was employed in the feedback path to isolate the base and collector biasing signals.

The oscillator was prototyped on a 1.6-mm stack-up of DuPont GreenTape 9k7 ($\epsilon_r = 7.1$) LTCC board. Two gold layers with 0.4 mm separation were used for the circuit design while an additional 1.2 mm was added under the bottom metal layer to electrically isolate the circuit from the test fixture. The LTCC was fabricated using conventional LTCC fabrication techniques [13]. The prototype of the oscillator is shown in Fig. 3(a). The feedback inductor and the RF chokes were designed using the electromagnetic simulator of ADS and implemented as on-board spirals. L_F was realized using a $5\frac{1}{4}$-turn spiral inductor with a stripe width and spacing of 0.6 mm and 0.3 mm, respectively. The RF chokes were realized with 15-turn spiral inductors having both stripe width and spacing of 0.3 mm. The stripe width of the RF chokes were kept small to intentionally degrade their quality factor which, in turn, allowed them to provide high-impedance over a relatively wide frequency range around $f_\circ$. High-temperature capacitors from Presidio Components Inc. (rated up to 250 °C) were used for C_L, C_T and CB_1-CB_3. Similar capacitors were used previously up to 250 °C in [10], [14] and 500 °C in [11]. The capacitors were connected to the LTCC using a HT silver epoxy by PELCO. An SMA connector was screwed to the output of the oscillator to provide a microstrip-to-coax interface for measurements. The chip containing the SiC BJT was attached to the LTCC

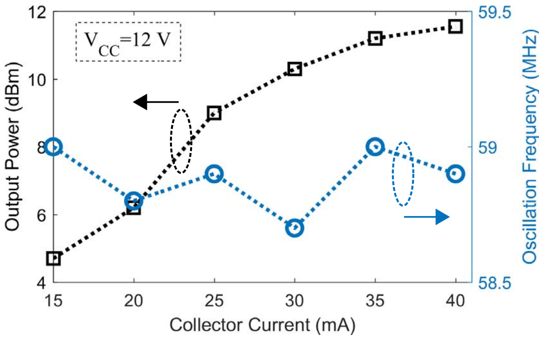

FIGURE 4. Measured output power and oscillation frequency at RT.

using a HT die-attach by ChemTech-AB. Finally, the BJT pads were connected to the LTCC using 25 μm thick gold bond wires, as shown in Fig. 3(b).

III. RESULTS AND DISCUSSION

A. MEASUREMENT SETUP

For HT characterization, the oscillator was placed on a thermal chuck as shown in Fig. 3(a). The circuit was heated by varying the chuck temperature while the temperature on the top of the LTCC was monitored using an IR thermometer. Thus, the temperatures reported in this work are on top of the LTCC, in the vicinity of the chip. Thermal vias were added around the oscillator core and the chip (outlined in red) to improve the heat transfer. The biasing to the oscillator was provided with Keithley SCS-4200 using three DC probing needles. The RF output of the oscillator was connected to a 50 Ω signal analyzer (R&S FSQ-26) through the SMA connector in conjunction with a 0.5 m coaxial cable.

B. MEASUREMENT RESULTS

For determining the proper biasing for the oscillator, the collector current (I_C) was swept from 15 mA to 40 mA (by varying I_B), and the fundamental oscillation frequency (f_{out}), and the output power at the fundamental frequency (P_{out}) were recorded. V_{CC} was kept at 12 V during the sweep. Fig. 4 shows both P_{out} and f_{out} as a function of I_C at room-temperature (RT). Note that P_{out} exhibits a sharp initial increase but begins to saturate around 11 dBm as I_C approaches 35 mA. f_{out} shows only 0.5% variation across the whole range of collector currents and is slightly smaller than the design frequency of 59.5 MHz. Based on these results, a collector current of 35 mA was selected for biasing since increasing I_C further results in marginal improvement in P_{out}. Under the aforementioned biasing, P_{out} and f_{out} at RT are 11.2 dBm and 59 MHz, respectively. The same I_C was maintained throughout the HT characterization of the oscillator by increasing I_B from 819 μA at RT to 1.64 mA at 400 °C. The circuit ceased to oscillate beyond 400 °C, as will be discussed shortly. The maximum DC power consumed by the oscillator was 431 mW.

The spectrum and phase noise of the oscillator was recorded in 25 °C increments from RT up to 400 °C. The measured spectrum of the oscillator is shown in Fig. 5(a). Note that f_{out} decreases from 59 MHz at 25 °C to 57.3 MHz at 400 °C whereas P_{out} degrades from 11.2 dBm at 25 °C to 8.4 dBm at 400 °C. The measured values of P_{out} and f_{out} at every temperature setting are shown in Fig. 5(b). The output power of the oscillator remains fairly constant with temperature up to 300 °C. However, with further increase in temperature, the output power degrades rapidly and at 400 °C, P_{out} becomes 2.8 dB smaller than its value at 300 °C. The oscillation frequency of the oscillator varies by only 3.3% in the entire temperature range. Fig. 6 shows the fundamental and higher order harmonics of the oscillator at 25 °C and 400 °C. It can be seen that the harmonics remain 29 dB below the output power at the fundamental frequency.

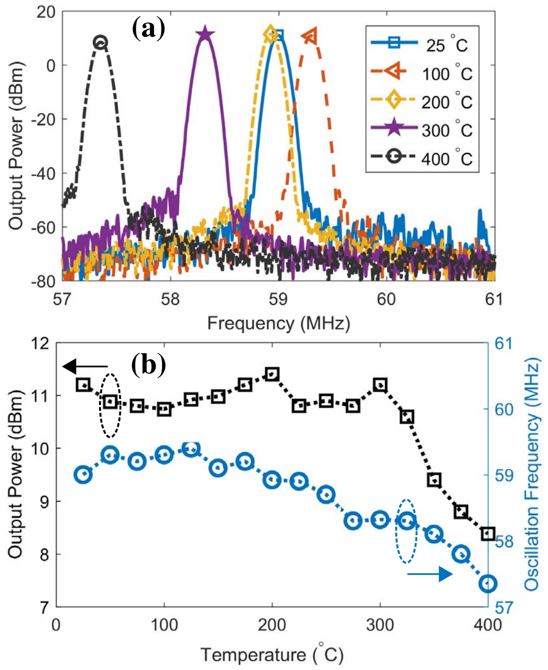

FIGURE 5. (a) Measured output spectrum of the oscillator. (b) Peak output power and oscillation frequency versus temperature.

The phase noise of the oscillator was measured using the built-in phase noise routine of FSQ-26. Fig. 7 shows the phase noise of the oscillator from 25 °C up to 400 °C. Although we did not find any definite trend in the variation of phase noise with temperature, the oscillator exhibited relatively good noise performance ($<$ 95 dBc/Hz at 100 kHz offset) throughout the measured temperature range. The slope of the phase noise is approximately -30 dBc/decade up to 1 MHz offset frequency, indicating that the noise in that region is dominated by 1/f noise of the BJT [15].

The circuit ceased to oscillate as temperature was increased to 425 °C. The failure was permanent and persisted even when the circuit was cooled down to RT. The post-failure analysis showed that the oscillations ceased due to the dielectric breakdown of the DC block capacitor in the feedback (CB_3). Although similar capacitors were utilized

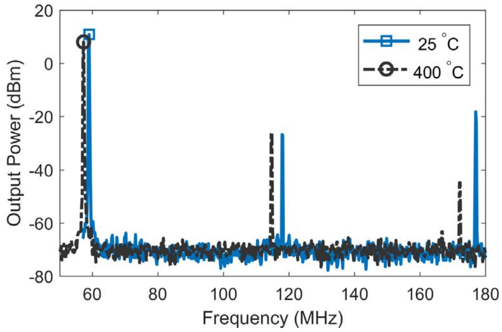

FIGURE 6. **Fundamental frequency and higher order harmonics of the oscillator at 25 °C and 400 °C.**

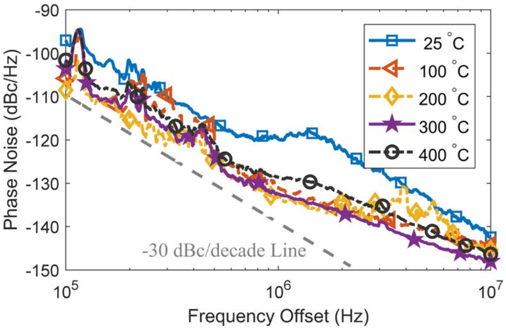

FIGURE 7. **Phase noise of the oscillator as a function of temperature.**

successfully for many hours at 500 °C in our previous work [11], such failures indicate the intrinsic reliability issues associated with utilizing the commercial passives beyond their rated temperatures. This demonstrates the need to develop in-house HT capacitors similar to the ones reported in [9].

IV. CONCLUSION

In this brief, a negative resistance oscillator based on a 4H-SiC BJT has been demonstrated. Oscillations into a 50 Ω load were achieved from room-temperature up to 400 °C. Measurements have shown that the oscillator delivers 11.2 dBm at 25 °C and 8.4 dBm at 400 °C, with 3.3% variation in the oscillation frequency. The dielectric breakdown of one of the capacitors caused the oscillations to stop at 425 °C, which suggests further research into high-temperature capacitors. Nevertheless, the reported performance demonstrates the potential of in-house SiC BJT-based oscillator for high-temperature communications systems.

REFERENCES

[1] P. G. Neudeck, R. S. Okojie, and L.-Y. Chen, "High-temperature electronics—A role for wide bandgap semiconductors?" *Proc. IEEE*, vol. 90, no. 6, pp. 1065–1076, Jun. 2002.

[2] J. D. Cressler and H. A. Mantooth, *Extreme Environment Electronics*. Boca Raton, FL, USA: CRC Press, 2012.

[3] T. Feng, J. M. Salem, and D. S. Ha, "High temperature VCO based on GaN devices for downhole communications," in *Proc. Int. Symp. Circuits Syst. (ISCAS)*, May 2017, pp. 1–4.

[4] X. Lu, J. Ma, C. P. Yue, and K. M. Lau, "A GaN-based lamb-wave oscillator on silicon for high-temperature integrated sensors," *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 6, pp. 318–320, Jun. 2013.

[5] Z. D. Schwartz and G. E. Ponchak, "High temperature performance of a SiC MESFET based oscillator," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Long Beach, CA, USA, Jun. 2005, pp. 1179–1182.

[6] Z. D. Schwartz and G. E. Ponchak, "1-GHz, 200 °C, SiC MESFET clapp oscillator," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 11, pp. 730–732, Nov. 2005.

[7] G. E. Ponchak, M. C. Scardelletti, and J. L. Jordan, "270 °C, 1 GHz oscillator-type active antenna," *IEEE Electron. Lett.*, vol. 45, no. 8, pp. 386–387, Apr. 2009.

[8] M. C. Scardelletti and G. E. Ponchak, "Characterization of 720 and 940 MHz oscillators with chip antenna for wireless sensors from room temperature to 200 and 250 °C," in *IEEE Radio Wireless Symp. Dig.*, Jan. 2011, pp. 49–52.

[9] G. E. Ponchak, M. C. Scardelletti, and J. L. Jordan, "30 and 90 MHz oscillators operating through 450 and 470 °C for high temperature wireless sensors," in *Proc. Asia–Pacific Microw. Conf. (APMC)*, 2010, pp. 1027–1030.

[10] M. W. Hussain *et al.*, "An intermediate frequency amplifier for high-temperature applications," *IEEE Trans. Electron Devices*, vol. 65, no. 4, pp. 1411–1418, Apr. 2018.

[11] M. W. Hussain *et al.*, "A 500 °C active down-conversion mixer in silicon carbide bipolar technology," *IEEE Electron Device Lett.*, vol. 39, no. 6, pp. 855–858, Jun. 2018.

[12] G. Gonzalez, *Foundations of Oscillator Circuit Design*. Boston, MA, USA: Artech House, 2007.

[13] J. Larry, R. Rosenberg, and R. Uhler, "Thick-film technology: An introduction to the materials," *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, vol. CHMT-3, no. 2, pp. 211–225, Jun. 1980.

[14] J. M. Salem and D. S. Ha, "A high temperature active GaN-HEMT downconversion mixer for downhole communications," in *Proc. Int. Symp. Circuits Syst. (ISCAS)*, May 2016, pp. 946–949.

[15] T. H. Lee and A. Hajimiri, "Oscillator phase noise: A tutorial," *IEEE J. Solid-State Circuits*, vol. 35, no. 3, pp. 326–336, Mar. 2000.

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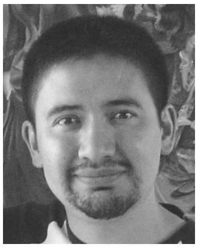

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