Low Cost Coplanar 77 GHz Single-Balanced Mixer Using Ion-Implanted GaAs Schottky Diodes

R. Shimon, D. Caruth, J. Middleton, H. Hsia, and M. Feng
Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, IL 61801

J. Mondal and S. Moghe
Northrop Grumman Corporation, Rolling Meadows, IL 60008

Abstract—A W-band single-balanced mixer and W-band LO amplifier, suitable for automotive collision-avoidance radar, have been designed and fabricated using a 0.18 µm direct ion-implanted GaAs MESFET process developed at the University of Illinois at Urbana-Champaign. As a downconverter with an LO frequency of 77 GHz and an RF frequency of 77.1 GHz, the coplanar rat-race mixer achieves a conversion loss of 14.7 dB at an LO power of +3.5 dBm. The coplanar LO amplifier exhibits 5 dB of gain over a 4 GHz bandwidth centered at 77 GHz.

I. INTRODUCTION

In recent years there has been increasing interest in the use of monolithic millimeter-wave integrated circuits in commercial markets. In particular, significant progress has occurred in the implementation of W-band automotive collision-avoidance radar. This high volume market demands a high yield, low cost manufacturing solution. While ion-implanted MESFETs may be logical choice in terms of cost, devices fabricated in other technologies have outperformed MESFETs at millimeter-wave frequencies. MESFETs have been shown to be a viable alternative to p-HEMTs at Ka-band [1],[2], but present efforts at W-band have used expensive epitaxial HEMT or HBT technologies for low-noise and power amplifiers [3],[4], as well as epitaxial Schottky diode structures for mixers [5],[6]. In contrast, this work presents the measured and simulated performance of a 77 GHz single-balanced, Schottky diode mixer and a 77 GHz LO amplifier fabricated in a simple, 0.18 µm direct ion-implanted MESFET process. These initial results demonstrate that a small gate-length MESFET process may be a low cost alternative to more expensive epitaxial device technologies for high volume W-band applications.

II. 0.18 µm ION-IMPLANTED PROCESS

A low cost, 0.18 µm direct ion-implanted GaAs MESFET process has been developed at the University of Illinois at Urbana-Champaign [7]. The active region is formed by direct ion implantation of silicon and beryllium into 3-inch semi-insulating (100) LEC GaAs substrates. A high dose Si surface implant forms an ohmic contact layer. A lower dose, higher energy Si implant forms the channel. Finally, a buried Be implant compensates the tail of the channel implant, producing a sharp implant profile. The implants are activated by a capless anneal in an arsine atmosphere, forming a 1500 Å deep active region with a measured sheet resistance of 400 /sq. Schottky diodes and FETs are then fabricated in a series of processing steps. Modifications were required in the gate photoresist structure, the recess etch and most notably in the e-beam writing technique to ensure high uniformity across the wafer.

A. Schottky Diode

The Schottky diode is formed from the gate-to-channel junction of a standard FET structure. The gate metallization forms the anode of the diode. The source and drain electrodes, electrically connected with a plated airbridge, form the cathode. No efforts were made to optimize the process for improved diode performance, however multiple, parallel anode fingers were used to reduce the diode's series resistance.

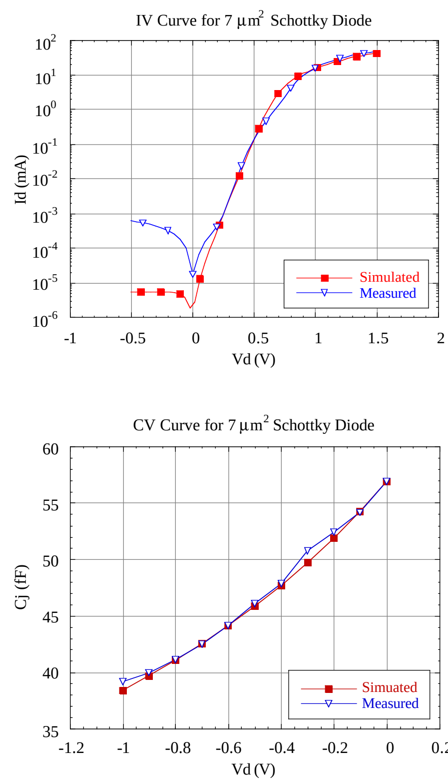

Fig. 1. IV and CV characteristics of a 7 µm² Schottky diode.

0-7803-4471-5/98/$10.00 (c) 1998 IEEE

A standard large-signal model [8] was used to characterize a four finger, 7 µm^2 diode. Fig. 1 shows the measured and simulated IV and CV characteristics. Table I lists the element values of the model. The cutoff frequency for this device, defined as the reciprocal of the product of the series resistance *Rs* and the zero-bias junction capacitance *Cjo*, is 161 GHz.

TABLE I
Large-Signal Model for 7 µm^2 Schottky Diode

Element	Units	Value
Io	nA	5.390
n	-	1.922
Rs	Ω	17.38
Cjo	fF	56.89
Φ	V	2.094
γ	-	1.008

B. MESFET

The measured dc characteristics of a 4×25 µm MESFET are shown in Fig. 2. The device draws a zero gate-voltage current of 220 mA/mm, produces a zero-bias transconductance of 315 mSie/mm, and exhibits a pinch-off voltage of -1.1 V.

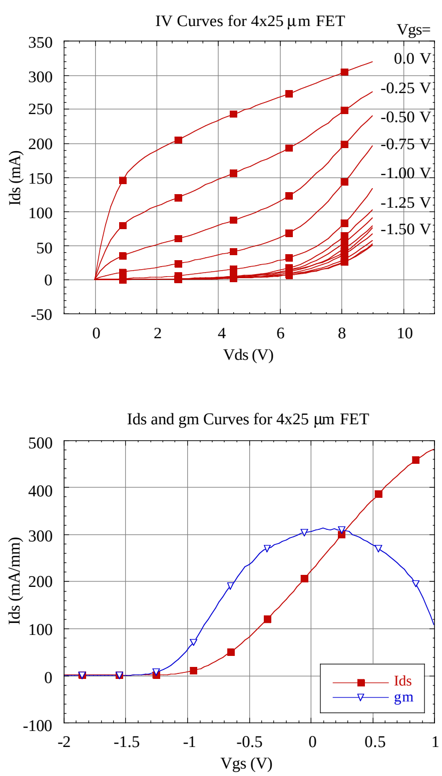

Fig. 2. Typical dc characteristics of a 4×25 µm MESFET. The y-axes are normalized to a gate width of 1 mm.

S-parameter data, measured at a bias of V_{ds}=3 V and V_{gs}=0 V, was used to generate a small-signal circuit model for the FET. The element values, derived using the method of Berroth [9], are listed in Table II. The extrinsic f_t and f_{max} for the device are 50 GHz and 120 GHz, respectively.

TABLE II
Small-Signal Model for 4×25 µm MESFET

Element	Units	Value
Gm	mSie/mm	345
Tau	pS	1.11
Rgs	·mm	-0.49
Rgd	·mm	4.40
Gds	mSie/mm	21.30
Cgs	fF/mm	970.4
Cgd	fF/mm	173.8
Cds	fF/mm	404.7
Rg	/mm	183
Rd	·mm	0.90
Rs	·mm	0.93
Lg	pH	10.98
Ld	pH	4.76

III. MMIC CIRCUIT RESULTS

A. Single-Balanced Mixer

Fig. 3 is a photograph of the single-balanced mixer. A circular rat-race topology was used to implement the 180° four-port hybrid. The LO and RF signals are applied to the hybrid at the two input ports. Series capacitors on both ports act as dc blocks and IF filters. The two diodes are connected to the hybrid at the Σ and Δ ports through two-section transmission line matching transformers. The cathode of one diode is grounded. DC bias is applied to the anode of the other diode through a simple 77 GHz quarter-wave filter. The IF is extracted from the hybrid through another 77 GHz quarter-wave filter.

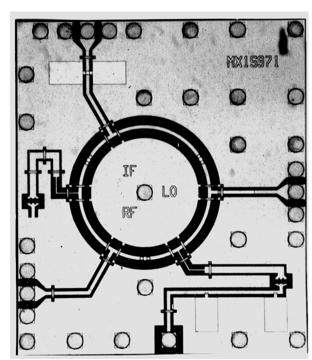

Fig. 3. Photograph of the single-balanced mixer. The die is 1.6×1.7 mm^2.

The LO signal was generated by a W-band source module. An external W-band amplifier mounted in a WR-10 waveguide fixture added additional gain. The second harmonic of a Ka-band amplifier driven into saturation by a synthesized source was used as the RF signal. The amplifier was also mounted in a WR-10 waveguide fixture that served as a filter for the 38 GHz fundamental. Both signals were applied to the mixer through W-band coplanar probes. With this configuration, the maximum LO and RF powers, measured at the coplanar probe tips, were +3.5 dBm and –21 dBm, respectively. The IF signal was extracted from the mixer through a 40 GHz coplanar probe and fed to a spectrum analyzer through a bias tee with a lower cutoff frequency of 10 MHz.

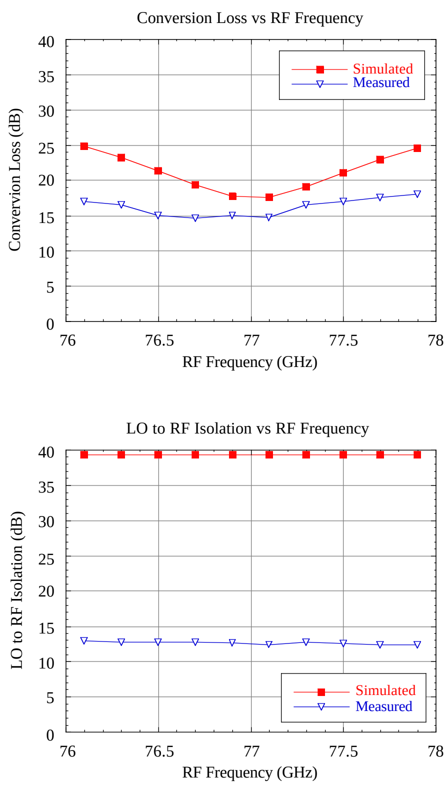

Fig. 4. Measured and simulated conversion loss and LO to RF isolation.

Fig. 4 displays the measured and simulated conversion loss and LO to RF isolation versus RF frequency for an LO frequency of 77 GHz and a bias of 1.2 V. The minimum measured conversion loss was 14.7 dB, 2.7 dB higher than the simulation. The measured isolation was only 13 dB, considerably less than the simulated value of 39 dB. An electromagnetic simulation of the mixer predicts considerably lower isolation than predicted by the circuit simulator and seems to indicate that poor models of the coplanar tee junctions and diode matching structures are, at least in part, the cause of the discrepancy.

The degradation in conversion loss with a reduction in LO power is plotted in Fig. 5. It indicates that the mixer is capable of providing acceptable conversion performance for LO powers as low as –5 dBm. Figure 5 also shows the variation in conversion loss with dc bias. The optimal bias was found to be 1.2 V, while the mixer's conversion performance degrades significantly for biases less than 1.0 V and greater than 1.5 V.

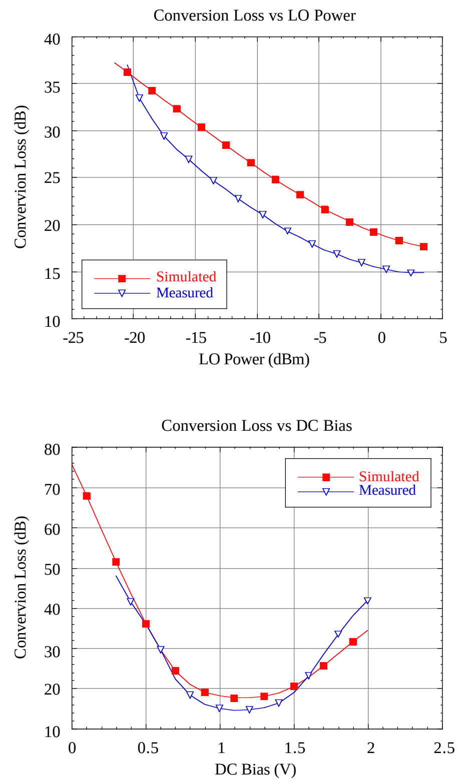

Fig. 5. Measured and simulated conversion loss as a function of LO power and dc bias.

B. LO Amplifier

The LO amplifier, shown in Fig. 6, is a reactively matched, self-biased design. Three 4×25 μm FET stages are separated by double stub matching networks. One stub of each network grounds the gate of the stage; the other provides a dc path through which the drain is biased. The source is biased through the top plate of a bypass capacitor. Shunt RLC networks on the gates of the second and third stages reduce low frequency gain and improve amplifier stability.

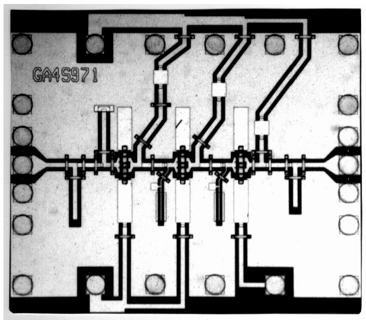

Fig. 6. Photograph of the LO amplifier. The die is 1.5×1.2 mm^2.

Because the S-parameter test set-up could not support the three dc probes required to bias the amplifier, the two source bias pads were wire-bonded to nearby ground plane pads. This modification allowed the amplifiers to be tested with only one dc probe, but fixed the current of each stage at 100% I_{DSS}. Fig. 7 shows the amplifier's measured and simulated gain and return loss at a drain bias of 3 V. It exhibits a gain of greater than 4.5 dB over a 4 GHz bandwidth centered at 77 GHz. The input return loss is 5 dB at 77 GHz, while the output return loss is greater than 10 dB throughout the measured frequency range.

A measurement of amplifier's output power indicates that it operates in its linear region up to an input power of -1 dBm, the maximum output power available from the mm-wave source. This amplifier is thus suitable as an LO amplifier for the single-balanced mixer. An integrated downconverter would require -10 dBm of LO power for adequate conversion performance.

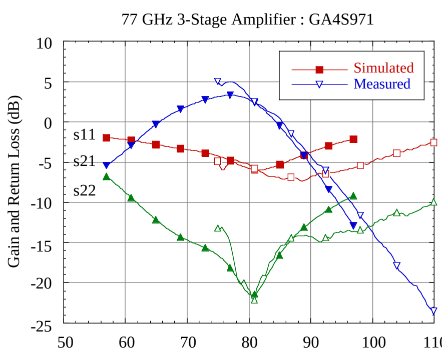

Fig. 7. Measured and simulated gain and return loss of the LO amplifier.

IV. CONCLUSION

These results demonstrate that a downconverter consisting of a 77 GHz single-balanced mixer and an LO amplifier, fabricated in a direct ion-implanted MESFET process, possesses conversion characteristics suitable for automotive collision-avoidance applications. While mixers fabricated in expensive epitaxial technologies, often with a separate epitaxial Schottky diode structure, have been demonstrated with lower conversion loss in W-band, and amplifiers in the same technologies have been demonstrated with higher gain, the low cost and high yield offered by a simple MESFET process may outweigh the advantages of using these expensive epitaxial processes for high volume, low cost applications at W-band.

REFERENCES

[1] M. Feng, D. Scherrer, P. J. Apostolakis, J. Middleton, M. McPartlin, B. Lauterwasser and J. Oliver, Jr., "Low Cost Millimeter-Wave Monolithic Integrated Circuits Using Direct Ion Implanted GaAs MESFETs," *1995 IEEE GaAs IC Symp. Dig.*, pp. 207-209.

[2] A. Kurdoghlian, K. N. Fry, G. Luong, D. Hou, M. Sokolich, W. Lam, C. D. Chang and Z. Bardai, "Comparison of Ka-Band LNA Performance Using Ion Implanted MESFET and p-HEMT Processes," *Dig. 1997 Int. Conf. GaAs Manufacturing Technol.*, pp. 62-65.

[3] K. W. Chang, H. Wang, G. Shreve, J. G. Harrison, M. Core, A. Paxton, M. Yu, C. H. Chen and G. S. Dow, "Forward-Looking Automotive Radar Using a W-Band Single-Chip Transceiver," *IEEE Trans. Microwave Theory Tech.*, vol. 43, no. 7, pp. 1659-1668, July 1995.

[4] L. Verweyen, A. Bangert, H. Massler, T. Fink, M. Neumann, R. Osorio, T. Krems, T. Jakobus, W. H. Haydl and M. Schlechtweg, "Compact Integrated Coplanar T/R-Modules for Automotive Applications," *1997 IEEE RFIC Symp. Dig.*, pp. 203-206.

[5] E. W. Lin, H. Wang, K. W. Chang, L. Tran, J. Cowles, T. Block, D. C. W. Lo, G. S. Dow, A. Oki, D. Streit and B. R. Allen, "Monolithic Milllimeter-wave Schottky-diode-based Frequency Converters with Low Drive Requirements Using an InP HBT-compatible Process," *1995 GaAs IC Symp. Dig.*, pp. 218-221.

[6] R. S. Virk, L. Tran, M. Matloubian, M. Le, M. G. Case and C. Ngo, "A comparison of W-Band MMIC Mixers Using InP HEMT Technology," *1997 IEEE MTT-S Int. Symp. Dig.*, pp 435-438.

[7] H. Hsia, J. Middleton, Z. Tang, R. Shimon, D. Caruth, D. Becher, J. Fendrich and M. Feng, "A Low Cost 77 GHz MMIC Process Using Direct Ion-Implanted GaAs MESFETs," accepted for publication in *1998 Int. Conf. GaAs Manufacturing Technol.*

[8] Stephen A. Maas, *Microwave Mixers*, 2nd ed. Boston: Artech House, 1993.

[9] M. Berroth and R. Bosch, "Broad-Band Determination of the FET Small-Signal Equivalent Circuit," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 7, pp. 891-895, July 1990.