Intermodulation-Distortion Performance of Silicon–Carbide Schottky-Barrier RF Mixer Diodes

Rainee N. Simons, *Fellow, IEEE*, and Philip G. Neudeck, *Senior Member, IEEE*

***Abstract*—This paper presents the fabrication and characterization of silicon carbide (SiC) Schottky-barrier mixer diodes of 25- and 50-μm diameter on a conducting 4H–SiC wafer. The single-balanced mixer circuits with a diode in each arm (two diodes total) were tested at 200 MHz (VHF) and 1.5 GHz [global positioning system (GPS)]. The experiments show that the conversion loss/input third-order intercept point (IP3) are 8.0 dB/+25 dBm and 7.5 dB/+22 dBm at these frequencies, respectively. The measured second-order intercept point (IP2) over the VHF frequency band is +38 dBm. The above conversion-loss values are about the same as that of commercially available single-balanced mixers with silicon Schottky-barrier diodes. However, to achieve a comparable input IP3 performance with Si Schottky-barrier diodes, a more complex mixer design involving double-balanced mixers with two diodes in each arm of a quad (eight diodes total) is required. Applications include RF-based navigational instruments on board commercial/general aviation aircraft and GPSs.**

***Index Terms*—Global positioning system (GPS), intermodulation distortion (IMD), mixers, Schottky diodes, silicon carbide (4H–SiC), VHF circuits.**

I. Introduction

ELECTROMAGNETIC (EM) emissions from carry-on electronic devices can potentially degrade the minimum detectable signal level of important RF-based navigational instruments on board commercial and general aviation aircraft [1]–[3]. In some situations, the interfering signal frequencies may not coincide, but may be very close to the navigational instruments operating frequencies. For example, the lowest frequencies used for VHF omni-directional range (VOR) and instrument landing system (ILS) localizer instruments are just above commercial FM broadcast frequencies. In such cases, the intermodulation distortion (IMD) products are located adjacent to the desired signal spectrum at the output. The IMD products are generated because of nonlinear circuits, such as mixers, within the instruments.

The IMD products could be second, third, fifth order, etc., [4]. The second-order IMD products takes place when a second signal (f_2) arriving at the mixer RF port interacts with the desired incoming signal (f_1). Since the second-order IMD products arise at frequencies $(f_1 - f_2) - f_{\rm LO}$ and $(f_2 - f_1) - f_{\rm LO}$, they are located far away on either side of the desired IF signal, namely, $f_1 - f_{\rm LO}$, in the IF band. The second-order IMD products are serious in the case of wide-band systems and are commonly specified as an input second-order intercept point ($\rm IP_2$) [4]. The signals resulting from the interaction at frequencies $(2f_1 - f_2) - f_{\rm LO}$ and $(2f_2 - f_1) - f_{\rm LO}$ are the third-order IMD products and are located very close to the desired IF signal. The third-order IMD products are the most serious in the case of the above instruments since the bandwidth of these systems is narrow. Thus, the third-order IMD is a measure of the mixer linearity and is commonly specified as an input third-order intercept point ($\rm IP_3$) [4]. The higher the $\rm IP_3$, the lower the IMD products are and, consequently, the spurious-free dynamic range is wider.

In the literature, several schemes have been proposed to suppress diode mixer IMD products [5]–[7]. The schemes include adding resistance in series with the diodes, or using two or more diodes in series, or using diodes with higher turn-on voltage. The disadvantage of the first scheme is higher conversion loss, while the penalty of the second scheme is higher cost and lower reliability because of the increased number of components. The third scheme was not validated until the experiments using Schottky-barrier diodes with higher turn-on voltage fabricated from wide-bandgap semiconductor material [silicon carbide (SiC)] were reported [7]. Furthermore, the linearization scheme in [6] requires two double-balanced mixers, two power dividers, a power combiner, two phase shifters, two attenuators, two filters, and two amplifiers. The disadvantage of this approach is that it requires many more components and, hence, is more difficult to implement. The Si and SiC Schottky-barrier diodes have a forward bias turn-on voltage of approximately 0.3 and 1.0 V, respectively. Since the local oscillator (LO) drive power is proportional to the square of the voltage, this translates into an order of magnitude increase in the turn-on power requirement for the SiC diode [7], [8]. The assumption here is that the LO current waveform in the SiC and Si diodes are similar. Other properties of SiC are higher RF burn-out levels, high breakdown field strength, high thermal conductivity, and a high-saturation electron drift velocity. These characteristics are beneficial for the design of robust mixer diodes. In this paper, the $\rm IP_3$ of single-balanced mixers with two SiC Schottky-barrier diodes is investigated and found to have comparable IMD performance with that of

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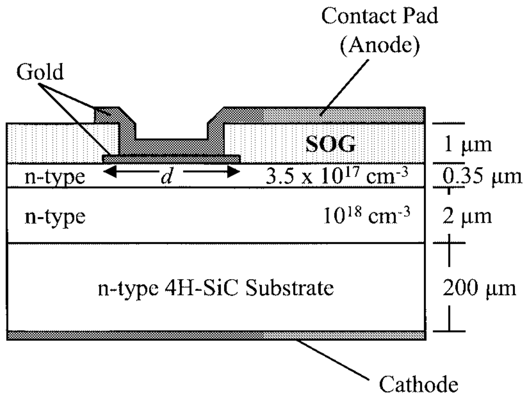

Fig. 1. Schematic showing the cross section of the SiC Schottky-barrier mixer diode.

commercially available more complex double-balanced mixers with eight Si Schottky-barrier diodes.

II. SiC Diode Fabrication

The SiC Schottky-barrier diodes were fabricated on a commercially purchased (silicon-face 0.036 $\Omega \cdot$ cm) n-type 4H–SiC substrate with homoepitaxial layers of doping and thickness depicted in Fig. 1. The as-received wafer was thinned from the backside to a thickness around 0.2 mm. In the first step, the opposite side of the wafer was metallized with nickel and furnace annealed at high temperature to form the cathode contact. The second step was the Schottky-barrier metal deposition (0.1-μm-thick gold) and patterning using a liftoff process for the anode. Diodes with diameters ranging from 5 to 50 μm are fabricated on each 1 mm $\times$ 1 mm die arrayed on the wafer. Third, an insulating layer to support a large anode contact pad is applied to a thickness of 1.0 μm by a multiple application of spin-on-glass (SOG). Fourth, using photoresist and dry etching, the SOG over the anode was removed creating a circular via opening. Fifth, the large anode contact pad (100 μm $\times$ 100 μm) was fabricated using gold by a liftoff process. In this step, the circular opening was also metallized to ensure continuity between the anode and the contact pad. The wafer was initially dc probed and then sawed into individual dies for wire-bond packaging and RF characterization.

III. SiC Mixer Circuits

The diodes were characterized for linearity by inserting them into single-balanced mixer circuits. The mixer circuits for the VHF and global positioning system (GPS) bands are shown schematically in Fig. 2(a) and (b), respectively. Full details of two-tone second-order/third-order IMD measurements including complete equipment schematic can be found in [9]. The operation of a single-balanced mixer is well known and can be found in [10].

IV. Expermental Results and Discussions

In this section, the experimental results for single-balanced mixers operating at VHF and in the L-band for general aviation and GPSs are presented, respectively.

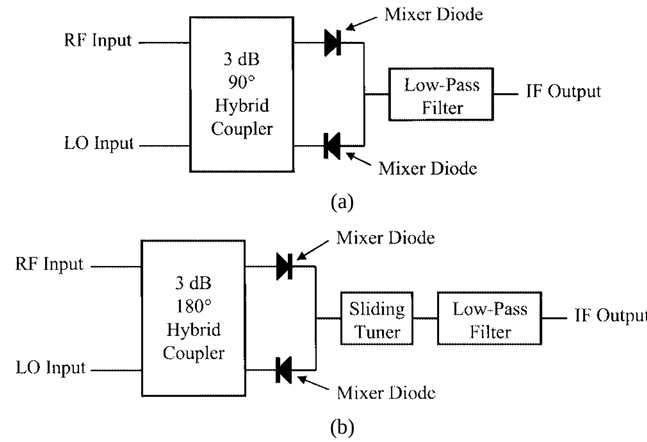

Fig. 2. Schematic of the experimental single-balanced mixer circuits. (a) For the VHF band with 3-dB 90° hybrid coupler. (b) For GPS band with 3-dB 180° hybrid coupler.

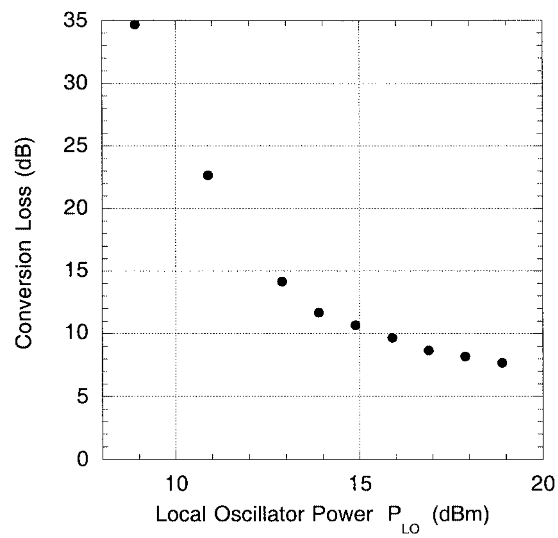

Fig. 3. Conversion loss as a function of the LO power. $P_{\rm RF} = 11.0$ dBm, $f_{\rm RF} = 195$ MHz, $f_{\rm LO} = 175$ MHz, $d = 50$ μm.

A. VHF Mixer Circuit Characteristics

The measured conversion loss as a function of the LO power $(P_{\rm LO})$ at a constant RF signal input power $(P_{\rm RF})$ is shown in Fig. 3. In this figure, $f_{\rm LO}$ and $f_{\rm RF}$ denote the frequency of the LO and RF signals, respectively. It is observed that, as $P_{\rm LO}$ increases from approximately +9.0 dBm to approximately +19 dBm, the conversion loss monotonically reduces to a minimum value of approximately 8.0 dB. The upper limit of +19 dBm for $P_{\rm LO}$ was set by the maximum power output of the synthesizer used in the experiment.

The measured conversion loss as a function of the RF power at a fixed LO power is shown in Fig. 4. This figure shows that the conversion loss remains constant at approximately 8.0 dB when the RF power is increased from -35.0 dBm to approximately +5.0 dBm.

The measured conversion loss as a function of the IF at a fixed RF and LO power is shown in Fig. 5. This figure shows that the conversion loss is a minimum at an IF of 15 MHz and is equal to 7.0 dB. The conversion loss increases to 9.0 dB at the band edges.

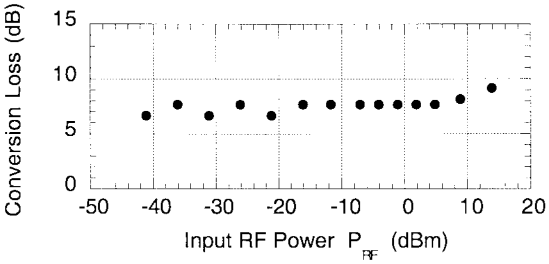

Fig. 4. Conversion loss as a function of the input RF power. $P_{\rm LO} = +19.0$ dBm, $f_{\rm RF} = 195$ MHz, $f_{\rm LO} = 175$ MHz, $f_{\rm IF} = 20$ MHz, $d = 50$ μm.

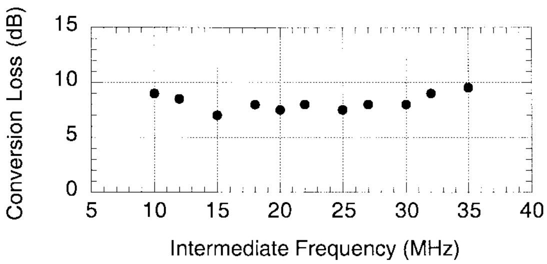

Fig. 5. Conversion loss as a function of the IF frequency. $P_{\rm RF} = -10.0$ dBm, $P_{\rm LO} = +19.0$ dBm, $f_{\rm LO} = 175$ MHz, $f_{\rm RF}$ = variable, $d = 50$ μm.

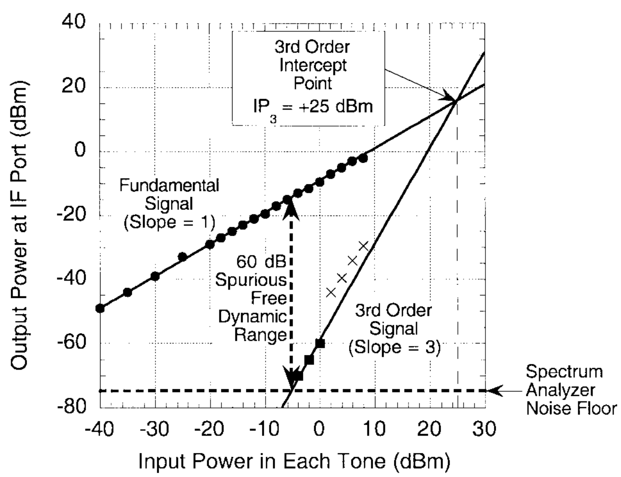

Fig. 6. Power output at the IF port as function of the input power in each tone. $f_1 = 199.9$ MHz, $f_2 = 200.1$ MHz, $f_{\rm LO} = 175$ MHz, $P_{\rm LO} = +19.0$ dBm, $d = 50$ μm.

The third-order intercept point ($\rm IP_3$) is experimentally determined as outlined in [4], [5], and [9]. For the VHF mixer circuit with SiC Schottky-barrier diodes, the measured power output at the IF port as a function of the input power in each tone is shown in Fig. 6. The frequency of the two tones and the LO power are indicated in this figure's caption. The input $\rm IP_3$ is approximately $+25$ dBm. The spurious-free dynamic range shown in Fig. 6 is approximately 60 dB.

In an analogous manner, the second-order intercept point ($\rm IP_2$) is also experimentally determined. The measured characteristics, the frequency of the two tones, and the LO power are presented in Fig. 7. The input $\rm IP_2$ for the VHF mixer circuit is approximately $+38$ dBm.

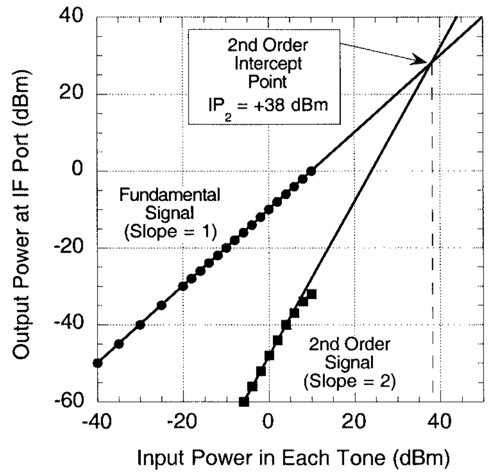

Fig. 7. Power output at the IF port as function of the input power in each tone. $f_1 = 155$ MHz, $f_2 = 160$ MHz, $f_{\rm LO} = 250$ MHz, $P_{\rm LO} = +20.0$ dBm, $d = 50$ μm.

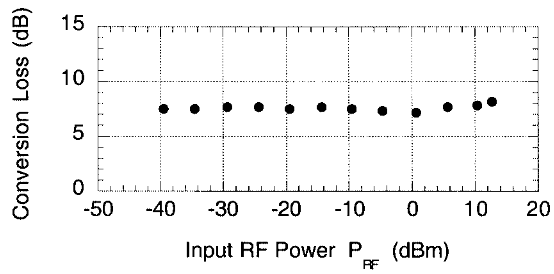

Fig. 8. Conversion loss as a function of the input RF power. $P_{\rm LO} = +19.5$ dBm, $f_{\rm RF} = 1.5845$ GHz, $f_{\rm LO} = 1.5645$ GHz, $f_{\rm IF} = 20$ MHz, $d = 25$ μm.

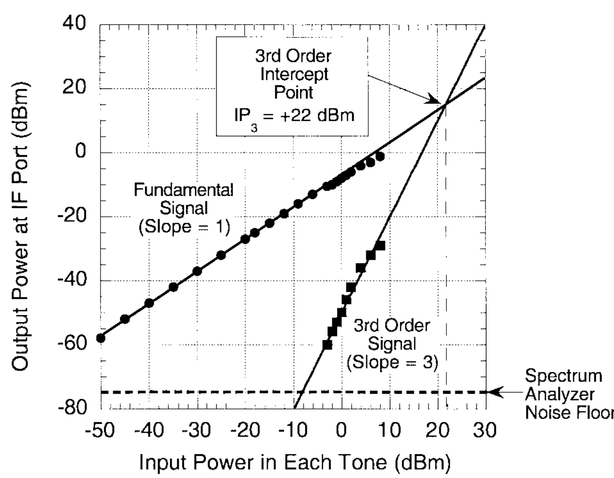

Fig. 9. Power output at the IF port as function of the input power in each tone. $f_1 = 1.57542$ GHz, $f_2 = 1.57842$ GHz, $f_{\rm LO} = 1.55542$ GHz, $P_{\rm LO} = +19.5$ dBm, $d = 25$ μm.

B. GPS Mixer Circuit Characteristics

The conversion loss as a function of the input RF power at a fixed LO drive level is shown in Fig. 8. The conversion loss is observed to remain constant at approximately 7.5 dB over the input power range. This value of conversion loss is about the same, as that reported in [11] for an SiC single-balanced mixer. The intercept diagram is shown in Fig. 9. The input IP_3 is approximately +22 dBm. The spurious-free dynamic range is approximately 60 dB.

The conversion-loss value in the above measurements is about the same as that of a commercially available single-balanced mixer with silicon Schottky-barrier diodes. However, to achieve a comparable input IP_3 performance with silicon Schottky-barrier diodes, a more complex design involving a double-balanced mixer with two diodes in each arm of a quad is required [9], [12]. Thus, a total of eight silicon diodes in a double-balanced configuration is required to achieve the same performance as two SiC diodes in a single-balanced circuit. The SiC single-balanced mixer also compares favorably with mixers based on the linearization technique [6], which requires far greater circuit complexity and more components.

V. Conclusions

This paper has presented the fabrication of SiC Schottky-barrier mixer diodes, as well as the results of conversion loss and two-tone intermodulation measurements conducted on single-balanced SiC diode mixer circuits with only two SiC diodes. These circuits are configured to operate over the VHF and GPS frequency bands. The experiments demonstrate that the conversion loss/input IP_3 is 8.0 dB/+25 dBm and 7.5 dB/+22 dBm over these frequency bands, respectively. The IP_2 over the VHF frequency band is +38 dBm. The above conversion-loss values are about the same as that of commercially available single-balanced mixers with silicon Schottky-barrier diodes. However, to achieve a comparable input IP_3 performance with silicon Schottky-barrier diodes, a more complex design involving double-balanced mixers with at least eight diodes in a quad configuration is required.

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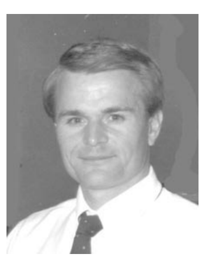

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