C-band Linear Resistive Wide Bandgap FET Mixers

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Abstract — **In this paper the performance of two C-band resistive FET mixers are presented and compared. The first mixer uses a SiC-MESFET as a mixing element and the second uses an AlGaN/GaN-HEMT. The mixers have a minimum conversion loss of 7.8 dB and 7.3 dB respectively. The maximum third-order input intercept points are 30 dBm and 36 dBm respectively; for LO drives of 23 dBm and 30 dBm.**

I. INTRODUCTION

Wide bandgap semiconductor devices have foremost found use in high-power applications such as power-amplifiers and limiters. However Fazi [1] made a simple experiment showing that mixers utilizing wide bandgap diodes as mixer elements could have better dynamic-range and intermodulation performance compared to mixers using more traditional III-V semiconductors like GaAs. This was later demonstrated by Eriksson [2], reporting a single-balanced SiC Schottky diode mixer with a third order intermodulation intercept point (IIP_3) of 31 dBm. Even better linearity can be achieved in mixers using FETs operating in the resistive region [3]. We have previously reported a S-band resistive SiC-MESFET mixer with a conversion loss of 10.2 dB and an IIP_3 of 35.7 dBm [4].

In this paper we re-examine a resistive SiC-MESFET mixer operating in C-band [5] and compare the results with an identical mixer with an AlGaN/GaN-HEMT.

II. WIDE BANDGAP FETS

Both transistors used in this experiment are designed and processed in-house.

A. SiC-MESFETs

The MESFET epi-structure was grown on a semi-insulating 4H-SiC substrate by Cree Inc. The MESFET structure consists of a 0.35 μm p-buffer with $N_A=5\cdot10^{15}$ cm^{-3}, a 0.4 μm channel with $N_D=2\cdot10^{17}$ cm^{-3}, a 0.15 μm cap-layer wit $N_D=1.1\cdot10^{19}$ cm^{-3}. The process steps are: mesa and recess etching, ohmic contact formation, oxidation, sputtering of dielectrics, definition of gates with EBL, pad formation, passivation, air-bridge formation, and dicing. The mesa and recess were defined by dry etching using a CF_4/O_2 plasma. Ohmic contacts were formed by annealing nickel at 1000 °C. The gate length is 0.5 μm and the gate metalization is Au/Pt/Ti. The devices are passivated with Si_3N_4.

The saturated drain current, I_{dss}, is 160 mA/mm and the DC-transconductance, g_m, is 24 mS/mm. From S-parameter measurements on a 200 μm MESFET an extrinsic transit frequency, $f_{T,ext}$, of 6.3 GHz and a maximum frequency of oscillation, f_{max}, of 37 GHz at a V_{ds} of 40 V were calculated. The Class A output power were measured with load-pull at 3 GHz and V_{ds}=80 V. The power density is 1.6 W/mm (measured for a gate width of 0.4 mm). The device used in this experiment has 16 gate fingers of 200 μm each, giving the total gate periphery of 3.2 mm.

B. AlGaN/GaN-HEMT

The device structure was grown by MBE on a sapphire substrate by SVT Associates, Inc. The modulation doped structure consisted of a 20 Å GaN cap layer and a 300 Å undoped ($N_D<10^{16}$ cm^{-3}) $Al_{0.25}Ga_{0.75}N$ layer grown on a 2 μm undoped ($N_D<10^{16}$ cm^{-3}) GaN buffer. Hall measurement showed a room temperature low field mobility of 1100 $cm^2\cdot V^{-1}\cdot s^{-1}$ and a sheet carrier density greater than $1\cdot10^{-13}$ cm^{-2} in the 2DEG formed at the AlGaN/GaN interface.

The devices were processed using classical reactive ion etching for mesa isolation. Ohmic contacts were obtained by evaporation of a Ti/Al/Ni/Au multilayer followed by a rapid thermal annealing in a N_2 environment. The gates, defined by EBL, were 0.7 μm long and the metalization was Ni/Au. The HEMTs were passivated with Si_3N_4 prior air-brigde formation.

The saturated drain current, I_{dss}, was 950 mA/mm and the DC-transconductance, g_m, was 150 mS/mm. An extrinsic transit frequency, $f_{T,ext}$ of 25 GHz and a maximum frequency of oscillation, f_{max} , of 50 GHz were calculated from S-parameter measurements performed on a 100 μm HEMT. The transistor used in this experiment had 10 gate fingers, of 50 μm each and thus a total gate periphery of 0.5 mm.

C. Device Comparison

For resistive mixer applications the most important characteristic of the transistor is the non-linear function

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of the channel-resistance versus gate voltage. The limiting factor for low conversion loss is the difference of the off- and the on-state reflection coefficient [6]. The value of the reflection coefficient at the output is, for 'low' frequencies, dominated by the channel-resistance, thus we can state that conversion loss is limited by the *conversion efficiency*:

$$\eta_{CL} = \frac{Z_0\left(R_{\max} - R_{\min}\right)}{(R_{\max} + Z_0)(R_{\min} + Z_0)} \quad (1)$$

Where Z_0 is the system impedance e.g. 50 Ohms. In Fig. 1 the measured drain-source resistance, effectively the channel-resistance, is plotted versus gate-source voltage. From this we can conclude that the AlGaN/GaN-HEMT is superior to the SiC-MESFET with respect to conversion loss, for a given LO power. In Fig. 2 the conversion efficiency is plotted versus the peak gate-source voltage; assuming a bias well below pinch-off. For minimum conversion loss the SiC-MESFET has to be driven with a high LO drive – the swing has to be at least 5 V.

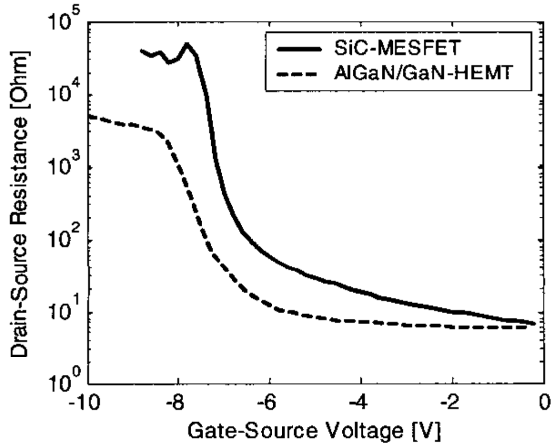

Fig. 1. Measured drain-source resistance versus gate-source voltage for the two transistors.

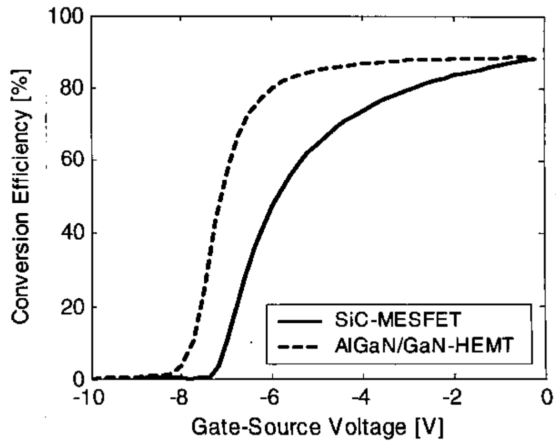

Fig. 2. Conversion efficiency versus peak gate-source voltage for the two transistors. It's assumed that the gate bias is below pinch-off.

For high frequency operation the maximum output capacitance can degrade the performance by shunting the channel-resistance and thus decrease the conversion efficiency. A crude measure of the output capacitance is the slope of the imaginary part of Y_{22} when plotted versus angular frequency. The maximum output capacitance is then 710 fF (0.22 pF/mm) and 430 fF (0.86 pF/mm) for the SiC-MESFET and AlGaN/GaN-HEMT respectively. One can therefor expect the AlGaN/GaN-HEMT to have better mixer performance at higher frequencies than the SiC-MESFET, for a given on-resistance since the on-resistance is much higher for a SiC-MESFET.

II. Mixer Circuit

The mixer is implemented as a hybrid circuit on a soft substrate (IsoClad933, εr=2.33). Gate termination at f_{LO} and f_{RF} are realized by a periodic open-stub configuration using three stubs. Drain termination are realized at f_{LO} and f_{RF} with a folded two section coupled Chebysheff band-pass filter and two additional open-stubs. The f_{IF} termination is done by a quarter-wave length (at approx. f_{RF}) high impedance line and with two open radial-stubs for terminating f_{LO} and f_{2LO}. Gate bias is fed through two 5k-ohm resistors and a high impedance quarter-wave section with an open radial-stub, additional capacitors are used for decoupling. As DC-block at the LO-port a 6.9 pF capacitor is used.

The substrate is soldered to a gold-plated brass plate. The transistors are glued to a ridge on the brass plate and wire-bonded into the circuit. Through-plated via-holes are used for ground connections through the substrate.

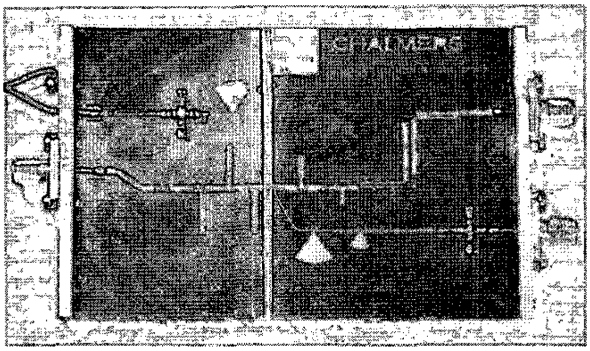

Fig. 3. Photograph of the fabricated mixer circuit. The LO-port is to the left and the RF-port and IF-port at top-right and low-left respectively. The dimensions are 60x90 mm (PCB including ridge).

III. Characterization

The mixers are characterized with respect to conversion loss and input third order intermodulation intercepts. Conversion loss is measured at an IF-frequency of 250 MHz and an LO-frequency of 4925 MHz. Optimum gate bias is selected by first measuring the conversion loss for a low LO drive while varying the bias. The optimum bias is then kept constant for the rest of the characterization.

The minimum measured conversion loss was 7.8 dB and 7.3 dB for the SiC- and GaN-mixer respectively.

The input third order intercept is measured with a standard two-tone test; applying two equal powered RF-carriers 10 MHz apart (f_{RF1}=5175 MHz, f_{RF2}=5185 MHz) and then measure the power at the four resulting in-band tones (240, 250, 260 and 270 MHz). The resulting maximum input third order intercept point (IIP3) was 30 dBm and 36 dBm for the SiC- and GaN-mixer respectively; at LO power 23 dBm and 30 dBm.

V. Conclusion

Two linear resistive mixers were fabricated and characterized; one using a SiC-MESFET and the other an AlGaN/GaN-HEMT. Minimum conversion loss for the mixers was 7.8 dB and 7.3 dB. Maximum IIP3 were 30 dBm and 36 dBm at LO powers 23 dBm and 30 dBm respectively.

If we plot he IIP3 results versus LO power for different mixers (Fig. 8) we see that there is a linear dependence of IIP3 as a function of LO power. This indicates that the limiting factor in resistive FET mixers, concerning linearity, is the LO drive. This is a strong motivator for pursuing development of even more robust transistors (concerning gate-breakdown etc.) for use as mixing-elements in applications where high linearity is a necessity.

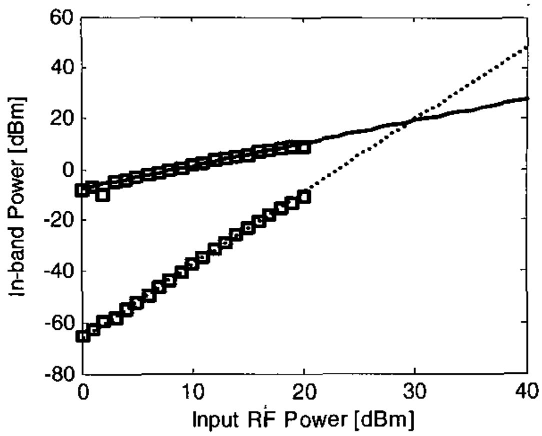

Fig. 4. Measured IF-power and IM-power for the SiC-MESFET mixer. The LO power was 23 dBm.

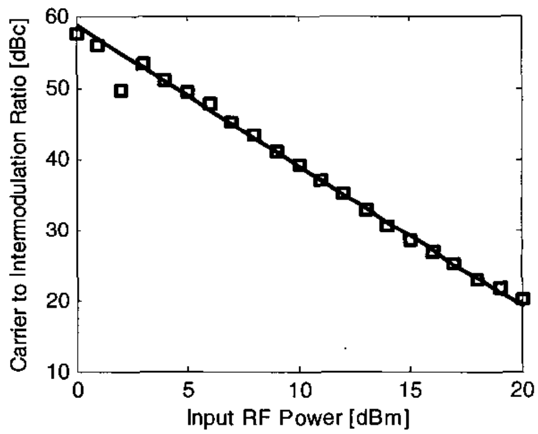

Fig. 5. Carrier to Intermodulation ratio for the SiC-MESFET mixer. The LO power was 23 dBm. The solid line is a linear fit to the measured values.

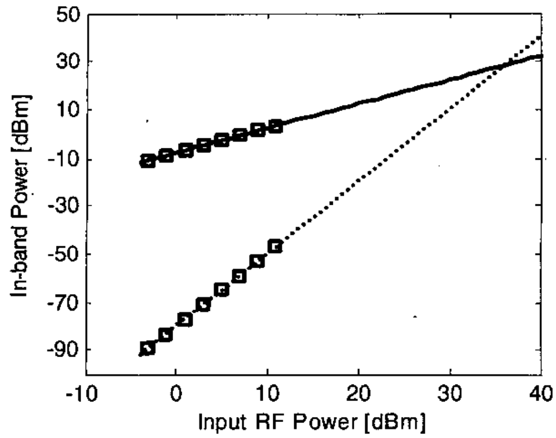

Fig. 6. Measured IF-power , and IM-power for the AlGaN/GaN-HEMT mixer. The LO power was 30 dBm.

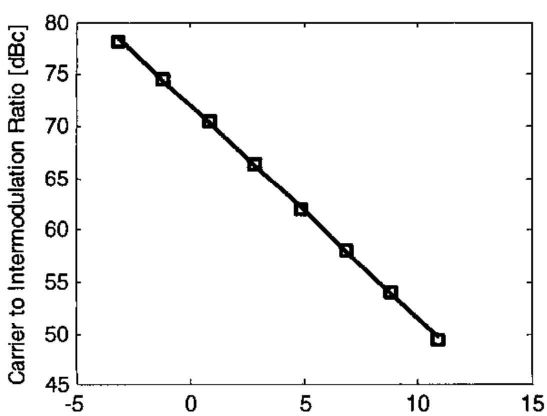

Fig. 7. Carrier to Intermodulation ratio for the AlGaN/GaN-HEMT mixer. The LO power was 30 dBm. The solid line is a linear fit to the measured values.

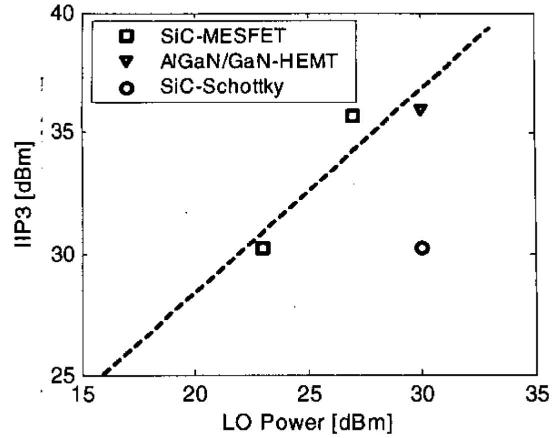

Fig. 8. Extrapolated IIP3 as a function of LO power for various wide bandgap mixers. The dotted line is a linear fit to the resistive FET mixer results.

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