A 500 °C Active Down-Conversion Mixer in Silicon Carbide Bipolar Technology

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Abstract—This paper presents an active down-conversion mixer for high-temperature communication receivers. The mixer is based on an in-house developed 4H-SiC BJT and down-converts a narrow-band RF input signal centered around 59 MHz to an intermediate frequency of 500 kHz. Measurements show that the mixer operates from room temperature up to 500 °C. The conversion gain is 15 dB at 25 °C, which decreases to 4.7 dB at 500 °C. The input 1-dB compression point is 1 dBm at 25 °C and -2.5 dBm at 500 °C. The mixer is biased with a collector current of 10 mA from a 20 V supply and has a maximum DC power consumption of 204 mW. High-temperature reliability evaluation of the mixer shows a conversion gain degradation of 1.4 dB after 3-hours of continuous operation at 500 °C.

Index Terms—4H-SiC BJTs, high-temperature, RF, mixer.

I. INTRODUCTION

Semiconductor devices based on wide bandgap materials like silicon carbide (SiC) and gallium nitride (GaN) can operate at extreme temperatures [1]. The high-temperature (HT) capability of SiC and GaN makes them attractive candidates for the development of HT communication systems, which are desired for applications like turbine industry, deep well drilling telemetry [2] and future space exploration missions [3].

A mixer is a critical building block of all communication systems. It is a frequency translation circuit with three ports which are generally referred as radio frequency (RF), local oscillator (LO) and intermediate frequency (IF). An active down-conversion mixer performs the following frequency translation in the communication receiver: $f_{IF} = f_{LO} - f_{RF}$, where f_{IF} , f_{LO} and f_{RF} are the frequency of signals at the output IF port and the input LO and RF ports, respectively. In addition, it also provides conversion gain. Previously, active and passive mixers, based on commercial GaN HEMTs, have been demonstrated up to 250 °C in [4], [5]. The HT limitation of these mixers was governed by the rated junction temperature of their constituent active devices. In this work, we present a 500 °C active mixer which is based on in-house HT SiC bipolar technology [6]. The mixer is prototyped on a low temperature co-fired ceramic (LTCC) board, which is a suitable technology for realizing hybrid HT RF circuits [7], [8]. The proposed mixer down-converts a 59 MHz RF input signal to a 500 kHz IF output to allow signal processing by HT baseband circuits [9], [10]. The values of f_{RF} and f_{IF} are dictated by the system specifications that we envision for our

Fig. 1. (a) Forward current gain and (b) transconductance versus I_C .

HT communication receiver. To the best of our knowledge, this is the first demonstration of a mixer working up to 500 °C.

The SiC BJT used in this work was fabricated on a 4-in, 4H-SiC wafer with six epi-layers [11]. Fig. 1(a) shows the measured current gain (β) of the BJT versus collector current (I_C). It can be seen that the maximum value of β decreased by almost 55% as the temperature was increased from 25 °C to 500 °C. Fig. 1(b) shows the transconductance (g_m) of the BJT which was calculated from the numerical differentiation of the measured transfer characteristics. Irrespective of the temperature, g_m is much smaller than the theoretical value of I_C/V_T due to the large base resistance of in-house SiC bipolar transistors. In addition, g_m is decreasing with temperature for relatively large values of I_C . For instance, at 10 mA, the decrease in g_m from 25 °C to 500 °C is about 20%. More information on the fabrication process and the high-frequency performance of SiC BJTs can be found in our previous work on an HT amplifier design [11].

II. CIRCUIT DESIGN AND PROTOTYPING

A. Circuit Design

The schematic of the mixer is shown in Fig. 2. The active device in the mixer circuit is a SiC BJT in a common-emitter configuration, biased at $I_C = 10$ mA. The biasing current is selected as a trade-off between acquiring maximum β (refer to Fig. 1(a)) and the DC power consumption considerations. The LO port is coupled to the base of the BJT through $C_{LO} = 6$ pF. The selected value of C_{LO} presents a 0.21 dB return loss to the RF signal, thereby preventing its leakage through the LO port. However, as f_{RF} (59 MHz) is very close to f_{LO} (59.5 MHz), C_{LO} also attenuates the LO signal

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Fig. 2. Schematic of the down-conversion mixer.

reaching the base of the BJT by around 13 dB. The 50 Ω RF port is conjugately matched to the combined impedances looking into the base terminal and the LO branch (Z_{IN}'). The matching network is designed in Advanced Design System by Keysight Technologies Inc. using the measured small signal S-parameters of the BJT. The matching network is a high-pass, L-section consisting of $C_{RF} = 10.7$ pF and $L_{RF} = 330$ nH. The non-standard value of C_{RF} is implemented using two standard valued parallel capacitors, $C_1 = 6$ pF and $C_2 = 4.7$ pF. The selected configuration of the matching network also acts as bias-tee i.e. L_{RF} provides a low resistance path to the DC base current (I_B) whereas C_{RF} acts as DC block. The collector of the BJT is connected to the supply voltage (V_{CC}) through $R_C = 1$ k Ω . R_C is realized using four 1 k Ω resistors (R_1 - R_4) instead of a single 1 k Ω resistor to reduce power dissipation induced heating across each resistor. $C_C = 47$ pF and an RC low pass filter (LPF) formed by two series 1 k Ω resistors (R_5 - R_6) and $C_3 = 4.7$ pF are used to improve RF-IF and LO-IF isolation. The bypass capacitors $C_{B1} = C_{B2} = 0.01$ μ F provide a low impedance path to the AC signals whereas $C_{B3} = 0.01$ μ F is a DC block capacitor. The SiC BJT was unconditionally stable, so the circuit does not require any stabilization network.

B. Mixer Prototyping

The mixer circuit was prototyped on a 1.6-mm stack-up of DuPont GreenTape™ 9k7 LTCC. Two metal layers with 0.8-mm separation were used for the circuit design while an additional 0.8-mm was added under the bottom metal layer to electrically isolate the circuit from the test fixture. The 9k7 co-fired gold metal system was selected to minimize the thermal expansion effects of the ceramic to the SiC and to allow for wire-bonding. The LTCC was fabricated at the University of Arkansas's High-Density Electronics Center using thick-film fabrication methods [12], which included processes such as screen printing, co-firing, and dicing.

Fig. 3(a) shows the mixer prototype. The L_{RF} (330 nH) was realized using two on-board spiral inductors in a stacked configuration, i.e. one on the top metal and the other on the bottom metal. The spacing between the coil spirals and their width was kept at 0.3 mm and 0.6 mm, respectively. HT Vishay resistors and NPO capacitors by Presidio Inc. were used for the remaining circuit passives. The components were attached

Fig. 3. (a) Mixer prototype. (b) Die photograph. (c) Measurement setup.

to the LTCC pads using the conductive silver epoxy by PELCO® (rated up to 927 $^{\circ}$ C). Though the temperature rating of resistors and capacitors was 250 $^{\circ}$ C, their performance and reliability were evaluated up to 500 $^{\circ}$ C. At 500 $^{\circ}$ C, the capacitances and resistances remained within -2% and +3.5%, respectively, as compared to their 25 $^{\circ}$ C values. Moreover, negligible parameter variation with time, even after several hours of continuous operation at 500 $^{\circ}$ C was observed. Two SMA connectors in conjunction with around 1-cm copper wires were screwed to the LTCC to provide a coaxial interface for the RF and LO signals. To tap the IF output, a 2-cm copper wire was epoxied to the corresponding on-board metal trace. The chip with the SiC BJT was diced from the wafer and attached directly to the LTCC using an HT alumina adhesive by ChemTech AB (rated up to 1650 $^{\circ}$ C). The pads of the on-chip BJT were connected to the traces on the LTCC board using 25 μ m thick gold bond wires, as shown in Fig. 3(b).

III. MEASUREMENT RESULTS AND DISCUSSION

A. Measurement Setup

For HT measurements, the LTCC board was placed on a thermal chuck as shown in Fig. 3(c). The biasing was provided with semiconductor characterization system by Keithley (SCS-4200) using HT probing needles. The IF output voltage was measured with a Keysight oscilloscope (MSO-X-3024A) using a high-frequency probe.

The RF interfacing, required to characterize HT RF circuits, is relatively simple to realize using SMA connectors as compared to some other alternatives [13]–[15]. These alternatives range from RF probing [13], inductive coupling [14] to employing a chip antenna [15]. Nevertheless, the temperature rating of SMA connectors limit their reliable operation to around 200 $^{\circ}$ C. To circumvent this issue, LTCC board was designed to extend beyond the chuck boundary (marked by the red lines). This extension, supplemented by the additional 1-cm long copper wires, has resulted in a thermal gradient between the chuck and the SMA connectors. It was empirically determined that this thermal gradient was sufficient to allow the SMA connectors to work within their rated temperature, even when the chuck temperature was at 500 $^{\circ}$ C.

Fig. 4. Conversion gain of the mixer versus (a) local oscillator power and (b) frequency of the RF signal.

B. Measurement Results

The mixer circuit was heated by varying the chuck temperature. Thermal vias (outlined in green in Fig. 3(a) and (c)) around the mixer core improved the heat transfer from the chuck to the top of the LTCC board. The reported temperature, around the chip, was measured using an IR thermometer. Throughout the temperature range, I_C was kept at 10 mA by varying I_B whereas V_{CC} was fixed at 20 V.

Fig. 4(a) shows the conversion gain (CG) of the mixer as a function of LO power (P_{LO}), where CG is defined as the ratio of the output voltage amplitude at f_{IF} ($V_{out,IF}$) to the input RF voltage. The RF power (P_{RF}) was -16 dBm whereas f_{RF} and f_{LO} were 59 MHz and 59.5 MHz, respectively. It can be seen that CG increases linearly with P_{LO} up to the onset of saturation at about 15 dBm. The relatively large P_{LO} required for reasonable CG is a consequence of insertion loss due to C_{LO} . Furthermore, CG generally decreases with temperature, e.g., for $P_{LO} = 15$ dBm, CG drops from 15 dB at 25 °C to 4.7 dB at 500 °C. The analysis and simulations based on the models in [16], [17] showed that the CG degradation is mainly affected by the temperature dependence of the BJT's transconductance, loss in matching network inductor and the resulting loss due to the input mismatch. It was found that the latter two factors dominate and that the CG reduction can be predicted with a margin of 1.6 dB up to 300 °C (S-parameters of the BJT were unavailable above this temperature). Fig. 4(b) shows CG as a function of f_{RF} . f_{LO} was $f_{RF} + 500$ kHz whereas P_{RF} and P_{LO} were -7 dBm and 15 dBm, respectively. Note that CG of the mixer exhibits relatively wideband characteristics, with the peak around 59 MHz. Moreover, the bandwidth increases with temperature, as it can be observed by comparing CG roll-offs at values of f_{RF} below 59 MHz. This increase is due to the quality factor degradation of the matching network passives.

To evaluate the linearity of the mixer, P_{RF} was swept from -16 dBm to the onset of gain compression while P_{LO} was kept constant at 15 dBm. The corresponding $V_{out,IF}$ and CG as a function of P_{RF} are shown in Fig. 5(a) and Fig. 5(b), respectively. The input 1-dB compression point increases from 1 dBm at 25 °C to 8.8 dBm at 400 °C. This improvement in linearity, from 25 °C to 400 °C, is due to the corresponding decrease in the CG. However, at 500 °C, the 1-dB compression point decreases to -2.5 dBm. This sharp linearity degradation

Fig. 5. (a) Amplitude of the down-converted voltage and (b) conversion gain versus the RF power.

at 500 °C requires further investigation. The RF-IF and LO-IF isolations, mainly governed by C_C and LPF, remain fairly constant with temperature, at 24 dB and 28 dB, respectively.

The BJT mixer is working in the forward active region (class-A) for all the applied LO power levels. Therefore, its power consumption was directly estimated from the DC operating point and showed a non-monotonic variation with temperature with a peak of 204 mW at 300 °C. The non-monotonicity of the power consumption was caused by the necessary increase in base current to account for β degradation (to maintain a constant I_C) and the decrease in the corresponding base-emitter voltage due to bandgap-narrowing.

The mixer was continuously operated for 3-hours at 500 °C to evaluate its reliability. After 3 hours of continuous operation, CG dropped by almost 1.4 dB as compared to its initial value. This performance degradation was permanent and persisted even when the mixer was cooled back to 25 °C. The onset of failure mechanism, due to the accelerated electromigration in the Al-based metallization system [18], is believed to be the cause of permanent performance degradation with time at 500 °C. The electromigration manifests as a permanent increase in the access and contact resistances of the BJT with time, which not only degrades g_m but also increase the mismatch losses, therefore leading to a CG degradation. Consequently, the long-term reliability of the in-house SiC BJT based circuits at elevated temperatures requires stable metallization systems e.g. as reported in [19] for SiC JFETs.

IV. CONCLUSION

A 500 °C active down-conversion mixer based on 4H-SiC BJT has been presented. Measurements have shown that the proposed mixer down-converts a 59 MHz input signal to a 500 kHz output with a conversion gain of 15 dB at 25 °C and 4.7 dB at 500 °C. The circuit exhibited relatively good linearity with an input 1-dB compression point of 1 dBm at 25 °C and -2.5 dBm at 500 °C. The reported performance demonstrates the potential of 4H-SiC BJT mixer for high-temperature communication receivers.

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