Silicon Carbide BJT Oscillator Design Using S-parameters

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Abstract. Radio frequency (RF) oscillator design typically requires large-signal, high-frequency simulation models for the transistors. The development of such models is generally difficult and time consuming due to a large number of measurements needed for parameter extraction. The situation is further aggravated as the parameter extraction process has to be repeated at multiple temperature points in order to design a wide-temperature range oscillator. To circumvent this modelling effort, an alternative small-signal, S-parameter based design method can be employed directly without going into complex parameter extraction and model fitting process. This method is demonstrated through design and prototyping a 58 MHz, high-temperature (HT) oscillator, based on an in-house 4H-SiC BJT. The BJT at elevated temperature (up to 300 °C) was accessed by on-wafer probing and connected by RF-cables to the rest of circuit passives, which were kept at room temperature (RT).

Introduction

High-temperature wireless systems find various applications in the turbine industry, deep well drilling telemetry and future space exploration missions. Radio frequency oscillators are widely used in such wireless systems for frequency conversion in conjunction with mixers.

The enabling technologies in the development of HT RF circuits are the wide bandgap semiconductors like GaN and SiC. Previously, a voltage controlled oscillator based on GaN HEMT has been shown to work up to 230 °C [1]. Commercial SiC MESFETs have been used to design HT oscillators working up to 200 °C [2] and 470 °C [3], while a SiC JFET has been employed in the 300 °C oscillator presented in [4]. As shown in our recent work on HT mixers [5], SiC bipolar technology is another alternative for developing HT RF circuits. However, the conventional HT oscillator design methodology requires large-signal, high-frequency simulation models for the transistors, which are more challenging to develop for BJTs as compared to FETs. In addition, these models have to be developed at multiple discrete temperature points in the temperature range of interest. This issue can be circumvented by employing small-signal techniques of oscillator design [6,7], although at the cost of the inability of these methods to predict the oscillator fundamental output power and its harmonic content. Out of these linear techniques, the two-port method [6] is relatively straightforward as compared to the open-loop method [7]. In this paper, we present the potential of the two-port method through the design of an HT negative resistance oscillator (NRO). The oscillator employs an in-house 4H-SiC BJT and is designed for a centre frequency of 58 MHz.

Device Fabrication and Characterization

The SiC BJT used in this work were fabricated on a 4-inch, 4H-SiC wafer with six epi-layers. More information on the device fabrication and HT characterization can be found in [8]. The BJT's S-parameters, required for the oscillator design, were measured for a collector current (I_C) of 11 mA and a collector-emitter voltage (V_{CE}) of 10 V. The magnitude of measured S-parameters from RT up to 300 °C are shown in Fig. 1. Unilateral power gain (GTU) of the transistor is also shown in Fig. 1.

It can be seen that GTU is greater than 0 dB in the measured frequency range. This implies that the maximum oscillation frequency (f_{MAX}) for the BJT is larger than the target frequency of 58 MHz, indicating the potential of the BJT to sustain oscillations at 58 MHz even at 300 °C.

Circuit Design

The proposed oscillator circuit used to demonstrate the two-port method is a negative resistance topology as shown in Fig. 2. The on-wafer SiC BJT is placed on a thermal chuck at a controlled temperature T . The BJT is connected on either side by the coaxial cables of lengths $L_1=L_2=0.5$ m. The BJT is characterized by its temperature dependent S-parameter matrix $[S]_D(T)$, whereas coaxial cables are characterized by their RT S-parameter matrices $[S]_1$ and $[S]_2$. The RF probes (not shown) serve as the interface between the coaxial cables and the on-wafer BJT. This cascade of cables and on-wafer BJT, is referred as embedded BJT. The inclusion of coaxial cables shifts the reference ports of the on-wafer BJT from B-E and C-E (at T) to B'-E' and C'-E' (at room temperature), respectively. This shifting of BJT ports facilitates showcasing the design methodology without dicing the on-wafer transistor. In addition to the BJT, NRO is made up of three reactive components: load (X_L), terminating (X_T) and feedback (X_F). Z_{IN} and Z_T represent the impedances looking into the input port and X_T , respectively. The oscillator was designed specifically to drive a load resistor, R_L ($=50 \Omega$) to facilitate measurements with 50Ω instruments. Z_L represents the impedance of X_L in series with R_L . The RF chokes (RFC) for biasing, DC block capacitors and bypass capacitors are also shown.

Figure 1. S-parameters of the BJT at $I_C = 11$ mA and $V_{CE} = 10$ V. GTU of the BJT also shown.

Figure 2. Schematic of the proposed oscillator. Red region indicates that the on-wafer BJT is placed on the thermal chuck at a temperature ranging from 25 °C to 300 °C.

The two-port method for NRO design involves: i) making the active device potentially unstable at the desired frequency of oscillation (f_o), ii) creating sufficient small signal negative resistance at the input port at f_o and iii) resonating the small signal reactance looking into the input port at f_o . The embedded BJT was initially unconditionally stable in the entire measured frequency range and at all measured temperatures (25 °C, 100 °C, 200 °C and 300 °C). Through small-signal simulations in Advanced Design System (ADS), a feedback inductor, X_F ($=120$ nH) was selected to make the embedded BJT potentially unstable at 58 MHz and at all four temperatures. A potentially unstable active device can generate oscillations (equivalently, negative resistance) at the input port for a properly selected X_T . Based on the simulations, a terminating capacitance, X_T ($=18$ pF) was chosen to generate sufficient negative resistance at the input port, so to fulfill the following start-up condition:

$$|\text{Re} \{Z_{\text{IN}}(58 \text{ MHz}, T)\}| > R_L. \quad (1)$$

where Z_{IN} (58 MHz, T) is the small-signal impedance looking into the input port at 58 MHz and controlled chuck temperature, T. A load capacitor, X_L (=33 pF) was used to fulfill the following resonance condition at 300 °C:

$$\text{Im} \{Z_{IN} (58 \text{ MHz}, 300 \text{ }^\circ\text{C})\} = -\text{Im} \{Z_L (58 \text{ MHz})\}. \quad (2)$$

The simulated Nyquist plots of the oscillator are shown in Fig. 3. Nyquist criteria states that for oscillations to occur, the open loop polar plot of the oscillator should have at least one net clockwise encirclement of (1,0) point as the frequency is increased. It can be seen that the Nyquist criteria is satisfied for all four temperatures. Fig. 4 shows the three reactive components: X_F , X_T and X_L , mounted on a 1.6-mm thick FR-4 PCB (glass-transition temperature of 130 °C). X_T and X_L also serve as DC blocks. Furthermore, R_L was replaced by an SMA connector which can subsequently be connected to a 50 Ω spectrum analyzer. The DC blocking capacitor in the feedback path, RF chokes and bypass capacitors are also shown. The on-wafer SiC BJT and the PCB assembly (Fig. 4) were connected together with 0.5-m coaxial cables to complete the oscillator circuit as shown in Fig. 5. A 50 Ω signal analyzer by Rohde & Schwarz (FSQ-26) served as R_L .

Figure 3. Nyquist plots of the oscillator for a frequency sweep from 20 MHz to 110 MHz.

Figure 4. Reactive components, RF chokes and DC block of the NRO mounted on a PCB.

Figure 5. Measurement setup.

Measurement Results and Discussion

The oscillator was characterized from 25 °C to 300 °C by varying the temperature of the thermal chuck on which the BJT was placed. The biasing collector current was kept at 11 mA throughout the temperature range by varying the base current (I_B). The PCB was kept at RT during measurements. The output spectrum and phase noise of the oscillator were measured from 25 °C up to 300 °C using the FSQ-26 signal analyzer. These measurements at 300 °C are shown in Fig. 6.

From the output spectrum, the peak output power (P_{out}) and centre frequency of the oscillator can be extracted. These parameters, as a function of temperature, are summarized in Table 1. An increasing trend with temperature can be observed in P_{out} . The increase in P_{out} with temperature is due to the fact that both X_F and X_T were selected to maximize the negative resistance at 300 °C. This is indicated in Fig. 3, where the magnitude at zero-crossings beyond the (1,0) point is larger at 300 °C as compared to 25 °C. The oscillation frequency without any tuning is also shown in Table 1. The frequency variation in the entire temperature range is less than 1%. Finally, the variation of

Figure 6. (a) Power spectrum and (b) phase noise of the oscillator at 300 °C.

phase noise with the temperature at 100-kHz offset from the centre frequency is also summarized. The phase noise is governed by the quality factor of the reactive components and the noise of the BJT. Since the passive components were at RT throughout the measurement, the variation in the phase noise with temperature is proportional to the variation of the noise of the BJT with temperature. It can be seen that the variation of phase noise with temperature does not indicate any definite trend.

It should be noted that in this work only the BJT was kept at elevated temperatures while the remaining circuit components were at RT. However, the actual implementation of HT oscillators require the entire circuit and not just the active devices to be exposed to hot ambience. From the circuit design point of view using the two-port method, the only difference between the two cases is that the quality factor degradation of the reactive components with temperature should also be considered. This is the focus of our ongoing research.

Summary

In this paper, we have demonstrated the potential of S-parameter based design methodology for developing HT oscillators without undergoing the challenges associated with the development of large-signal, temperature-dependent simulation models for the active devices. Furthermore, this work also highlighted the potential of in-house SiC BJT technology for developing HT RF systems.

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Table 1. Oscillator parameters versus temperature.

Temp. [°C]	P _{out} [dBm]	f _o [MHz]	Phase Noise [dBc/Hz]
25	5.9	57.7	-106
100	8.1	58.2	-100
200	8.4	58.1	-103
300	8.8	58.1	-101