A Paradigm Shift in MMIC Mixers Using Novel Schottky Diode Technology

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Abstract — **In this article, we discuss MMIC mixers designed using high performance GaAs Schottky diodes. As opposed to fixed Schottky diode options already on the market, we describe, for the first time, GaAs diodes with forward voltages ranging from 0.29 V to 0.9 V. These diodes enable new circuit capabilities previously not possible in GaAs diode circuits. A state of the art MMIC mixer is developed and exciting new performance characteristics are demonstrated including low LO drive for power sensitive applications and high LO drive for high linearity applications.**

I. INTRODUCTION

Historically, mixers based on diode technology have split into two camps: hybrid mixers using discrete diodes, and MMIC mixers using integrated diodes. Generally, hybrid mixers are thought of as being higher performance, broader band and more flexible in terms of optimization for specific performance specifications. MMIC mixers, on the other hand, overcome the limited flexibility by offering significantly smaller form factors at significantly lower cost. In fact, it is generally the case that hybrid mixers and MMIC mixers are so different in performance that suitable applications for the two technologies are distinct and non-overlapping. In other words: if highest performance and/or tunability is needed, hybrid mixers must be used, and if cost and size are most important, MMIC mixers must be used. With few exceptions, these truisms have existed for at least two decades.

The “hybrid/MMIC divide” is explained by many physical causes:

1. Hybrid mixers use suspended substrate balun structures on low dielectric
2. MMIC mixers are most commonly built on GaAs, which is a grounded substrate with high dielectric constant
3. Hybrid mixers use discrete diodes that are hand assembled, limiting size reduction
4. Hybrid mixers can be designed on almost ANY material platform giving the designer many options to modify performance characteristics.
5. MMIC mixers have strict design rules for the stack-up thus limiting design flexility
6. Hybrid mixers can use any kind of diode (e.g. low barrier silicon, GaAs, beam lead, flip chip, etc) while MMIC mixers must use the *diode device offered by the process*

This final point regarding diode options is essential to understanding why hybrid mixers have survived over half a century in the marketplace; because GaAs devices have, to date, only been offered with a single barrier potential (0.7 V, nominal), hybrid mixers (mostly based on Si schottky diodes) have prospered in niche applications where very low forward voltage (V_f) or very high V_f is most appropriate.

In this paper, we demonstrate a new GaAs Schottky process from GCS that is capable of creating industry leading GaAs Schottky diodes with a variety of barrier potentials ranging from 0.29 V to 0.9 V. MMIC mixers are designed on these processes and we compare performance. Results will show that with little effort, the designer can use this process to make low power mixers, or high power (i.e. high linearity) mixers without modifications to the mask set.

II. THE SCHOTTKY DIODE PROCESS

Since 2010, GCS has offered a commercially available Schottky diode GaAs foundry process. This process is based on GaAs MMIC process. The process includes Schottky diode and passive components (thin film resistors, MIM capacitor, inductors and transmission lines) that can be integrated on a single chip.

The new feature of this process, that alternative diode V_f options can be made, is enabled by careful engineering of the epi-layer and Schottky contact on GaAs substrate.

The diode forward and reverse I-V characteristics are shown in Fig. 1. DC parameters of a 1.6x8um^2 Schottky diode is summarized in Table 1. All diodes offer tremendous performance characteristics including N ~ 1.1 with THz bandwidth capability (as calculated by the RC time constant). By engineering the epi-layer and fabrication processes, forward voltages ranging from about 0.29 V (@ 1 mA) to 0.9 V are demonstrated. In principle, alternative diode characteristics can also be achieved. In this case, the goal is to offer a high quality GaAs diode that will compare favorably with existing Si diodes in terms of V_f, C and R. Owing to the obvious speed advantages of GaAs versus Si, it is clear that if GaAs diodes can be made with virtually the same V_f as Si, the GaAs alternative can offer significantly superior RC characteristics. For example, a low barrier Si diode (~ 0.3 V_f) for high frequency use might have a C = 100 fF and R = 15 Ohm. A comparable GaAs diode would have a C = 30 fF and R = 3 Ohm. This RC improvement directly impacts circuits like mixers, mulitpliers and detectors since, generally speaking, diode resistive losses are unwanted and high frequencies are limited by diode capacitance. What is also important to note is that in Si Schottky diodes, diode resistance and reverse breakdown voltage are often traded to realize low capacitance. By comparison, GaAs diodes have an outstanding reverse breakdown of ~10x the V_f and a resistance ~2.5-3 Ohm.

III. MMIC MIXER: 7-26.5 GHZ

A common mixer band for diode mixers is 7-26.5 GHz. Typically, in the <6GHz regime, a multiplicity of solutions exist for frequency conversion including hybrid mixers (e.g. Marki Microwave T3 Mixers®), Silicon IC based mixers (CMOS and SiGe), FET mixers, etc. Moreover, below 6 GHz, digital processing is becoming sufficiently fast that many of the <6 GHz mixers "slots" are now being replaced by ADC/DAC solutions. Generally, if a solution can be offered by digital means, that is the preferred method over analog circuitry, and trends continue toward this end.

Above 6 GHz, fewer options exist. First, Silicon IC solutions only have financial incentive in high volume applications, so microwave frequency solutions are not cost effective. Second, ADC/DAC is not optimal, so analog processing of signals is primarily performed using diode based frequency mixers.

For these reasons, a 7-26.5 GHz mixer with a DC-10 GHz IF response is designed on the GCS diode process. (Actually the mixer performs well to 38 GHz, data was truncated by the 26.5 GHz test setup). The mixer is based on the standard double balanced topology, typically referred to colloquially as the "horsehoe" topology (Fig. 2). The mixer design was conducted primarily in HFSS™ (for FEM analysis of the balun structures) and Microwave Office™ (National Instruments-AWR) harmonic balance engine. This design flow is identical to the procedures outlined in [1]. The authors have demonstrated from experience that if the diode models are accurately generated, near perfect agreement with measurement and simulation can be achieved. Although simulations are not shown here, excellent agreement was confirmed. In other words, the diode models, as supplied in the PDK from GCS, are very accurate and suitable for computer aided design, optimization and tape-out of the masks.

The tested ICs were mounted into a test fixture with SMA connectors and wire bonded on all I/O ports (Fig. 3). The linear performance specs are shown in Fig. 4. It was measured that all the mixers exhibited nearly identical isolation and VSWR on all ports, regardless of forward voltage. This is expected because *diode level does not impact linear specs of a double balanced mixer as long as the LO drive signal is sufficiently large to switch the diodes*. Hence, in Fig. 3, it is witnessed that conversion loss (an outstanding 6 dB) is achieved for all the diode types tested, the only difference is the LO drive is higher on higher V_f ICs.

In circumstances where high linearity mixing is required, the easiest modification is to use higher level diodes. The intuitive explanation is that when the diode V_f is higher, incoming small signal RF tones are less prone to intermodulating the I-V characteristics of the diodes, thereby limiting unwanted higher order spurious tones. When V_f is low, incoming RF can experience a greater influence of perturbations of the I-V curve, leading to: lower P1dB, lower IP3, and higher spurious content.

Indeed, all these trends are confirmed in Fig. 5. For the exact same mask set, but with different wafer design for different V_f, different nonlinear performance is witnessed. As expected, low barrier diodes yield the worst nonlinear performance while the high barrier diodes yield the best nonlinear performance, albeit at the expense of high LO drive power. *This tradeoff has been exploited for over half a century by mixer designers, the primary difference is that for the first time, this flexibility is achieved in a commercial GaAs IC process*! Furthermore, new mask sets, which represent the biggest cost driver for IC development, are unnecessary. In all the results of this paper, one mask set was used obviating the need for multiple setup and tooling fees. Multiple applications can be serviced as long as the mixer passive circuitry (i.e. the balun/magic tee structures) is designed properly.

IV. MMIC MIXER: 25-67 GHZ

A final mixer design was fabricated to highlight the tremendous frequency capability of the process. Here, the lowest barrier process was combined with the low capacitance (~15 fF) diode design to create an extremely broadband and high frequency mixer that covers 25-67 GHz with an IF response of DC-30 GHz. The novelty of this mixer is that in previous GaAs MMIC mixers, typical V_f around 0.7 necessitated LO drive level > +15 dBm. As frequency increases, increased losses lead to higher required LO drive, possibly as high as +20 dBm. Therefore, if one wants to use a fundamental mixer at mm-wave frequency, a very large LO drive would be required. Very few options exist to generate such powers over a broad band, and there exists a practical challenge to using GaAs MMIC mixers with "normal" barrier levels.

By designing a mm-wave mixer with the low barrier process, a very power efficient mixer is possible with modest +10 to +15 dBm LO levels. Conversion Loss is reported in Fig. 6. As it is shown, if conversion loss is not critical, the mixer can be operated "backwards" (i.e. LO into RF port, instead of LO into LO port) to make use of the higher efficiency RF balun to drive the mixer. In this power efficient (but lossy) configuration "B", the mixer could be reliably operated with only +6 dBm at 67 GHz. Because this mixer is built using the horseshoe topology, the IF response is flat within 2-3 dB from DC to 30 GHz. The performance advantages, and uniqueness of this design, were considered compelling enough that Marki Microwave now offers this mixer commercially [2].

V. CONCLUSION

Until now, GaAs MMIC processes did not offer flexibility in terms of diode levels. With GCS' offering of a novel process option with different diode levels, designers can build MMIC ICs previously only possible using discrete Si Schottky diodes. The RC advantages of GaAs make this process especially compelling for Schottky circuits >6 GHz where either higher linearity or lower power are required.

REFERENCES

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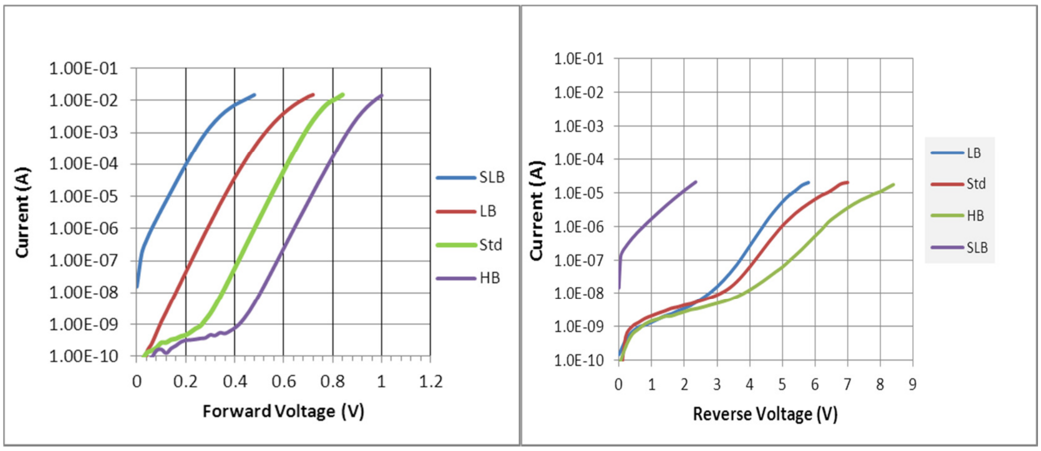


(a) (b)

Fig. 1. Forward (a) and reverse (b) I-V characteristics for a 1.6x8 um^2 diode.

Parameters	Unit	SLB	LB	Std	HBT
Idearity factoer		1.17	1.16	1.17	1.23
Forward Turn On Voltage at 1mA, Vf	V	0.29	0.51	0.69	0.86
Rewerse breadown voltage at 10uA	V	1.95	5.1	6.4	8
Forward Biase series Resistance	Ohm	2.97	2.85	2.57	2.69

Table 1. Summary of DC parameters of a 1.6x8um^2 Schottky diode.

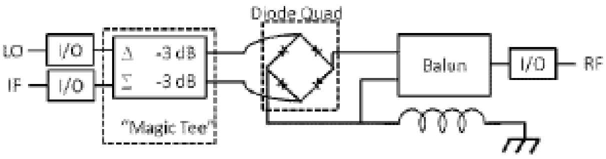


Fig. 2. Double Balanced Mixer circuit schematic for a "horseshoe" configuration.

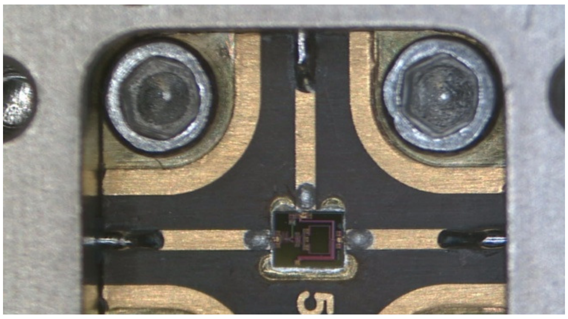


Fig. 3. Mixer MMIC mounted in a connectorized fixture with gold wire bonding. Chip size is 1.4 mm x 1.1 mm. Left port is RF, Top port is LO, Right port is IF.

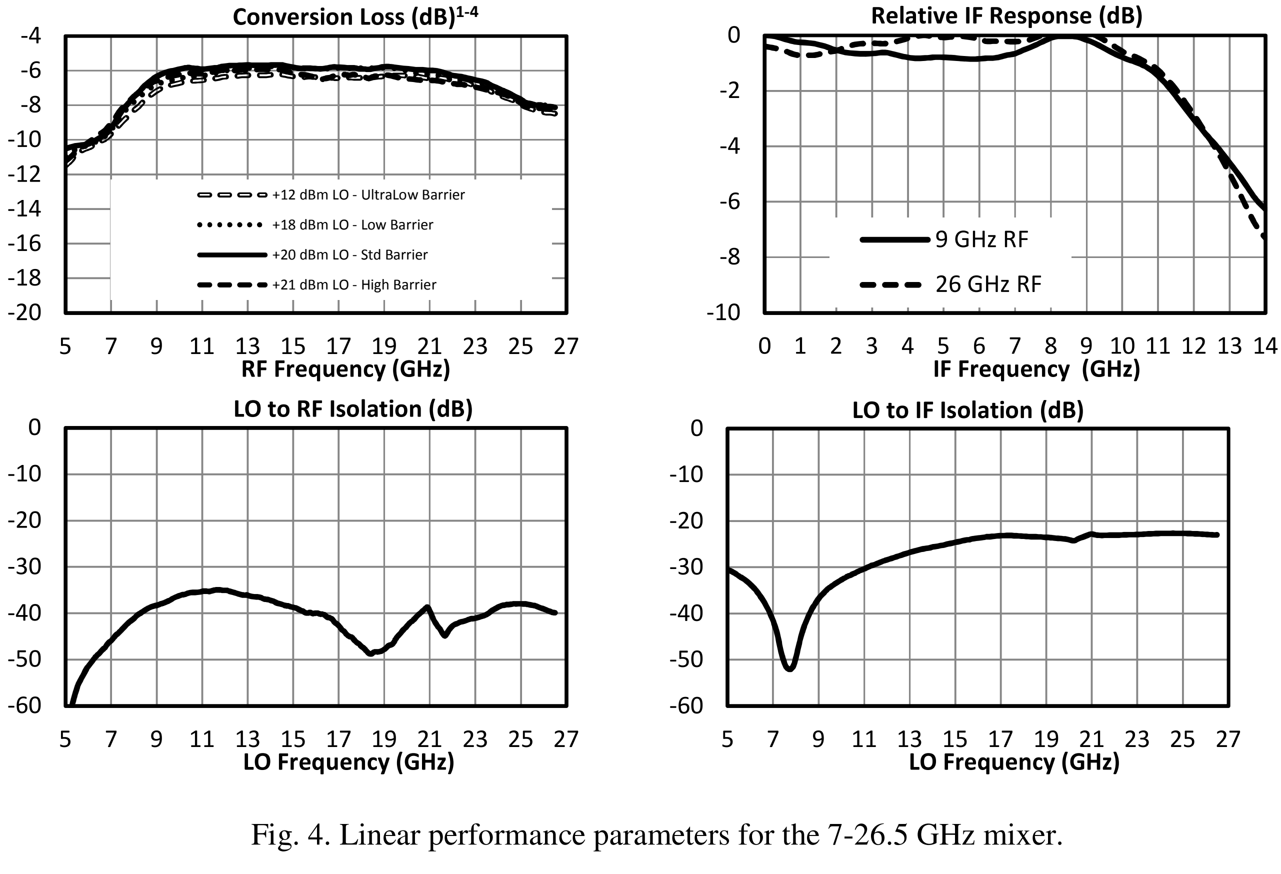
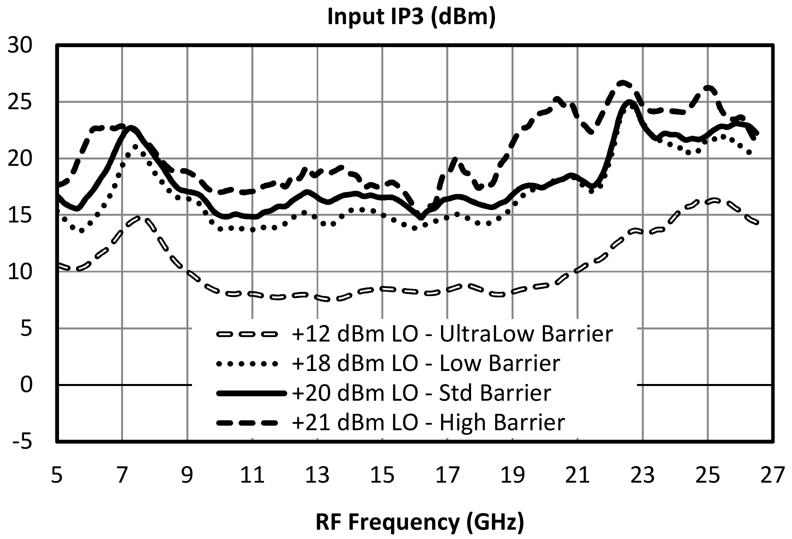


Fig. 4. Linear performance parameters for the 7-26.5 GHz mixer.



MM0726 Normal Downconversion Ultra-Low/Low/Std/High

-10 dBm RF Input	0xLO	1xLO	2xLO	3xLO	4xLO	5xLO
1xRF	16/15/16/15	Reference	17/16/16/15	10/10/10/10	19/17/17/18	21/23/23/22
2xRF	63/68/68/70	47/58/58/61	48/57/59/61	46/55/56/58	51/58/61/64	47/52/53/58
3xRF	79/90/91/92	50/63/66/74	54/68/71/77	55/69/71/76	53/67/70/78	58/65/68/71
4xRF	112/114/117/111	80/85/90/101	79/93/99/103	80/95/100/106	78/95/100/107	82/95/101/108
5xRF	122/124/124/124	90/105/114/121	86/106/112/118	88/111/117/120	88/109/116/120	92/112/118/125

Fig. 5. Nonlinear performance parameters for the 7-26.5 GHz mixer. All spurious values are averaged as a downconversion over the entire 7-26.5 GHz band to a fixed IF <100 MHz. Spurious variation typically is +/- 5 dB. Spur levels < 100 dBc subject to measurement equipment dynamic range floor.

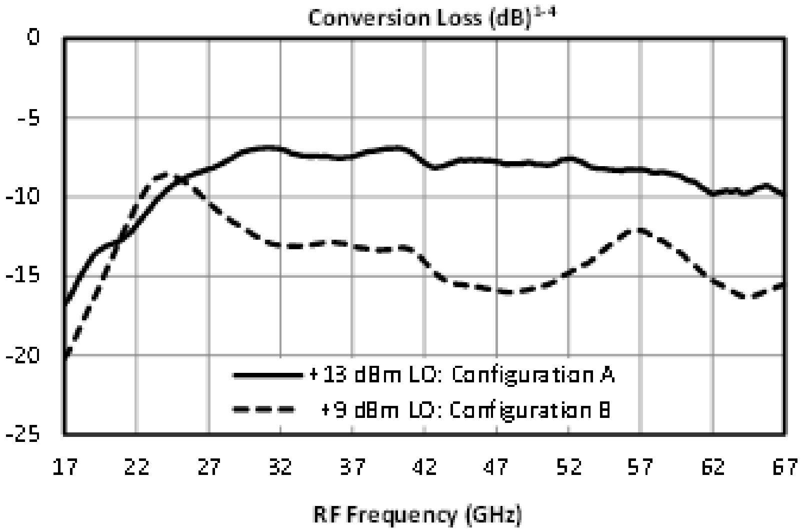


Fig. 6. Down-Conversion Loss (fixed IF = 91 MHz) for the 25-67 GHz mixer. High frequency performance is limited by test equipment of the Agilent PNA. High frequency roll-off predicted to be 80 GHz from simulations.