SILICON BIPOLAR DOUBLE BALANCED ACTIVE MIXER MMIC'S FOR RF AND MICROWAVE APPLICATIONS UP TO 6 GHZ

Jim Wholey, Issy Kipnis, and Craig Snapp

Avantek Inc.
Advanced Bipolar Products
39201 Cherry St., Newark, Calif. 94560

ABSTRACT

A monolithic silicon bipolar technology based on transistors with f_T's of 10 GHz and f_{MAX}'s of 20 GHz has been used to develop double balanced active mixers. These circuits are based on Gilbert cell multipliers and exhibit conversion gain for RF and LO bandwidths to 6 GHz and IF bandwidths to 2 GHz. This paper presents an overview of the bipolar technology used. It discusses the basic mixer circuit design and presents a novel technique for modeling its noise figure. Finally RF measurements for two representative designs are summarized.

BACKGROUND

The frequency conversion function necessary in virtually all receivers is commonly implemented by double balanced diode mixers. Groups of Schottky barrier diodes with pairs of baluns ideally multiply the RF input by ±1 at the LO frequency. This multiplication produces the desired frequency conversion (Fif = Frf ± Flo) and suppresses the RF and LO signals at the IF output.

Many features of the diode-based double balanced mixers require attention. Conversion losses (ideally 3.9 dB, normally 6 to 8 dB) exists between the RF input signal and the desired IF output. The LO signal must be moderately strong (7 to 27 dBm) to set the conductivities of the diodes. Impedance levels of various ports are strongly dependent on opposing port impedances and LO power levels. Finally the hybrid structure of the device limits the smaller sizes achievable and may induce ripple in frequency characteristics if internal reflections are present.

Recent advances in silicon bipolar technology [1] have made possible monolithic bipolar active double balanced mixers circuits that operate to several GHz and overcome many of the concerns of the diode-based mixers. The process technology to manufacture these circuits will be discussed. The Gilbert cell based circuits will then be reviewed with emphasis on cost effective techniques such as accurate modeling that silicon based devices enjoy. RF characteristics of two active mixers will then be reviewed.

PROCESS OVERVIEW

The foundation of any monolithic microwave bipolar technology must be devices themselves with high f_T and f_{MAX} and minimal parasitic capacitances resulting from interconnections and isolations. Figure 1 shows a profile of Avantek's Isolated Self-Aligned Transistor (ISOSAT™) process used for the active mixers.

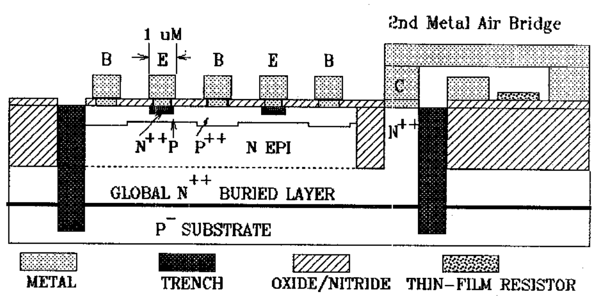

Figure 1. Cross section of Isolated Self-Aligned Transistor process.

Microwave transistors with 0.7 um emitters on a 4.0 um pitch are fabricated with a nitride self-aligned method. The fully ion implanted structure creates shallow arsenic emitters and basewidths of less than 0.1 um. This leads to transistors with f_T's of 10 GHz and f_{MAX}'s of 20 GHz.

Parasitic capacitances are also minimized with this process technology. A trench

1989 IEEE MTT-S Digest

isolation technique reduces collector to substrate capacitances while maintaining tight geometries. Capacitances are further reduced by placing resistors and interconnecting metal on a thick field oxide and incorporating a second level metal air bridge technology.

Table 1 gives a partial listing of modeling parameters for a typical bipolar transistor built with this technology. The device has 4 emitter fingers each of 20 um length and is normally operated at currents of 4 to 6 mA and has BVceo > 12V with 1.5 um epi thickness. The table also presents values of various parasitic capacitances associated with the IC process.

	Parameter	Value
BF	ideal maximum forward beta	100
TF	ideal forward transit time	12 pS
RE	emitter ohmic resistance	1.04 Ω
RB	0-bias (max) base resistance	30 Ω
RC	collector ohmic resistance	29 Ω
CJE	b-e 0-bias p-n capacitance	0.23 pF
CJC	b-c 0-bias p-n capacitance	0.10 pF
CJS	isolation 0-bias p-n cap	0.14 pF

Parasitic Elements		
CM1	Metal-subs. cap.	0.017 fF/um^2
CR	Resistor-subs. cap.	0.017 fF/um^2
CMX	Metal_1 to Metal_2 bridge cap. (4 um line width)	0.14 fF
CT	trench col-subs or col-col cap./um trench perimeter	0.035 fF/um

Table 1. SPICE modeling parameters for Q40420 bipolar transistor and IC parasitic elements.

CIRCUIT DESIGN

Two mixers of similar circuit design but different power levels have been designed, fabricated, and tested. They are the IAM01 (5v, 12mA) and the IAM02 (10v, 50mA). A simplified schematic of the IAM01 is shown in Figure 2. The similar higher power IAM02 mixer includes an additional emitter follower.

The RF signal enters an amplifier formed by the emitter coupled pair (QR1,2), the load resistors (RL), and an emitter resistor (RE) which will ultimately provide the basis for the conversion gain of the mixer. These elements will determine the gain, bandwidth, and input power handling capability of the mixer and are summarized in table 2 for both mixers.

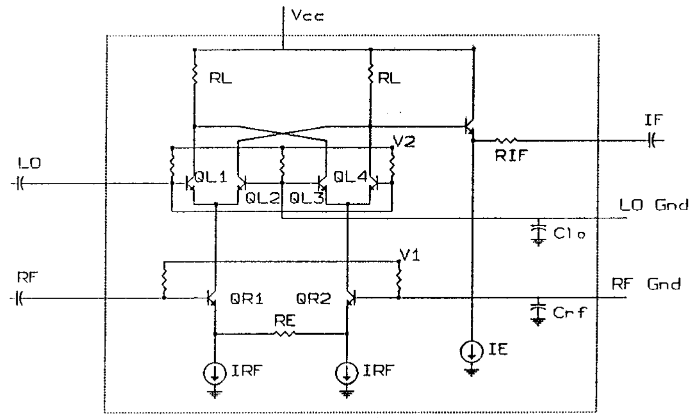

Figure 2. Simplified schematic of active bipolar mixer.

Element	IAM01	IAM02
VCC	5 V	10 V
RL	400 Ω	700 Ω
RE	20 Ω	40 Ω
IRF (each branch)	1.8 mA	4.3 mA

Table 2. Amplifier elements of the active mixer circuit.

The LO signal enters the cross coupled quad of devices that completes the Gilbert cell multiplier leading to the actual frequency mixing [2]. A noteworthy feature is the very low power required to alter the states of these 4 devices (typically -5 to 0 dBm) and produce the necessary multiplication of the RF signal by ±1 at the LO rate.

Wideband impedance matching is set by 50 ohm resistors in shunt with the high input impedances of the RF and LO devices and by a 25 ohm resistor in series with the low output impedance of the emitter follower. These techniques produce load insensitive impedance matching for the active mixer.

Figure 3 shows a SEM view of the die layout for the IAM02 mixer, on a 20 mil by 30 mil chip. Mounting is done in an 8 lead 180 mil square glass-metal package, with internal capacitors provided to enable single ended operation of the RF and LO ports (cf fig 1). Typical pc board layouts would require 50 ohm lines with blocking capacitors for the three ports and dc power and ground connections. Unlike some GaAs based active mixers no user supplied baluns are necessary [3].

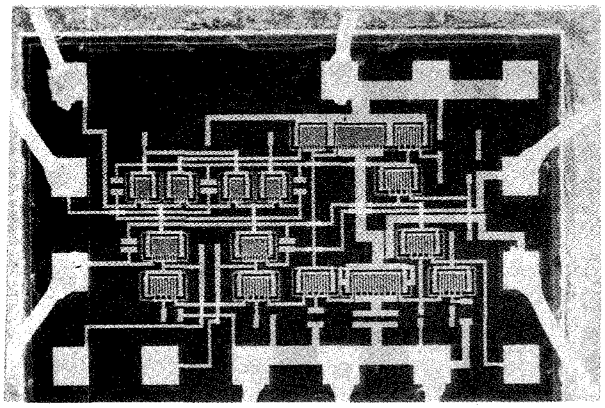

Figure 3. SEM photo of IAM02 active bipolar mixer.

ACTIVE MIXER MODELING

The ability to accurately model MMIC's is essential to their cost effective development. Although active mixers are highly nonlinear circuits, silicon bipolar based MMIC's can be adequately modeled as lumped or semi-distributed devices and SPICE based programs are appropriate evaluation tools [4].

Although SPICE has been used extensively to analyze the conversion gain and distortion properties of active mixers [5], little has been reported on its use in analyzing noise figures. A novel methodology to analyze the noise performance of an active mixer has been developed and will be described by the calculation of the single side band noise figure of an active mixer. Due to the mixers internal frequency conversions this becomes a lengthy calculation, and is illustrated as follows:

1) Noise sources are identified. These consists of thermal and shot noise sources as shown in Figure 4 with appropriate noise spectral density $\langle Inoise^2 \rangle$. Transistors are modeled with base resistances separated as shown. Frequency bands where noise could affect the output are assumed to be the IF, LO+IF and LO-IF bands.

2) Conversion factors are calculated from each noise source and in each frequency band to the IF output. These involve separate transient analyses for each source with a small signal at the noise source (eg. 1 mA) and the LO operating to provide possible frequency conversions. Use of a Fourier analysis on the output gives the IF signal and hence the conversion factor.

3) Noise factor contributions are calculated. These are:

$$\frac{\text{Pout from } \langle Inoise \rangle}{\text{Pout from Rs in RF band}}$$

$$= g^2 \langle Inoise^2 \rangle \, Rs/4kT$$

where g is the normalized current gain (noise source to IF)/(RF to IF).

4) Noise figure is computed by common summing of noise factors.

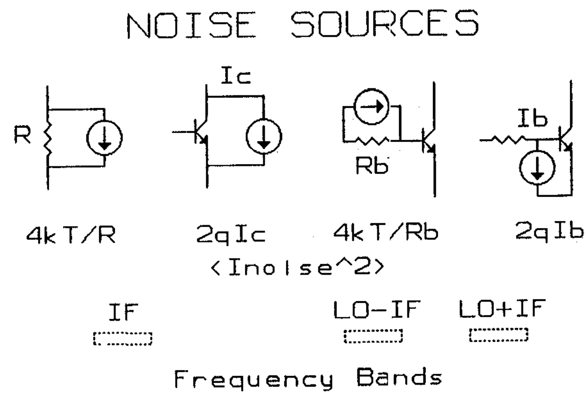

Figure 4. Noise sources for active bipolar mixer.

The results of a noise figure calculation on the IAM01 mixer are summarized in Table 3. Listed there are elements (cf fig 1) whose noise sources contribute appreciably to the output noise factor. The calculated SSB noise figure of 16.1 dB was in good agreement with measured values of 15.5 to 16 dB (RF 500MHz, IF 100MHz).

Noise Factor Contribution (%)

Source	(LO+IF)+(LO-IF) bands	IF band	total contrib.
Rb(QR1)	7.7		7.7
Rb(QR2)	7.7		7.7
RE	5.3		5.3
RL2		3.0	3.1
Ic(QL1)	3.7	5.0	8.7
Ic(QL2)	3.8	5.1	8.9
Ic(QL3)	3.9	4.9	8.7
Ic(QL4)	3.7	5.2	8.9
Ic(QR1)	3.7		3.7
Ic(QR2)	3.4		3.4
Rsource	4.9		4.9

Table 3. Significant noise sources for active mixer (IAM01).

DEVICE MEASUREMENTS

Figures 5a and 5b show the conversion gains of the IAM01 and IAM02 mixers versus RF and IF frequencies. The significantly greater gain of the IAM02 results from the combination of higher device currents (g_m's) and load resistors. Some high frequency gain peaking also noticed in the IAM02 mixer resulting in a steeper frequency roll off.

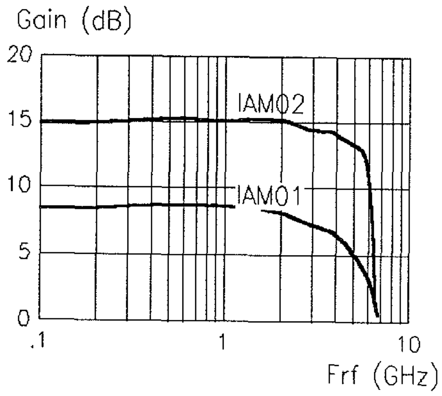

Figure 5a. Conversion Gain vs RF frequency; swept RF and LO, IF = 70 MHz

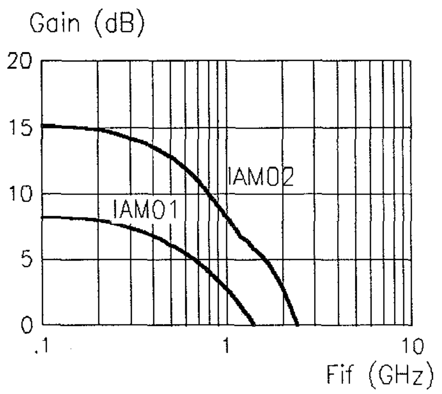

Figure 5b. Conversion Gain vs IF frequency; swept LO, RF = 2 GHz.

The measured VSWR's for the two mixers ranged from better than 1.5:1 to 2:1 over a 6 GHz RF, LO bandwidth. A significant degree of load insensitivity was observed with only minor VSWR changes with changes in opposing port impedances or power levels.

Device isolations are summarized in table 4 with other relevant data for the two mixers. The fact that conversion gain rather than loss exists contributes significantly to achieving a reduction in RF leakages relative to IF carrier signals. Similarly, small LO power levels required give the mixer a significant advantage in keeping LO power level at opposing ports minimized. The various leakages result primarily from the common mode signal and can be reduced by an additional 15 to 20 dB if differential signals were applied to the RF and LO ports.

Parameter	IAM01	IAM02
R-I isolation	-17 dB	-15 dB
L-I isolation	-20 dB	-20 dB
L-R isolation	-30 dB	-30 dB
RF feedthrough at IF	-25 dBc	-30 dBc
LO Power level	-5 dBm	0 dBm

Table 4. Active mixer isolations (RF 2 GHz, LO 1.75 GHz, IF 250 MHz).

Various other mixer measurements relating to power, noise figure and dynamic range are summarized in Table 5. In comparing this to a diode based mixer one must add an IF amplifier with gains of 15 to 25 dB to the latter. This will increase the comparable diode based mixer's noise figure although dynamic range of the active mixer will still be somewhat lower than the diode unit.

Parameter	IAM01	IAM02
DC Power	5 V 12 mA	10 V 50 mA
LO Power	-5 dBm	0 dBm
Conversion Gain	8 dB	15 dB
SSB Noise Figure	15.5 dB	16 dB
3rd Order Output Intercept Point	3 dBm	18 dBm

Table 5. Power, noise and dynamic range parameters of the active mixers (RF 2 GHz, LO 1.75 GHz, IF 250 MHz).

CONCLUSION

Silicon bipolar MMIC active mixers have been developed for applications to 6 GHz. IF bandwidths extend to 2 GHz and the mixers have conversion gains of up to 16 dB with exceptionally low LO power requirements.Load insensitive performance is achieved and wideband on chip impedance matching exists. Small chip size is obtained with low to moderate power dissipations. Dynamic range however is partially sacrificed due to the fundamental circuit topology chosen. These active mixer designs are expected to be practical as basic macrocells in future complex single chip receiver frontends.

ACKNOWLEDGMENTS

The authors wish to thank Jose Kukielka for his assistance with the active mixer design, Manjari Dutta for her help with the wafer processing, and Chris Mohr and Kim Fischer for their assistance with wafer probing and device characterization respectively.

1 I. Kipnis et al "A Wideband, Low-Power, High-Sensitivity and Small-Size Static Frequency Divider IC" Proc. 1988 IEEE Bipolar Circuits and Tech. Meeting, pp. 150-152

2 Gray and Meyer, Analysis and Design of Analog Integrated Circuits, 2nd Edition, J Wiley & Sons, 1984, pp. 469-479.

3 Ramachandran et al, "An 8 - 15 GHz GaAs Monolithic Frequency Converter" IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.(Las Vegas), 1987, pp. 31-34

4 Estreich, "Nonlinear Modeling for MMIC's" IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.(Las Vegas), 1987, pp. 93-96

5 I.Kipnis and A.P.S.Khanna, "Large Signal Computer Analysis and Design of Silicon Bipolar MMIC Oscillators and Self-Oscillating Mixers", IEEE Trans Microwave Theory Tech., vol MTT-37 pp 558-564, March 1989.